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If They Come, Will You Build It? Urban Transportation Growth Models

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This report develops several models of historical roadway improvements in the Twin Cities metro area. Planners respond to, and try to shape, demand by recommending investments in new infrastructure and changes in public policy. Sometimes capacity is added to existing facilities. Other times, building new roads is the response. As a result of this research, the ways in which current network expansion or contraction decisions alter the choices of future decision-makers has become clearer. This research develops a theoretical framework, constructs a comprehensive time series database describing network investment, utilization and capacity, estimates several statistical models, and interprets the results to guide planning.

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If They Come, Will You Build It?
Urban Transportation Network Growth Models

Final Report

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Executive Summary

Previous research in transportation planning models has focused on understanding travel behavior, taking the supply side as given. Planners respond to, and try to shape, demand by recommending investments in new infrastructure and changes in public policy. While small segments of the network may be changed at any given time, those investments are limited by decisions that have come before; and perhaps more importantly, today's decisions constrain future choices. This report develops several models of historical roadway improvements in the Twin Cities metro area. Sometimes capacity is added to existing facilities, other times building "new" roads is the response. As a result of this research, the ways in which current network expansion (or contraction) decisions alter the choices of future decision-makers has become clearer. This research meets its stated objectives. It develops a theoretical framework, constructs a comprehensive time series database describing network investment, utilization, and capacity, estimate several statistical models, and interprets the results to guide planning.

The network growth problem can be considered from macroscopic and microscopic perspectives on network evolution in turn. The macroscopic perspective examines cumulative network development curves (S-curves) and changes in investment patterns over time. The microscopic perspective divides into three problems: node formation, link formation, and link expansion. While there has been some prior literature on this question, it has been limited, and largely speculative. This study considers the link formation and link expansion problems in depth and with data. The node formation problem is considered qualitatively.

The study first develops an empirical model of the link expansion. The study examines the growth of a highway network based on the present and historical conditions of the network, traffic demand, demographic characteristics, project costs, and budget. The effects of expanding a link on its upstream and downstream neighbors, as well as on parallel links are also considered. Data span two decades (1980-2000) and consist of physical attributes of the network, their construction and expansion history, and traffic levels on each of the links. An algorithm is developed to designate adjacent and parallel links in a large network. A non-linear cost model for new construction and highway expansions is developed for the Twin Cities Metropolitan Area. Results of a logit (and a mixed logit) model to predict whether a link would be expanded show that high capacity links are less likely to be expanded and a higher budget results in more links being expanded. Traffic drives expansion, corroborating the *induced supply* hypothesis. However, the rate of network expansion has decreased over time. While there are differences by type of road, they are small, indicating that the model estimated is reliable for general use. The models developed here should be applicable for forecasting the future state of the network.

The new link construction (or link formation) problem predicts (using a logit and a mixed logit model) new highway construction based on the present conditions of the network, traffic demand, project costs, and budget constraints. Results show that new links providing higher potential access are more likely to be constructed. As with link expansion, a higher budget results in more links being constructed, supporting the underlying economic theory.

We then look at the new road construction problem from an area level. We classify the transportation system in the Twin Cities Metropolitan Area into three levels: interstate highways, divided highways, and secondary highways. We make a qualitative analysis of the Interstate

development. For divided highways and secondary highways, binary logit models are estimated to predict their growth probability in geographical cells based on the land-use, population distribution and roadway data. High-quality GIS data for the Twin Cities Metropolitan Area from 1958 to 1990 are developed for this study. We find that the further growth of divided highways tends to be close to employment zones and also tends to agglomerate. Cells with a higher percentage of urban settlement area are more likely to have secondary highway growth.

An improved understanding of long term network dynamics should lead to better planning and design of transportation networks and schedules to exploit network externalities. Immediate users of the research include the state departments of transportation and regional councils of government, which must decide how to invest scarce resources, for instance, whether to invest more resources in existing transportation corridors or develop new ones. These decisions will help transportation and land-use planners, and ultimately the public at large. Decision makers will benefit from seeing how previous investment decisions impact or limit our future choices.

The next step for this research is application to predict the shape and scope of future street networks using base year data. These predictions can be used for modeling the impacts of land-use on the transportation system. They can also be used as "business-as-usual" scenario to compare with the visions of agencies and citizens to see if the most likely future is desirable, or whether policies should be changed to direct future growth in a better direction.

Chapter 1 Introduction

Previous research in transportation planning models has focused on understanding travel behavior, taking the supply side as given. Planners respond to, and try to shape, demand by recommending investments in new infrastructure and changes in public policy. While small segments of the network may be changed at any given time, those investments are limited by decisions that have come before; and perhaps more importantly, today's decisions constrain future choices. This report develops several models of historical roadway improvements in the Twin Cities metro area. Sometimes capacity is added to existing facilities, other times building "new" roads is the response. This research aims to understand transportation network dynamics – how networks grow and decline. In particular the ways in which current network expansion (or contraction) decisions alter the choices of future decision-makers will become clearer. This research meets its stated objectives. It develops a theoretical framework, constructs a comprehensive time series database describing network investment, utilization, and capacity, estimate several statistical models, and interprets the results to guide planning.

This report has four main parts.

Chapter 2 overviews the Network Growth Problem, reviewing the literature and developing much of the underlying theory. This chapter considers macroscopic and microscopic perspectives on network evolution in turn. The macroscopic perspective examines S-curves and changes in investment patterns over time. The microscopic perspective problematizes node formation, link formation, and link expansion and reviews each. The chapter concludes with some notes about future research and applications.

Chapter 3, drawn from the Master's Thesis of Ramachandra Karamalaputi, consists of an empirical model of the Network Expansion Problem. This chapter examines the growth of a highway network based on the present and historical conditions of the network, traffic demand, demographic characteristics, project costs, and budget. The effects of expanding a link on its upstream and downstream neighbors, as well as on parallel links are also considered. Data span two decades and consist of physical attributes of the network, their construction and expansion history, and traffic levels on each of the links. An algorithm is developed to designate adjacent and parallel links in a large network. A non-linear cost model for new construction and highway expansions is developed for the Twin Cities Metropolitan Area. Results show that high capacity links are less likely to be expanded and a higher budget results in more links being expanded, supporting the underlying economic theory. Increasing usage of a highway has a significant effect on the expansion corroborating the *induced supply* hypothesis. An observation of this research is that the rate of network expansion has decreased over time. The pattern of expansion for each type of highway was found to differ only marginally, indicating that the model estimated is reliable for general use. The models developed here have important implications for planning and forecasting.

Chapter 4, also drawn from the Master's Thesis of Ramachandra Karamalaputi, considers the new link construction problem. This chapter examines new highway construction based on the present conditions of the network, traffic demand, project costs, and budget constraints. Results show that new links providing higher potential access are more likely to be constructed and a higher budget results in more links being constructed, supporting the underlying economic theory. Mixed logit modeling was used to account for taste variances of the individual links. The taste of the links is based on the decision-makers deciding to build them. The models developed here have important implications for planning and forecasting.

Chapter 5, written with Wei Chen, looks at the new road construction problem from an area level. In this chapter, we present our recent study of transportation network evolution. The transportation system in the Twin Cities Metropolitan Area is classified into three levels, Interstate highways, divided highways, and secondary highways. We make a qualitative analysis of the Interstate development. For divided highways and secondary highways, binary logit models are estimated to predict their growth probability in geographical cells based on the land-use, population distribution and roadway data. High-quality GIS data for the Twin Cities Metropolitan Area from 1958 to 1990 are developed for this study. We find that the further growth of divided highways tends to be close to employment zones and also tends to agglomerate. For secondary highway, cells with a higher percentage of urban settlement area are more likely to have secondary highway growth.

An improved understanding of long term network dynamics should lead to better planning and design of transportation networks and schedules to exploit network externalities. Immediate users of the research include the state departments of transportation and regional councils of government, which must decide how to invest scarce resources, for instance, whether to invest more resources in existing transportation corridors or develop new ones. These decisions will help transportation and land-use planners, and ultimately the public at large. Decision makers will benefit from seeing how previous investment decisions impact or limit our future choices.

Chapter 2 Network Growth Problem

2.1 Introduction

Between 1900 and 2000, the length of paved roads in the United States increased from 240 km to 6,400,000 km (Peat 2002, BTS 2002) with virtually 100% of the U.S. population having almost immediate access to paved roadways. Similarly, in 1830 there were 37 km of railroad in the United States, but by 1920 total track mileage had increased more than ten-thousand times to 416,000 km miles, however since then, rail track mileage has shrunk to about 272,000 km (Garrison 1996, BTS 2002). The growth (and decline) of transport 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 transport, geography, and regional science. This is revealed time and again in the long-range planning efforts of metropolitan planning organizations (MPOs), where transport network changes are treated exclusively as the result of top-down decision-making. Changes to the transport network are rather the result of numerous small decisions (and some large ones) by property owners, firms, developers, towns, cities, counties, state department of transport districts, MPOs, and states in response to market conditions and policy initiatives. Understanding how markets and policies translate into facilities on the ground is essential for scientific understanding and improving forecasting, planning, policy-making, and evaluation.

Charles Darwin laid out the idea we refer to as evolution, survival of the fittest, or natural selection in his *Origin of Species*. He constructed natural selection in analogy with the artificial selection that animal breeders use to create new varieties. The idea that species randomly change over time, and the fitter variations are more likely to survive and propagate than the less fit variations has now become commonplace. Darwinian evolution has been used as a metaphor in statistical analysis (the genetic algorithm) (Holland 1975), artificial intelligence (Minsky 1986) and in brain development (neural Darwinism) (Edelman 1987). In particular the logic of brain development seems particularly relevant, as the neural connections in the brain (the neural network) are analogous to other networks such as transport. The neural Darwinism argument suggests that at birth there are many connections in the brain, some of which are more useful than others. More useful connections are reinforced, while less useful connections are deprecated. These approaches contrast with creationist arguments, that species (along with their ecological niches) were designed, or that we are born hard-wired, that are no-longer favored in the biological community.

Without becoming theological, it is clear that the idea that planning, engineering, and the intentions of decision-makers drives the topology of networks is a top-down creationist viewpoint, in contrast with a model which suggests that networks evolve, with successful facilities being expanded, and less successful transport sections allowed to whither. The top-down approach is analogous the rational planning paradigm, while the bottom-up approach is more consistent with an incremental planning paradigm. Limited financial and political capital argue in favor of the bottom-up approach, though such decision processes risk devolving to myopic suboptimal outcomes. Normatively, there are strategies, such as mixed scanning, that attempt to balance top-down and bottom-up approaches.

This chapter considers the theory and evidence surrounding network evolution models. The aim of network evolution models is to describe *reality* rather than *optimality*; there is no obligation to maximize welfare directly. This is in contrast to the long line of research on the Network Design Problem (Abdulaal and LeBlanc 1979, Davis 1994, Friesz 1985, Friesz et al. 1998, Huang and Bell 1999, Sanderson 2001). However, the deviation of actual decisions from welfare-maximizing decisions is worth noting.

The evolutionary perspective considers how species come to be and how ecological niches are filled. Using this metaphor, one could think of links as being the equivalent of species, and the links they are connected to being higher or lower on the food chain (traffic being consumed in a predator-prey relationship). Alternatively, we can consider the network as an individual organism that develops over time. An analogy for that circumstance is to what extent "nature" or the genetic programming drives development of an organism (measured in various ways: physical structure, intelligence, personality, language, etc.), in contrast with "nurture" or the influence of relatives (especially parents), friends, and peers, as well as the availability of resources (food, clean air and water, education, etc.) on that same development. If we apply the nature vs. nurture argument to networks, the question is to what extent simple rules (the rules by which travelers choose to use certain links over others, the rules by which resources for network expansion are obtained, the rules which give us the cost of network expansion, and the rules by which investments are made) drive development in contrast with decisions being made for political or other circumstances determining where the network will be expanded and contracted.

As with the nature vs. nurture argument in human development, this may be a false dichotomy. It is clear that without the genetic programming, intelligence would be impossible. But without resources, education, and care, intelligence would also be impossible. At best we can assess the marginal contribution of each to something that doesn't vary too much across the general population.

This chapter considers macroscopic and microscopic perspectives on network evolution in turn. The macroscopic perspective examines S-curves and changes in investment patterns over time. The microscopic perspective problematizes node formation, link formation, and link expansion and reviews each. The chapter concludes with some notes about future research and applications.

2.2 A Macroscopic Perspective

The macroscopic perspective on network evolution has been examined in a great deal of research, especially at the Institute for Applied Systems Analyses (IASA) in Austria (Garrison 1987, 1989; Nakicenovic 1988, 1989; Marchetti 1988; Batten 1989; Grübler 1990). What has been most noted is the emergence of "S-curves", which relate time to deploy a network (or any technology) with market saturation. For a period of time (the growth phase), as knowledge of a technology (a mode) and realization of its benefits spreads, the rate of adoption increases. In the phrasing of a once overplayed Faberge hair products commercial "I'll tell two friends, and they'll tell two friends, and so on, and so on." Each project acts as a demonstration to potential new users. Furthermore, the advantages to adoption may increase with the number of users if there are network or inter-firm scale, scope, or sequence economies. As the technology diffuses, those who expect to attain the most benefit adopt it first. After a point, diminishing marginal returns set in. (That is, once more than half the people know, many of the friends they tell already have the product or have decided against it). It is expected that, after complete exposure, technology is adopted by those who gain the most, and then by those who gain less and less from it, until it is fully deployed.

Diminishing marginal returns limits growth, but there is also the issue of decline. Canals, for instance, were made obsolete by railroads, illustrating that the life of a technology may be cut short by competition. Alternatively, as in the case of plank roads, a technology may collapse because a technological problem is discovered shortly after deployment (wooden planks deteriorated much sooner than expected). Figure 1.1 illustrates S-curves for a number of transport technologies in the United States.

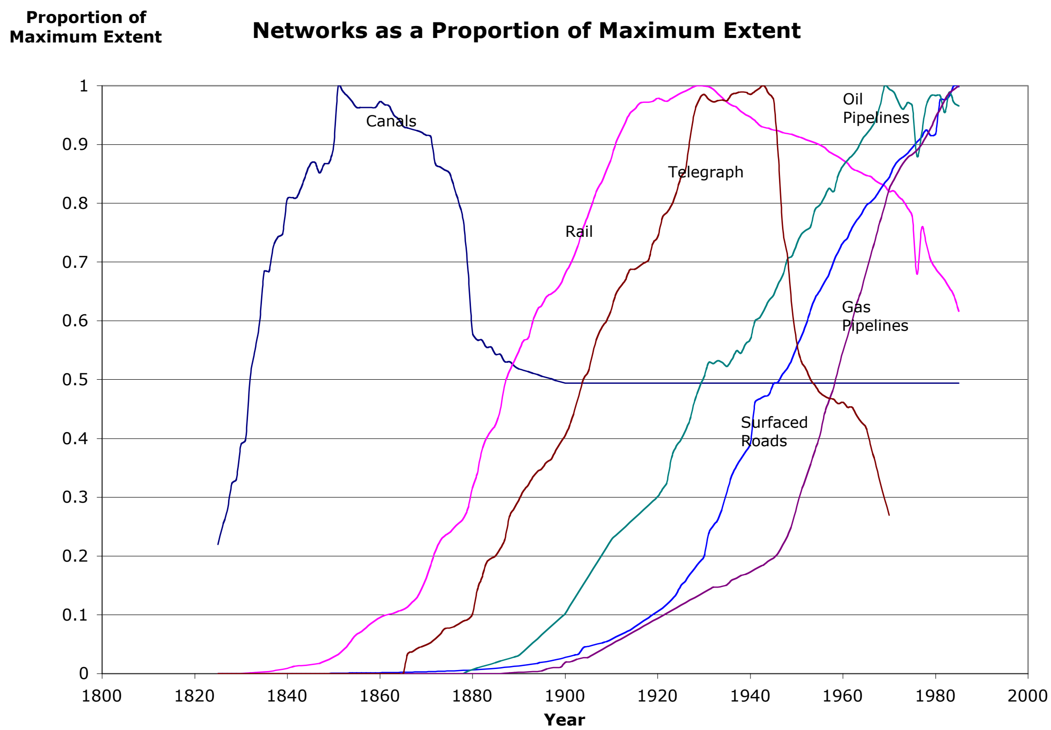


Figure 2.1. U.S. Networks as a Proportion of Maximum Extent

One would expect S-shaped curves, because transport, a product like others, enters and floods a market. Observation suggests that it takes 60 to 70 years for a transport system to run its growth cycle from launch to saturation in the first major market. (However, in places where the technology is adopted later, growth occurs faster because the course is well trodden and learning can be cut short by simpler copying).

To aid in understanding the behavior of a system as it runs its S-curve, the life-cycle metaphor may help. Broadly there are three main phases: birth, growth, and maturity. There may be subsequent phases of decline and death, as the S-curve runs backwards (perhaps it should be called a Z-curve). The period of birth is one of possibility, many new technologies and networks are conceived, yet few are realized. There is an explosion of possible evolutionary paths, yet only one is taken. To illustrate, consider automobile technologies. At the onset of the twentieth century, the form of the auto was unclear. Loosely, it would be similar in size to horse and carriage, but would it be powered by steam, electricity, gasoline, or otherwise? Would it serve business travel or leisure travel predominantly (it started as a toy for weekend trips, but later took on a more serious role)? For various reasons, a particular technical path is selected, and ultimately locked-in; in the case of the auto that path was the gasoline powered engine. The more gasoline engines that have been purchased, the more valuable it is for new autos to have gasoline engines, since the gasoline distribution network is already in place. These network externalities are established by the point of transition from birth to growth. The growth phase sees process improvements and technological honing; economies of scale and scope take hold, and costs drop while benefits increase. In the third phase, the network has saturated its market niche, and the focus switches from deployment to management, from growth to maintenance. Because the system is mature, there little additional to be gained (by the existing system) from technological advances, advances will rock the boat and move the status quo, with which most players are comfortable. Of course change does eventually occur, but it is often the "next new thing" rather than a modification of the network in place.

Systems seem to face diminishing investment in new technology as a system moves through its life cycle. It would be only rational to make the most cost-effective improvements in a process first, and then the next best thing and so on. While previous improvement may open new opportunities, it is likely that each improvement is slightly less effective than the previous, at least after some point. For instance, the fan jet engines used by jet aircraft are approaching the limits on the thrust that can be obtained from them; the Otto cycle engine is just about as fuel efficient as it can be made to be. Batten and Johannsson (1985) observed that investment in product development is high during early days of the life cycle, but that as time passes, more-and-more attention is paid to processes of production.

The relationship to these S-curves for dominant technologies and the economy as a whole has not gone unnoticed. Researchers have associated "long-waves" in the economy of prosperity, recession, and depression (Kondratieff cycles), with waves of innovation, often waves of transport and communication technologies. Mensch (1979) argues for waves of innovations that trigger investment and jobs, but as those technologies begin to age there is recession and then depression. Recovery begins as another wave of innovations begins. Yet this process leaves open the question of what causes waves of innovation. Garrison and Souylerette (1996) present the Companion-Innovation hypothesis, which says that opportunities created when transport (and communication) systems are innovated and deployed trigger waves of innovations. In other words, transport (and communication) systems create new opportunities in other economic sectors, allowing people not only to do the same things better (faster, cheaper), but to do new things that were previously inconceivable. Those innovations drive further changes.

A line of research examines how transport investment affects the economy at large, but tends to treat transport (or highways) as a black box, and makes no distinctions between different kinds of transport investment (Aschauer 1989, Gramlich 1994, Nadiri 1996, Boarnet 1997, Button 1998). The input is investment in transport (or infrastructure), and output is gross domestic product, typically measured at the state level. The research has shown that in the United States investment in transport has been declining, and that the effectiveness of transport investments (the rate of return) has also been declining over the last 40 years of the twentieth century. Investments to increase speed by reducing congestion are not nearly as significant as investments to reduce travel time by providing direct connections where none previously existed. Consider the marginal velocity gain early automobiles gave over horse drawn vehicles, say, from 8 to 24 km/hr (5 to 15 mph). As speed tripled from 8 to 24 km/hr, time spent traveling 1 km dropped 5 minutes from 7.5 min to 2.5 min. As speed increases 16 km/hr from 88 km/hr to

104 km/hr, the time drops from 41 seconds to 35 seconds – a mere 6 seconds – which hardly seems worth discussing. There are diminishing returns to speed increases in the highway system.

NOTE: Though a time savings of 6.3 seconds per vehicle sounds small it still adds up to 175 person hours a day (or 7.3 person days/day) on a busy road with 100,000 cars per day). The lives of 7.3 persons per day, at a value of life of about $3,000,000 suggests the speed hike is saving in economic terms $21,875,000. Alternatively, at a $10/hour value of time, the speed increase saves $1750/day, or $638,750 per year, or $19,157,100 over 30 years with 0% interest rates. Those numbers might be worth talking about, but whether small values of time are additive in such a fashion is a controversial question in transportation economics, though most practices do add them. In brief, since time is likely the dominant benefit, if the project to save 6.3 seconds per vehicle costs much less than $19,000,000 it is probably worthwhile; but if it costs much more, it probably isn't. Ezra Hauer has an interesting paper comparing value of time and value of life "Can one estimate the value of life of is it better to be dead than stuck in traffic?"

Those observations are consistent with transport (particularly highways) being in a mature stage. Just as transport investment affects the economy, the economy affects investment patterns. Carruthers and Ulfarsson (2001) find that various public service expenditures like roadways are influenced by demographic and political characteristics. The New Jersey Office of State Planning (1996) also finds a similar pattern in roadways expenditure.

Miyao (1981) developed macroscopic models to take transport 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 Companion-Innovation hypothesis of Garrison argues that transport is not only unlikely to be an exception, but may be the most important transformation agent in the economy: through revenue sources like the gas tax, transport investment drives the growth that funds it.

The life-cycle model can be represented by the following equation

$$\frac{f}{1-f} = e^{at+b}$$

Where:

f = fractional share of technology (technology's share of final market share)

t = time

a, b = model parameters

Such a tool may help in forecasting, because if the final size of the market can be assessed, and some deployment has already taken place, the pace of future growth can be understood broadly. On the other hand, this cannot tell what the microscopic decisions are that will situate a network in space, or will indicate small upturns and downturns. Further, for many technologies, the final size of the market is unclear until after the fact. For instance, how large will the internet be?

Despite the continued growth of the market, most technologies (modes) have reached market saturation levels, because at some point, the technology is replaced by a newer one. The issue of roads, which tends to grow with population, is uncertain as few old roads have been abandoned to date. On the other hand, the number of roads at the top of the hierarchy (freeways), does seem to be nearing build-out.

Macroscopic models allow us to identify a general process for describing how technologies are deployed. But they do not really help us understand the underlying individual decisions on deployment, except to the extent those networks are deployed faster (in percentage terms) the younger they are.

2.3 Microscopic Models

Few researchers have considered the process of transport network growth at the 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, finding 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.

The network evolution question at the microscopic level divides itself into several related problems. The first considers the location of network nodes. The second considers the connection of nodes with links. The third considers the sizing of links and the hierarchy of roads.

2.4 The Node Location Problem

The location of network nodes reminds us of the geographer's central place question (Christaller 1933, 1966). Christaller's Central Place Theory (CPT) arose in response to the question of how urban settlements are spaced, more specifically, what rules determine the size, number and distribution of towns. The question of network evolution is in many respects similar, but we may think of it as the question of what rules determine the size, number, and distribution of links (or nodes). Christaller's model made a number of idealizing assumptions, especially regarding the ubiquity of transport services, in essence, assuming the network problem away. His world was a largely undifferentiated plain (purchasing power was spread equally in all directions), with central places (market towns) that served local needs. The plain was demarcated with a series of hexagons (which approximated circles without gaps or overlaps), the center of which would be a central place. However some central places were more important than others because those central places had more activities. Some activities (goods and services) would be located nearer consumers, and have small market areas (for example a convenience store) others would have larger market areas to achieve economies of scale (such as warehouses).

The preceding paragraph does not do justice to Christaller, but his research has been extended by geographers and regional scientists (Losch 1938, Heilbrun 1987). Models developed by Batty and Longley (1985), Landis (1994), Krugman (1996), and Waddell (2001) all use newer modeling ideas, treating the problem in a decentralized fashion, and consider land-use dynamics, allowing central places to emerge. However, those models, too, take the network as given.

In a more empirical sense, observation suggests that nodes emerge for a variety of reasons. Nodes occur at points of resource extraction (e.g. a mining town). Nodes occur at points of energy extraction (a waterfall) where a natural energy source can be exploited. Nodes also occur at points of trans-shipment, where nature's links (rivers and oceans) can be exploited. Nodes may also be located for military advantage (to protect an area against incursion by other forces). These nodes may then be connected with each other by links. Links may then cross, creating new nodes with high levels of accessibility. Table 2.1 shows the twenty largest U.S. cities and their principal natural feature that was exploited.

If this argument is believed, it was in a sense inevitable that there would be nodes at these places. However, what may not have been inevitable was the size of the node, that is, there are a number of places which may have had equivalent natural bounty, but never became a top 20 city. However investigation of the history of these cities suggests that transport was the dominant reason for their existence, be it the movement of goods, energy, or water for irrigation. In most cases waterways acted as conduits of travel, in several (Detroit, Dallas), the waterway was largely a barrier that was narrowest at these points compared with others, and in Phoenix, it was the water that was the resource. That said, it further argues that it is geographical asymmetries that drive the growth of nodes (a node has some advantage over all places that were not selected as nodes). Most nodes also had access to desired natural or agricultural resources, access being another transportation component. That access however, was seldom exclusive to the node.

Table 2.1. Important US nodes: Largest Metropolitan Areas

City	Feature in dominant city
New York-Northern New Jersey-Long Island, NY-NJ-CT-PA	harbor
Los Angeles-Riverside-Orange County, CA	harbor
Chicago-Gary-Kenosha, IL-IN-WI	harbor, river/canal connections to Mississippi
Washington-Baltimore, DC-MD-VA-WV	harbor (Baltimore), capital (Washington)
San Francisco-Oakland-San Jose, CA	harbor
Philadelphia-Wilmington-Atlantic City, PA-NJ-DE-MD	harbor
Boston-Worcester-Lawrence, MA-NH-ME-CT	harbor
Detroit-Ann Arbor-Flint, MI	strategic crossing
Dallas-Fort Worth, TX	trading post/crossing of Trinity River
Houston-Galveston-Brazoria, TX	harbor
Atlanta, GA	rail terminus
Miami-Fort Lauderdale, FL	rail terminus, resort
Seattle-Tacoma-Bremerton, WA	harbor
Cleveland-Akron, OH	river/canal terminus, Great Lakes port
Minneapolis-St. Paul, MN-WI	St. Anthony Falls on Mississippi River, most northerly navigable location
Phoenix-Mesa, AZ	site of an ancient Native American irrigation system, Salt River
San Diego, CA	harbor
St. Louis, MO-IL	confluence of Missouri and Mississippi rivers
Pittsburgh, PA	confluence of Allegheny and Monongahela rivers with Ohio river
Denver-Boulder-Greeley, CO	gold discovery at the confluence of Cherry Creek and the South Platte River (resource extraction)

2.5 Link Formation Problem

The construction of new links can be modeled in several ways. In the first set of considerations, we assume we know the location of nodes. We could assume that all (or a very large number of) nodes are connected, but at some very low speed, and then use a network expansion model (such as discussed below) to reinforce selected links and allow others to whither, much as neurons develop in the brain of an infant (Edelman 1987) or a neural network model learns. In contrast with this Darwinian selection process, we could assume that, for every node, there is a set of possible nodes it can connect with (neighbors within a certain radius that it does not already connect with directly). Constraints about crossing existing links could be established. We could incorporate forecasts or expected demand were the link to be built. Then a choice model, based on accessibility added or expected volume served based on the traffic of existing links using that node, would select new links to be added. In this vein, Garrison and Marble (1965) observed connections to the nearest large neighbor explained the sequence of rail network growth in Ireland.

Alternatively, we could specify a process for simultaneous link formation and generation of new nodes. It is reasonable that nodes are generated by one of three processes: the location of natural features (e.g. harbors and waterfalls), the location of artificial features (e.g. the intersection of two roads connecting different places), or explicit design (the nodes shall be in a grid spaced every 1 mile). The first two are most interesting for exploring network evolution. A more general process then can be formulated: First each step adds a node (networks are assembled one node at a time). Second attach each node to two other nodes with two links. The rules for attachment then become critical. As Barabasi et al. (1999) note, if nodes were more likely to connect with already well-connected nodes, we would have a scale-free network (resembling airline hubbing). But if nodes connected randomly to neighbors, we would have a random network that more resembles highways. Scale-free networks follow a power rule in the distribution of node-connectedness. However while the connection structure of highways is limited to nodes being connected to usually at most 4 others, the links that connect them have attributes that differentiate them. Just as hubs are hierarchically organized in node-based system, some links are more important in the hierarchy than others: they are faster, wider, and carry more traffic. Yamins et al. (2003) develop a simulation that grows urban roads using simple connectivity rules proportional to the activity at locations.

To some extent both the Darwinian and the choice process reflect aspects of the growth of real networks. The Darwinian process is probably best suited to undeveloped areas being opened, with access provided and cost of construction being the main offsetting factors. In particular we can think of the Darwinian process being appropriate in areas without developed transport planning, where animal trails are adopted by humans on foot, and later roads are built over those trails. The choice process better reflects the more sophisticated process of building a new link in already developed areas (or areas adjacent to developed areas). Even rural areas that already have a road network can be considered developed from this perspective.

2.6 Link Expansion (Contraction) Problem

When a transport facility is built or expanded, travel increases on that facility both due to re-routing and re-scheduling and due to what is often called *induced* or *latent demand*, a finding confirmed at both the macroscopic level (states and counties) (Noland 1998, Strathman et al. 2000, Fulton et al. 2000) and at the microscopic level (individual links) (Parthasarathi et al. 2002). As travel costs for commuters are lowered, the number of trips and their length increase. In market sectors of the economy, as population grows and preferences shift, leading to higher demand, suppliers produce more of a good. While surface transport decisions are often made in the political arena rather than the market, politicians and officials also respond to their customers – the voter and taxpayer. Although over the short-run transport supply is relatively inelastic; in the long run it varies. However, it is not known to what extent changes in travel demand, population, income, and demography drive these long run changes in supply. Answering this *induced supply* question in transport is a critical step in understanding the long-term evolution of transport networks.

Observation suggests the hypothesis that decisions to expand transport networks are largely myopic in both time and space, usually ignoring non-immediate and non-local effects. This myopic decision process, when applied sequentially, tends to improve the relative speeds and capacities of links that are already the most widely used, and thereby expand their use. The rate and extent of this process is constrained by the cost of those improvements and limited budgets. The full ramification of network expansion on future infrastructure decisions is seldom considered. Improving one link will cause complementary (upstream and downstream) links to have greater demand, and competitors (parallel links) to have lesser demand (and be less likely to be improved). These network effects both complicate the problem and may suggest a structure for analysis.

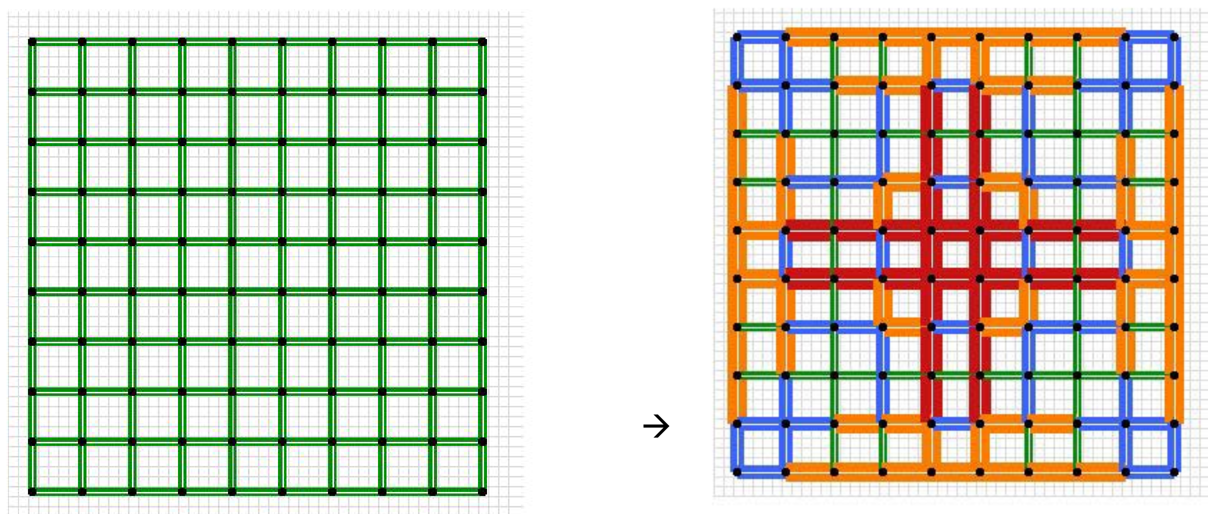
In particular, the phenomenon of network hierarchy is an important issue. For instance, roads are classified in a way that designates most roads as relatively low speed, low volume links. Only a few links on the hierarchy of roads carry the bulk of traffic. Although planners and engineers design for the hierarchy of roads, those designs are constrained by previous decisions. In many respects, the hierarchy of roads is the network analogue of geography's central place theory, which seeks to explain how hierarchies of places develop (Christaller 1966).

Yerra and Levinson (2003) simulate the link expansion problem, showing how a network can differentiate into a hierarchical network from either a random or a uniform network. The network, like observed networks, exhibits power-rule type of behavior, a few very fast links, some moderate speed links, and many slower links. They observe that the hierarchical structure of a network emerges as a function of induced demand (travelers take advantage of additional capacity by making longer trips as well as rerouting), cost functions with certain economies of scale, revenue proportionate to demand, an investment rule that embeds a "rich get richer" (but not "winner take all") logic, reflecting that important links get reinforced, and an underlying network structure (grid, radial etc.). This model contained no comprehensive master plan applied to a *tabula rasa*. In brief, the hierarchy of roads would exist even if no planners or engineers intended it.

We can think of each link as an agent that chooses its speed based on preferences and constraints. There are several exogenous inputs: the base network, the distribution of land uses and demographics, and user specified events. There is also a travel demand model that translates land-use data into traffic flows and speeds on network links. Those traffic flows and speeds inform the network investment model. Those flows also determine the revenue and costs of maintaining and improving the link. When each link has exhausted its resources, the time period is incremented, population grows, land uses are updated, the travel demand is recomputed on the new network, and the process repeats.

Figure 1.3 shows the evolution of link speeds on 2 stylized grid networks using the above formulation. The thickness (and color) of the line indicates the speed of the link divided into 4 categories with the widest bars being fastest. As can be seen, the network with an initial uniform distribution of link speeds develops into a hierarchical network with some faster links attracting more traffic and slower links serving local land uses and less traffic. Clearly the degree to which the network differentiates depends on particular model parameters. The 10x10 grid with an even number of streets in the North-South and the East-West direction maintains symmetry with two major North-South and East-West streets. (A 15x15 grid, with an odd number of streets in the North-South and East-West direction, and thus an equal number of streets to both the left and right of the center street, has only one). Though the network is symmetric, it has boundaries, and it is those boundary conditions (the links at the edge serve traffic differently than links in the interior as traffic at the edge tends to go inward) that allow differentiation to occur even with a uniform land-use and equally spaced links of identical initial speed. The economies of scale (additional flow increases costs less than linearly) along with increasing costs for higher speed links drive the system to the equilibrium where link costs equal link revenue. The second case, showing a random initial distribution of link speeds, illustrates a more complex hierarchical emergence, one that is not symmetric. It is one where initial conditions strongly determine final results. Research shows that other types of initial differences (for instance a higher density downtown, natural topographical features, or random events or random distribution of other initial conditions) further differentiate the system.

Case 1: 10 x 10 Grid, Uniform Initial Speed = 1, Uniform Land Use



Case 2: 10 x 10 Grid, Random Initial Speed (Distributed between 1 and 5), Uniform Land Use

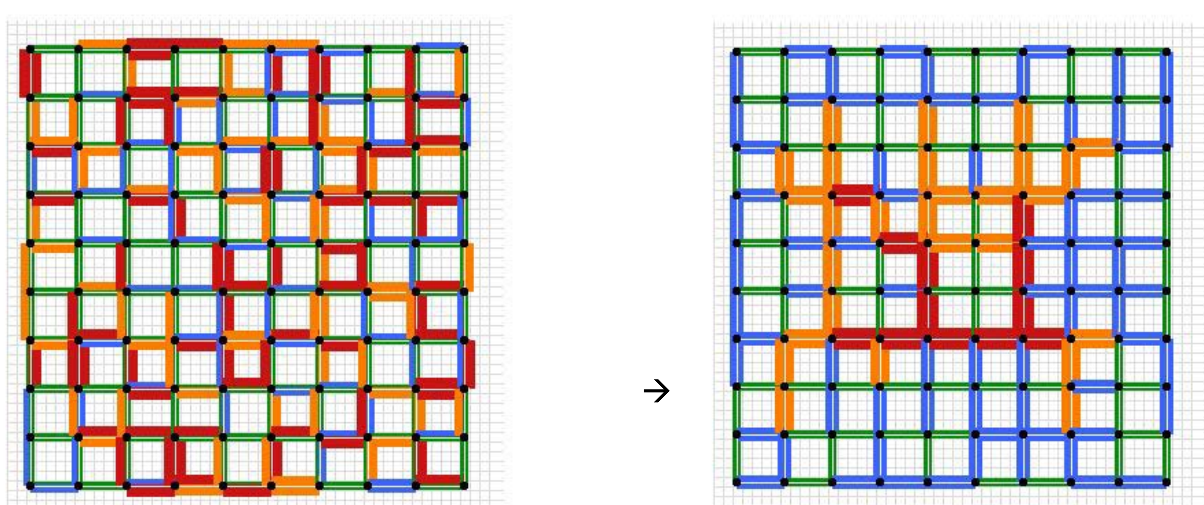


Figure 2.2. Link Expansion: the Evolution of an abstract grid network (Yerra and Levinson 2002)

2.7 Conclusions

The physical network as an object of study is a relatively new endeavor, which complements studies of land use, traffic flows, and social networks (Watts 1999). The development of network evolution models at the macroscopic and microscopic perspectives offers new insights into processes that previously were thought to result from the visible hand of planners, engineers, and politicians. While there is of course a residual to the analysis that can be explained as the product of conscientious decision-makers, there is a large part of network growth that is driven by the underlying geography, economy, and technology. Both the estimation of individual component models and their integration into a simulation of network growth (and decline) will increase our heretofore-limited understanding of network evolution processes. This new understanding will have broad impacts on transport planning practice, and ultimately on the shape of cities and regions. In particular, it will provide a tool to illustrate the implications of current decisions on the future shape of the network, a consideration that is lacking in most planning and engineering studies. By providing a glimpse into a suggested future network configuration, cognizant policy can aim to redirect investment to produce an alternative set of preferred future investments.

Incorporating explicit measures of network externalities in decision-making will lead to better plans, network routing decisions, and implementation strategies. Understanding and illustrating how decisions at one point of time affect future choices should help guide planners and decision-makers desiring to shape the future. The long-term consequences of incremental changes will be assessed. This will help decision-makers assess the effects of changed policies, expanding existing facilities or routes, or building in new rights-of-way or offering new services. This improved understanding of long-term network dynamics would lead to better planning and design of road networks to exploit network externalities and maximize future choice for decision makers.

It is worth speculating about the implications of network evolution on the future of transportation technology. Transportation and telecommunications serve as both complements and substitutes. The capacity of telecommunications networks to provide 'virtual' presence in contrast to the 'physical' presence provided by the transportation network may affect the long term demand for, thus provision of, new transportation networks. Figure 1.2 illustrated the potential growth of the internet, which is but one of many emerging communications networks. The increasing use of communications networks undoubtedly changes individual daily activity patterns as it has already changed business. Whether we will see a pattern of the expansion of communications resulting in a diminished investment in transportation (much as steamboats replaced sail or the airplane replaced intercity rail), or an expansion (the telegraph enabling the long distance railroad) remains to be seen, but merits continued monitoring.

One of the key applications of communications technology in the transportation domain has been in the intelligent transportation systems arena, which have absorbed a great deal of research effort over the past two decades. While many of the investments are responses to maturity (traveler information to slightly improve the quality of a trip, or ramp meters to slightly improve capacity), the long term goal is in the direction of vehicles which can drive themselves. This may be seen as an effort to give birth to a new mode rather than an incrementalist response to an existing mode.

Chapter 3 Link Expansion Model

3.1 Introduction

Traffic demand is shaped by investments in new infrastructure and changes in public policy, while that investment in highway network supply is itself induced by demand. Although highway agencies choose to expand small segments of the transportation network, those investments are limited by decisions that have come before; and perhaps more importantly, today's decisions constrain tomorrow's choices. This chapter explicitly considers the growth of highway networks as an endogenous process, in contrast with current transportation planning practice that strives to exogenously direct that growth. A 20-year database of network expansion is constructed to analyze the dynamics of network expansion decisions, which have been largely unstudied at the microscopic level.

The objective of this chapter is to develop insight into the growth of transportation networks. Specifically, to aid in planning and design, we want to know the investment rules governing agency decisions to expand transportation networks. However, available (annual) budget limits network growth. When an existing link is improved; we need to establish the conditions of single-lane versus double-lane expansion. We want to find whether improving one link will cause upstream and downstream links to have greater demand, and parallel links to have lower demand. We posit the pressure to expand a link will decrease if we expand parallel links. The underlying question in this research is whether network changes can be predicted, and if so, to what extent? In a sense, this chapter is about modeling the behavior of bureaucracies in response to the factors hypothesized to be the driving forces of network growth. The discrete nature of capacity expansion complicates the issue. This model can be used as a policy tool to predict how government transportation agencies direct network growth as a function of projected future traffic, given demographic characteristics and budget.

Section 2 describes the underlying economic theory of network expansion. Section 3 consists of data used in this study. Some of the issues with regard to designating adjacent and parallel links in a transportation network are dealt with. In Section 4, a cost function is developed to estimate the cost of expanding a link given the year of construction, length of the section, number of lanes to be constructed and hierarchical level of the road. A cost function is necessary to obtain a cost estimate for expanding links on which we do not have data. Section 5 describes the model used to predict network expansion, and poses the specific hypothesis. Results are presented in Section 6 while Section 7 summarizes and concludes.

3.2 Theory

The decision by transportation agencies to increase the capacity of a link often comes in the wake of congested flow conditions on the link or as an attempt to divert the traffic from other competing routes. Alternatively, in undeveloped areas, capacity expansion anticipates the development of that area. However, expansion of links is constrained by the available annual budget for such purposes. Specifically, we want to test if capacity increases on the network depend on the capacity of the link in consideration, flow present and previous, as well as flows and capacities of connected and parallel links.

The traditional supply and demand curves for infrastructure supply are shown in Figure 2.1. The X-axis in the figure is new lane kms of capacity (*C*), the Y-axis shows the unit cost per lane km (e). Each of the above variables affects either the supply or the demand curve resulting in a new equilibrium. A higher annual budget (*B*) is agency income (allotted by the residents of the community the agency serves) that increases the willingness and ability to pay to expand or construct highways. A higher income results in a shift of the demand curve to the right. From the curve, it can be seen that higher cost of expansion per lane mile (*e*) decreases the willingness and ability of agencies to construct new infrastructure. Studies have shown that infrastructure growth rates in mature systems decline with time (Grübler 1990), i.e., the supply curve becomes more inelastic (more vertical) with time.

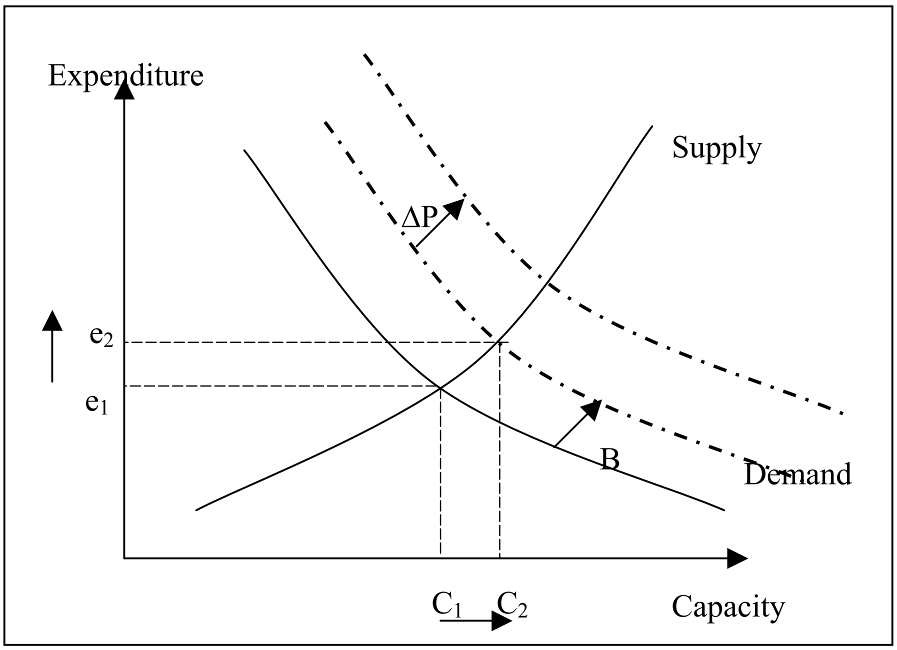


Figure 3.1. Infrastructure Supply -Demand Curve

Due to diminishing marginal returns, the likelihood of widening a highway decreases with its capacity. There are diminishing returns because costs rise with scarcity of land for expansion. Increasing road use over time due to population growth (ΔP) or changes in travel demand is also reflected by the outward shift of the demand curve. Due to the shift in the demand curve, a new equilibrium is reached with an increased supply of infrastructure (more capacity). Note that the new equilibrium has a higher equilibrium price (unit cost of infrastructure).

Changes in capacity of the network induce additional trips on that link due to re-routing and re-scheduling of the trips (Fulton 2000, Noland 1999). Although the presence of induced demand is now widely accepted, the exact relationship between a capacity increase and induced demand is not clear. Parthasarathi et al. (2003) has studied this relationship at the link level using the same dataset as has been considered for this study.

The shaded area in Figure 3.2 is the consumer surplus resulting from the lower price and additional demand after an increase in infrastructure supply. Although consumers' surplus increases after construction, traffic is inconvenienced during construction. If the project takes a long time to be executed, the negative effects might overrun the consumers' surplus of future years. Duration of construction is then an important consideration in the benefit-cost analysis of the expansion. Since we do not have data on duration for unbuilt projects, length of the link is used as a surrogate. Regressions on available data showed length to be a good indicator of the duration of the project. In view of this, longer road segments are less likely to be expanded. Networks tend to grow more in the peripheries once they reach saturation levels near downtown areas. Land scarcity and heavy traffic in the downtown areas make it an inconvenient place to expand the network. Higher capacity is needed to cater to the traffic needs but again land acquisition problems in such areas act as a deterrent.

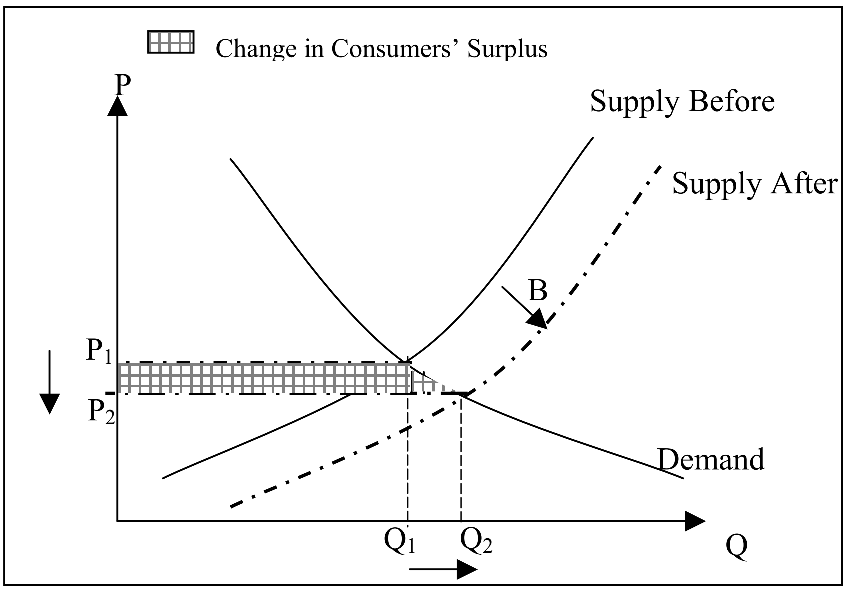


Figure 3.2. Induced Demand and Consumers' Surplus

3.3 Data

To study network dynamics, data has been collected on construction of new links and on expansion of existing links spanning two decades (1978-1998). Data were obtained from the following sources:

a) Network data from the Twin Cities Metropolitan Council.
b) Average Annual Daily Traffic (AADT) data on each link from the Minnesota Department of Transportation.
c) Link investment data was obtained from two sources:
   - Twin Cities Transportation Improvement Program published by the Metropolitan Council.
   - Hennepin County Capital Budget published by Hennepin County.
d) Population of Minor Civil Divisions (MCD) from the State Demography Center, Minnesota Planning.

Network data obtained from the Metropolitan Council gave a physical description of each link in the network in terms of number of lanes, length of the link, capacity of the link, type of highway, and its physical position. Each link is uniquely identified by its start node and end node. Each node is associated with a set of geometric coordinates that define the orientation of a link. The Twin Cities network has around 15,000 links of which 1,525 links are Interstate highways, 2,362 links are Trunk highways, and 4,394 are County highways. Of the county highway links, only those in Hennepin County are used for analysis, which reduces the number to 1,802 links, as investment data on other county highway links could not be obtained. Hennepin is the largest county of the seven in the Metro area and contains the city of Minneapolis. Remaining links are local roads and ramps to highways that are not considered for the analysis because investment data and AADT data could not be obtained for these links. Each type of road is analyzed separately because of the inherent differences in the utilization of these roads and in the financing these roads. Table 2.1 summarizes investment data and Table 2.2 shows the number of links added in each hierarchy of the road during this period.

New construction projects follow different criteria and are not dealt in this chapter. Data in the four separate data sets were merged using ArcView GIS and through some custom computer programs. The database was then split by road type to form separate databases for Interstate Highways, Trunk Highways, and County Highways.

Adjacent and Parallel links in a Network

To input the surrounding conditions for each link in the network, we need to identify links connected to it and its most parallel link. Each two-way link is divided into two one-way links. Adjacent links are divided into two categories: supplier links, and consumer links. Supplier links have traffic flow in the same direction as the link in consideration and are physically attached to the start node of link in consideration. Consumer links are similar to supplier links but are attached to the end node of the link in consideration. A computer program was written to enumerate the adjacent and parallel links. Figure 2.3 shows supplier and consumer links of a link in a hypothetical network. For link 2-4: 1-2 and 3-2 are supplier links and links 4-5 and 4-7 are consumer links.

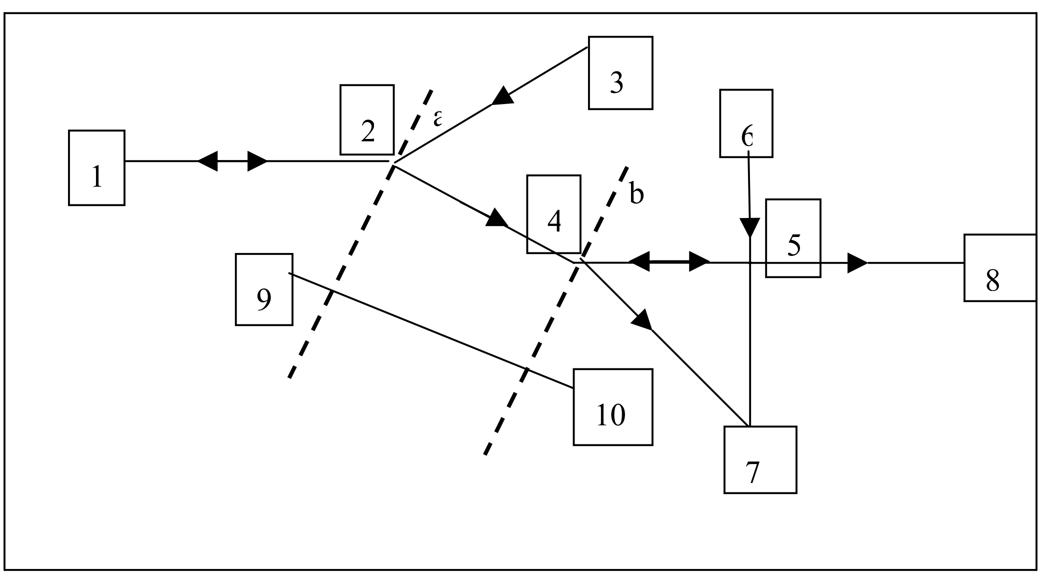


Figure 3.3. Adjacent and Parallel Links in a Network

Parallel link description is a little more complicated. A parallel link can be thought of as the link that would bear the maximum brunt of diverted traffic if the link under consideration were closed. Note that a parallel link may or may not be in physical contact with the link in consideration. Merely looking at the mapped data and selecting a parallel link to a given link is a subjective choice. We need to define the attributes of parallel link to have a "feel" of the type of link to be identified as a parallel link. Crudely put, we are searching for a link that is in the proximity of the link L, approximately parallel to L in the literal sense, and of comparable length. Attributes have been defined based on this. The first attribute is how parallel the links are. The angular difference between the two links should be as small as possible.

The second attribute is the perpendicular distance from the mid-point of link L to the other link divided by length of link L. The third attribute is the sum of distances between start nodes and end nodes of the two links being compared. The final attribute takes the ratio of lengths of the two links into consideration. Note that each of the attributes takes a range of values. Fuzzy logic has proven useful in this kind of case (Zadeh 1992, Kosko 1993).

Fuzzy theory assumes a continuous truth-value rather than the deterministic Boolean values used conventionally. The sum composition method combined with appropriate weights has been found suitable for our purposes. In sum composition, the combined fuzzy output is obtained by computing the truth-value of each attribute and summing these values. Here, we modified this method by weighing the truth-values of the attributes based on the importance of that attribute in relation to others.

The algorithm to find the parallel link needs some explanation. For a link L in consideration, we need to throw out links that are highly improbable to be parallel. In no case should we identify a link in the continuous chain of links of which link L is a part, as the parallel link. For instance, in Figure 3.3, link 5-8 should never be identified as parallel link to 2-4.

We need to remove all links of this type before evaluating attributes. One way to do this would be to drop perpendiculars from the nodes of the link L and check if the link we are comparing with, has any point on it that falls between these perpendiculars. Further all the links whose angular difference with link L is greater than 45 degrees are removed. The values of the attributes are given by:

1. *Para* = 1 – (*angular difference*) / 45
2. *Perp* = 1 – a*(*perpendicular distance*) / length of link L
3. *Dist* = 1 – b*(*sum of node distances*) / length of link L
4. *Comp* = 1 – c*(*lratio*-1)

Where:

perpendicular distance is from the center of link *L* to the other link,

node distances are distances between the corresponding start nodes and end nodes,

lratio is the ratio of length of probable parallel link to the length of link *L* or the inverse of it, whichever is greater.

Each of the attributes is also given a weight when determining the parallel link. It was found that giving a smaller weight to attribute *Para* led to favorable results. The values of parameters *a,b,c* and weights used are given in Table 3.3. The program was run for the Twin Cities network and the results have been manually inspected for accuracy.

3.4 Cost Function

To frame the network investment decision, a cost function is needed to estimate the cost of new construction or expansion of an existing facility. Data collected on previous investments are used to estimate a cost function for the Twin Cities network. Cost of construction can be modeled as:

$$E_{ij} = f\,(L_{ij} * \Delta C_{ij}, F, N, T, Y, D, X)$$

where,

E_{ij} = cost to construct or expand the link (in 1000's of dollars)

$L_{ij} * \Delta C_{ij}$ = lane kilometers of construction

F = dummy variable for type of funding program

N = dummy variable to check if it is a new construction or expansion

T = dummy variables for Interstate highways and State highways

Y = year of completion – 1979

D = duration of construction

X = Distance of the link from the nearest downtown (in km)

A Cobb-Douglas model is estimated to predict the cost of expanding a link. Initially, all the variables mentioned above were entered into the model. It was found that both funding source and road type were insignificant. But examining the data reveals that most interstate highway construction is built under one funding source and non-interstate highways under a different program. To overcome this problem, funding source was dropped, as road type was sufficient for segregation. Also, subsequent models suggested that reconstruction, widening, etc., could be grouped into one category. The model was re-estimated to give the implicit rate of inflation with respect to the highway construction sector, shown in Table 2.4 (Model 1).

Note that the modified year variable has been introduced into the model in a non-logarithmic fashion. If the model were written in exponential form, (exp.(0.078)-1)*100= 8.14 gives the rate of inflation. This is quite high compared to the overall rate of inflation in the United States. One of the reasons may be due to an increase in the costs of transportation materials at a rate larger than general goods and services. Increase in labor costs, additional attributes on roads such as bike and pedestrian features, and evolving safety measures also account towards it. Also, highways are being constructed with better materials due to improvements in technology resulting in an increase in cost. Cost per lane km was also considered as the dependent variable, but it did not improve results.

Finally, duration of construction (*D*) and distance from the nearest downtown (*X*) variables were also introduced into the regression. In general, other than interstate highways, construction was only one year in duration. One might then be tempted to say that duration would also be accounted by the road type variable. But, interstate construction projects took a variable amount of time. Distance from nearest downtown was negative and significant indicating that the project cost would decrease as we move away from downtown areas. The best model taking duration of construction and distance from the nearest downtown into consideration with all the variables significant at 5% level is shown in Table 3.4 (Model 2).

The coefficient of lane kilometers of construction is less than one, indicating economies of scale in construction. As can be expected, cost of a new construction project is higher than expanding an existing link. The cost of construction increases with the hierarchy of the road. This is so because of the greater thickness of pavements on higher-class roads, the use of concrete rather than asphalt, and their larger width including shoulders. Higher duration projects cost more and construction becomes costlier over time. Distance from nearest downtown, which was entered as linear variable, shows that the project cost would decrease as we move away from downtown areas. Downtown areas have higher traffic flows and land costs, and hence restrict the construction flexibility justifying the extra cost. Note that in the final model, modified year has been entered as a logarithmic variable. This may be a better model due to the non-linear increase in costs with date of construction. According to Model 2, a lane-km of interstate highway taking 3 years to construct in the year 2000 would cost approximately 21.8 million dollars.

3.5 Model

Capacity in the next time period (C_{ijt+1}) can be modeled as a function:

$$C_{ijt+1} = f(C_{ij}, L_{ij}, Q_{ij}/C_{ij}, Q_p/C_p, \Delta(Q_{ij} * L_{ij}), B, \hat{E}_{ij}, Y, X, (Q_{hi} + Q_{jk}),$$
$$(C_{hi} + C_{jk} - C_{ij}), \Delta(Q_{hi} + Q_{jk}), \Delta(C_{hi} + C_{jk}), P, \Delta P)$$

where,

C_{ijt+1} = Capacity on arc ij (arc running from node i to node j) at time t+1

C_{ij} = Capacity on arc *ij*

L_{ij} = Length of arc *ij*

Q_{ij} = Flow on arc *ij*

Q_p = Flow on parallel link

C_p = Capacity of parallel link

$\hat{E}_{ij}$ = Unit expense of construction of improvements on arc *ij* (from cost function)

B = Budget for year *t*

Y = Year of proposed construction- 1979

X = Distance from the nearest downtown

Q_{hi} = Sum of flows on arcs *hi*

Q_{jk} = Sum of flows on arcs *jk*

C_{hi} = Sum of capacities on arcs *hi* (arcs supplying flow)

C_{jk} = Sum of capacities on arcs *jk* (arcs receiving flow)

P = Population of the surrounding Minor Civil Division (MCD)

None: All variables are vectors. Flows are bi-directional. Δ indicates change between time period t and (t-n)

Budget is pre-determined for a particular year but it varies over years. For each year, the budget is simply the total expenditures on link expansions considered in the model. Only a few links are expanded in the network in a given year. There have been no instances of expanding the same link twice in the years considered for this study. Since previous expansion of a link predicts failure to expand in a given year perfectly, observations of such links are dropped from the data after its expansion. A strict capacity measure was unavailable and hence the number of lanes was used as a surrogate for capacity in modeling. Modeling was directed at predicting the increase in the number of lanes rather than predicting the absolute number of lanes in the next time period as a whole. This is because the number of lanes in the previous time period largely explains the number of lanes for a given period (since most links do not change each year). It should be noted that the increase in number of lanes is a discrete number and the increase is zero for most of the links in a given time period. To overcome this problem and to consider the discrete nature of the increase in number of lanes, discrete choice modeling was considered appropriate.

While logit models have been successfully used in a wide variety of multi-variate discrete choice contexts, multinomial logit models exhibit the restrictive property of Independence of Irrelevant Alternatives (IIA). IIA states that the presence of a third alternative does not affect the relative probabilities of any two alternatives. Also, coefficients of variables are assumed fixed across individuals in this setting. In Mixed logit models, the coefficients are random across individuals with a specified distribution (McFadden and Train 2000, Train and Brownstone 1999, Hensher 2000). This relaxes the IIA property of multinomial logit models and allows for correlation across alternatives. Mixed logit models are estimated by integrating the likelihood function of the multinomial logit model over the distributions of the random coefficients. The mixed logit likelihood function is given by:

$$\int \frac{\exp(\beta' x_{ij})}{\sum_j \exp(\beta' x_{ij})} f(\beta / \Omega)\, d\eta$$

The parameters are estimated using simulated maximum likelihood due to the lack of a closed form solution to these integrals. Halton sequences, which are shown to be more efficient and guarantee uniform coverage of the distribution, are used for this study (Bhat 2001, 2002).

The presence of induced demand presents the problem of a circular relationship between capacity increase and change in demand, i.e., the problem of endogeneity. The problem is overcome by substituting the endogenous variables in the model with instrumented variables. For the purpose of this study, change in demand has been instrumented using models estimated by Parthasarathi et al. (2003) on the same dataset. The change in demand predicted there was in terms of change in vehicle kilometers traveled and the same is used in our study. Based on the theory described above, the hypotheses are as follows:

- It is posited that the links with higher capacity (C_{ij}) and longer length (L_{ij}) are less likely to be expanded.
- Congestion on a link (Q_{ij}/C_{ij}) increases the probability of its expansion or of the link parallel to it. The same is expected to be reflected in the congestion measure of the parallel link (Q_p/C_p).
- Increase in Vehicle Kilometers Traveled (VKT) on a link ($\Delta Q_{ij} * L_{ij}$) should increase the likelihood of its expansion.

- The higher the cost of a link expansion (E_{ij}), the lower is its probability of expansion.
- A higher budget for a year would result in more links being expanded and thus increase the probability of expansion of a particular link.
- Capacity expansion on a parallel link decreases the chances of the link under consideration to be expanded.
- Higher VKT of upstream and downstream links increases the chances of link expansion to facilitate the incoming traffic.
- Increase in capacity of a downstream link or an upstream link (ΔC_{hi} or ΔC_{jk}) would cause the link in consideration also to be expanded to take the burden of the resulting traffic.
- Chances of re-expansion of a link are assumed to be low since alternate routes will also be considered for expansion.
- Distance from the nearest downtown favors the expansion of a link.
- Increase in population in an area (ΔP) would result in expansion of the links in that area to take care of the excess traffic.
- As can be observed, expansions are decreasing over time, this may be due to costs rising faster than budgets, or it may be due to some other factors (e.g. network saturation or declining benefits of new expansions over time), and this should be reflected in the time variable (Y) of the regression.

Each of the road types was modeled separately due to their functional differences. The decision to construct or expand county highways differs from state highways, as they have separate funding sources. Also, in the data set considered, there were no two-lane expansions of trunk highways and county highways, warranting separate modeling for each hierarchy of the network.

3.6 Results

A multinomial logit model was used to model the increase in number of lanes (ΔC_{ijt+1}) over the previous year. Results of the regression for interstate highway are given in Table 2.5. Variables C_{ij}, L_{ij}, Q_{ij}/C_{ij}, E_{ij}, $C_{hi}+C_{jk}-C_{ij}$, and Y are negative and significant while the variables $\Delta 02(Qij*Lij)$, $\Delta 24(Qij*Lij)$, $\Delta 46(Qij*Lij)$, $Q_{hi}+Q_{jk}$, B and ΔP are positive and significant. This shows that as the number of lanes increases, the probability of its expansion decreases and the probability of a two-lane increase is still lower in this case, supporting the hypotheses. So, we find that links that already have higher capacities are less likely to be expanded due to decreasing marginal returns. Links with lower capacities would then be more likely to be expanded in order to achieve uniformity in the network. Long links that take more time to build tend to be overlooked for expansion in favor of other shorter links. It is difficult to divert traffic for a long time, required for construction on longer links. It has been noted in previous studies (Miyagi 1998) that the overall welfare can be negative in some cases if high volumes of traffic are inconvenienced for a longer period of time. Higher capacity on downstream and upstream links deters link expansion, again indicating decreasing marginal returns.

Increasing traffic demand for a particular link increases its probability for both one-lane expansion and two-lane expansion. Here we see the response of infrastructure supply to increases in travel demand. The probability of a link expansion increases if the flow on downstream and upstream links is high, showing again that links with greater inflow demand get expanded. Cost is negative and significant showing that links that involve higher expenditure are less likely to be expanded. The budget available is positive and significant as expected; a higher budget favors expansion of more links.

A very interesting trend comes into light with the linear variable year of construction (*Y*). The negative coefficient on the year of construction for two-lane expansion is considerably higher than that of single lane expansion. The expansion rate of the network has decreased and the relative probability of two-lane expansions (compared with one-lane expansions) declines with time.

Surprisingly, the congestion measure on the link is negative and significant for both one-lane and two-lane expansions. However, congestion on the parallel link is positive and significant for one-lane expansion. Interstate highways are less likely to be expanded and their parallel links, typically of a lower level of the hierarchy, tend to be expanded in the wake of congestion on an interstate highway.

Distance from downtown is positive and significant for one-lane expansion and negative and significant for two-lane expansions. This implies that two-lane expansions are preferred near downtown where traffic demand is high and one-lane expansions are sufficient in the peripheries where traffic demand is comparatively low, although this may have to do with nonlinear effects of downtown distance. Improvements may be favored in first or second ring suburbs over both the downtown and the exurban fringe. Population in the adjacent Minor Civil Divisions (MCD) has a positive effect on one-lane expansions. Since rights for land acquisition would be costly in such areas, a one-lane increase is feasible to cater to the traffic generated but a two-lane expansion might overrun the budget. A higher population increase in a MCD favors expansion to meet the additional demand generated as expected.

Results with the trunk highway network are as expected. All of the trunk highway expansions are one-lane expansions in each direction and only new construction had two-lanes built in each direction. The results of this binomial logit model are given in Table 2.6. Capacity and length of the link are negative and significant as earlier. Flow and capacity variables of its adjacent links also behave in the same manner as for interstate highways. Again congestion on the link in consideration is negative and significant but it is insignificant on the parallel link. Some of the changes in VKT in the last eight years are positive and significant. Cost of expansion is insignificant and budget is positive and significant as usual. Both population and increase in population have the effect of favoring an expansion. Year is again negative and significant indicating gradual decline in network growth with time, after controlling for budget and expenditure.

Results of the county highways network in Hennepin County are also given in Table 3.6. As earlier, capacity and length of the link are negative and significant. This is the first network in which the congestion measure is positive and significant. As in the case of trunk highways, the spillover effects on the parallel link are not significant. This is because trunk highways and county highways have lower capacity compared to interstate highways and their expansion does not interrupt traffic significantly. Change in VKT has a positive effect on its expansion. Higher flow on adjacent links decreases its chances of expansion. Cost of expansion is again insignificant and the reason might be the necessity to expand lower capacity links (compared to interstate highways) to facilitate smoother traffic flow within the Metropolitan area. Surprisingly, both population and population increase have a negative effect on the chances of expanding.

Results of the mixed logit models are as given in Table 2.8. Standard deviations of only two variables, change in demand over the previous two years and length of the link, were found to be significant. Initially, models were estimated assuming the coefficients to be distributed independently and normally across the population. This resulted in non-significance of the standard deviations. The assumption of a normal distribution places an important constraint on the behavior of the links, although theory suggests the same sign on the coefficients for all the links. Another way is to specify a distribution that may result in negative coefficients but does not necessarily impose such a situation. The triangular distribution satisfies this property and was chosen here. The two year change in VKT (Δ*02(Qij*Lij)*) has a standard deviation comparable to the coefficient itself, indicating a wide range of response of individual links to this variable. In the time period considered, there were 73 lane expansions in the interstate highway network of 1525 links. Of the 73 most probable link expansions predicted by the models, multinomial logit identified 52 links that were actually expanded while mixed logit predicted the same 52 links and an additional 3 links correctly. Standard deviation of random variables for trunk highways is comparatively small although significant. County highways did not have any significant standard deviations in the coefficients. This shows that links on the hierarchy below interstates have a fixed response to the variables. Mixed logit models with unobserved taste as a random parameter failed to converge for all the highways. It should be noted that the final model significance depends on the significance of the input variables as well as the significance of the cost and induced demand models.

3.7 Conclusions

This chapter developed for the first time a model to predict how transportation agencies expand their networks as a function of traffic flow, flow on adjacent and competitor links, flow on parallel links, and estimated cost using data from the Twin Cities metropolitan area. In all the three models, capacity, length, change in VKT, total inflow and budget have similar coefficients and significance. It is interesting to note the differences in the models. While expansion of interstate highways depends on both the budget and cost of expansion, the lower hierarchies of roads are seemingly unaffected by cost (over the range of values observed). Congestion positively and significantly affects agency decisions to expand county highways while being negative and significant for other highways. Interstates and trunk highways show a decline in their growth with time that is not reflected in county highways. The elasticities of variables for trunk highways are generally higher except for the population variables. These differences by type of highway give us a picture of the change in policy for each type of road.

The results are promising and suggest that a number of measurable properties drive network expansion. While it is obvious that politics factors into network expansion decisions, this model is based on empirically measurable attributes. The importance of this is in extension for modeling the implications of transportation planning decisions. Any decision made today will lead to a chain of events, future network expansion decisions that are not considered in most static modeling frameworks. Endogenous network growth, and the pressures placed on future decision-makers because of today's decision are critical factors for planning and modeling.

Future research can be directed toward analysis of the allocation of resources in the Transportation Improvement Plans that Metropolitan Planning Organizations are required to conduct (Crain and Oakley 1995, Dueker 2002). In particular, the model could be extended to endogenously treat the budget within the model.

Tables

Table 3.1. Summary of Investment Data

Year	No: of Projects in TIPS*	Total cost of projects in TIPS ($ 1000's)	No: of Projects in Hennepin County Budget*	Total cost of projects in County ($ 1000's)
1979	11	229633	Data unavailable	Data unavailable
1980	7	80197	Data unavailable	Data unavailable
1981	5	132176	3	2780
1982	8	27120	1	6124
1983	2	38980	2	7760
1984	6	50711	3	13655
1985	3	214031	2	3677
1986	2	8538	4	13577
1987	0	0	1	2436
1988	0	0	3	10370
1989	1	55300	4	8338
1990	0	0	2	15312
1991	0	0	3	15443
1992	0	0	2	7158
1993	7	253700	3	38353
1994	1	8600	3	10380
1995	4	187500	5	16991
1996	0	0	7	35835
1997	0	0	8	35762
1998	0	0	4	22435
1999	4	268200	6	21647
2000	1	70000	4	18606

* Projects costing more than a million or of length more than 1 mile only have been included.

Sources: Local Transportation improvement program and Hennepin county capital budget

Table 3.2. Number of Links Expanded or Constructed by Road Type (1978-Present)

	One-lane Expansion	Two-lane expansion	New Construction	Total
Interstate	104	43	35	182
TH	53	-	40	93
County Highway	86	-	3	89
Total	243	43	78	364

Table 3.3. Values of Weights & Parameters of Parallel link Attributes

Attribute	Weight	Parameter
Para	0.5	-
Perp	0.5	a=0.40
Shift	1.0	b=0.25
Comp	0.5	c=0.50

Table 3.4. Coefficients of Regression for Cost Models

Ln(Eij)		Model 1		Model 2	
Description of the Variable	Variable	Coef.	Std. Dev	Coef.	Std. Dev
Lane kilometers of Construction	Ln(Lij*ΔCij)	0.48	0.114*	0.50	0.118*
Dummy for new constructions	N	0.38	0.184*	0.39	0.187*
Dummy for Interstate roads	Inter	1.68	0.271*	1.97	0.300*
Dummy for State Roads	TH	0.57	0.212*	0.56	0.226*
Year-1979	Y	0.08	0.009*	-	-
Log of year-1979	Ln(Y)	-	-	0.75	0.110*
Log of duration of construction	Ln(D)	-	-	0.16	0.142
Distance from nearest downtown	X	-	-	-0.03	0.016*
	_cons	6.17	0.248*	5.56	0.329*
Number of Observations		110		76	
Adj. R-squared		0.65		0.77	

* Significance at 90% confidence interval

- Variable not present in that model

Table 3.5. Multinomial Logit Model for Interstate Highways

	ΔCijt+1=1			ΔCijt+1=2		
Variable	Hypo.	Coef.	P>|z|	Hypo.	Coef.	P>|z|
Cii	-S	-1.92E+00	5.25E-01*	-S	-2.22E+00	5.46E-01*
Lij	-S	-2.20E+00	9.98E-01*	-S	-3.54E+00	1.21E+00*
Qij/Cij	+S	-1.82E-05	8.28E-06*	+S	-3.84E-05	1.13E-05*
Qp/Cp	+S	1.82E-05	8.30E-06*	+S	1.79E-06	1.09E-05
Δ02(Qij*Lij)	+S	4.58E-04	1.22E-04*	+S	3.63E-04	1.01E-04*
Δ24(Qij*Lij)	+S	5.34E-04	6.97E-05*	+S	5.33E-04	7.27E-05*
Δ46(Qij*Lij)	+S	5.34E-04	6.97E-05*	+S	5.33E-04	7.27E-05*
Δ68(Qij*Lij)	+S	-8.04E-04	2.22E-04*	+S	-3.53E-04	2.06E-04
Eij	-S	-6.54E-09	1.29E-09*	-S	-3.19E-09	6.25E-10*
B	+S	4.16E-06	1.63E-06*	+S	7.83E-06	3.15E-06*
Y	-S	-1.12E+00	1.57E-01*	-S	-1.72E+00	2.59E-01*
X	+S	2.09E-01	6.04E-02*	+S	-1.54E-01	6.28E-02*
Qhi+Qjk	+S	1.17E-05	2.60E-06*	+S	1.13E-05	2.97E-06*
Chi+Cjk- Cij	-S	-7.18E-01	1.41E-01*	-S	-5.27E-01	1.52E-01*
P	-	7.78E-06	1.81E-06*	-	-3.09E-06	2.35E-06
ΔP	+S	1.63E-04	1.63E-05*	-	4.97E-04	2.37E-05*
_cons		3.02E+00	1.48E+00*		7.59E+00	1.64E+00*
Number of Observations: 10986 Initial L L=-572.29 Final LL = -277.65 LR chi2 = 575.55 Psuedo R2: 0.51						

* Significance at 90% confidence interval

Table 3.6. Logit Model for Trunk Highways and County Highways

		Trunk Highways		County Highways	
Variable	Hypo.	Coef.	Std. Dev	Coef	Std. Dev
Cij	-S	-8.15E+00	2.07E+00*		
Lij	-S	-2.28E+01	3.91E+00*	-5.52E-01	5.46E-01
Qij/Cij	+S	-9.30E-05	3.74E-05*	1.97E-04	2.85E-05*
Qp/Cp	+S	1.05E-05	3.81E-05	-1.99E-05	1.53E-05
Δ02(Qij*Lij)	+S	1.67E-03	6.09E-04*	2.81E-03	2.99E-04*
Δ24(Qij*Lij)	+S	4.89E-04	3.40E-04	2.72E-03	2.41E-04*
Δ46(Qij*Lij)	+S	4.89E-04	3.40E-04	2.72E-03	2.41E-04*
Δ68(Qij*Lij)	+S	4.54E-03	1.10E-03*	3.80E-03	3.05E-04*
Eij	-S	-8.18E-10	6.15E-09	6.84E-10	2.49E-09
B	+S	7.32E-05	1.92E-05*	1.07E-05	4.44E-06*
Y	-S	-1.17E+00	5.02E-01*	8.37E-02	1.02E-01
X	+S	1.13E-01	6.47E-02	5.19E-02	3.69E-02
Qhi+Qjk	+S	2.37E-05	6.15E-06*	-1.71E-05	6.10E-06*
Chi+Cjk- Cij	-S	-5.49E-01	2.46E-01*	5.43E-02	9.88E-02
P	-	1.28E-05	5.35E-06*	-1.63E-05	2.00E-06*
ΔP	+S	1.17E-03	1.95E-05*	-1.40E-04	5.73E-06*
_cons	-	3.86E+00	4.73E+00	-1.40E+01	1.25E+01
		No. of Obs: 17926 Initial LL = -108.46 Final LL = -41.34 LR chi2 = 114.75 Psuedo R2 = 0.61		No. of Obs: 6531 Initial LL = -366.42 Final LL = -202.98 LR chi2 = 284.98 Psuedo R2=0.29	

* Significance at 90% confidence interval

Table 3.7. Comparison of Elasticities of Highway

		Interstate		Trunk Highways		County Highways	
Variable	Hypo.	Coef.	Elasticity	Coef.	Elasticity	Coef.	Elasticity
Cii	-S	-2.06E+00*	-4.04E+00	-8.15E+00*	-1.40E+01		
Lij	-S	-2.62E+00*	-9.39E-01	-2.28E+01*	-1.19E+01	-5.52E-01	-2.87E-01
Qij/Cij	+S	-2.50E-05*	-9.40E-01	-9.30E-05*	-1.48E+00	1.97E-04*	1.72E+00
Qp/Cp	+S	1.57E-05*	4.55E-01	1.05E-05	1.54E-01	-1.99E-05	-2.99E-01
Δ02(Qij*Lij)	+S	3.98E-04*	7.12E-01	1.67E-03*	2.03E+00	2.81E-03*	1.66E+00
Δ24(Qij*Lij)	+S	5.10E-04*	-9.63E+03	4.89E-04	-4.10E+03	2.72E-03*	2.96E+04
Δ46(Qij*Lij)	+S	5.10E-04*	9.63E+03	4.89E-04	4.10E+03	2.72E-03*	-2.96E+04
Δ68(Qij*Lij)	+S	-5.96E-04*	-1.55E+00	4.54E-03*	6.60E+00	3.80E-03*	3.74E+00
Eij	-S	-3.21E-09*	-1.22E+00	-8.18E-10	-8.25E-02	6.84E-10	4.32E-02
B	+S	4.38E-06*	6.68E-01	7.32E-05*	1.41E+00	1.07E-05*	4.05E-01
Y	-S	-1.09E+00*	-7.26E+00	-1.17E+00*	-7.77E+00	8.37E-02	5.50E-01
X	+S	-6.23E-03	-5.28E-02	1.13E-01	1.21E+00	5.19E-02	5.53E-01
Qhi+Qjk	+S	1.09E-05*	1.50E+00	2.37E-05*	1.52E+00	-1.71E-05*	-5.58E-01
Chi+Cjk- Cij	-S	-6.07E-01*	-2.64E+00	-5.49E-01*	-2.31E+00	5.43E-02	1.95E-01
P	-	2.56E-06*	3.24E-01	1.28E-05*	9.45E-01	-1.63E-05*	-1.47E+00
ΔP	+S	2.54E-04*	1.23E-01	1.17E-03*	7.26E-01	-1.40E-04*	-1.18E-01
_cons	-	5.22E+00	-	3.86E+00	-	-1.40E+01	-
		No. of Obs:10986 LL= -293.92 Psuedo R2 = 0.46		No. of Obs:17926 LL= -41.34 Psuedo R2 = 0.61		No. of Obs:6531 LL= -202.98 Psuedo R2 = 0.29	

* Significance at 90% level

Table 3.8. Mixed Logit Model for Interstate and State Highways

		Interstate		Section 1.01 Trunk Highways
Variable	Hypo.	ΔCijt+1=1	ΔCijt+1=2	ΔCijt+1
Cii	-S	-2.15E+00*	-2.27E+00*	-6.83E+00*
Lij	-S	-2.21E+00*	-3.69E+00*	-1.55E+01*
Qij/Cij	+S	-1.12E-05*	-2.94E-05*	-6.17E-05*
Qp/Cp	+S	2.12E-05*	8.62E-06	1.26E-05
Δ02(Qij*Lij)	+S	5.41E-04*	2.29E-04*	-1.20E-03*
Δ24(Qij*Lij)	+S	6.51E-04*	5.10E-04*	3.99E-04
Δ46(Qij*Lij)	+S	6.51E-04*	5.10E-04*	3.99E-04
Δ68(Qij*Lij)	+S	-1.24E-03*	-2.13E-04	3.51E-03*
Eij	-S	-7.39E-09*	-3.35E-09*	-1.22E-08
B	+S	4.73E-06*	8.59E-06*	-1.34E-05*
Y	-S	-1.20E+00*	-1.82E+00*	-1.69E+00*
X	+S	2.44E-01*	-1.46E-01*	8.62E-02
Qhi+Qjk	+S	1.17E-05*	1.15E-05*	1.91E-05*
Chi+Cjk- Cij	-S	-7.35E-01*	-6.46E-01*	-4.80E-01*
P	-	7.65E-06*	-3.50E-06	1.12E-05*
ΔP	+S	1.34E-04*	5.27E-04*	8.62E-04*
_cons		3.47E+00*	8.79E+00*	1.18E+01
Section 1.01 Triangular Variances Triangular Variances				
Lij		6.13E-02*	7.45E-01*	1.21E-07*
Δ02(Qij*Lij)		2.92E-04*	4.41E-05*	2.13E-10*
		No. of Obs:10986 LL= -232.99		No. of Obs:17926 LL= -38.27

*Significance at 90% confidence interval

Chapter 4 Link Construction Model

4.1 Introduction

This study focuses on understanding the conditions where new links are constructed (as opposed to existing links being improved) on a highway network. The construction of new links can be modeled in several ways, assuming we do have the location of possible (and existing) nodes. We could assume that all (or a very large number of) nodes are connected, but at some very slow speed, and then use a network investment model to improve selected links while allowing others to whither, much as a neural network learns. In contrast to this process, we could assume that, for every node, there is a set of possible nodes it can connect with (neighbors within a certain radius to which it is not already connected). It is this second approach that this chapter investigates. Specifically, we need to understand the effects of travel demand, cost of construction, budget and the surrounding conditions on the generation of new links. A highway network is thought to be expanded or constructed due to congested traffic conditions or in anticipation of regional economic development. Limited budgets and existing land uses constrain the number of new links constructed in a given period. The traffic level on parallel links is expected to be a highly significant factor in new construction. Also, the number of potential trips on the new link is thought to be an important factor in its initiation.

Theory used for this study is explained in Section 2. Section 3 provides a description of the data used and its assembly. In that section, adjacent and parallel links are designated. Section 4 describes the model used and poses the specific hypotheses. Results are presented in Section 5 followed by conclusions in Section 6.

4.2 Theory

Construction of a new link may alleviate traffic congestion or open a new area to development by increasing accessibility. Such a link could lead to the availability of additional routes and thus bring a change in traffic patterns. The traditional supply-demand curve for infrastructure is shown in Figure 3.1. Each of the variables considered affect either the supply curve or the demand curve and thus shifts the equilibrium.

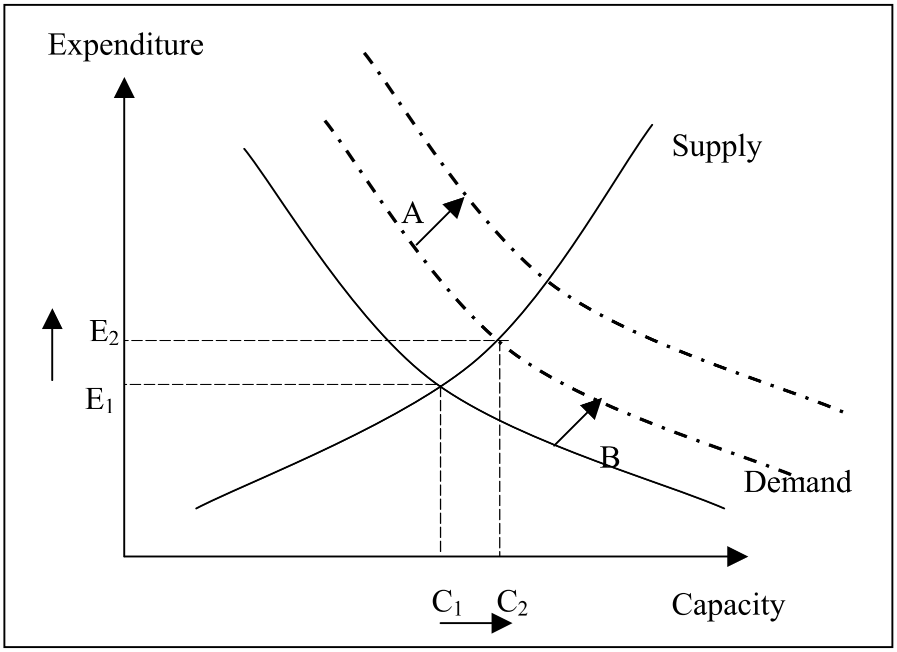


Figure 4.1. Infrastructure Supply -Demand Curve

A higher transportation department budget (*B*) for a year increases the demand to expand or construct highways, resulting in an outward shift in the demand curve. High cost of construction decreases demand and can be seen as moving upward along the demand curve. The pressure to construct a link increases if it has the potential of serving a large amount of traffic (access *A,* defined in section 4). In mature networks, the capacity added to the system decreases over time. Due to the upward slope of the supply curve, a marginal increase in capacity decreases average travel demand per lane as existing capacity increases.

Expanding a link induces additional trips on that link due to re-routing and re-scheduling of the trips, and also due to induced demand. In light of induced demand, the effect of roadway expansion in reducing traffic congestion is not fully understood. Although consumers' surplus increases after the expansion, travelers are inconvenienced during its expansion. Long links take longer to expand and diverting traffic during that period is difficult. The possibility of constructing a new link increases in such scenarios and hence the condition of traffic in the surrounding links is a crucial factor for new link construction. Networks tend to grow more in the peripheries once they reach saturation levels near downtown, because of land scarcity.

4.3 Data

The dataset for this study is built using data from three different sources. The Metropolitan Council of the Twin Cities of Minneapolis and St. Paul, Minnesota provided network data for the year 1995 with length and location of each link. Each link is identified by its start node and end node. Data on AADT were obtained from the Transportation Information Systems Division of the Minnesota Department of Transportation. Data on construction of new links and expansion of the existing links were obtained from the local Transportation Improvement Program and

Hennepin County Capital Budget for the years 1978-1998. Data on new county highways in other counties were unavailable. Hennepin is the largest of the seven counties and contains the city of Minneapolis. Using the investment data, a network for each of the years is built with the network of year 1995 as the base network. The remaining dataset was integrated using ArcView GIS and through some custom computer programs.

While the link to be expanded is chosen from the existing network, construction of a new link has to be chosen from a set of possible links between nodes. Hence, construction of a new link cannot be modeled taking the present network on which the new links were built as the basis of comparison. In the case of the Twin Cities network, creation of new nodes (at the higher level of the hierarchy of roads) because of new construction was not observed. The possible set of new links is based only on existing nodes. Theoretically, a node can be connected to any of the remaining nodes.[1] There were a total of 76 bi-directional new links (all highways) constructed in the past two decades.

The mean length of newly constructed links was 0.68 km and the maximum length of a new link was 4.54 km. Because of the large number of possible connections, and high redundancy levels within the radius of 4.54 km, a shorter range of possible lengths was considered. In the new scenario, only links of length between 200 meters and 3.2 km were considered. These lengths were arrived at by removing new construction in the five percentile regions on both ends of the dataset. Since we have observed that new nodes are seldom created by new construction in the specific case of the Twin Cities network, the possible set of new links should be such that they do not cross any of the existing links at the higher end of the hierarchy. However, they can cross lower level roads without technically intersecting them by overpasses. With the above restrictions, each node was found to have on average a set of ten possible connections. There were a total of 29,804 possible new links.

4.4 Model

Due to the few new links built over the last two decades, construction is assumed to happen in five-year intervals and the dataset is built accordingly. The budget over these five years is summed to act as a budget constraint. Nodes connecting only local roads (below county highways) were not considered in modeling since we do not have data on new construction of such types of roads. New construction in the next time interval can be modeled as:

$$N_{ijt+1} = f(L_{ij}, C_p, L_p, Q_p/C_p, A, E_{ij}, B, Y, X, D)$$

where,

N_{ijt+1} = Dummy for new construction of link ij in period (t+1)

L_{ij} = Length of link ij, along the road

C_p = Capacity of the parallel link

L_p = Length of the parallel link

Q_p/C_p = Congestion measure on the parallel link

A = Product of total supplier links flow and total consumer links flow (access)

E_{ij} = Cost of constructing the new link (from Expenditure model in previous chapter)

B = Transportation department's budget constraint

T = time period of expansion

X = Distance from nearest downtown

D = Number of nodes within the interval of 200 meters and 3.2 Km

All links are bi-directional. Volumes on the links are directional.

Variable A can be considered as an accessibility measure of the new link. It represents the effect of supplier link flows and consumer link flows on the probability of new construction. The effect of surrounding conditions is expected to be prominent in the construction of a new link compared to a link expansion. Based on that theory, the hypotheses are as follows:

- High congestion on the parallel link (Q_p/C_p) favors the construction of the link to cater to the traffic on the parallel link.
- Higher capacity of the parallel link (C_p) decreases the likelihood of new construction, as capacity is already available. However, we have noticed that high capacity links are less likely to be expanded.
- Longer links (L_{ij}) are less likely to be expanded because of the longer duration of construction.
- Longer length of parallel link (L_p) favors the construction because longer links tend not to be expanded as often due to the duration involved in such an expansion.
- High expected cost of construction (E_{ij}) on the new link decreases its probability of getting built while a higher transportation budget (B) increases that probability.
- A higher access score (A) for a link increases its chances of construction.
- As was observed in literature, road construction declined over time and this is expected to be reflected in the year (T) variable.
- New links have a higher probability of being constructed far from downtown (X) as land acquisition is easier there.
- A large node density (D) in the surrounding area results in fewer new links being constructed as the number of links is high in such areas.

Binomial logit and mixed logit modeling have been used to analyze the dataset and the results are shown in the following section.

4.5 Results

A binomial logit model was used to model the construction of a new link between existing nodes. Results of the regression are given in Table 3.3. Variables C_p, E_{ij} and X are negative and significant while the variables L_p, A, Y, and B are positive and significant.

As has been noted earlier, the construction of a new link depends significantly on its surrounding conditions and alternate route conditions. The longer the parallel link (L_p), the higher is the probability of a new link. This might be interpreted as reflecting the cost involved in the expansion of the larger parallel link and also as a result of the traffic diversion problems on the parallel link if it were expanded.

Capacity of the parallel link (C_p) is negative and significant, supporting this hypothesis. High capacity links already serve high volumes of traffic in an area (generated in or passing through that area) and hence reduce the need for a new link.

A high access measure (A) between two nodes tends to increase the probability of new construction connecting those nodes. Access is directly proportional to the total time savings due to new construction and hence it is logical that high demand between two nodes has this effect.

A higher cost of constructing a new link (E_{ij}) reduces its probability of expansion as expected. Also, more new construction is possible when the budget (B) is higher.

The distance to the nearest downtown (X) variable is negative and significant, indicating that new links are likely to be built nearer downtown than in the suburbs. This is probably reflects the completion of the interstate highway system in the Twin Cities, which saw the urban links finished last (in the past twenty years), while suburban links were completed as long as 40 years ago.

More new links are being constructed with the passage of time (T), refuting the hypothesis. We have noted earlier that studies showed decreasing expansion rate of the existing links. This may reflect a policy shift from expansion to new construction. Expanding a road leads to traffic inconvenience during construction. This problem is avoided by new construction and this may explain the reasoning behind more new construction.

A mixed logit model was estimated to allow for the taste variances of individual links (i.e., of decision-makers). The results of the model are also given in Table 3.3. The log likelihood value was improved by 3% indicating a better model. As has been mentioned earlier, changes in traffic demand were not considered due to the low number of new links. Considering changes in demand would require dropping one period of observations. The random term was assumed to have a triangular distribution and its estimated standard deviation is given in the table. Models with other possible distributions for the random term did not improve significance. The significant variance in the constant term reflects the variance in the links due to the effects of these omitted variables and the inherent taste variance (of decision-makers). More data are needed to model new construction with other influencing variables.

However, a mixed logit model can to some extent encompass the effect of these variables. Omitted variables in a model increase the standard error of the estimated variables and thus cloud the significance of some variables.

For instance, the number of nodes in the surrounding area (D) is significant in the new model, supporting the hypothesis. Although significance of other variables did not change, the coefficients changed significantly when the unobserved variance was accounted for. The z-values of the mixed logit model are higher than logit model indicating increased reliability of the estimated coefficients.

Out of a network of 29,804 possible new links, there were 69 new links in the time period considered. Of the 69 most likely new construction projects as predicted by the models, the logit model identified 17 links that were actually built. The mixed logit model performed better predicting those same 17 links and an additional 5 new links correctly. In view of these results, mixed logit performs better than conventional discrete choice models.

4.6 Conclusions

This chapter developed a model to predict the location of new highway construction based on surrounding conditions of the new link, the estimated cost of construction, and a budget constraint. A new process for identifying potential construction projects is developed. Several assumptions were made in this process based on the analysis of data. The methodology used here reduces the number of possible newly constructed link drastically and paves the way for feasible modeling. A practical solution was provided to the problem of identifying adjacent and parallel links in a large network.

Results indicate significant dependence on parallel link attributes and potential access to traffic due to the new link. A newly constructed link provides an additional route; hence, its construction depends on the attributes of the links that presently serve the region. A high capacity route is sufficient to cater to the traffic generated in or going through the region and usually does not require a new construction project. New construction projects are less likely to be undertaken if they are costly and are limited by the available budget. New links are unnecessary when the region is well connected, as reflected by the node density variable. Two different types of discrete choice models were estimated to compare their performances. It was found that mixed logit models perform better than logit models, and account for unobserved taste variance.

Although politics factor into these decisions, it should be noted that they are constrained by the decisions made in the past and the present conditions of the network. The models suggest a number of significant driving factors that lead to new highway construction. The models estimated here can be used to monitor the growth of the network given projected traffic demand for the existing links and values of model variables at present conditions. This would improve transportation planning by enabling modelers to predict pressures for additional links. Forecasting future demands on the transportation network requires a forecast of the network structure itself. Only with models of new link construction and link expansion can these forecasts be made.

Freeways interchanges were treated as a single node for this purpose. With the network in the present form, this possible connection can be made with any of the nodes at interchanges. To overcome this feature in the dataset, all the nodes within 50 meters of each other were given the same node number. A computer program was written to accomplish this task and the resulting node set was used to investigate new construction.

Halton draws are generated using a prime number, p, as a seed. The interval (0,1) is divided into n intervals and those form of the first numbers of the sequence. Each of the n intervals is again divided into n intervals. The new set of numbers is arranged in a particular fashion to continue the sequence. For a detailed discussion, please refer to the reference provided.

Tables

Table 4.1. Values of Weights & Parameters of Parallel link Attributes

Attribute	Weight	Parameter
Para	0.5	-
Perp	0.5	a=0.40
Shift	1.0	b=0.25
Comp	0.5	c=0.50

Table 4.2. Regression Coefficients for Cost Models

Description of the Variable	Variable	Coef.	P>|t|
Cost of Construction	(E_{ij})	-	-
Lane-kilometers of Construction	$Ln(L_{ij}*\Delta C_{ij})$	0.50	0.00*
Dummy for new constructions	N	0.39	0.04*
Dummy for Interstate roads	H_I	1.97	0.00*
Dummy for State Roads	H_S	0.56	0.02*
Log of (year-1979)	Ln(Y)	0.75	0.00*
Log of period of construction	Ln(P)	0.16	0.06*
Distance from nearest downtown	X	-0.03	0.04*
Constant		5.79	0.00*
Number of Observations: 76 Adj. R-squared: 0.77			

* Significance at 90% confidence interval

Table 4.3. Models for New Construction

		Logit		Mixed Logit	
Variable	**Hypo.**	**Coefficient**	**z**	**Coefficient**	**z**
Length of the link (L_{ij})	-S	-5.91E-01	-1.35	1.84E-01	0.27
Capacity of the Parallel Link(C_p)	-S	-3.31E-01*	-1.86	-4.87E-01*	-1.67
Length of the Parallel Link(L_p)	+S	4.93E-01*	1.58	1.42E+00*	1.97
Congestion on Parallel link(Q_p/C_p)	+S	-1.96E-05	-1.25	-5.23E-05*	-1.87
Access (A)	+S	4.24E-05*	4.7	1.92E-04*	2.71
Time period of Expansion (T)	-S	7.31E-01*	2.24	3.00E+00*	3.27
Cost of Construction (E_{ij})	-S	-2.82E-01*	-2.48	-8.97E-01*	-3.36
Budget (B)	+S	5.68E-06*	3.06	7.78E-06*	3.96
Distance from downtown (X)	+S	-1.21E-01*	-5.69	-3.08E-01*	-6.62
Node Density (D)	-S	-6.32E-04	-0.18	-1.27E-02*	-1.73
_Constant		-6.09E+00*	-6.02	-1.24E+02*	-2.92
Triangular Deviation					
Constant		-	-	4.72E+01*	2.36
Number of Observations		89031		89031	
Log Likelihood		-473.19		-459.68	

* Significant at 90% confidence interval

Chapter 5 Area-Based Models of Transportation Network Growth

5.1 Introduction

Transportation networks shape cities and speak to people's everyday lives. Despite their long existence and constant variation, researchers seldom question how the networks have evolved to their current configurations and what were the factors leading or related to transportation network growth. Transportation networks have simply been assumed to be results of top-down decision-making, and based on that belief, the future growth and evolution of transportation networks are taken to be subjectively decided by the planners and policy-makers.

This study constitutes a portion of a larger research project to understand the evolution of transportation networks at a theoretical and empirical level, recognizing the inter-dependence of supply and demand, and to develop agent-based models to replicate that process. This study analyzes the transportation network evolution in the Twin Cities Metropolitan Area from 1958 to 1990, because we have well-developed GIS data for this period. The roadway system of this period can be classified into three levels, each of which generates its own hypotheses: Interstate highways, divided highways, and secondary highways (we do not estimate the growth of local streets that serve land access rather than movement function). Binary logit models are estimated for predicting the growth probability of divided highways and secondary highways in geographical cells based on land-use, population distribution and roadway network data for the base years. Interstates, however, are not modeled here and will only be qualitatively analyzed because the Interstate system was developed for the nation in its entirety and at a minimum requires a larger geographic scope. Interstates are used as a predictor in modeling the growth of divided highways and secondary highways.

In the ensuing sections, we firstly provide the background of the study, which consists of the summary of network evolution from 1920 to 1990 and the development of Interstate system. Then we describe the data for this study, and present the hypotheses, statistical models and result analyses for divided highways and secondary highways respectively, finally conclusions are drawn.

5.2 Background

5.2.1 Network evolution from 1920 to 1990

We can find the following three evolutionary tendencies for the roadway network of Minneapolis-St. Paul Metropolitan Area in the past eight decades:

a. The increase of both total mileage and link connectivity, which were accompanied by the increase of population, the decentralized population distribution, and the industrialized, commercialized and residentialized land use.
b. The improvement in surfacing and geometry. At the earlier years (before 1951), roadways were classified based on their surfacing conditions because almost all the roadways were single-lane at that time and their primary distinction was the pavement. The four main categories were paved, bituminous, graveled and earth. With the improvement of roadway qualities, most of the roadways were well paved and the

surfacing-based categorization was gradually inapplicable, and it was substituted by geometry-based categorization. Four-lane highway appeared in 1952 as a new category and it represented the highest level of roadway until Interstate era started in 1961. From 1962 till now, the categorization was geometry-based and the main roadway categories were Interstate, divided highways, undivided highways and secondary roads.

c. The emergence of hierarchies. Clear-cut hierarchies did not exist for roadway system in the earlier years, for example in 1920, roadway system consisted of surfaced, not surfaced, and lower-level earth roads. But in 1990's roadway system, we can find distinct hierarchies. As the highest hierarchy, Interstate is controlled access, multiple divided lanes, and of the highest capacity serving both local and Interstate traffic; as the second hierarchy, divided truck highways have multiple divided lanes with high capacity and speed serving local, especially working-related traffic; and as the lowest hierarchy, secondary highways are undivided highways with the lowest capacity and travel speed serving mainly as connecting links between urban settlements and the higher hierarchical highways. Besides, Interstates are the shortest in mileage but carry the most traffic with the fastest speed, while secondary highways are much longer but carry little traffic with the slowest speed. This is quite similar to other complex systems, such as arterial circulation network that contains three hierarchies - artery, arterial capillary and capillary. Artery is at the highest hierarchy which is the shortest in length but carries the largest volume, while capillary shares the largest length but carries little volume. The formation of hierarchies is a very important aspect of network evolution, and we think network self-organized into hierarchies, that is, the emergence of hierarchies was intrinsic properties of networks. The hierarchy topic will be analyzed in our next step of study.

5.2.2 Interstate

In the analysis of Interstate growth, we should first set the scope as the whole US instead of a single region since the Interstate system was planned for the nation in its entirety. The 1944 Federal-Aid Highway Act, Section 7 authorized designation of a 65,000-km "National System of Interstate Highways" to be selected by joint action of the state highway departments. Interstate Highways should be "... so located as to connect by routes, as direct as practicable, the principal metropolitan areas, cities, and industrial centers, to serve the national defense, and to connect at suitable border points with routes of continental importance in the Dominion of Canada and the Republic of Mexico." (Weingroff, 1996), and Interstate Highways should also serve the regions with peak traffic volumes based on statewide planning surveys of the 1930s (Figure 4.1).

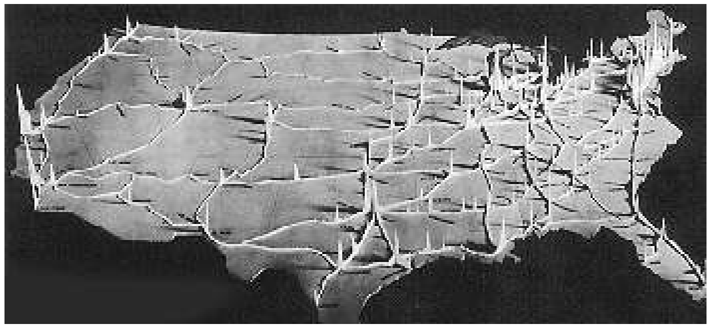


Figure 5.2. Illustration of peak traffic volumes based on statewide planning surveys of the 1930s. (Weingroff, 1996)

As a component of the whole picture, the development of the Interstate system in Minneapolis-St. Paul Metropolitan Area adhered to the requirements of connectivity with the neighboring states as well as catered to the needs of local traffic. Figure 4.4 describes the evolution of the Interstate network of Minneapolis-St. Paul Metropolitan Area. Each of the Interstate corridors serves for specific purpose. For convenient analysis, we classify the interstates into three groups: I-494&I-694 Beltway, I-35(W&E) North-South Through-Corridors, and I-394&I-94 East -West Through-Corridors and I-94 Northwest Stretch (Figure 4.2). The original purpose of I-494&I-694 beltway was to divert traffic passing through the area from congested local commute routes, and provide for better distribution of non-CBD (Central Business District) oriented trips within the area (Payne-Maxie Consultants,1980). Most part of the I-494&I-694 Beltway was completed in the 1960's, which were within 'Beltway-Boom' period for the whole US. Since 1950s, approximately 100 complete or partial beltways have been built in US. I-35(W&E) North-South Through-Corridors serve as the "gateway" to the Twin Cities metropolitan area from the south and the north. To the south, they connect to cities such as Des Moines, Kansas City, Oklahoma City, Dallas/Fort Worth, San Antonia, and the Mexican border at Laredo, TX. Their northern terminus is in Duluth, MN, and it further connects to International Falls and Thunder Bay, Ontario. I-35W and I-35E also cross Minneapolis and St. Paul respectively serving as the major North-South commuting routes. Similarly, I-394&I-94 East -West Through-Corridors cross Minneapolis and St. Paul serving as the major East -West commuting routes. I-94 Eastern Stretch serves as the "gateway" to the Twin Cities from Wisconsin and the Chicago area and I-94 Northwest Stretch is the main gateway to downtown Minneapolis from the north and northwest.

(Source: http://www.ajfroggie.com/roads/minnesota/state/).

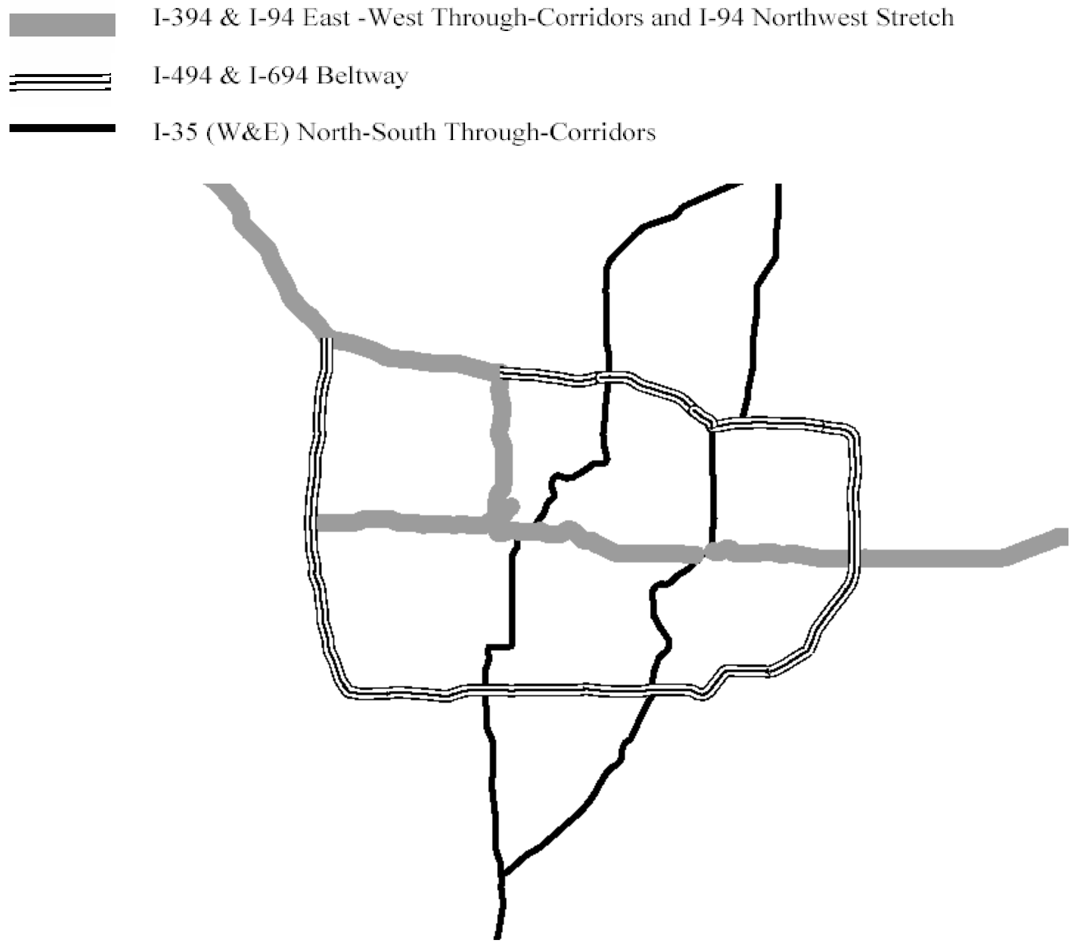


Figure 5.3. Classifying the Interstates into three groups

Of all the highways, Interstates are least likely to get further growth. No additional Interstate appeared after I-394 (the construction of I-394 began in the middle of 1980's) and the Interstate network by itself has formed a consummate system. However, although there was no further growth of Interstates, a noticeable change after 1990 is that the highest hierarchy was not only composed of Interstates, some divided highways were upgraded into freeways. These improved divided highways share similar geometric design (such as controlled access) as Interstates. The network development after 1990 will be continued in the next step of work.

This study concentrates on modeling the growth of divided highways and secondary highways based on population and land-use distribution. The similar analysis is not conducted for Interstates because each Interstate corridor serves for specific purpose, and Interstate route selection typically overwhelmed local factors, and we do not expect to find strong correlation between Interstates' growth and local population and land-use distribution. In the ensuing sections, we will present the data, models and result analyses for divided highways and secondary highways respectively.

5.3 Data

We developed high-quality GIS maps from paper maps for this study which are summarized in Table 4.1. The study period began with 1958 when the earliest land-use map was created for the Twin Cities Metro Area. Both land-use and census data were issued decennially.

Table 5.4. GIS data summary

GIS Map	Source
Twin Cities Metropolitan Area Population Distribution 1960, 1970 and 1980.	Twin Cities Metropolitan Area, 1960, 1970 and 1980 Census Tracts, issued by U.S. Census Bureau.
Twin Cities Metropolitan Area Land-Use Distribution 1958, 1968 and 1978.	Twin Cities Metropolitan Area, Generalized Land-use 1958, 1968 and 1978, issued by Twin Cities Metropolitan Council.
Twin Cities Metropolitan Area Roadway Networks 1962, 1965, 1968, 1971, 1975, 1978, 1981, 1985, and1990.	Minnesota Official Transportation Maps, issued by Minnesota Department of Transportation *(before 1978, they were called Minnesota Official Highway Maps and Minnesota Department of Highway).*

Then we overlaid a lattice layer composed of 30,729 square cells (0.375×0.375 km), which shares the same corridor system with land-use, population distribution and roadway network layers. We merged the population distribution layer, land-use layer, and roadway network layer into the lattice layer (Figure 4.3), so that each cell of the lattice layer contains the spatial information of population, land-use and roadways.

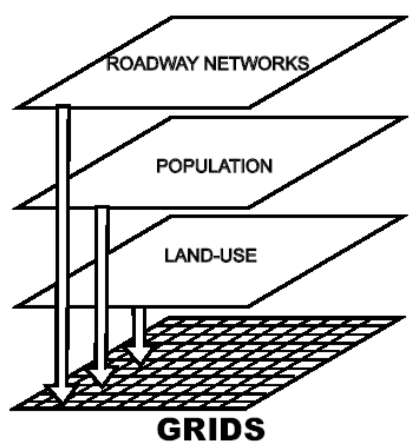


Figure 5.4. Merging Layers

Now each of the cells can be viewed as one observation. We will use land-use, population distribution and roadway network data of the base years and roadway network data of the predicted years to estimate the roadway growth probability models. The models are estimated for the roadway growth of three-year, five-year, and ten-year respectively. Table 4.2 summarizes the base year data and the predicted year data.

Table 5.5. The base year data and the predicted year data used for model estimation.

Three-Year Roadway Growth	
Base Year Land-use, Population Distribution and Roadway Network Data	Predicted Year Roadway Network Data
1968 Land-use, 1970 Population Distribution, and 1968 Roadway Network	1971 roadway network
1978 Land-use, 1980 Population Distribution, and 1978 Roadway Network	1981 roadway network
Five-Year Roadway Growth	
Base Year Land-use, Population Distribution and Roadway Network Data	Predicted Year Roadway Network Data
1958 Land-use, 1960 Population Distribution, and 1962 Roadway Network*	1965 roadway network
1968 Land-use, 1970 Population Distribution, and 1968 Roadway Network	1975 roadway network
1978 Land-use, 1980 Population Distribution, and 1978 Roadway Network	1985 roadway network
Ten-Year Roadway Growth	
Base Year Land-use, Population Distribution and Roadway Network Data	Predicted Year Roadway Network Data
1958 Land-use, 1960 Population Distribution, and 1962 Roadway Network	1968 roadway network
1968 Land-use, 1970 Population Distribution, and 1968 Roadway Network	1978 roadway network
1978 Land-use, 1980 Population Distribution, and 1978 Roadway Network	1990 roadway network

* Note: 1958 Roadway Network should be used as the base year data, but before 1962, the Twin Cites Metro Area just covered very small area in the Minnesota Official Highway Maps and more than half of the observations would be dropped if 1958 Roadway Network were used. Therefore, we use 1962 Roadway Network as a substitute.

5.4 Divided Highways

Divided highways are separated roadways for traffic moving in opposite directions. They are the second level in the hierarchy of the roadway system (below Interstates) and mainly serve local commuting traffic.

5.4.1 Hypotheses

Hypotheses of the growth tendency of divided highways are presented as follows.

Agglomeration. Agglomeration is the phenomenon of roads of a particular class to be built near (or connecting to) similar roads. The agglomeration growth of divided highways includes both the emergence of alternative routes and also the extension of the existing corridors. First, as major commuting corridors, divided highways typically locate at or close to regions with relatively intense economic activities. Moreover, divided highways may lead to further economic development nearby, which means more traffic demand in the neighborhood of the existing corridors. Therefore, when the existing routes show rising demand, neighboring cells should have a high likelihood of alternative route development. Second, the requirement of connectivity induces the further extension of existing corridors or the addition of new links adjoining the old ones. After new routes (the alternative routes and/or the extension routes) appear, the boosted economic activity and traffic growth nearby may lead to another round of agglomeration growth.

Generally we expect that the neighboring cells of the existing divided highways should be associated with a higher route growth probability. To test the hypothesis of agglomeration, we make a 1-kilometer buffer area of the existing divided and undivided highways (The reason for including undivided highways is that undivided highways have the highest probability of upgrading into divided highways.). Variable A is defined as $A = 1$ if the observed cell is within or intersects the buffer area, otherwise $A = 0$. The cells with $A=1$ should be associated with a higher growth probability than the cells with $A = 0$.

Population density. *We expect that moderately populated areas should be associated with a higher route growth probability, while both the sparsely populated areas and the densely populated areas should have a lower growth probability.* For the densely populated areas, although their neighboring areas may have more traffic demand, they are usually associated with high land-prices and costly relocation. Therefore, the final decision of route development in the densely populated areas should be the balance of demand, costs and the availability of cheaper alternative routes. Cells are classified into four groups based on the natural-breaks data classification method: P_S (sparsely populated area), P_{M1} (moderately populated area 1), P_{M2} (moderately populated area 2), and P_D (densely populated area). Table 4.3 lists the ranges of P_S, P_{M1}, P_{M2}, and P_D for the three base years – 1958, 1968 and 1978.

Table 5.6. The number of population per cell for P_S, P_{M1}, P_{M2}, and P_D.

Base Year	1958	1968	1978
P_S,	≤ 53	≤ 39	≤ 36

P_{M1}	54 – 168	40 – 116	37 – 104
P_{M2}	169 – 488	117 – 346	105 – 304
P_D	≥ 489	≥ 347	≥ 305

Employment zones. As we have mentioned before, divided highways mainly serve local commuting traffic. Therefore, *we expect the further growth of divided highways should also tend to be close to employment zones*. To test this hypothesis, we make a 0.5-kilometer buffer area of the employment zones (including airports), and the variable U_E is defined as $U_E = 1$ if the observed cell is within or intersect the buffer area, otherwise $U_E = 0$. The cells with $U_E = 1$ should have a higher probability of divided highway growth than the cells with $U_E = 0$.

Commercial zones. *We expect that commercial zones and their neighborhood should have high highway growth probability.* To test this hypothesis, we construct a 0.5-kilometer buffer area of the commercial zones, and variable U_C is defined as $U_C = 1$ if the observed cell is within or intersects the buffer area, otherwise $U_C = 0$. The cells with $U_C = 1$ should have a higher probability of divided highway growth than the cells with $U_C = 0$.

Agricultural areas. Variable U_A is defined as the percentage of agricultural areas within each cell, and *we expect that U_A should generally be negatively associated with route growth.* However, it should be noted that although agricultural areas typically have low traffic demand, they are also the areas of low land-prices; furthermore, one purpose of divided highways is to connect urban and suburban areas and spur economic development of the undeveloped areas. These factors may lead to route growth in the agricultural areas.

Water areas. Water is a barrier for highway development. Variable U_W is defined as the percentage of water areas within each cell, and *we expect that U_W should generally be negatively related to route growth.*

5.4.2 Model

A binary logit model is estimated to predict the divided highway growth based on the population distribution, land-use and roadway network data of the base years. It should be noted that the model estimates the probability of divided highway growth in each cell, but it does not estimate the extent of growth. The extent of growth is influenced by many factors (such as the direction of the highway segment, the path to cross the cells, the connection with other links and other factors such as the geographical or geological conditions, etc.) that can not be controlled in this study. The problem of extent will be addressed in our future research. Of the models we have tested, the following model is the best in overall model fit, and the regression results of the model are presented in Table 5.4.

$$G_D = f\,(P_S, P_{M1}, P_{M2}, P_D, A, U_S, U_E, U_C, U_A, U_W, L_I, L_D, L_U, L_S, D, Y)$$

Where,

G_D (Dependent Variable) - Divided Highway Growth, if from the base year to the predicted year there is growth in divided highways in the observed cell, $G_D = 1$, otherwise $G_D = 0$.

P_S, *P_{M1}*, *P_{M2}*, and *P_D*, - Population predictors. All the cells are classified into four groups based on the natural-breaks data classification method: P_S (sparsely populated area), P_{M1} (moderately populated area 1), P_{M2} (moderately populated area 2), and P_D (densely populated area).

A - Agglomeration predictor, if the observed cell is within or intersect the 1-kilometer buffer area of the divided and undivided highways of the base year, $A = 1$, otherwise $A = 0$.

U_S, U_E, U_C, U_A, and U_W - Land-use predictors. They are defined as follows:

U_S - The percentage of urban settlement within each cell; here, the urban settlement include residential areas, commercial areas, industrial areas, institutions, offices, airports and transportation infrastructure;

U_E - If the observed cell is within or intersect the 1-kilometer buffer area of employment zones (including airports) of the base year, $U_E = 1$, otherwise $U_E = 0$;

U_C - If the observed cell is within or intersect the 1-kilometer buffer area of the commercial areas of the base year, $U_C = 1$, otherwise $U_C = 0$;

U_A - The percentage of agricultural areas within each cell;

U_W - The percentage of water areas within each cell.

L_I, L_D, L_U, and L_S – the base years' roadway length within each cell. There are four levels of roadways: L_I (the kilometers of Interstates), L_D (the kilometers of Divided Highways), L_U (the kilometers of Undivided Highways), and L_S (the kilometers of Secondary Highways).

D – The distance from the center of each cell to the nearest CBD; there are two CBDs, Minneapolis CBD and St. Paul CBD.

Y – The dummy variable of the base year.

**We categorize both undivided highways and secondary highways as secondary highways, but undivided highways are to some extent superior to secondary highways and more likely to be upgraded into divided highways. Therefore, in analyzing divided highway growth, we separate out undivided highways as an independent variable by itself.*

5.4.3 Results

For three predictions in Table 5.4, the overall model is significant at the .01 level according to the Model chi-square statistic, and the model predicts more than 98% of the responses correctly. The McFadden's R^2 ranges from 0.14 to 0.19. The results of the predictors that test the hypotheses are summarized as follows:

Table 5.7. Logit regression results for divided highway growth prediction

Dependent Variable = G_i	Logit Regression Results								
Independent Variable	Three_Year_Growth			Five_Year_Growth			Ten_Year_Growth		
	Odds Ratio	Coef.	P>|z|	Odds Ratio	Coef.	P>|z|	Odds Ratio	Coef.	P>|z|
P_{M1}	1.282	*0.248	0.084	1.799	*0.587	0.000	1.793	*0.584	0.000
P_{M2}	1.096	0.092	0.575	1.417	*0.348	0.005	1.266	*0.236	0.033
P_D	0.439	*-0.824	0.000	0.435	*-0.832	0.000	0.356	*-1.034	0.000
A	1.349	*0.300	0.020	1.000	*0.000	0.033	1.000	*0.000	0.003
U_S	0.858	-0.153	0.519	1.483	*0.394	0.041	1.310	*0.270	0.095
U_E	7.430	*2.006	0.000	3.481	*1.247	0.000	2.775	*1.021	0.000
U_C	1.512	*0.413	0.002	1.187	*0.172	0.059	1.040	0.040	0.617
U_A	0.769	-0.263	0.278	1.629	*0.488	0.012	1.358	*0.306	0.057
U_W	0.144	*-1.938	0.001	0.209	*-1.564	0.001	0.165	*-1.804	0.000
L_I	1.000	0.000	0.901	1.000	0.000	0.731	1.000	0.000	0.834
L_D	1.002	*0.002	0.000	1.002	*0.002	0.000	1.002	*0.002	0.000
L_U	1.005	*0.005	0.000	1.005	*0.005	0.000	1.004	*0.004	0.000
L_S	1.003	*0.003	0.000	1.003	*0.003	0.000	1.003	*0.003	0.000
D	1.000	*0.000	0.055	1.000	0.000	0.357	1.000	*0.000	0.008
Y_{58}			NA	0.550	*-0.599	0.002	0.854	-0.157	0.259
Y_{68}	2.077	*0.731	0.000	1.660	*0.507	0.000	1.701	*0.531	0.000
Y_{78}			NA			NA			NA
Number of obs			48119			63560			63560
Prob > chi2									
McFadden's-R^2			0.1908			0.1587			0.1395
% Correct Predictions			98.93%			98.54%			98.14%

* Indicates that the coefficients are statistically significant at 0.10 level.

For Population Groups (P_S, P_{M1}, P_{M2}, and P_D), the group with the lowest population density P_S *was* dropped due to collinearity. The densely populated group P_D always has negative and significant results, which indicates that the densely populated areas have lower divided highway growth probability than other areas. P_{M1} is always positive and significant and P_{M2} is positive and significant for two of the three predictions, which indicates that moderately populated areas have higher divided highway growth probability than both the densely populated areas and the sparsely populated areas. These results accord with our hypothesis.

The coefficient of A is positive and significant for all the three predictions, which indicates that the new divided highways were more likely to emerge in the neighborhood of the existing corridors, and these results accord with the hypothesis of agglomeration tendency, the neighborhood of the existing corridors should be more likely to have new route development.

U_E is positive and significant for all the three predictions, which indicates that the cells within or intersect the 0.5-kilometer buffer area of employment zones (including airports) have a higher likelihood of divided highway growth than the cells out of the region. Also for all the three predictions U_E has the highest odds ratio, and in the three-year growth prediction the odds ratio of U_E is as high as 7, which means that employment zones and their neighborhood are 7 times more likely to have divided highway development than other regions. These results support our hypothesis that the further growth of divided highway routes should tend to be close to employment zones.

U_C, is positive and significant in the three-year and five-year growth predictions, and positive and insignificant in the ten-year growth prediction, which indicates that the commercial zones and their neighborhood are generally related to a higher likelihood of divided highway growth. But clearly commercial zones are not as significant as employment zones in the likelihood of divided highway development.

U_A is negative and insignificant in the three-year growth prediction and positive and significant in the five -year and ten-year growth predictions, which means that agricultural areas are not necessarily associated with low divided highway growth probability. We generally expect agricultural areas to be related to low growth probability since there is less traffic demand in these areas. But this can be overruled if the purpose of divided highway development is to connect urban and suburban areas and to spur economic development of the undeveloped areas. In addition, diverting from the highly urbanized areas saves construction costs.

U_W is negative and significant for all the three predictions, which supports the hypothesis that water areas should be negatively related to route growth.

5.5 Secondary Highways

5.5.1 Hypotheses

Secondary highways are below divided highways and above local roads, and composed of undivided highways and county highways. They are the longest in mileage but carry less traffic at slower speeds. The hypotheses about the growth of secondary highways are summarized as follows:

Urban settlements. Secondary highways serve local traffic, they are the proximate and ultimate connecting highways of urban settlements, so the growth of secondary highways should be related to the settlement areas, which include residential areas, commercial areas, industrial areas, institutions, offices, airports and transportation infrastructure. *We expect that the cells with larger settlement areas should be more likely to have secondary highway growth.* To test this hypothesis, we use the percentage of urban settlement areas within each cell as an independent variable U_S, and we expect this variable to be positively and significantly related to the secondary highway growth probability.

Percentage of water areas and agricultural areas within each cell. *The percentage of water areas should be negatively related to the secondary highway growth probability, but we do not expect the similar relationship for agricultural areas.* Agricultural areas have the demand for product transport, and the more important is agricultural areas usually have no major (Interstate or divided) highways and secondary highways are the only commuting routes. On the one hand, the cells with a higher percentage of agricultural areas have less urban settlements and less traffic demand, which may lead to low secondary highway growth probability; on the other hand, however, secondary highways are more relied on in the agricultural areas for product transport and commuting service due to the lack of higher hierarchical highways, which may lead to secondary highway growth.

5.5.2 Model

As with divided highways, we use logit models to predict the secondary highway growth based on the population distribution, land-use and roadway network data of the base years. Of the models we have tested, the following model is the best in overall model fit, and the regression results of the model are presented in Table 4.5.

$G_S = f\,(P_S\ , P_{M1}, P_{M2}\ , P_{D},, U_{S},, U_{E},, U_{C},, U_{A}, U_{W},\ L_{I},, L_{D},\ L_{US},, D,\ Y)$

Where,

G_S (Dependent Variable) - Secondary Highway Growth, if from the base year to the predicted year there is growth in secondary highways in the observed cell, $G_S = 1$, otherwise $G_S = 0$.

The definitions of the other predictors are the same as those for divided highways.

5.5.3 Results

Of the three predictions in Table 5.5, the overall model is significant at the .01 level according to the Model chi-square statistic, and the model usually predicts more than 90% of the responses correctly. The McFadden's R^2 ranges from 0.05 to 0.08.

Table 5.8. Logit regression results for secondary highway growth prediction

Dependent Variable = G	Logit Regression Results								
Independent Variable	Three_Year_Growth			Five_Year_Growth			Ten_Year_Growth		
	Odds Ratio	Coef.	P>|z|	Odds Ratio	Coef.	P>|z|	Odds Ratio	Coef.	P>|z|
P_{M1}	1.945	*0.665	0.000	1.514	*0.415	0.000	1.713	*0.538	0.000
P_{M2}	2.104	*0.744	0.000	1.510	*0.412	0.000	1.578	*0.456	0.000
P_D	2.651	*0.975	0.000	1.311	*0.271	0.014	1.220	*0.199	0.034
U_S	1.342	*0.294	0.072	1.590	*0.464	0.000	1.797	*0.586	0.000
U_E	1.394	*0.332	0.000	1.489	*0.398	0.000	1.345	*0.296	0.000
U_C	1.259	*0.231	0.005	1.091	0.087	0.109	0.994	-0.006	0.890
U_A	1.375	*0.318	0.039	1.465	*0.382	0.000	1.593	*0.466	0.000
U_W	0.087	*-2.443	0.000	0.358	*-1.026	0.000	0.360	*-1.022	0.000
L_I	1.001	*0.001	0.065	1.000	0.000	0.352	1.000	0.000	0.875
L_D	1.000	0.000	0.119	1.000	0.000	0.157	1.000	0.000	0.685
L_{US}	1.001	*0.001	0.000	1.001	*0.001	0.000	1.001	*0.001	0.000
D	1.000	*0.000	0.000	1.000	*0.000	0.005	1.000	*0.000	0.002
Y_{58}									
Y_{68}	2.392	*0.872	0.000	1.218	*0.197	0.000	0.433	*-0.837	0.000
Y_{78}				0.408	*-0.896	0.000	0.207	*-1.577	0.000
Number of obs			48119			63560			63560
Prob > chi2			0.0000(13)			0.0000(14)			0.0000(14)
McFadden's-R^2			0.0622			0.0484			0.0784
% Correct Predictions			97.55%			95.89%			93.91%

* Indicates that the coefficients are statistically significant at 0.10 level.

For Population Groups (P_S, P_{M1}, P_{M2}, and P_D), P_S was dropped due to collinearity. P_{M1}, P_{M2}, and P_D have positive and significant results for all the predictions, which indicates both moderately populated areas and densely populated areas have a high secondary highway growth probability. For the five-year and ten-year predictions, P_{M1}, and P_{M2} are more significant than P_D. U_S is always positive and significant, which supports our hypothesis that cells with larger settlement areas are more likely to have secondary highway growth. Employment zones and their neighborhood (U_E) have a high likelihood of secondary highway growth. Water area and their neighborhood (U_W) always have low growth probability. The agricultural area (U_A), however, is positive and significant for all the predictions which indicates that agricultural area is associated with a high likelihood of secondary highway growth, this result can be explained by the fact that secondary highways are more relied on in the agricultural areas for product transport and commuting service due to the lack of higher hierarchical highways.

5.6 Conclusions

This study analyzes the evolution of highway networks in the Twin Cities Metropolitan Area. The growth probability of divided highways and secondary highways is modeled using binary logit models based on population distribution, land-use and roadway networks data. The major findings of this study are summarized as follows:

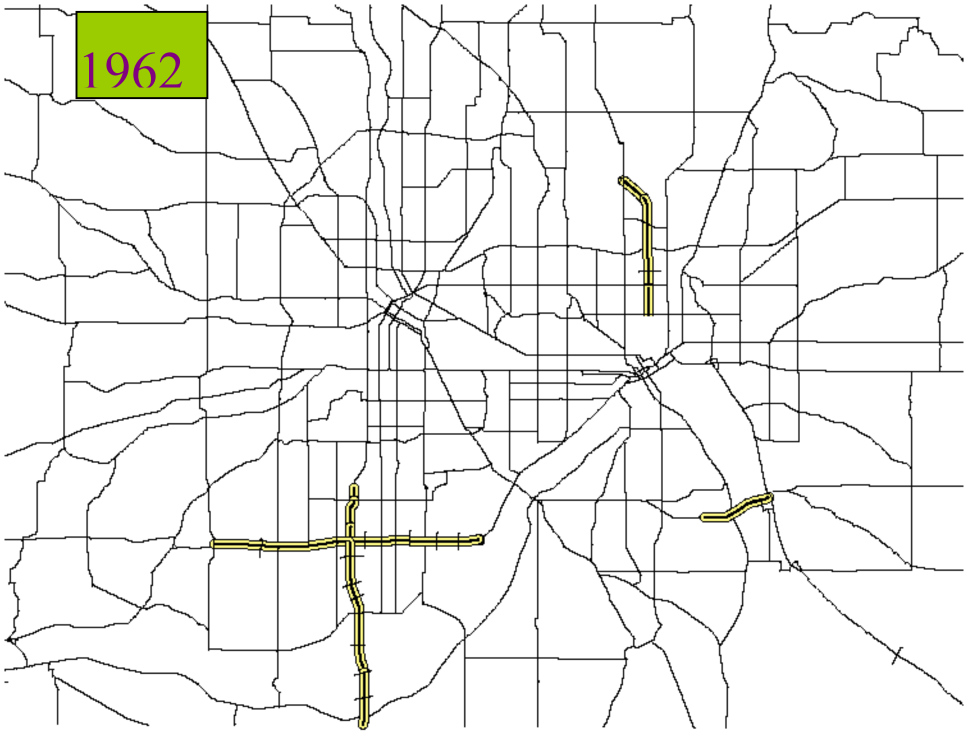
Since they serve as the major local commuting routes, the further growth of divided highways are more likely to be close to employment zones. Also divided highway growth follows the agglomeration tendency, that is, the neighboring areas of the existing corridors have a higher likelihood of new route development. As to population density, we find moderately dense areas have higher route growth probability than both the densely populated areas and the sparsely populated areas. Generally commercial zones and their neighborhood are positively and significantly related to divided highway growth probability, but they are not as significant as employment zones.

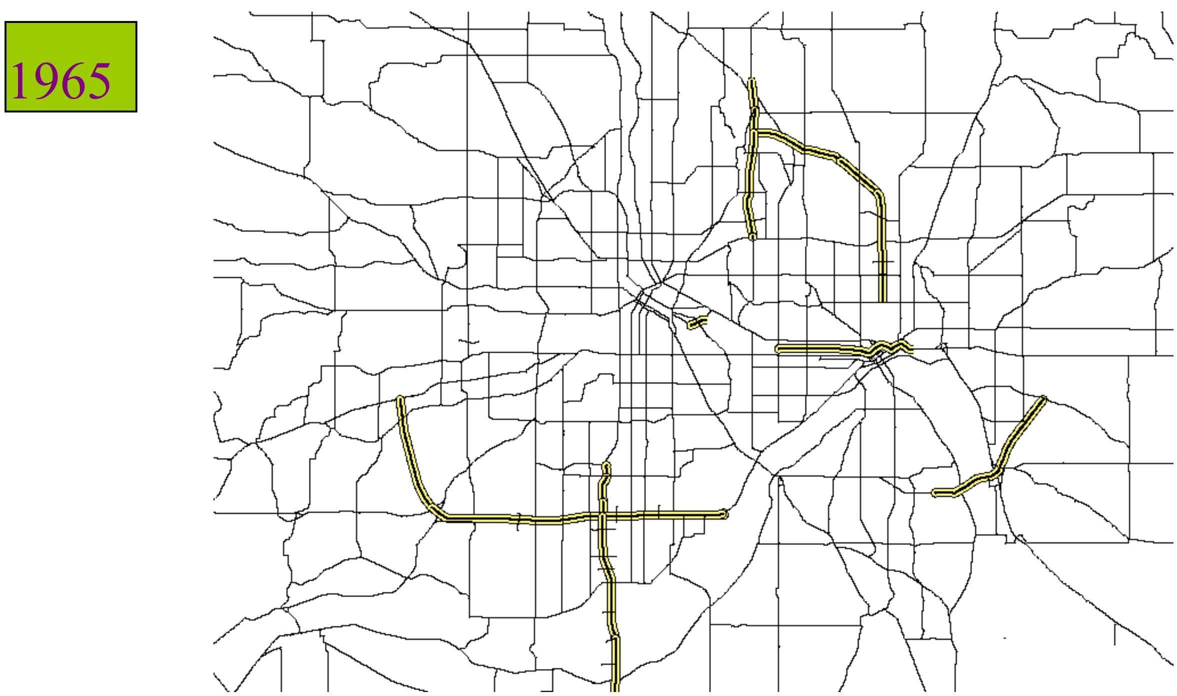
Water areas have low divided highway growth probability. But agricultural areas sometimes are related to high growth probability, and we speculate that it may be because diverting from the highly urbanized areas save construction costs or divided highways connect urban and suburban areas and is used to spur economic development of the undeveloped areas.

For secondary highways, since they are the proximate and ultimate connecting highways of urban settlements, the growth of secondary highways is strongly related to the settlement areas, and we find cells with a higher percentage of urban settlement area are more likely to have secondary highway growth. Besides employment zones and their neighborhood have a high likelihood of secondary highway growth. As to population density, both moderately populated areas and densely populated areas have a high secondary highway growth probability.

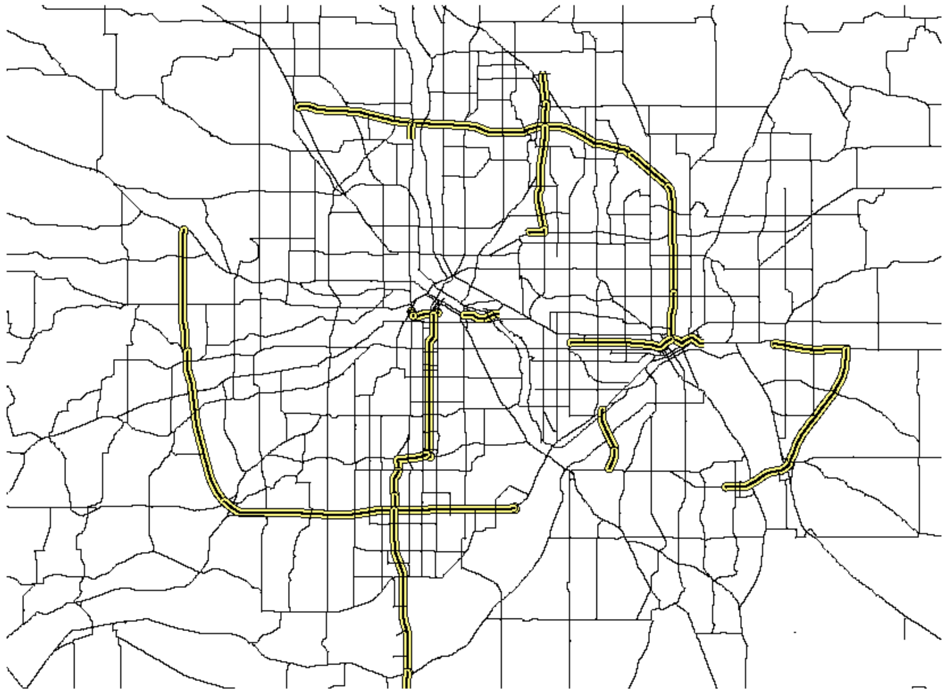
Water areas and their neighborhood always have low secondary highway growth probability. The agricultural areas, however, are associated with a high likelihood of secondary highway growth, which may be due to agricultural areas’ high reliance on secondary highways for product transport and commuting service.

Figure 5.4. The development of Interstate system in Minneapolis-St. Paul Metropolitan Area.

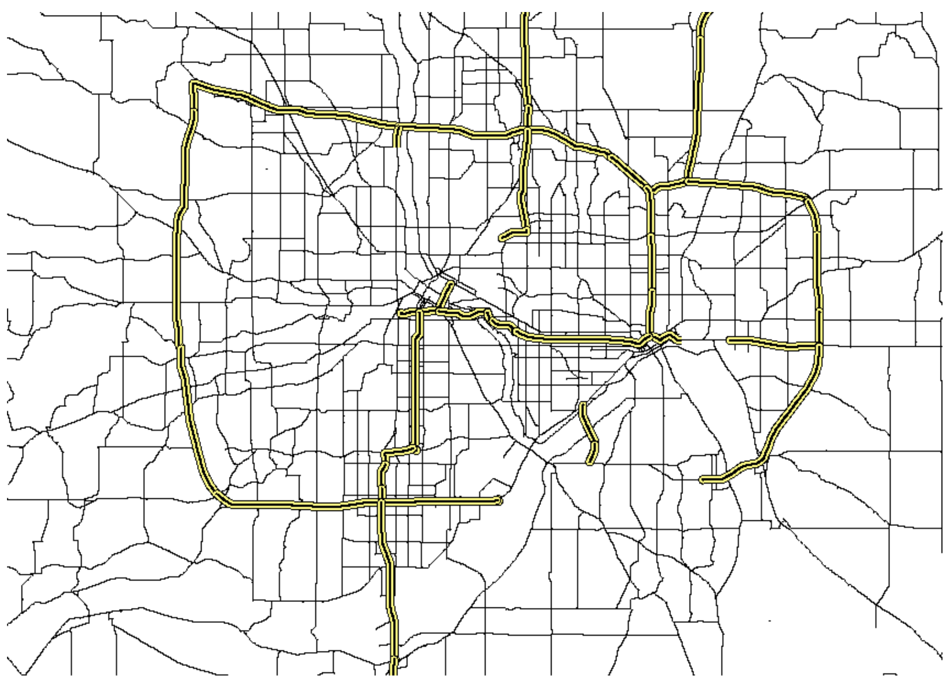




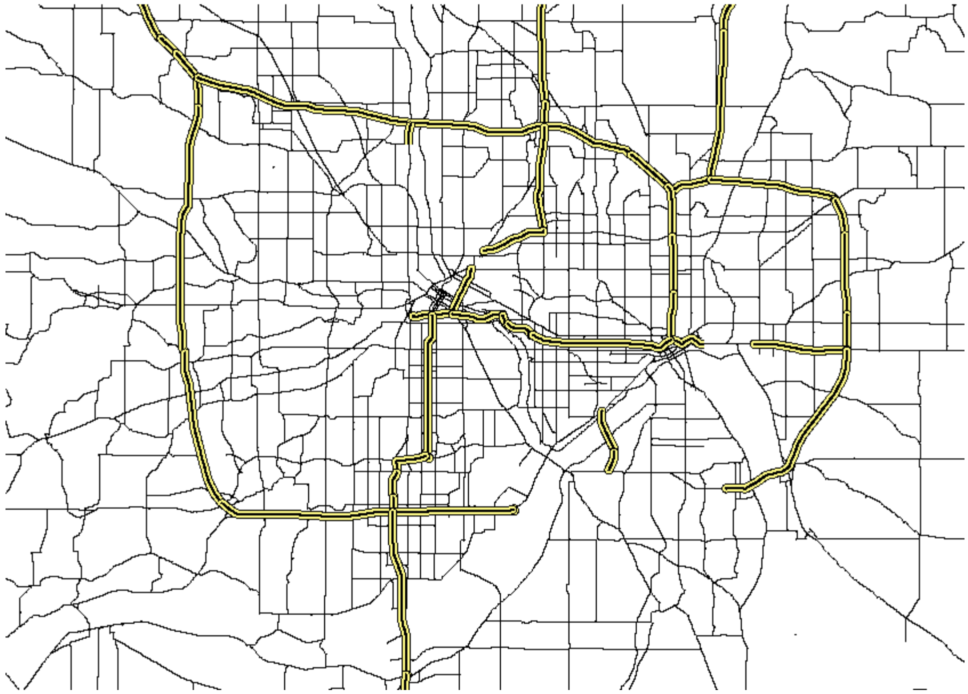
1968



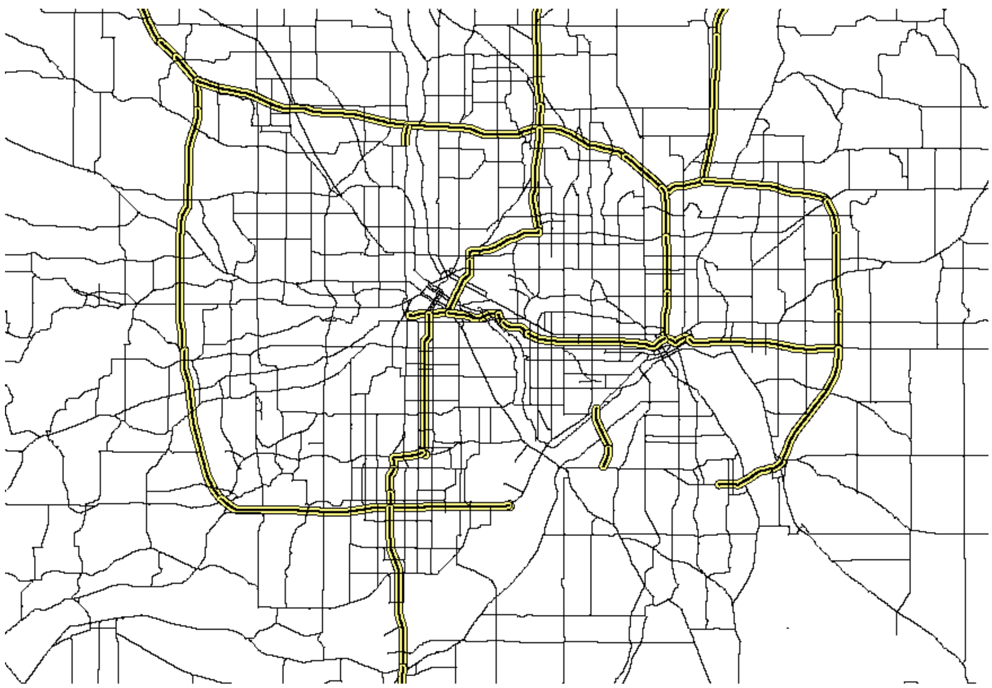
1971

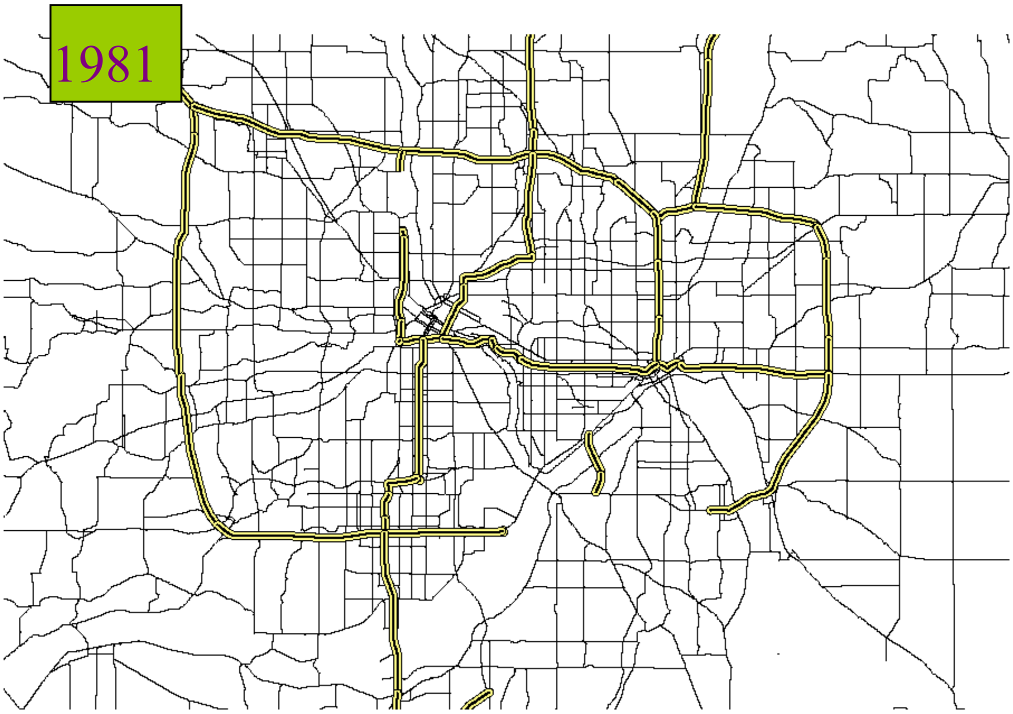


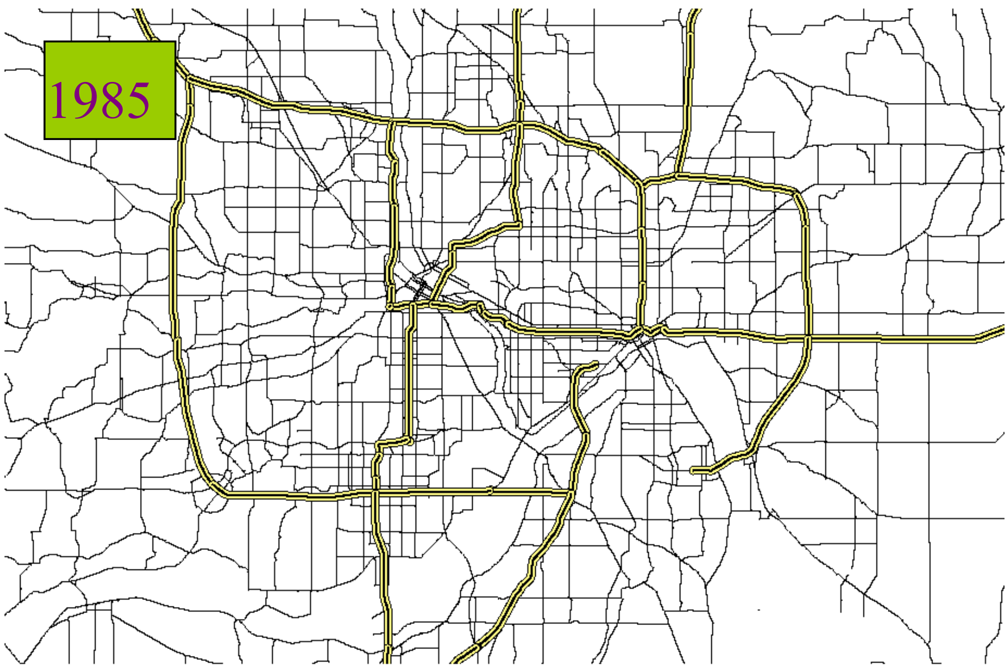
1975

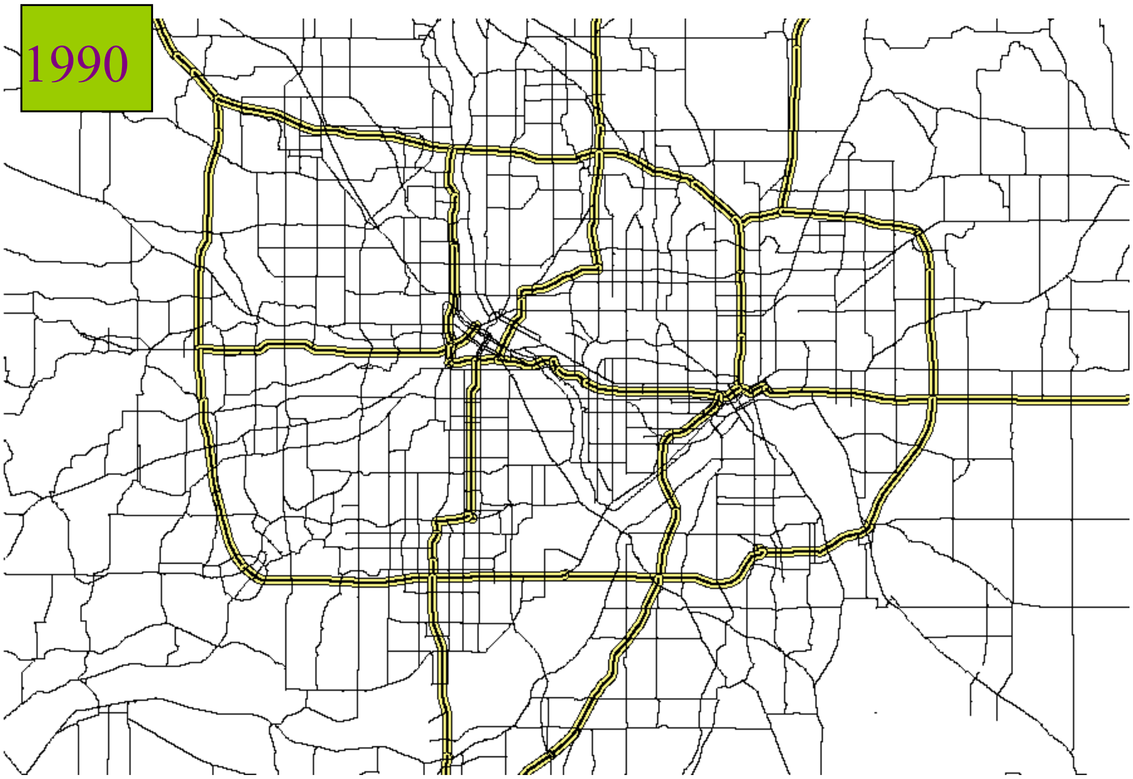


1978




1981


1985


1990

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