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Topological evolution of surface transportation networks

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ABSTRACT

This study explores the topological evolution of surface transportation networks, using empirical evidence and a simulation model validated on that data. Evolution is an iterative process of interaction, investment, and disinvestment. The temporal change of topological attributes for the network is also evaluated using measures of connectivity, density, heterogeneity, concentration, and connection patterns. The simulation model is validated using historical data from the Indiana interurban network. Statistical analyses suggest that the simulation model performs well in predicting the sequence of link abandonment in the interurban network as well as the temporal change of topological attributes. The simulation model is then applied on different idealized network structures. Typical connection patterns such as rings, webs, hub-and-spokes, and cul-de-sacs emerge in the networks; the spontaneous organization of network hierarchies, the temporal change of spacing between parallel links, and the rise-and-fall of places in terms of their relative importance are also observed, providing further evidence for the self-organization property of surface transportation networks.

1. Introduction

Scientific interest in the structure of complex networks have been aroused by the observation of a power-law distribution in a variety of so-called "scale-free" networks, such as the World Wide Web, metabolic networks, citation networks, and the network of human sexual contacts (Albert, Jeong, & Barabasi, 1999; de Solla Price, 1965; Jeong, Gombor, Albert, Oltwai, & Barabási, 2000; Liljeros, Edling, Amaral, Stanley, & Aberg, 2001). As the physics community became interested in surface transportation networks, however, it was recognized that they exhibit topological attributes that differ from other classes of networks: Csányi and Szendröi (2004) demonstrated a clear dichotomy between large real-world networks which are small worlds with exponential neighborhood growth, and fractal networks with a power-law distribution. Typical examples of the latter are networks with strong geographical constraints, including power grids and surface transport networks; Gastner and Newman (2006), revealing that the structure of geographical networks are distinct from non-geographical ones, provided a connection between the two classes of networks in that they both can result from the same optimization model with one parameter varied. Specifically, Montis (2006) studied the interurban commuting network of the Sardinia region in Italy, and disclosed that the statistical properties of traffic structure exhibit complex features and non-trivial relations with the underlying topology; Jiang and Claramunt (2004) and Jiang (2005, 2007), after analyzing the street–street intersection topology (in which all named streets are represented as nodes, while street intersections as links) of urban street networks across North America and Europe, found that urban street networks exhibit a scale-free property characterized by a connectivity distribution with a power-law regime followed by a cutoff. The scale-free property with street topologies further suggests that "street networks or street topologies are self-organized" from an evolutionary perspective; Lämmer, Gehlsen, and Helbing (2006) analyzed urban road networks of the 20 largest cities in Germany and discovered scaling of several aspects of the networks, such as the number of nodes reachable within a travel time budget, which were only known for non-spatial networks. While the main efforts have been put to describe the topological dynamics of the networks in statistical physics (Barabasi & Albert, 1999; Dorogovtsev & Mendes, 2002), it remains unclear how surface transportation networks could spontaneously evolve into unique topological patterns as they grow and decline over time.

This question unavoidably requires an evolutionary view. The analysis and modeling of the evolution of transportation networks has been the subject of interest for more than half a century, and the literature has followed the following three main streams.

During the early days of the quantitative geography regional science economic geography movement, a few studies modeled the structural transformation of surface transportation networks. Kansky (1969) developed a quantitative predictive model of network structure and applied it to the Sicilian railroad. Taaffe, Morrill, and Gould (Taaffe, Morrill, & Gould, 1963) proposed a four-stage model to describe the process of road network development in an

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undeveloped country. Garrison and Marble (1962) simulated the changing topology of the Northern Ireland railroad system between 1830 and 1930 using Monte Carlo methods, while Morrill (1965) reported parallel studies on the rail networks of central Sweden. These studies simply replicated the observation of network topologies using heuristics, while not taking into consideration inherent demographic and behavioral mechanisms that drive the evolution of transportation networks, largely due to limited data and computing abilities at that time. This stream of studies remained dormant for the following 30 years.

The attempts to extract or generate the optimal structure of networks represent another strand of evolutionary studies. Gastner and Newman (2006) presented an optimization model to minimize the cost of building and maintaining a network. Optimized network structures were able to replicate the qualitative features of the networks with or without spatial constraints, with one parameter in the cost function varied. Barthélemy and Flammini (2006) proposed a model of traffic networks via an optimization principle. The topology of the optimal network turns out to be a spanning tree and, by changing model parameters, different classes of trees are recovered. Schweitzer, Ebeling, Rose, and Weiss (1998) investigated the evolution of road networks during the optimization process by which a minimized travel detour is compromised with a minimized cost of constructing and maintaining roads. In the field of transportation planning, the prevalence of travel demand forecasting models since the 1970s made it possible to predict traffic flows on a transportation network in a more realistic way, thereby enabling the investigation into the optimal network structure that maximizes the efficiency of travel. In recent years, the travel demand model has been widely adopted to solve the network design problems (LeBlanc, 1975; Yang & Bell, 1998), which derives the design of an optimum amount of transportation supply given the constraints of limited resources. Optimization studies have made significant contributions in predicting travelers' route choice behaviors at the demand level and optimal network structures at the supply level. These studies, however, assume changes to networks are made by a central authority subject to an explicit objective function, neglecting the continuous interplay between decision-makers, suppliers, and users with independent interests, which has served an essential role in shaping the structure of transportation networks from a long-term point of view. Moreover, little empirical evidence has been provided to show that the sequential deployment of transportation networks actually follows an optimal design.

In contrast to optimization, the concepts of agent-based interaction and self-organization have been introduced to interpret the evolution of various complex systems (Barabási, 2002; Newman, 2003). Agent-based simulation also found its application to interpret the formation of surface transportation networks based on simple individual travel behaviors. Lam and Pochy (1993) proposed an active-walker model (AWM) to describe the dynamics of a landscape, in which walkers as agents moving on a landscape change the landscape according to some rule and update the landscape at every time period. Helbing, Keltsch, and Molnr (1997) adopted the active walker model to simulate the emergence of trails in urban green spaces shaped by pedestrian motion. Starting from a homogenous ground, frequently used trails got reinforced since they are chosen by pedestrians more while rarely used trails withered. Consequently, the trails bundled and emerged into different patterns, which the authors claimed "reproduce many of the observed large-scale spatial features of trail systems." In recent years, limited efforts have been put to model the evolution of large-scale transportation networks employing agent-based simulation, bringing out some interesting findings regarding the emergent topological features of the networks studied. Yamins, Rasmussen, and Fogel (2003) presented a simulation of road growing dynamics on a land use lattice that generates global features as beltways and star patterns observed in urban transportation infrastructure, which however did not consider the dynamics of traffic flows. Yerra and Levinson (2005) and Levinson and Yerra (2006) demonstrated that a transportation network with a fixed structure can differentiate into a hierarchical structure from either a random or a uniform state, suggesting that the hierarchy of roads, rather than necessarily following an optimal design, is an emergent property of network and traffic dynamics.

To summarize the literature, network scientists have widely recognized that surface transportation networks, though different from non-spatial ones, also exhibit scale-free properties, suggesting surface transportation networks could be self-organized, although little evidence has been provided in this regard. Efforts to model the evolution of transportation networks have ranged from geographical studies that aim to replicate network geometries based on intuitive and heuristic rules, optimization studies that predict optimal network designs subject to an explicit objective function, to simulation studies that model network formation employing agent-based methods. These efforts, however, have been limited in three folds: first, with a few exceptions, many studies impose a top-down design of network structure, thereby neglecting the self-organization process that may drive the formation of transportation networks; second, the structural transformation of a network is not associated with a broader context that allows for the interactions between demand (travelers) and supply (infrastructure); third, little empirical evidence has been provided for the claim that existing models can replicate the topological change of transportation networks observed in reality.

The aim of this study is to fill these gaps. Differing from previous studies, our analysis implements a variable network topology in a spontaneous process of demand–supply interaction based on decentralized local optimal decisions. Another main contribution of this study is to validate the model against empirical facts extracted from historical observations and apply it to idealized networks, providing both empirical and simulation evidence for the self-organization property of surface transportation networks.

The rest of the paper takes the following form: we first introduce a simulation model that incorporates individual links as independently operating agents. While the weakest member in the network is shuttered, it enables a variable network topology forming from a bottom-up process. This is followed by a validation of the model using historical data from the Indiana interurban network. Then experiments are outlined applying the simulation model on idealized networks, and results presented. The conclusion summarizes our findings and indicates future directions.

2. Simulation model

The temporal development of a surface transportation network can be viewed as a degeneration process: starting from an underdeveloped area where all point-to-point paths can be used, those paths which are more valuable are reinforced while less used ones shrink and are finally abandoned. Taking road infrastructure as an example, while dirt trails and turnpikes built in the early stage of surface transportation disappeared on less used routes (such as those connecting villages to villages), those on valuable routes (such as those connecting towns to villages and to other towns) survived and were replaced by paved roads, some of which may be further upgraded into into arterial, highways or freeways. If our focus were on paved roads rather than the whole spectrum of road infrastructure, we would observe a network of paved roads that gets increasingly connected through time until they are replaced by infrastructure constructed with a newer technology. In this sense, the degeneration process represents the same "growth" process of transportation networks we have observed in reality.