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RESEARCH ON FRACTAL CHARACTERISTICS OF URBAN TRAFFIC NETWORK STRUCTURE BASED ON GIS

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ABSTRACT: Traffic network is an importance aspect of researching controllable parameters of an urban spatial morphology. Based on GIS, traffic network structure complexity can be understood by using fractal geometry in which the length-radius dimension describes change of network density, and ramification-radius dimension describes complexity and accessibility of urban network. It is propitious to analyze urban traffic network and to understand dynamic change process of traffic network using expanding fractal-dimension quantification. Meanwhile the length-radius dimension and ramification-radius dimension could be regard as reference factor of quantitative describing urban traffic network.
KEY WORDS: urban traffic network; expanding fractal dimension; characteristics; GIS

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1 PREFACE

An urban traffic network is very importance during the development of a city. And it acts as framework role on urban spatial morphology evolvement. Domestic and international research on traffic network mostly based on the graph theory, and abstractly describe urban traffic network as topological diagram with correlative measurable indexes, such as β index, the loop number, α index, γ index, etc. There is another measurable index, non-liner coefficient. With certain positive effect on quantitative research of the structural characteristic of traffic network, these indexes can not describe the complexity and structure of traffic network. In this paper, on the basis of GIS technique, using fractal theory, the authors quantitatively analyze and research the structural characteristic of urban traffic network.

2 FRACTAL CHARACTERISTIC OF TRAFFIC NETWORK

Describing the spatial shapes and structures of things in the real world is an important content. The shapes and structures of complicated geographical phenomena are confined to understand completely by the traditional mathematics method. While the self-similarity of fractal geometry can be used to describe objects of morphology, which has retractility symmetry and is difficultly represented with Euclidean geometry. Here we use radius-analysis method to represent the traffic network's density and the connectivity of traffic network.

2.1 Length-dimension and Network Density

Fractal-dimension describes the quantitative characteristic of intrinsic features of objective thing. Generally, if object's length is L, area is S and volume is V, there is the following relation:

$$L \propto S^{1/2} \propto V^{1/3} \quad (1)$$

If L is magnified k times, then so be $S^{1/2}$ and $V^{1/3}$ too; if the quantity with d dimension measurement is supposed as X, the equation (1) could be expressed in the general form of the equation:

$$L \propto S^{1/2} \propto V^{1/3} \propto X^{1/d} \quad (2)$$

The parameters L, S, V and X denote length, area, volume and general quantity respectively, and X can replace any one of the others. "∝" denotes direct proportion and d means Euclidean's dimension. When $X = L$, $d = 1$; when $X = S$, $d = 2$; If the researched ob-

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ject has fractal characteristic with a certain measurement, accordingly the value d is not integer, then d becomes a fractal dimension D_L. The traffic network length of a city within an area S has fractal characteristic, then equation (2) equal to:

$$L_{(r)}^{1/D_L} \propto S^{1/2} \quad (3)$$

When the city area is defined as a circle, $S \propto r^2$, equation(3) can be expressed:

$$L_{(r)}^{1/D_L} = kr \quad (4)$$

where r is slewing radius, $L_{(r)}$ is the total length of traffic network in the circular region, k is a shape factor. Take logarithm to both sides equation (4):

$$\ln L_{(r)} = D_L \ln k + D_L \ln r \quad (5)$$

And if constant $C = D_L \ln k$, then equation (5) can be written:

$$\ln L_{(r)} = C + D_L \ln r \quad (6)$$

Based on equation (6) by means of linear regression method, we got the fractal dimension D_L:

$$D_L = \frac{\sum_{i=1}^{n} \ln r_i * \ln L_{(i)} - \frac{1}{n}\left(\sum_{i=1}^{n} \ln r_i\right)\left(\sum_{i=1}^{n} \ln L_{(i)}\right)}{\sum_{i=1}^{n} (\ln r_i)^2 - \frac{1}{n}\left(\sum \ln r_i\right)^2} \quad (7)$$

D_L is the final length-dimension. The meaning of length-dimension can be analyzed further. Taken derivative and transforming on equation (4), the attenuation formula of network density can be educed: $\rho(r) \propto r^{D-2}$, when $D_L < 2$, it means that traffic network density descends with r increasing from the center to circumference; when $D_L = 2$, traffic network density don't change from the center to circumference; when $D_L > 2$, traffic network's density increases from the center to circumference. Thus it can be seen that the length-dimension reflect the complexity of the traffic network filling urban space, and the change speed of traffic network density from the center to circumference. Taking Shanghai, Wuhan and Lanzhou cities for example, we carry through spatial analysis for three cities traffic network based on GIS, taking urban CBD as measuring center, equal-interval increasing length as slewing radius r_i ($i = 1, 2 \cdots n$), calculate the total length $L_{(i)}$ of each radius scope(Fig. 1). Corresponding points could be drawn at double-logarithm coordinate system, then approach it with regressive fit, and work out the no-mark extent with "the correlative coefficient-standard error of estimated" intersected method. It can be concluded that Shanghai, Wuhan and Lanzhou's traffic networks have self-similarity in a certain extent with change of slewing radius, whose fractal length-dimensions are 1.6, 1.45 and 1.17 respectively(Fig. 2).

Fig. 1 Sketch map of traffic network and slewing radius

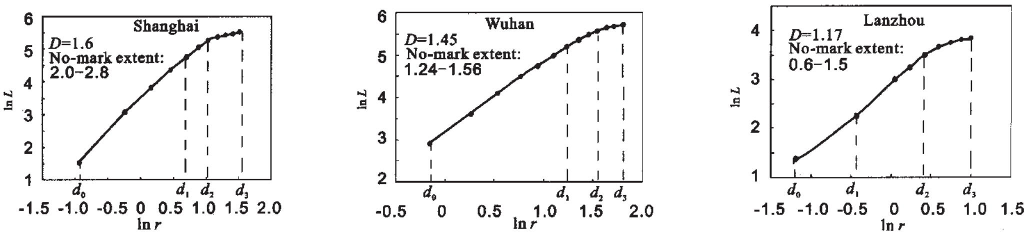

Fig. 2 Three cities' length dimension character index

2.2 Expansion of Fractal Dimension

In objective world, there is no ideal fractal of pure mathematics, but there is statistic fractal. Therefore, self-similarity only appears in a certain scope, namely the no-mark extent, where there is obvious self-similarity. Data mostly are ignored to overstep the no-mark extent in the studying process, which cause the loss of information. Moreover, radius analysis method is local analysis(FORTHERINGHAM and WEGENER, 2000) that researched object can be observed in certain research region according to certain radius and can not overlay whole research region so that information collection has been confined in a way. It is distinctly deficient that geography things are represented only with this fractal dimension, therefore it become very necessary of expanding fractal research. Generally, the self-similarity of researched object can retain one of subsections. The collected information data can be divided into three segments at double-logarithm coordinate system, the fractal dimension corresponding to the first segment (the section related to the scope [d_0, d_1]) is textural fractal dimension D_1 which manifests subtle structure and texture character; the fractal dimension corresponding to the second segment (the section related to scope [d_1, d_2]) is structural fractal D_2 which manifests strict self-similarity of research object; the fractal dimension corresponding to the third segment (the section related to scope [d_2, d_3]) is state fractal dimension D_3 which manifests the whole development trend of research object.

As for traffic network characteristics of three cities, their three fractal dimensions respectively count as: Shanghai: $D_{L_1} = 1.870$, $D_{L_2} = 1.600$, $D_{L_3} = 0.533$; Wuhan: $D_{L_1} = 1.640$, $D_{L_2} = 1.450$, $D_{L_3} = 0.702$; Lanzhou: $D_{L_1} = 1.360$, $D_{L_2} = 1.170$, $D_{L_3} = 0.509$. All collected data are used to reflect the dynamic change process in which traffic network density decreases with the slewing radius increasing. It would be shown that Shanghai's traffic network is densest, correspondingly its length-dimension is highest, and Lanzhou's traffic network is sparsest, its length-dimension is smallest from proper fractal dimension analysing. Based on expanding fractal method, inner density change of traffic network is not consistent, but it gradually changes, namely the network density goes through slowly declining to sharping from urban CBD to circumference, which is coincident entirely with status quo.

2.3 Ramification-dimension and Connectivity

An importance index representing traffic network characteristic is the connectivity of urban road network. Usually the total connectivity of traffic network is described with connectivity index $J = \sum M_i / N$ (M_i is edge number adjoining with i node, N is total node number of road net), which is a static index and can not describe the dynamic change process of network. Here fractal dimension is introduced to represent the dynamic change process of the degree of traffic network's connectivity using radius analysis method.

Still taking urban CBD as the center of circle and r_i as the slewing radius, ramification number in traffic network is counted statistically. Obviously, $N_{(r)}$ is accumulative total of traffic network ramification within certain circle, existing the following relation:

$$N_{(r)} \propto r^{D_b} \quad (8)$$

Equation (8) can be expressed as:

$$N_{(r)} = a * r^{D_b} \quad (9)$$

where a is constant. After regressive fitting, ramification-dimension is:

$$D_b = \frac{\sum_{i=1}^{n} \ln r_i * \ln N_{(r)} - \frac{1}{n}\left(\sum_{i=1}^{n} \ln r_i\right)\left(\sum_{i=1}^{n} \ln N_{(r)}\right)}{\sum_{i=1}^{n} (\ln r_i)^2 - \frac{1}{n}\left(\sum_{i=1}^{n} \ln r_i\right)^2} \quad (10)$$

Geographic significations of ramification-dimension reflect the change speed of network ramification numbers. It is a common phenomenon that the intersection of roads produces ramification in traffic network, whose fractal dimension is decided by the rate of change of ramification numbers so that it can depicte the connectivity and complexity of spatial organizing structure of urban traffic network. The higher dimension means that the structure of road is more complex and the connectivity is higher. Whereas, the traffic network's structure is simpler, and connectivity is lower.

Still taking Shanghai, Wuhan and Lanzhou cities for example, and taking urban CBD as center of circle, the equal-interval increasing length as slewing radius r_i ($i = 1, 2 \cdots n$), calculate the ramification numbers $N_{(r)}$ of traffic network within each radius scope, and draw corresponding points at the double-logarithm coordinate system. It could be seen from Fig. 3 that Shanghai's spatial organizing structure of network is most complicated, next is Wuhan City, Lanzhou's spatial organizing structure is simplest. As a complete unit, Shanghai's spatial accessibility decline slowest from urban CBD to circumference, next is Wuhan, Lanzhou's spatial accessibility decline fastest. Ramification-dimension show spatial accessibility and network growth otherness from network spatial organizing structure, and reflect developing size and upgrowth degree of difference cities.

As for cities inner, the changes of network accessibility are different also. The research region could be partitioned into three zone from center to circumference according to expanding fractal method, D_1 show the changes near measuring center; D_2 is a fractal dimension of strict statistical signification, and represents the whole change of network; D_3 displays the changes of network accessibility beyond measuring center. In these three cities, Shanghai's D_1 is 2.37, whose network ramification numbers gradually increase around center. It shows spatial accessibility around Shanghai's CBD is very high. Wuhan and Lanzhou's D_1 are smaller than 2, they are 1.96 and 1.51 respectively. In this scope, Wuhan's fractal dimension is near 2, its ramification numbers density is almost consistent, it shows the accessibility is high in this extent. But Lanzhou's ramification numbers density declines fastest from center to circumference. And that D_3 of Shanghai, Wuhan and Lanzhou are 0.592, 0.551 and 0.561 respectively. D_3 reflects developing trend, and it ramification numbers density of network would descend sharply in this extent, and urban spatial accessibility becomes poorer increasingly, this scope often lie to urban fringe. This index's description of urban traffic network change corresponds

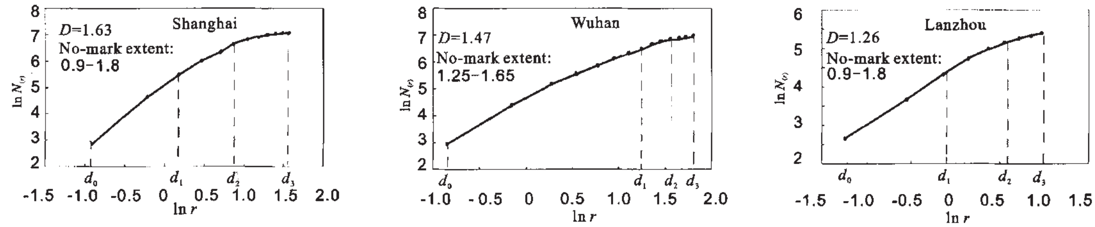

Fig. 3 Three cities' ramification dimension character index

to facts.

3 DISCUSSION

The quantitative research of urban traffic network is an important component of the study on the controllable factor of city spatial morphology. From the analysis and application above, the results can be given as:

(1) Radius analysis is partial analysis method, the process of getting the information for research object is from part to the whole. Make the use of the information, and re-comprehend observation data beyond no-mark extent, and make full of liveliness of fractal-dimension. The idea of fractal research has been penetrated into analysis of traffic network spatial structure, and has more practical meaning and easily comprehend complexity of spatial structure.

(2) Researching urban traffic network using fractal theory based on GIS not only improves the precision of quantitative index for describing traffic network complexity, but also offers the strong tool to research urban traffic in multi-level, multi-angle. Analyzing network density and connectivity, fractal method is differ from the other graph theories familiar, such as β index, α index, γ index and connectivity index etc., because these indexes are static, they could not dynamically reflect network inner difference. But fractal dimension shows not only the whole feature of network, but network inner difference and it's gradual change instance on space can be compared and analyzed using expand fractal dimension, which is most merit that fractal differs from other method. Otherwise, fractal dimension increases research meaning of people's understanding traffic network, such as ramification-dimension, it not only reflects complexity of spatial structure, but also describes connectivity of network, implies urban size and upgrowth degree. Length-dimension, ramification-dimension and expanding dimension have important reference for quantitative description and controllable parameter of urban traffic network spatial morphology.

(3) Gradual diffused radius analysis method from center to circumference. It's application isn't limited to urban traffic, but has higher reference value in other aspects, such as researching urban land-use distribution and evolvement from CBD to circumference, and layout characteristic of commerce and public service in urban area, it also be used to calculate their fractal dimension , in order to compare and analyse their morphologic features in difference cities. At present, this method is using widely in correlative geographic domain.

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