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Fractal dimensions of metropolitan area road networks and the impacts on the urban built environment

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ABSTRACT

The fractal dimension of road networks emerges as a measure of the complexity of road transport infrastructures. In this study, we measured fractal dimensions of both the geometric form (i.e., the layout of the roads) and structure hierarchy (i.e., the connections among roads) of the major road networks in the largest 95 U.S. metro areas. We explained the causes of the variances in these fractal dimensions, especially the one for structure hierarchy. Further, we hypothesized the impacts of these fractal dimensions on the urban built environment and validated our hypotheses using path analysis. We found that a larger geometric fractal dimension (D_g) shows a more uniform distribution of roads over the metro area, which provides the accessibility to suburban areas and incentives to low-density development. A larger structural fractal dimension (D_s) indicates the highly-connected roads (e.g., highways) tend to join to other highly-connected roads so that most roads can be reached by a small number of neighboring roads (i.e., the small-world phenomenon). As D_s increases and the small-world effect become more significant, daily vehicle miles traveled per capita (DVMT/Cap) decline. However, D_s should be kept low in order to reduce the DVMT/Cap as population size increases. We consider that the low D_s can contribute to more mixed, polycentric and more uniform on an urban area-wide basis. Overall, higher D_g and D_s of the major road network in a metro area leads to higher per capita carbon emissions of transport, and lower quality of life as population increases. In the end, we conclude that fractal dimensions can provide valuable insight into the nature of the transportation land use nexus.

1. Introduction

Recent literature has shown that the road transport system is a fractal object, whose form and structure is both essentially irregular, scale invariant and self-similar (Kalapala et al., 2006; Lu and Tang, 2004; Zhang and Li, 2012). Fig. 1 displays the geometric topology and structural architecture of the metro Atlanta road network including freeways, arterials, and collectors. In Fig. 1b of the structural architecture, nodes represent the roads and the links between nodes means the corresponding roads are connected. A fractal dimension D is an index for characterizing fractal patterns by measuring the change in detail in response to the change in geographic scales (Mandelbrot, 1983). There are two types of D measures that have been developed for road networks. One is geometric D (D_g), which can distinguish how more or less uniformly road infrastructure is distributed in 2-dimensional space (Thomas and Frankhauser, 2013). The other measure is structural D (D_s), which was first computed by Zhang et al. to determine the fractal architecture of road networks in terms of how roads are connected with each other over a range of scales (Zhang and Li, 2012).

The D_g and D_s provides an overall measure for the complexity of the road network. The value of D_g is a measure of the space filling capacity of road networks in the two-dimensional space (Batty and Xie, 1996). If the space filling capability is high, the road network tends to occupy the space more uniformly within a given boundary in the two-dimensional space (Thomas and Frankhauser, 2013). Accordingly, the D_g of the road network can be large with an upper limit of two-dimensional (Chen, 2012). Instead, when the space filling capability is low, the distribution of the road network becomes less uniform and the D_g of the road network is small with a lower limit of one. A set of models including diffusion-limited aggregation (DLA) and dielectric breakdown model (DBM) have

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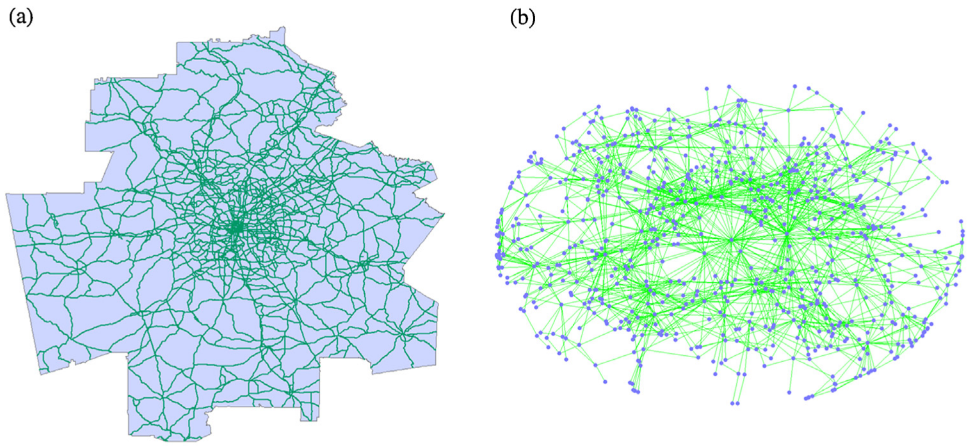

Fig. 1. Geometrical and structural representation of road network in the metro Atlanta: (a) geometrical form; (b) structural representation (i.e., connectivity).

been developed to explain the difference in D_g caused by the space filling capacity (Meakin, 1983; Niemeyer et al., 1984). In terms of the fractal architecture of networks, Song et al. proposed a mechanism for the growth of fractal complex networks (e.g., metabolic network of *Escherichia coli*) (Song et al., 2006). Built upon the findings from Song et al., we will explain the variance of D_s caused by the difference in the mechanism of how we assemble the road network.

The usefulness of D_g and D_s in planning more sustainable road networks and cities depends on the connections between the two fractal dimensions of road networks and the urban built environment. The exploration between fractal dimensions of the road system and urban growth started in 90s, encouraged by Batty and Longley(Batty and Longley, 1994). Thomas and Frankhauser explained the meaning of fractal dimension for built-up areas and the geometrical form of road networks (Thomas and Frankhauser, 2013). The lower ratio of fractal dimensions between built-up areas and the geometrical form of road networks in a certain area indicates where roads are available but the land remains underdeveloped. Abundo et al. investigated how urban population density and growth influences and is influenced by road network infrastructure(Abundo et al., 2013). Results show that cities on more developed continents tend to exhibit higher D_g road networks. This implies that road network infrastructures in more developed cities branches over more orders of magnitude than that in less developed cities. In addition, before the development of D_s of the road network, most studies only investigated the relationship between D_g and urban form (Lu and Tang, 2004; Thomas and Frankhauser, 2013). We will explicitly explain the linkages between D_s and the urban built environment.

In this study, we first made the hypotheses of the impacts of D_g and D_s on the urban built environment and employed path analysis to validate these hypotheses. The path analysis is a useful statistical technique for testing and estimating potentially causal relations (Etminani-Ghasrodashti and Ardeshiri, 2015; Ewing et al., 2014; Nasri and Zhang, 2014). The path analysis allows us to explore the direct and indirect paths between fractal dimensions and the urban built environment. Due to data sparsity, the measures of the urban built environment in this study include urban population density (UPD), per capita daily vehicle miles traveled (DVMT/Cap), annual per capita carbon emissions of transport (TCE/Cap/year), and the quality of life (QoL). We consider that lower TEC/Cap/year and higher QoL are more sustainable. If the effects of D_g and D_s on the urban built environment are statistically significant, we might offer another perspective from D_g and D_s to redesign road infrastructures and improve the urban built environment.

The paper is organized as follows: Section 2 is a brief summary of the theories to interpret D_g and D_s, hypotheses of the impacts of D_g, and D_s on the urban built environment; Section 3 describes the data and methods for calculating the D_g and D_s of road networks and the construction of path analysis; Section 4 represents the results of D_g, D_s and path analysis; Sections 5 and 6 is discussion and conclusion, respectively.

2. Theories and hypotheses

2.1. The theory to explain the change in D_g value of road networks

There are multiple mathematical models including DLA and DBM to understand the process that leads to the emergence of geometrical fractal patterns. The DLA describes the process how particles undergoing a random walk cluster together to form aggregates of particles. The DBM is a stochastic model to simulate dielectric breakdown. Considering the similarity between road expansion and the branching of discharge channels, the DBM is more suitable to understand the space filling capability. In the DBM, the space filling capability is defined as the dependence on local electric field. The low dependence means a high space filling capability of the electrons. If the dependence is low, then the discharge tends to breakdown the area more uniformly. As a result, the D_g of the branches tends to be large. Instead, if the dependence is high, the distribution of branches is less uniform and the D_g tends to be small. We can borrow the same underlying factor of dielectric breakdown to understand the geometric form of road infrastructure systems. The space filling capability of road infrastructures implies some dependences on local conditions, which might be caused by land use constraints, policies and economic development.

2.2. Hypotheses of the impacts of D_g on the urban built environment

A larger D_g represents a more uniformly distributed network. Because of the increasing supply of roads which provides accessibility to suburban areas and incentives to low-density development, we hypothesize that the UPD will decline as D_g increases. However, the negative impact of D_g on UPD can be mitigated as population increase and fill up the metro area. Meanwhile, although the supply of road infrastructures in the suburban areas increases in the case of a large D_g, housing and population density may not reach the same level as it does in more central urban areas and therefore the incentive for suburban shopping, foods, and other recreational