Chapter 2
Background

The city of Königsberg, Germany was set on both sides of the Pregel River. As shown in a sketch map of the city (Figure 2.1(a)), seven bridges across the river connected two large islands and the mainland to one another. The people of Königsberg wondered whether or not one could walk around the city in a way that would involve crossing each bridge exactly once. Euler approached this problem by collapsing areas of land separated by the river into points (Figure 2.1(b)), and representing bridges as curves (Figure 2.1(c)). In modern graph theory, points are often referred to as vertices and curves as edges. Euler observed that (except at the endpoints of the walk) whenever one enters a landmass by a bridge, one leaves the landmass by a bridge. In other words, during any walk in the graph, the number of times one enters a non-terminal vertex equals the number of times one leaves it. Now if every edge is traversed exactly once (except for the ones chosen for the start and finish), the number of edges touching a vertex is even (half of them will be traversed "toward" the vertex, the other half "away" from it). However, all four land masses in the original problem are touched by an odd number of bridges (one is touched by 5 bridges and the other three by 3). Since at most two land masses can serve as the endpoints of a putative walk, the existence of a walk traversing each bridge once leads to a contradiction.

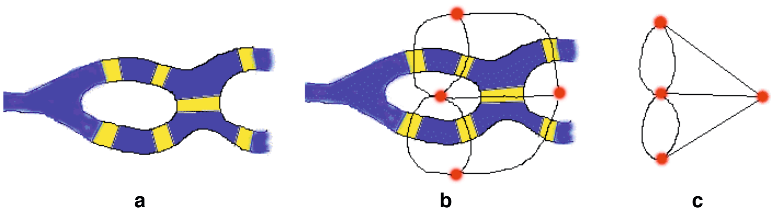

Fig. 2.1 The seven bridges of Königsberg. Source: Math Forum (2010)

F. Xie, D. M. Levinson, *Evolving Transportation Networks*,
Transportation Research, Economics and Policy,
DOI 10.1007/978-1-4419-9804-0_2,

The classical problem of the seven bridges of Königsberg introduced perhaps the first transportation network in a scientific sense. Since then there has been a long-established interest for scholars and professionals in gaining a greater understanding of transportation networks. Of particular interest for this book is the temporal changes of transportation network systems. The literature that discusses this subject has been prolific. Three comprehensive historical reviews, for example, came from Fullerton (1975), who introduced the development of British transportation networks, Taaffe et al. (1996), who outlined the evolution of the U.S. transportation systems, and Garrison and Levinson (2006), who examined transportation experience in the past centuries from the perspectives of transportation policy, planning, and deployment.

Despite the fact that the growth of transportation networks is complicated and multidimensional, and its duration is usually measured in decades, it may still be tractable and predicable with a further understanding of its underlying mechanisms. Under this belief, sustained efforts have been put in the modeling and analysis of transportation networks in a range of fields from geography, regional science, economics, network science, and urban planning, to transportation engineering.

Previous studies have mainly followed five streams.

- In the 1960s and 1970s, geographers viewed network growth as topological transformation, aiming to either extract the process of structural changes or replicate the emergent topologies of transportation networks.
- Since the 1970s, the prevalence of travel demand forecasting models has provided transportation planners and economists with an effective tool for predicting traffic flows on a network and modeling the optimal changes to the network, with the belief that network growth is the result of rational decisions by jurisdictions, property owners, and developers in response to market conditions and policy initiatives.
- Recent large-scale statistical analyses, made possible by the availability of sufficient historical geographic data and increasing data processing ability, related the temporal change of transportation supply (the presence or absence of infrastructure, change in service frequency or capacity, etc.) to the demographic and socioeconomic characteristic of tributary areas, as well as traffic conditions and other attributes of infrastructure.
- The economics of network growth had examined the formation and growth of a wide array of networks, and explored the growth of transportation networks in particular from various perspectives such as traditional transportation economics, urban economics, fiscal federalism, public economics, network effect, path dependence, and coalition formation.
- Since the “new network science” came onto the scene in the 1990s, interest has emerged in introducing the concepts of preferential attachment and self-organization, and the technique of agent-based simulation to model the evolution of a transportation network as a spontaneous process, by which independent initiatives and behaviors of individual travelers, providers, and regulators play out collectively into transportation development.

This chapter surveys this substantial body of studies with a particular focus on modeling and quantitative analysis. The next five sections introduce the five main streams of studies. The last section summarizes their subjects, methods, and connection rules.

2.1 Transportation geography

Transportation networks are commonly simplified as graphs with elementary components retained: nodes indicate centroids of human settlements (places), facilities, and intersections of routes; links represent segments of infrastructure or service routes; flows represent the actual patterns of movement on networks. It was not until 1962 that Garrison and Marble (1962) introduced graph theory to the study of transportation networks in the fields of geography, regional science, and urban studies (Lowe and Moryadas, 1975). During the heyday of the economic geography / regional science movement in the 1960s and 1970s, a few studies were conducted by geographers to model the growth of transportation networks in terms of their structural transformation and topological changes. The most comprehensive outlines of these are found in Haggett and Chorley (1969) and in Lowe and Moryadas (1975).

Attempts have been made to model the continuous growth of transportation networks in a series of discrete stages. Taaffe et al. (1963) proposed a four-stage model to describe the sequential process of road network development when colonial exploitation proceeds from the coastal baseline to the inland area in an underdeveloped country. The model is illustrated in Figure 2.2, where dots represent places while lines represent roads that connect these places. Size of dots and boldness of lines represent relative scale of places and roads, respectively. As shown in Figure 2.2, scattered ports with equally small size are located along the coast of a colonial region (A); later on, penetration lines are built from interior to reach selected ports (B); connected ports and inland feeders then develop because of the growth of inland trading (C); as more links are built to interconnect developed nodes, links are also differentiated and important links emerge (D). Pred (1966) applied the Taaffe model to Atlantic seaboard of the United States, while Rimmer (1967) applied the model to the South Island of New Zealand. Lachene (1965) developed a staged model of network development on a hypothetical isotropic transportation network. The model starts with a network of dirt trails and a more or less uniform distribution of economic activity. As towns form at some intersections, a road network is built to link these settlements. While some trails become paved roads, some less used links are abandoned in the countryside when economic activities concentrate in the urban centers. Finally a superior network, perhaps a railroad or a freeway, emerges connecting the urban centers.

Another strand of geographical studies, rather than describing network growth in stages, constructed models that would replicate observed network patterns. Garrison and Marble (1962) described their attempts to simulate the changing topology of the Northern Ireland railroad system between 1830 and 1930 using Monte Carlo sim-

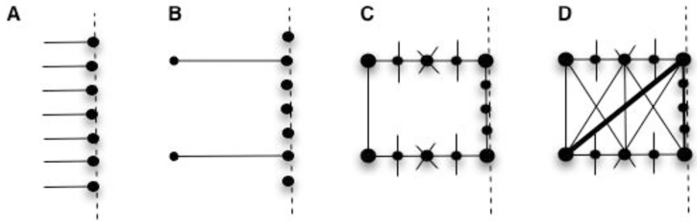

Fig. 2.2 An illustration of the four-stage model of network growth

ulation methods, while Morrill (1965) reported parallel studies on the rail network of central Sweden. Kansky (1963) developed a quantitative predictive model of network structure and applied it to the Sicilian railroad. He selected 16 settlements in Sicily which by 1908 would have been on the railroad network in a random process among 30 major settlements in this region. The first link is added to connect the two largest centers and then links are gradually added such that the next largest center joined the largest and closet center in the network. Kolars and Malin (1970) modeled the development of the Turkish railroad network employing an approach different from node connection, by which transportation links emerge on major ridge lines as defined by a population-accessibility surface. Black (1971) conceived of the railroad network in Maine as a tree branching out from Portland, growing outward to connect outlying peripheral nodes. The possibility of constructing a link is calculated as a function of potential revenue, construction cost, with a constraint of the angle of the link. The presence or absence of a link between a pair of vertices at a particular time is determined by whether the score exceeds a threshold.

While these studies provide insight into the structural change of transportation networks, they had to deal with simple networks using heuristic and intuitive rules for network growth and transformation, due to the lack of understanding on the inherent mechanisms with regard to why and how transportation networks evolve. Based on a review of these contemporary studies, Haggett and Chorley (1969) found that they were “somewhat fragmentary”, and suggested that “a general theory of network growth lies in future research”. The study of the growth of transportation networks remained largely dormant for the following thirty years.

2.2 Optimization and network design

In the late 1950s, Dr. J. Douglas Carroll, Jr. initiated an effort in the Chicago area to seek an optimal solution to investment in roads in terms of minimizing the total cost of road investment, users travel time, operating costs and accident costs. He and his team devised a sequence of forecasting methods to forecast the amount of personal travel that would occur on a typical weekday in 1980 by road and transit, and derived an expressway spacing formula to work out the extent and layout of the system of expressways and arterial roads to serve the existing and perspective pattern of urban activities. Boyce (2007) provides an account of this pioneering effort. The Chicago Area Transportation Study (CATS) soon became known worldwide as the premier example of travel demand forecasting for urban areas (Sheffi, 1985; Ortuzar and Willumsen, 2001). The prevalence of travel demand models enabled the prediction of traffic flows on transportation networks in a realistic way, and led to the marked revival of the interest in modeling the evolution of transportation networks.

Traffic flow plays an essential role in driving network growth. Newell (1980) and Vaughan (1987) examined traffic flows in shaping various network geometries. From a more practical perspective, Ewing (2000) proposed a sketch planning methodology to determine the optimal spacing of through streets that accounts for changes in mode share, trip length, time of travel, and intersection capacity as residential density increases. Vitins and Axhausen (2010) explored the generation of optimal network designs from a featureless plane using pre-existing network patterns and grammars.

In the last two decades, solution algorithms to user equilibrium enable the derivation of traffic flows across transportation networks, and have been widely incorporated to solve the network design problems (NDP) (LeBlanc, 1975; Yang and Bell, 1998). Typically the NDP is formulated as a bi-level framework in which the lower-level represents the demand-performance equilibrium for given investment while the upper level represents the investment decision-making of the transportation planner to maximize social welfare based on the unique equilibrium flow pattern obtained from the lower-level problem. A continuous NDP problem deals with the optimal capacity expansion of existing links while a discrete NDP derives the design of an optimum amount of transportation supply by changing the actual topology of the network, that is, by adding or removing links. Constrained by computational ability, the choice set of discrete changes has been limited to a small size.

If the NDP were how decisions are made, network changes would be due to planners' rational behaviors to maximize the efficiency of a given network, which has to be measured according to some quantifiable objective based on predicted traffic with budgetary and other constraints. When various factors come into play in reality, however, objectives may be ambiguous and decisions may be made with uncertainty. Curry (1964) claimed that while every locational decision may be optimal from a particular point of view, the resulting actions as a whole may appear to be random. Because of spatial lock-in, transportation networks may have a locational stability which is greater than individual components making up these networks. From the perspective of transportation economics, Zhang and Levinson (2007) argued that the NDP perspective simplified a network growth problem in three aspects: top-down investment decisions are considered independent of decentralized pricing and regulatory structures; only optimal investment rules are considered; and inter-dependencies of sequential decisions are ignored. Bertolini (2007), observing that conventional planning approaches do not adequately account for the irreducible uncertainty of future developments, proposed an evolutionary approach of urban transportation planning to address how individual decisions and actions could eventually accumulate into development processes which are both path dependent and unpredictable.

2.3 Empirical models of network growth

In the past, although statistical analysis had been widely used in regional science and transportation studies, it found limited application in analyzing the growth of transportation networks, largely due to the scarcity of historical data. Not until the last decade, with the availability of sufficient data and increasing data processing ability, especially powered by Geographic Information Systems (GIS), cross-sectional time-series analysis has seen widespread application to investigate the temporal change of transportation supply based on historical observations on a regional level.

The relationship between transportation supply (network) and demand (land use) has been widely examined as a two-way process by which one is the driver of the other. Early work by Gaudry (1975) and Alperovich et al. (1977) employed simultaneous equations to examine the mutual causality of transit demand and supply. Extending their research, Peng et al. (1997) developed a simultaneous route-level transit ridership model and estimated the model using the data from the Tri-County Metropolitan Transportation District of Oregon (Tri-Met) service area. The results indicate that simultaneity exists between transit demand and supply, especially the service supplied is influenced by the past ridership and current demand. Taylor and Miller (2003), on the other hand, accounted for the simultaneity between transit demand and supply using a two-stage least squared (2SLS) regression method. Cervero and Hansen (2002) employed a simultaneous equations system to estimate both vehicle miles traveled and lane miles of supply, suggesting that the relationship is two way, and that similar forces are at work affecting changes in both travel demand and infrastructure supply. Levinson (2008*a*) examined the mutual causality between the changes that occurred in the rail network and density of population in London. With panel data representing the 33 boroughs of London from 1841 to 2001, models were estimated using the panel corrected standard errors (PCSE) procedure and results disclosed the spatial co-development of rail networks and population in London. Levinson and Chen (2005) employed a Markov Chain Model to analyze the spatial co-evolution of transportation and land use for the Minneapolis-St. Paul Metropolitan Area from 1958 to 1990. A transition matrix records the interaction between transportation and land use and is used to predict the future development of transportation and land use.

Treating land use as exogenous, Mohammed et al. (2006*a*) explicitly modeled the temporal change in transit supply. In their attempt to model the changes that occurred over a 15-year period in the bus network of the City of Missisauga, Toronto, they employed multiple regression and simultaneous equation models to relate transit supply (measured by bus frequency) to a group of demographic, socioeconomic, and route-specific variables. In a subsequent study, they further introduced artificial intelligence to account for the behavior of transit agencies and simulate the growth of transit routes (Mohammed et al., 2006*b*). At a microscopic level, Levinson and Karamalaputi (2003*a*,*b*) examined in two parallel studies the expansion and new construction of a network, respectively, based on the present conditions of the network, traffic demand, demographic characteristics, project costs, and a budget constraint. Binary logit (and mixed logit) models were used to associate the expansion and new construction of each link with historic data including physical attributes of the network, their expansion and construction history and AADT values on each of the links. Levinson and Chen (2007) developed an area-based model of highway growth; binary logit models were adopted to estimate the new route growth probability of divided highways and secondary highways using high-quality GIS data of land-use, population distribution, and highway network for the Twin Cities Metropolitan Area from 1958 to 1990.

Another stream of empirical studies was focused on the correlation between the development of transportation networks and changes in collective network features. Blumenfeld-Lieberthal (2009), for instance, measured the concentration of modern air and rail transportation networks in Germany, Italy, Poland, the United Kingdom, and the United States and associated the connectivity of the network (measured by a clustering coefficient) with economic growth and GDP. Erath et al. (2009) investigated the development of the Swiss road and railway network during the years 1950-2000 using an array of topology, centrality, and local efficiency measures, and showed that the freeway network has become less tree-like (and thus more connected) over time, and similarly has become more efficient over this period. El-Geneidy et al. (2011), examining the historical growth of Montréal's indoor pedestrian network, calculated changes in the level of access to retail space, and indicated access to retail and public transit had a major impact on the growth of the Indoor City. Atack and Margo (2011) studied the impact of access to rail transportation on agricultural improvement using the American Midwest in 1850-1860 as a Test Case. Using a GIS-based transportation database linked to county-level census data, they estimated that at least a quarter of the increase in cultivable land can be linked directly to the coming of the railroad to the Midwest.

2.4 Economics of network growth

Economists have examined the formation and growth of a wide array of networks (social, industrial, tele-communication, physical infrastructure, etc.) from various perspectives of supply, demand, benefit, cost, financing, regulation, information, externalities, and so on. While transportation economics has widely introduced traditional supply-demand theories to address contemporary transportation issues, there are other aspects of economics that have been revealed to be essential to network growth, but have not yet seen application to the modeling and analysis of transportation networks. Examples include urban economics, fiscal federalism, network effect, path dependence, and coalition formation. This section surveys these branches in turn.

2.4.1 Transportation economics

Transportation economists have introduced traditional supply-demand theories to investigate a wide range of transportation issues such as congestion, pollution, road pricing, and project evaluation (Gómez-Ibáñez et al., 1999). For the purpose of this book, of particular interest is the investment in transportation infrastructure networks under alternative pricing and regulatory regimes. Quantitatively, this issue has been approached from two directions. Theoretical exploration focused on the endogenous choice of prices, investment, and ownership on transportation networks. Because of the computational complexity associated with large-size networks, this analysis has been largely focused on small networks with one Origin-Destination pair and two or more alternative routes (Button, 1998; de Palma and Lindsey, 2000; Verhoef et al., 1996; Verhoef and Rouwendal, 2004; Borger et al., 2005; Zhang and Levinson, 2007) or with stylized network geometries (Levinson, 2002). Empirical studies, on the other hand, were able to examine the financing of transportation networks of larger scales using econometric methods, with a primary focus on the relationship between the performance of transportation systems, economic / demographic characteristics of tributary regions, and the allocation of funds or decision-making power across regulatory hierarchies (Humplick and Moini-Araghi, 1996*b*,*a*; Levinson and Yerra, 2002).

2.4.2 Urban economics

A stream of urban economic studies has examined the evolution of urban space including transportation as one of the determining factors. The pioneering work by von Thünen (1910) presented a monocentric city surrounded by agricultural land and predicted the rent and land use distribution for competing socio-economic groups. Christaller (1933) introduced Central Place Theory and demonstrated that a hierarchy of central places will emerge on a homogeneous plain to serve the surrounding market while minimizing transportation costs. Krugman (1996) explored the phenomenon of self-organization in urban space. He developed an edge city model to demonstrate how interdependent location decisions of businesses within a metropolitan area could lead to a polycentric pattern under the tension between centripetal and centrifugal forces. Based on these theoretical investigations, a host of empirical land use-transport models have been developed to forecast land use development while considering transportation as an important factor. One of the first that gained substantive interest was the Lowry model (Lowry, 1963). Since the 1980s, many integrated land use models have seen applications in urban planning for real cities and some have been developed into commercial packages. Examples include START (Bates et al., 1991), LILT (Mackett, 1983, 1990, 1991), and URBANSIM (Alberti and Waddell, 2000). Comprehensive reviews of these integrated land use-transport models have been provided by Timmermans (2003) and Iacono et al. (2008). As evidenced by both theoretical and empirical studies of urban development (Hansen, 1959; Guttenberg, 1960; Huff, 1963; Murayama, 1994; Ahlfeldt and Wendland, 2010), the dynamics of urban space has been played out as the outcome of the location decisions made by residents, developers, and business owners, in which accessibility to land use activities such as employment and residence play essential roles.

2.4.3 Fiscal federalism

It has long been observed that the development of all transportation modes has been affected by "a constantly shifting mix of laissez-faire economics stressing private enterprise, on the one hand, and government initiatives at local, state, and national levels, on the other hand" (Taaffe et al., 1996). The organization of ownership has been essential in shaping transportation networks over time. In particular, the governmental provision of general public goods (including roads and other transportation infrastructure) in a federation has been a classic problem examined by a broad literature of financial federalism (Oates, 1972; Besley and Coate, 2003). A branch of this literature focuses on the discrete choice between centralized versus decentralized provision of public goods (Epple and Nechyba, 2004). In general, centralized provision of transportation infrastructure involves a single unitary government that is responsible for the financing, investment, maintenance, and operation of transportation networks (e.g., roads), while a decentralized pattern involves autonomous local jurisdictions that spend on networks independently. The fiscal federalism literature will be discussed in greater details in Chapter 13.

2.4.4 Network effect

The paper "The Economics of Networks" by Economides (1996) opened the way to examine a salient collective property of network industries, called alternatively a network externality or network effect. The network effect has been defined as a change in the benefit, or surplus, that an agent derives from a good when the number of other agents consuming the same kind of good changes. Since this type of side effect is known as an externality in economics, externalities arising from network effects are known as network externalities. Positive network effects are obvious as one's value increases from others' using the same product, while negative network effects also exist, especially where there are resource limits, such as on the overloaded freeway or crowded bandwidth. Shapiro and Varian (1998) illustrated network externalities using a simple demand and supply model, which predicts a typical process of network growth under network effect: the number of users connected to the network is initially small, and increases only gradually as costs fall; but when a critical mass is reached, the network growth takes off dramatically.

Network externalities have played a fundamental role in driving network dynamics in many network industries such as telecommunications, financial exchanges, software, and the Internet. Transportation, as a network industry, is no exception. When a new place or facility with residents and businesses is connected to a transportation network, the residents and businesses at other already connected places benefit from the new connection because they now enjoy accessibility to more activities. Evidence of network effects in transportation networks has been provided by studying the history of transportation networks. Nakicenovic (1998), by plotting a large number of curves for transportation systems, showed that S-curves fit the temporal realization of transportation networks very well. As suggested by the S-curves, there is a long period of birthing as the network is researched and developed, a growth phase as the network is deployed, and a slower mature phase as the network has occupied available market niches. For instance, the US highway network expanded very slowly from 1860 to 1920 and from then on started an exponential climb, before slowing again by the end of the twentieth century. These observations coincide with the prediction of Shapiro and Varian (1998)'s network growth model subject to network effect.

In a historical case study, Bogart (2009) examined how network externalities affected the growth roads, canals, and ports during the early English Industrial Revolution. The author found that there are positive inter-modal network externalities, and that the presence of roads increased the development of canals, as the necessary local feeder road network may have reduced the risks associated with canal development. Negative network externalities, on the other hand, may arise from decentralization and excessive competition between suppliers. Casson (2009), after studying the evolution of the British railway network during 1825-1914, claimed that the network was over-capitalized with excessive duplication of lines due to over competition between towns which the national government was too weak to control.

2.4.5 Path dependence

Today's transportation systems result from what happened in the past, thus the current conditions of a system have a sensitive dependence on its initial conditions, which is referred to as "path dependence" (Arthur, 1994). Liebowitz and Margolis (1995) indicated where information is imperfect, a certain form of path dependence may lead to lock-ins and market failure that are regrettable but costly to change, even in a world characterized by independent decisions and individually maximizing behavior. Despite an increasing realization that transportation development is a sequential process which clearly does not follow a socially optimal design, due to imperfect information when local or individual "optimal" decisions are made (Bertolini, 2007; Zhang and Levinson, 2007), how and to what extent imperfect information and path dependence affect network growth remain unclear to scholars.

2.4.6 Coalition formation

How groups form and are organized to conduct political, economic, and social activities are subject to intense game-theoretic research (Demange and Wooders, 2005). The seminal work by Jackson and Wolinsky (1996) aroused a new stream of contributions using networks (graphs) to model the formation of links among individuals. Marini (2007) provides an overview of recent developments in the theory of coalition and network formation for economic applications. These advances in economic theory also shed new light on the research of network growth. Transportation development cannot be divorced from the interplay of independent jurisdictions and (or) private companies that have provided transportation infrastructure at local, regional, and national levels. Taking the Interurban network of Indiana for example, the network had been constructed and operated by more than 20 private firms (Hilton and Due, 1960). As another example, Virginia State Route 267 consist of three sections (two toll roads of the Dulles Toll Road and Dulles Greenway and a free road for Dulles Airport access) that are operated by Virginia Department of Transportation, Toll Road Investors Partnership II (TRIP II), and the Metropolitan Washington Airports Authority, respectively. How jurisdictional or industrial providers and operators develop a transportation network in a joint process also deserves academic examination.

2.5 Network science

Traditionally, network scientists modeled the dynamics of a transportation network in the attempt to extract or generate the optimal structure of networks. Schweitzer et al. (1998), for example, investigated the evolution of road networks during the optimization process by which a minimized travel detour is traded-off against a minimized cost of constructing and maintaining roads. Gastner and Newman (2006) presented an optimization model to minimize the cost of building and maintaining a transportation 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. Adamatzky and Jones (2009), recognizing the similarity between road planning and plasmodium's behavior to span spatially distributed sources of nutrients with a protoplasmic network, studied the optimal layout of transport links between the ten most populated urban areas in United Kingdom from the "plasmodium's point of view". Simulation results show that during its colonization of the experimental space the plasmodium forms a protoplasmic network isomorphic to a network of major motorways except the motorway linking England with Scotland. In another effort to study biologically inspired adaptive network design, Tero et al. (2010) showed that the slime mold Physarum polycephalum forms networks with comparable efficiency, fault tolerance, and cost to the Tokyo rail system.

Since the 1990s, scientific interest in the structure of complex networks has 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 et al., 1999; de Solla Price, 1965; Jeong et al., 2000; Liljeros et al., 2001). Newman (2003) presented a comprehensive review of the literature. The book *Linked: The New Science of Networks* by Barabási (2002) popularized the new network science emerging from these findings.

As the physics community became interested in surface transportation networks, however, it was recognized that some networks exhibit topological attributes that differ from the typical "scale free" networks. Notable examples are networks with strong geographical constraints, including power grids and surface transportation 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 transportation 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, De Montis et al. (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); Jiang (2005) and Jiang (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. Derrible and Kennedy (2010), by looking at 33 metro systems in the world, found that most metros are indeed scale-free and small-world networks, but they show atypical behaviors with increasing size. Barthélemy (2010), reviewing the most recent empirical observations and cutting-edge models of spatial networks, investigated how spatial constraints affect the structure and properties of these networks.

In exploring how scale-free networks emerge and evolve, Barabási and Albert (1999) found that as new nodes enter a scale-free network, they are more likely to link to highly connected nodes than lesser connected nodes, and this feedback loop gives preference to the large nodes. They called this process "preferential attachment", which has been intensively studied to explain the dynamics of complex networks (Jeong et al., 2000; Barabási, 2002; Dorogovtsev and Mendes, 2002). Although this "rich get richer" growth mechanism of preferential attachment does not seem to perfectly apply to transportation networks due to geographical constraints, it provides some insight to transportation studies: First, preferential attachment may explain the emergence of hub-and-spoke systems in less constrained transportation networks such as airline and shipping networks. Second, when independent nodes link to a network, they tend to connect to established and more important nodes, although the importance of a node is not necessarily associated with the number of connections as it is in a scale-free network, and the direct connection may be realigned to reduce cost and avoid competition between redundant routes. Third, large-scale order and organization may emerge in transportation networks based on independent decisions, which has been extensively examined in another emerging scientific field, self-organization.

Self-organization exists in many complex systems that seem to spontaneously evolve into large-scale order, even based on simple behaviors of independent agents in the systems (Schelling, 1978). Since the late 1990s this concept has been introduced to interpret the evolution of various complex networks ranging from the Internet and social networks, to biological networks employing simulation methods (Newman, 2003). A branch of these studies modeled the emergence of morphologies and patterns in cities (Batty and Xie, 1994; Krugman, 1996; Samaniego and Moses, 2008; Courtat et al., 2010). In recent years, agent-based simulation has seen applications to interpret the dynamics of transportation networks. Lam and Pochy (1993) and Lam (1995) 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 step. Helbing et al. (1997) adopted the active walker model to simulate the emergence of trails in urban green spaces shaped by pedestrian motion. In this process, pedestrians directly walked to their respective destinations on a homogeneous ground at the beginning. Then frequently used trails got reinforced since they are chosen by pedestrians more while rarely used trails withered and were finally destroyed. Consequently, the trails bundled and emerged into different patterns. Helbing et al. (1997) found out that their model was "able to reproduce many of the observed large-scale spatial features of trail systems." Yamins et al. (2003) present 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. However, their simulation did not consider the dynamics of traffic flows. Zhang and Levinson (2004) examined the growth of a real-world congesting network - the Twin Cities (Minneapolis / Saint Paul) road network with autonomous links. Based on the network topology in 1978, simulation experiments were carried out to "predict" road expansions in twenty years, and the predicted 1998 network is compared to the real one. Yerra and Levinson (2005) and Levinson and Yerra (2006) demonstrated that a road network can differentiate into an organized hierarchical structure from either a random or a uniform state, suggesting that the hierarchy of roads, rather than necessarily being designed by planners or engineers, is an emergent property of network dynamics. Based on a principle of local optimality, Barthélemy and Flammini (2009) developed a simple model of formation and evolution of city roads which reproduced the most important empirical features of street networks in cities.

2.6 Summary and discussion

The temporal development of transportation systems such as inland waterways, turnpikes, rails, airlines, and roads over the last two centuries is complicated and multidimensional. The particular focus of this review is on the modeling and analysis of the growth of transportation networks. Efforts over the last half-century have aimed to model network growth in a broad range of fields including physics, geography, economics, natural science, urban planning, and transportation engineering, and not surprisingly, generated a wide literature that varies in subject, method, and growth mechanism. Table 2.1 summarizes a selection of these studies in chronological order for an overview.

As can be seen in this table, geographers in the early days had to limit their modeling efforts to heuristic and intuitive connection rules that allow them to replicate the observations of structural changes in networks, due to the lack of understanding of underlying growth mechanisms. It was not until the introduction of travel demand modeling and formal models of user equilibrium researchers were able to predict traffic flow across a network in a systematic way, thereby solving the "optimal" changes in transportation supply that minimize user cost on the network under budgetary constraints. Since then the concept of a bi-level optimal network design has dominated the decision-making mindset in urban transportation planning.

In contrast to the static, one-dimensional environment in which optimal network designs were solved, economists reveal a more complex world. In reality, transportation development has been the accumulative outcome of individual decisions that are made from independent economic and political initiatives. Organization of strategic providers from public vs. private and local vs. regional interests may significantly affect the course of network growth. Transportation development also demonstrates characteristics such as network effects and path dependence due to externalities and incomplete information that arise from an evolutionary process. These dimensions, however, have not been formally treated in previous network growth models. Time-series statistical analyses that relate the changes in transportation supply to various demographic, economic, and technical factors based on historical observation provide some insights, although they are costly and largely post hoc and case-specific. Thus it remains a challenge for researchers and practitioners to develop a systematic evolutionary approach of transportation planning by which transportation development could be modeled in a more realistic way and transportation supply could be provided more effectively.

Recent scientific advances in modeling complex systems and complex networks provide new opportunities. Tremendous interest has been aroused to interpret the growth of transportation networks adopting the concepts of preferential attachment and self-organization from natural science. Agent-based simulation has provided an effective tool by which independent initiatives, behavioral rules, and travel demand forecasting could be included in an integrated process, and has seen widespread applications in network growth models. One caveat is that due to the complexity of the issue examined, most agent-based simulations were only able to include simple and myopic objectives or behavioral rules of agents. Obviously realism of models could be improved at the cost of adding more complexity, but at which point the trade-off between realism and complexity should be made remains an open question. Additionally, most of these models have been exploratory, in the sense that theories are presented without validation and empirical models are validated only on some basic aggregate features (e.g., visual geometric similarity). Is this evidence sufficient to support a model of such a complex process? How far can scholars and practitioners go with these network growth models to predict the future, or at least provide insightful implications for transportation planning? These questions deserve further investigation.

While there have been some investigations of the evolution of transportation infrastructure and that of urban land use separately, few have examined the integrated development of transportation and urban space from an evolutionary perspective, leaving the co-evolution of transportation and land use still poorly understood.

Table 2.1: Summary of selected studies on network growth

Reference	**Market**	**Given**	**Rules**	**Method**
Garrison and Marble (1962)	Railroads in Ireland	Nodes	Connect to nearest neighbor	Heuristic
Taaffe et al. (1963); Pred (1966); Rimmer (1967)	Underdeveloped road networks close to costal line	Emerging ports, inland establishments	Staged node connection	Heuristic
Lachene (1965)	Idealized	Grid of dirt trails	Staged node connection	Theoretical
?	Sicilian railroads	Major settlements	Quantitative predictive	Empirical
Black (1971)	Maine rails	Places	Potential scoring of links	Heuristic
LeBlanc (1975)	Sioux Falls	Network, budget	DNDP	Theoretical
Lam (1995); Lam and Pochy (1993)	Idealized	Homogeneous space	Active Walker Model	Theoretical
Weidner (1995)	US air network	Airports	System dynamics	Theoretical
Helbing et al. (1997)	Human Trails	Origins, destinations	Active Walker Model	Theoretical
Schweitzer et al. (1998); Gastner and Newman (2006)	Idealized	Nodes	Minimization of cost function	Theoretical
Barabási and Albert (1999)	Idealized	Nodes	Preferential Attachment	Theoretical
Barabási (2002)	WWW, biochemical, communication, etc.	Nodes	Preferential Attachment	Empirical
Yamins et al. (2003)	Idealized	Land use lattice	Maximum potential	Theoretical
Levinson and Karamalaputi (2003*a*,*b*)	Twin Cities roads	Planning network	Heuristic expansion or construction rules	Statistical
Chen (2004); Levinson and Chen (2007)	Twin Cities roads and land use pattern	Planning network, land use lattice	Area-Based	Statistical
Levinson and Chen (2005)	Twin Cities roads and land use pattern	Planning network, land use lattice	Markov Chain	Statistical

Continued on next page

Table 2.1 – continued from previous page

Reference	Market	Given	Rules	Method
Xie (2005)	Idealized	Grids of different geometries	Network degeneration, ”weakest link” heuristic	Theoretical
Yerra and Levinson (2005); Levinson and Yerra (2006)	Idealized	Grid	Agent-based system dynamics	Theoretical
Zhang (2005)	Idealized, Twin Cities	Planning network	System Dynamics	Theoretical
Mohammed et al. (2006*a*); Mohamed (2007)	Toronto bus network	Planning network	Regression, simultaneous equation	Statistical
Montes de Oca (2006)	Twin Cities roads and land use pattern	Planning network	Stated decision rules of jurisdictions	Empirical
Xie (2008)	Indiana interurbans	The full network	Network decline, “weakest link” heuristic	Empirical
Xie and Levinson (2009)	Idealized	Places, hexagonal potential network	Incremental connection	Theoretical

Springer

http://www.springer.com/978-1-4419-9803-3

Evolving Transportation Networks
Xie, F.; Levinson, D.
2011, XVIII, 278 p., Hardcover
ISBN: 978-1-4419-9803-3