Spatial analysis and modeling of urban transportation networks

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Abstract

Transport systems in general, and urban transportation systems in particular, are the backbone of a country or a city, therefore play an intrinsic role in the socio-economic development. There have been numerous studies on real transportation systems from multiple fields, including geography, urban planning, and engineering. Geographers have extensively investigated transportation systems, and transport geography has developed as an important branch of geography with various studies on system structure, efficiency optimization, and flow distribution. However, the emergence of complex network theory provided a brand-new perspective for geographers and other researchers; therefore, it invoked more widespread interest in exploring transportation systems that present a typical node-link network structure. This trend inspires the author and, to a large extent, constitutes the motivation of this thesis.

The overall objective of this thesis is to study and simulate the structure and dynamics of urban transportation systems, including aviation systems and ground transportation systems. More specifically, topological features, geometric properties, and dynamic evolution processes are explored and discussed in this thesis. To illustrate different construction mechanisms, as well as distinct evolving backgrounds of aviation systems and ground systems, China’s aviation network, U.S. airline network, Stockholm’s street network, Toronto’s street network, and Nanjing’s street network are respectively studied and compared.

Considering the existence of numerous studies, a clear and comprehensive literature review in this field is presented as the first step. Most studies on transport systems from the complex network perspective published within the last decade are reviewed and summarized. It is found that a majority of the studies focused on topological features of transportation systems, however geometric properties have not earned sufficient attention. On the other hand, since there is a long history of transportation systems and limited availability of related data, it is difficult for researchers to develop empirical evolution analyses on real transportation systems; instead, computer simulations based on mathematical reasoning are considered as the most widely used way to depict evolution features of transport systems. These findings lay the foundation of the author’s thesis research.
world structure and a double Pareto distribution regardless of sizes and socio-economic states. A hierarchical structure is also detected for aviation systems of China and the US.

To study the geometric properties, the famous gravity model is introduced to detect the distance effect in aviation systems. It is found that a logarithmic hyperbolic model can better depict the distance decay effect than a power law model. In addition, the distribution patterns of the spatial distance of aviation systems and ground systems are explained. Spatial patterns of street networks in different urban development schemes are discussed and compared as well. Self-organized cities show more heterogeneity in both measures. In comparison, Toronto presents a single peak distribution for the cell area. The distribution of closeness centrality, which is regarded as a measure of accessibility, clearly depicts that the strictly planned city is better accessed from the overall perspective.

A static perspective is far from enough to understand and model transportation systems. The evolution process is an essential supplement to depict underlying features of complex systems. To further study network growth modeling, a model for the evolution of aviation systems is proposed. Both topological and geometric features are examined in the evolution process. The model suggests that the bigger the weight coefficient is, the slower the network efficiency decreases. The empirical analysis about the U.S. airline network during 1990–2010 is also developed to validate this model.

The main contributions of this thesis can be summarized as follows. First, it provides a comprehensive review of complex network topology of transportation systems for researchers from different backgrounds. It not only lists the research results from various subjects, but it also bridges and compares the results from different viewpoints and angles, which is necessary to explore this interdisciplinary topic. Moreover, a spatial perspective constitutes the main focus of this thesis, trying to bridge the traditional geographic analysis and complex network theory. Lastly, empirical analyses are developed to explore the evolving process of transportation systems, providing a valuable baseline for theoretical simulations in this field. However, as mentioned above, the spatial structures are preliminarily explored in this work, and more efforts are expected in the near future. On the other hand, this work is generally driven by data analysis and computer simulation. Although these approaches are effective to analyze and model transportation systems, more real-world factors, such as urban development variables and spatial constraints, should be considered in further studies from a geographic perspective.

Key Words
Complex networks, transportation systems, network growth, Evolving networks, centrality, urban systems, topology, space syntax, spatial networks, distance effects, gravity laws, planarity, street network patterns, US airline system, China’s aviation system, network efficiency, cellular structure, hierarchy, network representations