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Analysis of Road Networks Features of Urban Municipal District Based on Fractal Dimension

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Abstract: The structural characteristics of an urban road network directly affect the urban road network's overall function and service level. Because the hierarchical division and layout form of an urban road network has self-similarity and scale invariance, the urban traffic network has certain time-space fractal characteristics, and fractal theory has become a powerful tool for evaluating traffic networks. This paper calculates and compares five fractal dimensions (FD) of nine districts in Harbin. Meanwhile, each calculated FD is linearly regressed with the area, population, built-up area, building area, the total number and length of roads, and the number of buildings in the region. The results show that the fractal dimensions of the five types are between 1 and 2. In the same district, the values of the FD perimeter and FD ruler are lower compared to the FD box, FD information, and FD mass, whereas those of the FD box and FD information are higher. Compared to the FD box and FD information, the value of FD mass shows unevenly. Based on the current research results, this study discusses the feasibility of using relevant indicators in the fractal process to evaluate the layout of the urban road network and guide its optimization and adjustment.

Keywords: fractal dimension; GIS; road network; municipal district; effort of urban infrastructure

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1. Introduction

The continuous development of a city changes the existing road network structure. At the same time, the extension of roads expands the size of a city. The plan and layout of the urban road network (URN) attracts more and more public attention. URN is not only the product of urban development but also the basis for promoting the process of urbanization. The hierarchical division of URN structure is mainly based on the transporting and distributing functions of road systems at various levels. The process of dividing the road network level from the fast road network system to the branch network system is actually the transition process of the two distinct functions in the whole road network. Both the fast road network level and the branch network level satisfy their similarities with the whole road network [1,2]. In various URN layout forms, the layout of expressway network, arterial network, sub-arterial network, and branch network are consistent with the overall layout of the road network. The layout and level of the road network are only affected by environmental factors, such as climate and topography. This is a type of performance of the scale invariance. Therefore, it is practicable to utilize fractal geometry to assess internal structural characteristics of URN. Supposing that the space is a plane and that we only consider the object on the plane, the dimension of a line is 1 and the dimension of a surface is 2. However, the fractal does not fill space like simple and regular lines or even a surface. The fractal dimension (FD) can be described as being between 1 and 2 [3–5]. Numerous studies have shown that fractal dimensions of urban traffic systems or subsystems range from 1 to 2 [6–9]. Meanwhile, few studies have demonstrated that the FD value is greater than 2 [10].

Experts and scholars have conducted large amounts of relevant research on the hot issue of urban road network structure optimization. It is mainly divided into two categories:

one is based on traditional methods and based on obtaining regional road network density, road network connectivity, and other indicators, and it guides urban road network structure optimization through efficiency analysis, potential energy analysis, and other different data analysis methods [11–14]; the other is based on the fractal method and discusses the spatial structure characteristics of the road network and measures the coverage degree and access depth of the road network in the way of overall subdivision into local to represent the spatial topological relationship of the internal structure of the road network [15–19].

On the whole, urban road traffic network still has problems of uneven spatial distribution, unreasonable road network layout, and poor traffic accessibility. How to scientifically and objectively describe the characteristics of an urban traffic network, analyze the development characteristics of urban traffic network spatial structure, and then provide scientific and quantitative decision-making guidance for the planning and layout of an urban traffic network has become a subject of great practical significance. In order to better study the fractal dimension of the urban road network, high-resolution remote sensing data and big traffic data are widely extracted and collected. More real feature information, such as the complexity and nonlinearity of urban road networks, is implied in these data, which leads to the development of urban road network structure modeling method to the direction of refinement and micro and also puts forward higher requirements for research methods. The construction of a traditional urban road network model based on geography is mainly based on Euclidean geometry and linear algebra theory. Although these mathematical methods can solve linear problems well, they have limited functions in dealing with complexity and nonlinear systems. In order to solve this problem, postmodern mathematical methods (including fractal and chaos theory) are introduced into the study of the urban road network, represented by the fractal school of the urban road network. In short, fractal realizes the characterization of the iterative law of urban road network structure. However, the traditional road network fractal dimension index can only be used to describe the relevant characteristics of a single level of road network in a specific area. Still, it cannot be effectively used for an overall road network including all levels of roads [20,21]. Therefore, it is necessary to seek an analysis process that can establish the relationship between different levels of roads and then integrate this process into the calculation of the traditional road network fractal dimension. The improved measurement method is expected to effectively reflect the fractal characteristics of the road network at all levels at some levels in the road network. Supported by the fractal form of this study, combined with five fractal dimensions, the traffic network characteristics and spatial fractal characteristics are comprehensively studied, and the overall development degree of the traffic network and the interregional correlation tightness are intensively discussed.

There are various FDs, such as the Minkowski, Hausdorff, box-counting, information, capacity, mass, similarity, perimeter area, and ruler dimensions. For road networks, the box-counting dimension and the mass dimension are mainly employed to analyze the fractal properties of the network. In the present research, five FDs—including box (FDb), perimeter area (FDp), information (FDi), mass (FDm), and ruler (FDr) will be calculated.

(1) FDb evaluates the number of boxes needed to cover an object fully, and the sizes of boxes are different. In fact, this is achieved by overlaying regular grids on objects and calculating the number of occupied boxes. Nr (d) is used to represent the minimum number of n-dimensional cubes (boxes) with r edges needed to cover objects.

(2) FDp describes the association between the perimeter and the area of the objects for the buildings whose boundary length and measurement scale are closely related. In this method, by measuring the perimeter and area of each building, the average fractal dimension of the building group can be determined from the slope obtained from the double logarithmic drawing.

(3) FDi is established from the perspective of probability theory. It is similar to FDb, but it only considers the number of boxes containing objects instead of calculating the total number of boxes covering an object. In this method, the number of information entropy I (d) (the sum of mass mi in each box) is drawn to calculate the FDi of different edge lengths d.

(4) FDm describes the association between the area located within a certain radius and the size of this radius (or box). FDm can be determined based on the log–log plot of the area versus the radius [22–24].

(5) FDr assesses the relationships between the number of steps needed to cover the line length N (d) and the ruler length (d). FDr can be determined based on the log–log plot of N (d) versus (d) [25]. In urban spatial analysis, FD is mostly calculated using the box-counting dimension [26,27] and the mass–radius dimension [28,29].

There are several software tools for calculating FDs—for example, Fraclab, FracLac, TruSoftBenoit, Fractalyse, VESsel GENeration Analysis, etc. An FD-calculating module is embedded in some common GIS software, including SpaDiS, Exeter GS, Geostat Office, etc. [30]. In the present study, Benoit software was employed.

Much research in urban network analysis applies the FD model [31–33]. In general, fractal analysis for urban traffic networks can be divided into three categories: The first aims to reveal the fractal properties of the road system [34]. The second uses the fractal properties of traffic networks to display the urban developing patterns [35,36]. The third category focuses on FD calculation for a city traffic system or subsystem over a certain period [37].

This paper calculates and compares five FDs (FDb, FDp, FDi, FDm, and FDr) of nine districts in Harbin, China, and we analyze the influence of urban population, area and building area, total building number, and length of road networks on FD. These indicators are called "district patterns" later. In particular, this study focuses on the comparison of FD between different districts of Harbin. Then, the relationship between district patterns and FD in statistics will be revealed. Thirdly, the type of computational FD reflecting the spatial characteristics in the city will be demonstrated. The organizational structure of this paper is as follows: Section 2 shows the research area, data, and methods. Section 3 demonstrates analysis and results. Sections 4 and 5 discuss and conclude the topic, respectively.

2. Materials and Methods

2.1. Study Areas

This study takes Harbin, China, as an example. Harbin is a cultural, economic, and political center in the northern part of Northeast China. It has jurisdiction over 2 county-level cities, 7 counties, and 9 municipal districts. Due to the smaller area and population of county-level cities and counties, this study area is the municipal area.

By the end of 2022, the municipal area of Harbin was 10,249 km^2, the built-up area was 508.7 km^2, and the population was 6.9761 million. The total building number and the total building area are 105,907 and 60,965.796 km^2, respectively. Figure 1 provides the municipal map of Harbin and the main city of Harbin. The total number of roads in the main urban area is 12,800 strips, and the total length of the road network is 9757.934 km.

2.2. Data Collection

By collecting the road network map, area, population, building area, road number, building number, and road length of 9 districts in Harbin, the road network data required for a fractal dimension are calculated. Urban road network data were retrieved from an online resource, Open Street Map (OSM), using the shape file format, as shown in Figure 2. The population for the year 2022 was collected from the people's government of Harbin. The number and length of network roads were obtained with GIS software using the appropriate tools. The number and area of different area and building types were retrieved from Heilongjiang Surveying and Mapping Geographic Information Bureau since these data cannot be obtained from the OSM database. The characteristics of the district are shown in Table 1. The fractal city is a study of concrete calculation, description, and analysis of human history, natural landforms, and urban construction in the urban system using fractal thought and mathematical methods. For an object with a fractal structure, after being amplified n times, its occupancy space is larger than the original, and the fractal dimension is n. We use log calculation. Therefore, population, district and its built-up area,

building area, building number, and the total number and length of roads were used to assess the effects of district patterns on the FD, as shown in Table 2.

Figure 1. The geographical location of the urban area of Harbin, China (colored areas within the red circle).

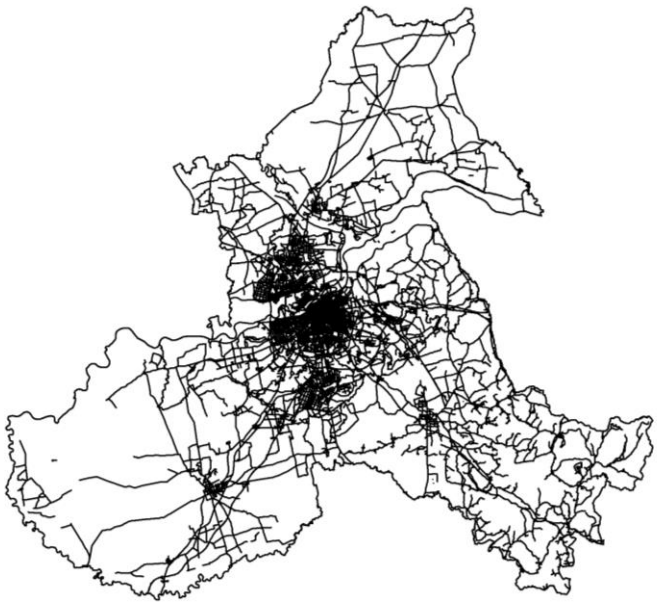


Figure 2. The road network in the urban municipal district of Harbin changes from dense to sparse from the city center to the outside.

Table 1. The characteristics of the district.

Districts	Population (in Lakhs)	District's Area (Km^2)	Built-Up Area	Road Number	Road Length (Km)	Building Area	Building Number
Nangang	13.907	182.8	72.4	2279	854.16	12,843.68	22,678
Xiangfang	11.202	344.5	101	2256	1121.38	16,899.16	28,335
Songbei	4.135	736.8	69	1908	1270.77	3875.67	6739
Acheng	5.003	2452	25.9	1886	1730.55	1966.27	7099
Daoli	10.974	479.2	74.8	1455	1020.9	7961.77	13,663
Hulan	7.700	2229	50.6	1117	1516.33	3409.21	5555
Daowai	8.112	618.6	53.8	1108	813.66	10,822.11	16,947
Shuangcheng	6.339	3112.13	22.7	522	1107.29	1294.55	2555
Pingfang	2.389	939.7	38.5	269	322.89	1893.37	2336

Table 2. Urban descriptive variable statistics.

Variables	Mean	Standard Deviation	Number of District
Log of Population	5.83605	0.22783	9
Log of District's Area	5.81579	0.49300	9
Log of District's Built-up Area	4.70739	0.20595	9
Log Total Road Number	3.07445	0.29689	9
Log Total Road Length	5.99745	0.19957	9
Log Building's Area	6.67510	0.38288	9
Log of Total Building Number	3.93032	0.36892	9

2.3. Data Processing

In this study, images in BMP file format (.bmp) are used as inputs to measure five types of fractal dimensions. The images contained white objects (roads, borders) and a black background. The shape file data are processed using GIS software. Nine maps were processed into the required format (.bmp) at a resolution of 500 dpi and at different sizes (width, height), as shown in Figure 3.

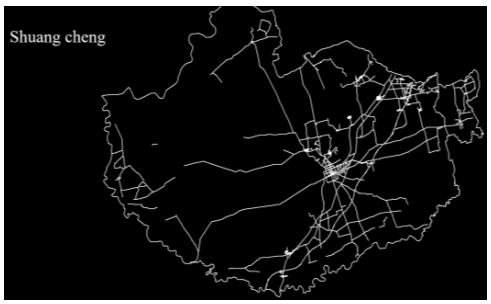
2.4. Computation of Fractal Dimensions

The basic principle of fractal measurement is to construct a basic unit with an equidistant scale "r" (such as the radius of an equidistant concentric circle) for spatial measurement of a specific type of ground object, and the measurement result is "M(r)". Changing the measurement scale r of the basic unit will cause the measurement result to change accordingly. If "r" and "M(r)" meet Equation (1) within a specific range, it can be considered that the type of ground object has fractal characteristics.

$$M(\lambda r) \propto \lambda^{\pm\alpha} M(r) \quad (1)$$

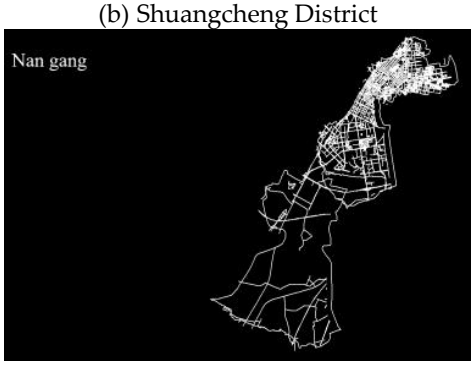
Among them, "λ" is the scale ratio, and "α" is a function with a fractal dimension; typically, "α" = "D". "D" is the fractal dimension. The law of degree invariance in fractal theory can be expressed as "D" not changing with the change in "r".

(a) Songbei District

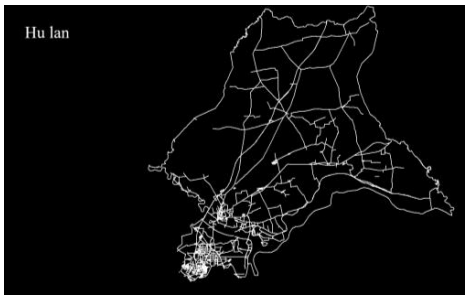


(b) Shuangcheng District

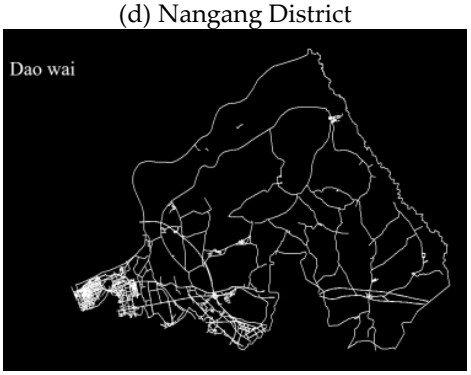
(c) Pingfang District



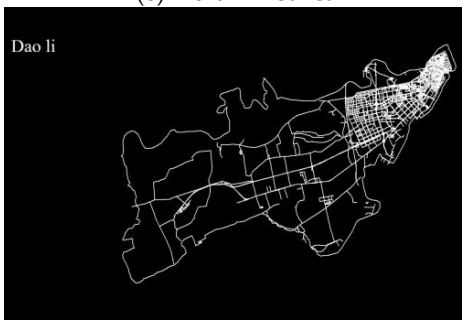
(d) Nangang District



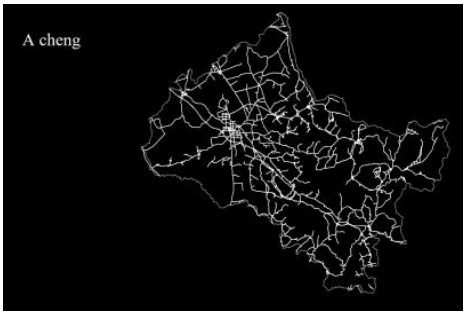
(e) Hulan District



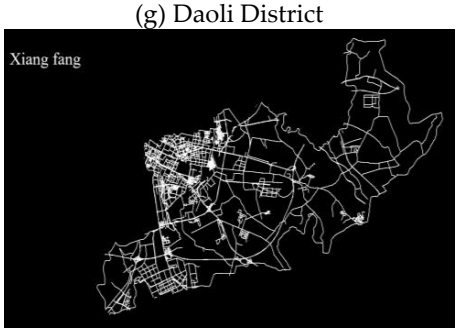
(f) Daowai District



(g) Daoli District



(h) Acheng District



(i) Xiangfang District

Figure 3. The road networks of 9 districts in Harbin at 500 dpi.

2.4.1. Two-Dimensional FD Box

FDb is sometimes known as the grid dimension because the box is a part of the grid for mathematical convenience. The logarithmic number of boxes N (d) with linear size (d) is drawn on the longitudinal axis, and the logarithmic number of boxes N (d) is drawn on the transverse axis. If the set is fractal, the graph appears linear, with a slope of -Db. Theoretically, for the size of each box, the grid must be superimposed in this way to occupy the smallest number of boxes. The grid of each box is rotated at 90 degrees, and the minimum N (d) value is plotted using the Benoit Software. The angular rotation increment is selected. The configurations employed in this study are as follows: the maximum edge length (d) of the box is automatically chosen by the software according to the size and shape of the object. The reduction coefficient of the box size coefficient is 1.3. The number of box sizes is set at 26, and the incremental value of grid rotation is 15. However, the FDb value does not change significantly when this variable changes.

2.4.2. FD Perimeter

FDp calculates various side lengths "d" by drawing the logarithms of A on the longitudinal axis and P on the transverse axis. If the relationship is fractal, the graph follows a straight line with a slope equal to 2/FDp. The configurations employed in this study are as follows: the edge length (d) of the maximum box was automatically chosen by the software according to the size and shape of the object. The reduction factor of the box size is 1.3, and 26 box sizes are automatically selected. The increment value of grid rotation was 15, but the FDp value does not change significantly by changing this variable.

2.4.3. FD Information

FDi efficiently assigns weight to the box so that boxes contain more points. Whether or not the box comprises one point or more points, it is occupied and inputs N (d) into the calculation. This method calculates FDi under different edge lengths "d" by drawing the logarithm of I (d) (the sum of mass mi in each box) and the logarithm of box edge length (d). If the set is fractal, then the I (d) and "d" logarithm graph will be drawn along a straight line with a slope equal to -FDi. The configurations employed in this study are as follows: The maximum side length box (d) is automatically chosen by the software according to the size and shape of the object. The reduction of the box is 1.3. The number of box sizes is set at 26. The increment of grid rotation is 15, but the FDi value does not change significantly when this variable is changed.

2.4.4. FD Mass

A circle with radius r is drawn on the dataset of points distributed on a 2D plane, and the number of points in the circle set is calculated. FDm is measured by drawing the logarithm m (r) and the logarithm of r. If the set is fractal, the graph follows a straight line with a positive slope equal to FDm. It can be proven that the quality dimension of a set is equal to the box dimension. This is true globally, i.e., for the whole set; in the local—i.e., in the part of the set—the two FDs may be different. The configurations employed in this study are as follows: The software automatically chooses the maximum radius of the circle according to the size and shape of the object, and this is reduced by the 1.3 coefficient or the radius of the circle. The maximum radius is automatically selected by the software according to the shape and size of the object, and the coordinates of the center of the circle are changed according to the position of the object in the image. If the object's position moves away from or toward the center, the FDm value will also change. Thus, it is crucial to place the center of the counting circle near the object's center.

2.4.5. FD Ruler

FDr is measured by drawing the logarithm of N (d), which is the number of steps taken by walking the dividing line (ruler) with length "d" and the logarithmic ruler length (d) on the straight line. If this line is fractal, this map will be drawn along a straight line with a

negative slope equal to − FDr. Notably, the scale of length "d" cannot completely cover this line, but a remnant will be left. This remainder is retained in the software, so users with non-integer values should ensure the number of steps covering the boundaries of all objects with closed shapes; otherwise, the software gives the wrong results. The configurations employed in this study are the most extended and least extended ruler lengths. The software automatically selects the scale size according to the shape and size of the object and uses the scale length reduction factor 1.3 to select the rollback number automatically.

3. Results

3.1. Fractal Characteristics of the Road Networks

The FD values of nine road networks ranged from 1 to 2, indicating that the fractal analysis is appropriate for the five FDs, as shown in Table 3. Based on the log–log plot of each FD, the results can be interpreted as follows: For FDb methods, log N (d) and Log (d) follow a straight-line slope equal to -FDb; for FDp methods, (log A and log P follow a straight-line positive slope equal to 2/FDp; for FDi methods, (log I (d) and log (d) follow a straight-line negative slope equal to FDi; for FDm methods, (log (m) and log r follow a straight line; for FDr methods, log N (d) and log (d) follow a straight-line negative slope equal to -FDr.

Table 3. Fractal dimension value and standard deviation.

District	Box-Counting Dimension		Perimeter–Area Dimension		Information Dimension		Mass Dimension		Ruler Dimension	
	FDb	SD	FDp	SD	FDi	SD	FDm	SD	FDr	SD
Nangang	1.60309	0.0297124	1.47504	0.4426676	1.64457	0.046617	1.85994	1.6505525	1.33492	0.0071907
Daoli	1.59088	0.0195396	1.44375	0.1248555	1.62448	0.0051172	1.99679	1.3596536	1.32172	0.0025732
Xiangfang	1.58296	0.0145486	1.46370	0.0096809	1.62021	0.0047240	1.83519	1.7266858	1.49005	0.0020899
Acheng	1.52534	0.0489187	1.37290	0.0359647	1.54457	0.0246617	1.59222	0.6598793	1.39695	0.0027351
Hulan	1.51377	0.0330254	1.40135	0.0172061	1.53842	0.0096695	1.80791	1.3439241	1.34229	0.0063766
Pingfang	1.51973	0.0348405	1.38941	0.0469070	1.54629	0.0317871	1.74839	0.9265217	1.17393	0.0070149
Songbei	1.56037	0.0149700	1.33030	0.0431832	1.60899	0.0063107	1.74794	0.2046030	1.31682	0.0052235
Shuangcheng	1.42155	0.0381518	1.41214	0.0706115	1.47041	0.0180293	1.70863	0.9587762	1.05687	0.0011493
Daowai	1.48226	0.0395263	1.12520	0.7512195	1.51845	0.0157313	1.93115	1.2756976	1.35094	0.0012670

In addition to the mass method, there is a significant correlation between the longitudinal and transverse axis values of all methods. It can be seen from the statistical data that the highest SD of FDm is higher than 1 and that the SD values of FDb, FDp, FDi, and FDr are close to 0. This means that the FDm value is not as obvious as the previous section because the methods are dependent on the users and the target center position related to the center of the circle radius. There are no absolute rules to compare the five FDs in each district, but generally, the FDb and FDi values in the same district have a strong linear relationship ($R^2 = 0.727$, $p < 0.01$). Because of the similarities between the two methods, the FDp value is higher than the weak linear relationship ($R^2 = 0.205$, $p = 0.034$). FDm has opposite behaviors, as it occasionally demonstrates higher and lower values than FDb and FDi, respectively, as shown in Figure 4.

Based on the SD data and log–log diagram behaviors, FDb, FDi, FDp, and FDr can reflect the fractal characteristics of road networks, but FDm cannot play the same role due to the higher SD. For a more accurate judgment, it is necessary to explore the impact of network characteristics on FD and explain it in the following sections.

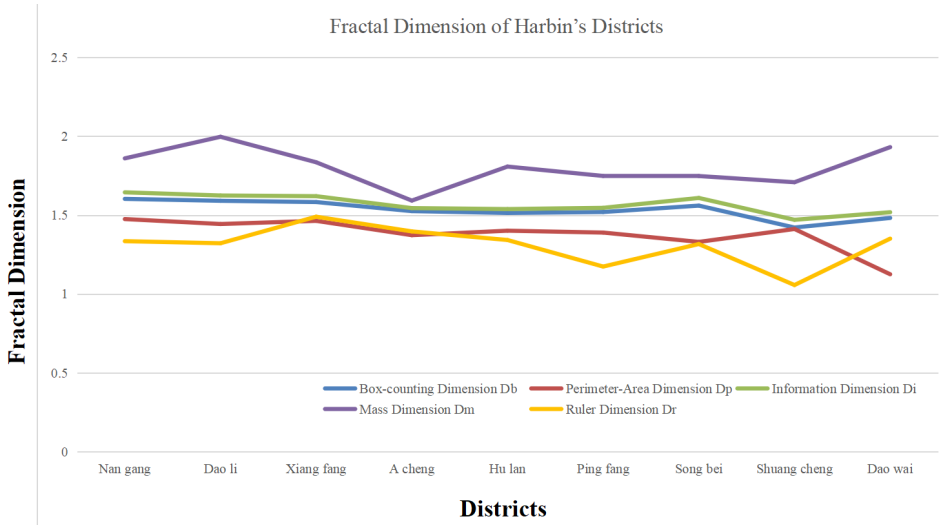


Figure 4. Five fractal dimensions of the road network in nine districts of Harbin City.

3.2. Comparison of Harbin's FDs and Harbin District's FDs

The maximum, minimum, and average values of each FD (as shown in Table 4) with the FD of Harbin on the whole and with the FD and SD values are as follows: FDb = 1.63727, SD = 0.0096429; FDp = 1.42904, 0.0156641; FDi = 1.70125, SD = 0.0042968; FDm = 2.09718, SD = 0.6667115; and FDr = 1.05470, SD = 0.0005961. The results show that FDb and FDi in Harbin are higher than the maximum FDb in all districts. FDp in Harbin is lower than the maximum FDp in all districts and higher than the minimum FDb in all districts; FDm in Harbin is higher than the maximum FDm in all districts and is greater than 1; FDr in Harbin is lower than the minimum FDr in all districts. Based on the concepts of complexity, FDb and FDi can serve as the best dimensions for assessing the fractal properties of road networks since the FDb and FDi values of the whole (Harbin) are higher than those of the parts (districts).

Table 4. Average, minimum, and maximum values of each FD for 9 districts.

Fractal Dimension	Average	Minimum	Maximum
FDb	1.53333	1.42155	1.60309
FDp	1.37931	1.12520	1.47504
FDi	1.56849	1.47041	1.64457
FDm	1.80313	1.59222	1.99679
FDr	1.30939	1.05687	1.49005

3.3. Effect of Districts' Populations on FDs

Based on the statistical analysis of Pearson's correlation coefficients (0.731, 0.715, −0.726) in the SPSS software, it can be seen that population has a strong positive impact on FDb and FDi and a negative impact on FDp. In addition, the impact of population on FDm and FDr is weak ($r < 0.4$). The logarithmic linear function of population for FDb, FDp, and FDi can produce reasonable estimates according to the R^2 and p-value (R^2 = 0.704, 0.519, and 0.659; p = 0.00, 0.00, and 0.00, respectively). Therefore, population data has an obvious impact on FDb, FDp, and FDi. Districts with larger populations have higher FDb, FDp, and FDi values.

3.4. Effects of Districts and Their Built-Up Areas on FDs

According to the statistical results, the influence of districts and built-up areas on all FDs is weak ($r < 0.4$). The increase in area is not necessarily accompanied by an improvement in development level. As we can see in Figure 3, some districts are large, but only a small part of them is developed, indicating that these results are reasonable.

3.5. Effects of Total Number and Length of Roads on FDs

Based on the results of statistical analysis, the total number of roads has a strong positive impact on FDi (r = 0.856), a slight impact on FDb (r = 0.667) and weak impacts on FDp, FDm, and FDr (r < 0.4). The logarithmic linear function of total road number on FDb and FDi can produce good Pearson estimates according to the R^2 and *p*-value (R^2 = 0.518 and 0.753; *p* = 0.00 and 0.00, respectively). The total road length had a moderate positive impact on FDi (r = 0.638) and had a weak impact on FDb and FDp. FDm and FDr (r < 0.4) were observed. The logarithmic linear function of total road length on FDi can be reasonably estimated based on the R^2 and *p*-value (R^2 = 0.414; *p* = 0.002, respectively). The influence of the total number of roads is more obvious in the comparison between the FDi fractal dimension and the total length of the road.

3.6. Effects of Total Number of Buildings and Building Area on FDs

According to the results of the statistical analysis, the building area has a strong positive impact on FDb and FDi (r = 0.762 and 0.711). The logarithmic linear function of building area on FDb and FDi can be well estimated based on the R^2 and *p*-value (R^2 = 0.535 and 0.608; *p* = 0.00 and 0.00, respectively). The influence of the building area on FDp, FDm, and FDr was weak (r < 0.4). The number of buildings has a strong positive impact on FDi (r = 0.728) and a moderate positive impact on FDb (r = 0.529). The logarithmic linear function of the number of buildings on the FDb and FDi based on R^2 and *p*-value can produce quite good estimates (R^2 = 0.488 and 0.486; *p* = 0.00 and 0.00, respectively). It was found that the number of buildings had little effect on the fractal dimensions of FDp, FDm, and FDr (r < 0.4). Compared with the area data, the number of buildings has a significant impact on the fractal dimension value, especially the FDb and FDi, indicating that the number of buildings and building area can better reflect the developmental status of the road network than the district's area and built-up area. Table 5 summarizes the fractal dimension of urban pattern variables.

Table 5. Correlations between each fractal dimension with urban pattern variables.

Fractal Dimension	Urban Pattern	Population	District's Area	District's Built-Up Area	Total Road Number	Total Road Length	Building Area	Building Number
FDb	R^2	0.704	0.012	0.007	0.518	0.185	0.535	0.488
	p-value	0	0.798	0.813	0	0.871	0	0
	Pearson Correlation	0.731	−0.051	−0.062	0.667	0.326	0.762	0.529
FDp	R^2	0.519	0.005	0.006	0.212	0.082	0.207	0.214
	p-value	0	0.653	0.649	0.071	0.330	0.031	0.051
	Pearson Correlation	−0.726	0.104	0.115	−0.468	−0.252	−0.465	−0.434
FDi	R^2	0.659	0.063	0.048	0.753	0.414	0.608	0.486
	p-value	0	0.425	0.517	0	0.002	0	0
	Pearson Correlation	0.715	0.733	0.136	0.856	0.638	0.711	0.728
FDm	R^2	0.032	0.008	0.001	0	0	0.002	0.003
	p-value	0.491	0.801	0.947	0.899	0.913	0.794	0.834
	Pearson Correlation	0.179	−0.093	−0.043	0.008	−0.007	0.068	0.047
FDr	R^2	0.078	0.079	0.070	0.047	0.097	0.032	0.009
	p-value	0.347	0.167	0.198	0.318	0.203	0.650	0.685
	Pearson Correlation	−0.216	−0.387	−0.362	−0.231	−0.343	−0.103	−0.091

4. Discussion

Fractal dimensions are widely used in practical applications to quantitatively evaluate the distribution density and network complexity of urban road networks and to judge the coverage degree, connectivity degree, and coverage depth of urban traffic [38,39]. The fractal dimension reflects the spatial distribution characteristics of the urban road network; the degree of change of road network density with space; and the complexity, development, and accessibility of the road network in the form of scores. To a certain extent, it improves the indicators, such as "road grade" and "road network density", that are not closely combined with urban spatial layout. When calculating the fractal dimension of the traffic road network, selecting the measurement center and measurement scale is necessary. At present, the measurement center is either the hub of the urban traffic network, the geometric center, or the city's center of gravity. The results obtained from different choices are different, so there is cognitive uncertainty in the center selection. Even if the transportation hub center of the urban road network is selected, there will be differences due to different researchers; that is, there is a point error (measurement point and real point) in the corresponding measurement center. For the selection of measurement scale, there is no fixed standard at present, and most of them are based on the characteristics of the study area to select the appropriate scale for measurement, which also increases the diversity of the fractal dimension of the regional transportation network.

The calculation data of fractal dimensions show that the fractal dimensions of FDb, FDp, and FDi successfully explain the fractal properties of the road network in the case study. As mentioned earlier, the FD cannot reflect the fractal properties of any road network alone, and the data of district patterns can be taken into account. Statistical analysis of all FDs and district patterns (population, roads, buildings and areas) shows that district patterns have outstanding positive effects on FDb and FDi. The two FDs have similar method concepts (box occupancy), and their values are very close, as shown in Figure 5. Moreover, the correlations between FD and each variable are demonstrated in Table 6.

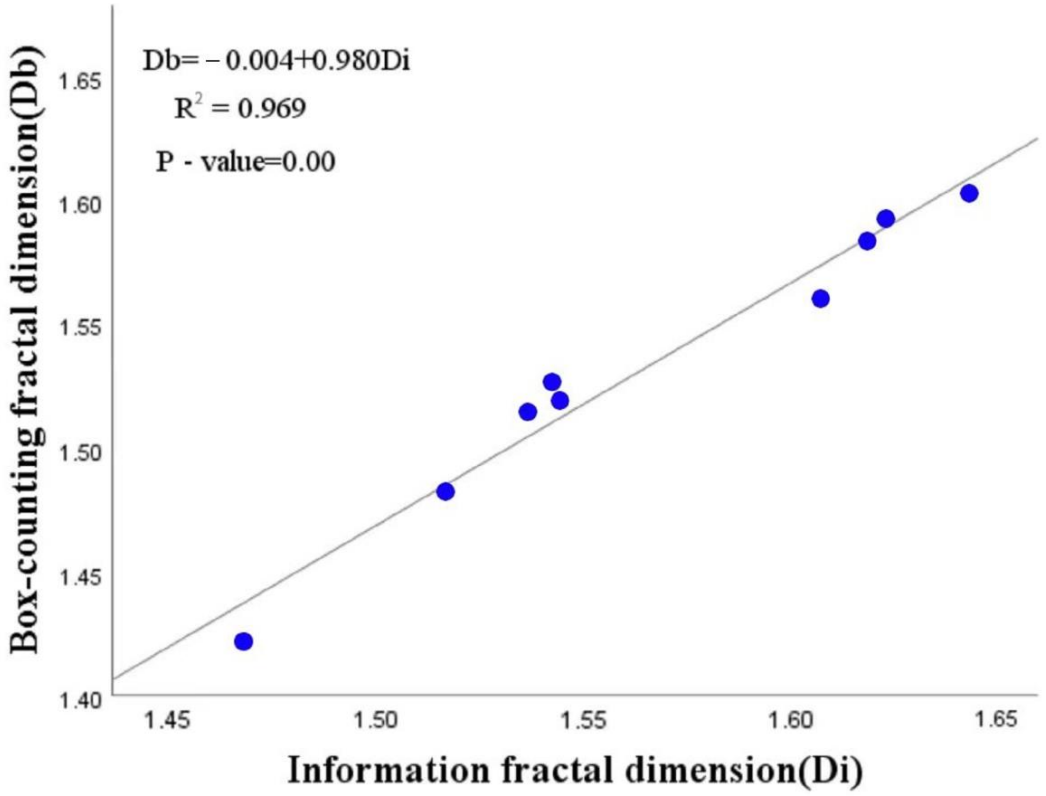


Figure 5. FDb as a linear function of FDi for 9 districts; FDb has a high correlation with FDi.

Table 6. Effects of districts' statistics on fractal dimension.

Fractal Dimension	Urban Pattern	Log of Population	Log of District's Area	Log of District's Built-Up Area	Log Total Road Number	Log Total Road Length	Log Building's Area	Log of Total Building Number
FDb	R^2	0.713	0.003	0.002	0.479	0.138	0.557	0.438
	p-value	0	0.838	0.748	0	0.919	0	0
	Pearson Correlation	0.8037	−0.0574	−0.0631	0.7011	0.3259	0.7149	0.6771
FDp	R^2	0.516	0.009	0.006	0.191	0.058	0.311	0.185
	p-value	0	0.741	0.680	0.040	0.317	0.037	0.038
	Pearson Correlation	−0.7539	0.0814	0.0791	−0.4523	−0.2470	−0.5105	−0.4341
FDi	R^2	0.704	0.064	0.039	0.711	0.351	0.665	0.561
	p-value	0	0.312	0.425	0	0.002	0	0
	Pearson Correlation	0.8116	0.2518	0.1949	0.8178	0.5931	0.8364	0.7665
FDm	R^2	0.041	0.006	0.001	0	0	0.004	0.002
	p-value	0.471	0.708	0.857	0.958	0.969	0.718	0.798
	Pearson Correlation	0.1921	−0.0815	−0.0469	0.0103	−0.0098	0.0792	0.0526
FDr	R^2	0.037	0.093	0.071	0.045	0.101	0.010	0.006
	p-value	0.398	0.197	0.208	0.3130	0.206	0.703	0.679
	Pearson Correlation	−0.2177	−0.3265	−0.2957	−0.2593	−0.0146	−0.1058	−0.0786

Districts with relatively similar patterns may not have the same FD. The calculation of FD can be influenced by different factors, such as image resolution, users, pattern distribution across the districts, etc. In addition, the populations and areas of different districts are similar. However, due to different construction years, road network structures, and construction areas, different FDs will also be caused. For instance, districts with relatively similar populations do not have the same FD. The population sizes of Xiangfang District and Daoli District are 1,120,200 and 1,097,400, respectively. Their FD values were: FDb = 1.58296, 1.59088; FDp = 1.4637, 1.44375; FDi = 1.62021, 1.62448; FDm = 1.83519, 1.99679; FDr = 1.49005, 1.32172. The population and the number of roads are positively correlated with the five dimensions of each district. In addition, as the economic and political center of Harbin City, Nangang District has more traffic policy pilots in the area, with a maximum value of three dimensions. However, Shuangcheng District has the largest area, with the lowest value of three dimensions due to the low number of built-up areas and buildings. As an essential transportation area from Harbin to the southern provinces, it can be developed in this area. The analysis applies to other patterns, such as area, length, and the number of buildings and roads; it also enriches the application of the fractal method at the meso and micro levels in the planning field and tries to supplement the evaluation index of road network structure. Quantitative research and analysis are carried out on the characteristics of road network structure in different city types and functional areas. The advantages of road network structure are analyzed based on fractal theory.

One of the fundamental purposes of urban planning is to cultivate a "good urban form". Only by restoring the planning to a specific urban form and social network can its value be realized. Studying urban road network structure is essential for urban planning, design, and management. The abstraction and generalization of the internal order formed

in a specific historical period and natural geographical environment imply an irregular form. At the same time, according to the future development trend of social and cultural environment and ecological environment, it is necessary to explore the future development trend of urban space to play a guiding role in planning and design. The study of urban road network structure can grasp the context of urban development, which is conducive to predicting and controlling future urban development. It can provide more direct guiding principles for urban planning and design. In addition, the systematic study of urban road network structure can also be used to strengthen and integrate the theoretical basis of urban design. Therefore, this research can provide an essential theoretical basis and technical support for urban planning and design practice.

5. Conclusions

This study quantifies the structural characteristics of the urban road network and explores the practical significance of fractal theory to the characteristics of the road network. The fractal characteristics of different road network spatial patterns are summarized based on the study of the road network structure characteristics of several urban centers. In the present work, five FDs (FDb, FDp, FDi, FDm, and FDr) of nine districts in Harbin were calculated according to the patterns of each district (population, districts' built-up areas, building number and built-up area, road number and lengths).

All types of available land in the main urban area of Harbin exhibit fractal characteristics of uniform density changes from the center to the outer circumference both in the plane and the road network. Large and small differences exist in the dimensionality measurement values of different land uses. Both dimensionality values are manifested as commercial land < all construction land < residential land < industrial and warehousing land, which reflects the spatial form of commercial land gathering in the central urban area of Harbin—residential land arranged in layers and industrial and warehousing land scattered around the periphery. For lands with similar functions, the scale range of the road network fractal dimension scale invariant area is wider than the radius dimension, and the space divisions are more precise.

Due to the positive linear correlation of FDb, the population and building areas can be fitted satisfactorily. Due to the negative linear correlation of FDp, the population can be fitted satisfactorily. Due to the positive linear correlation of FDi, the population, road number, building area, and building number can be satisfactorily fitted. FDm and FDr cannot satisfy any satisfactory district patterns. In summary, the results show that compared to other types of road networks, FDb, FDp, and FDi can better show the fractal properties of road networks in Harbin because they are associated with district patterns.

The city is a very complex integrated entity. For the urban road network form with fractal characteristics, the fractal dimension value does not only represent its complexity; the level of fractal dimension value is not strictly equal to the level of richness. The situation becomes more complicated with a natural environment or artificial landscape intervention. With the help of fractal theory, more comprehensive and in-depth quantitative research on a specific problem will lead to richer systematic conclusions.

In this study, only the static road network's structural fractal and self-similarity analysis was carried out. The source of the structural characteristics of the road network and the geographical driving factors and effects will be carried out in the follow-up study. In addition, in the actual situation, roads often have different road grades and have different importance. Further work should consider the road network's hierarchical and other attribute characteristics to study the road network's fractal structure based on different weight road planning as well as its application in different types of cities.

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