

The Evolution of Transportation Networks

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ABSTRACT

Transportation network planning decisions made at one point of time can have profound impacts in the future. However, transportation networks are usually assumed to be static in models of land use. A better understanding of the natural growth pattern of roads will provide valuable guidance to planners who try to shape the future network. This paper analyzes the relationships between network supply and travel demand, and describes a road development and degeneration mechanism microscopically at the link level. A simulation model of transportation network dynamics is developed, involving iterative evolution of travel demand patterns, network revenue policies, cost estimation, and investment rules. The model is applied to a real-world congesting network – the Twin Cities transportation network which comprises nearly 8,000 nodes and more than 20,000 links, using network data collected since year 1978. Four experiments are carried out with different initial conditions and constraints, the results from which allow us to explore model properties such as computational feasibility, qualitative implications, potential calibration procedures, and predictive value. The hypothesis that road hierarchies are emergent properties of transportation networks is confirmed, and the underlying reasons discovered. Spatial distribution of capacity, traffic flow, and congestion in the transportation network is tracked over time. Potential improvements to the model in particular and future research directions in transportation network dynamics in general are also discussed

General Terms

Algorithms, Management, Measurement, Performance, Design, Economics, Reliability, Experimentation,

Keywords

Transportation network dynamics, Urban planning, Road supply.

1. INTRODUCTION

In 1900 there were 240 km of paved road in the United States, and this total had increased to 6,400,000 by 2000 with virtually 100% of the U.S. population having almost immediate access to paved roadways. The growth (and decline) of transportation networks obviously affects the social and economic activities that a region can support, yet the dynamics of how such growth occurs is one of the least understood areas in transportation, geography, and regional science. This lack of understanding is revealed time and again in the long-range planning efforts of metropolitan planning organizations (MPOs), where transportation network change is treated exclusively as the result of top-down decision-making. Non-immediate and non-local effects are generally ignored in planning practices because the complete network effects are

incomprehensible with the current tools, which often results in myopic network expansion decisions. If one looks at the complexity and bureaucracy involved in transportation infrastructure investment, one might conclude that it is impossible to model the transportation network dynamics endogenously. However, changes to the transportation network are rather the result of numerous small decisions (and some large ones) by property owners, firms, developers, towns, cities, counties, state department of transportation districts, MPOs, and states in response to market conditions and policy initiatives. Though institutions make network growth (decline) happen on the surface, network dynamics are indeed driven by some underlying natural market forces and hence predictable. Understanding how markets and policies translate into facilities on the ground is essential for both scientific understanding and improving forecasting, planning, policy-making, and evaluation.

A transportation network is a complex system that exhibits the properties of self-organization and emergence. Previous research in dynamics related to transportation networks focuses on traffic assignment or traffic management. However, the dynamics of transportation network growth have not been adequately studied. If a transportation network is represented by a directed graph, there are several important questions yet to be answered: (1) How do the existing links (roads) develop and degenerate? (2) How are new links added to the existing network? (3) How are new nodes added to the existing network? This paper concentrates on the first question and focuses only on the rise and fall of existing roads, recognizing the inter-dependence of road supply and travel demand. The approach is microscopic in that network dynamics are modeled at the link level. The following key questions are examined:

- (1) Why do links expand and contract?
- (2) Do networks self-organize into hierarchies?
- (3) Are roads (routes) an emergent property of networks?
- (4) What are the parameters to be calibrated in a microscopic network dynamics model?
- (5) Is the model computationally feasible on a realistic transportation network?
- (6) Is the model capable of replicating real-world network dynamics?

One of the few previous studies (Yerra and Levinson 2005) in this area shows that even starting from a random or an uniform pattern, a transportation network tends to self-organize into a hierarchical pattern in which some roads attract more traffic, receive proper maintenance, and are gradually expanded, while some other roads are less popular, poorly maintained, and may eventually be abandoned. It is also demonstrated that although these hierarchies seem to be designed by planners and engineers,

they are actually intrinsic emergent properties of networks themselves. However, the simulation model developed in that study is restricted in several ways. First, the links are assumed to have unlimited capacities. The impacts of network congestion on travel demand are ignored. The assumption also results in another unrealistic property of the model - the growth and decline of links are only reflected by changes of their free-flow speeds. Secondly, their model is tested only on simple hypothetical networks and it is not clear if the conclusions regarding road hierarchies hold on large-scale realistic networks. Those two restrictions are relaxed in this study. Travel demand is represented by a more realistic user equilibrium pattern. In the network evolution process, links exhibit dynamics in both free-flow speed and capacity. The improved model is then applied to the Twin Cities transportation network with nearly 8,000 nodes and more than 20,000 links, which allows us to examine computational properties and predictive value of the proposed microscopic network dynamics model.

The next section presents a brief review of related literature in regional science and economics. Though the reviewed studies have dissimilar objectives and methodologies, they all shed some lights on the nature of transportation network growth and its social-economical impacts. The paper then develops a theoretical framework for studying the rise and fall of roads. The framework helps identify various influencing factors and inter-dependences among those factors, based on which a synthesis model of road expansion and contraction. The model is applied to the Twin Cities transportation network from year 1978 to 1998 with different model parameters and starting conditions. Conclusions and future research directions are offered at the end of the paper.

2. BACKGROUND

Few researchers have considered the process of transportation network growth at microscopic level, highlighting the importance of this research. Taaffe et al. (1963) study the economic, political and social forces behind infrastructure expansion in underdeveloped countries. Their study finds that initial roads are developed to connect regions of economic activity and lateral roads are built around these initial roads. A positive feedback between infrastructure supply and population was also observed. Barker and Robbins (1975) investigated the London Underground's growth, but did not develop a theoretical framework as we are considering here. Miyao (1981) developed macroscopic models to take transportation improvements as either an endogenous effect of urban economy or as an exogenous effect on the economy. Endogenous growth theory suggests that economic growth is a two-way interaction between the economy and technology; technological research transforms the economy that finances it (Aghion and Howitt 1998). The technology of transportation is unlikely to be an exception, suggesting transportation investment drives the growth that funds it. Macroscopically, the growth of infrastructure follows a logistic curve and that road infrastructure also has reached saturation levels in developed countries (Grübler 1990). Miyagi (1998) proposes a Spatial Computable General Equilibrium (SCGE) model interacting with a transportation model to study the interaction of transportation and the economy. Yamins et al. (2003) develop a road growth model to study co-evolution of urban settlements and road systems from an empty space with

highly simplified travel demand and road supply mechanisms meaningful only for theoretical works.

Geography's central place theory seeks to explain how hierarchies of places develop (Christaller 1966). Models developed by Batty and Longley (1985), Krugman (1996), and Waddell (2001) consider land use dynamics, allowing central places to emerge. However, those models take the network as given. Clearly, there is a need for research that makes the network the object of study. In many respects, the hierarchy of roads is the network analogue of the central place theory.

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