Economics of Road Network Ownership

Lei Zhang[1] and David Levinson[2]

1. Assistant Professor
Department of Civil, Construction and Environmental Engineering
Oregon State University
220 Owen Hall, Corvallis, OR 97331
V: 541-737-2072 F: 541-737-3052
lei.zhang@oregonstate.edu

2. Associate Professor
Department of Civil Engineering
University of Minnesota
500 Pillsbury Drive SE
Minneapolis, MN 55455
V: 612-625-6354 F: 612-626-7750
levin031@tc.umn.edu

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Abstract

This paper seeks to understand the economic impact of centralized and decentralized ownership structures and their corresponding pricing and investment strategies on transportation network performance and social welfare for travelers. In a decentralized network economic system, roads are owned by many agencies or companies that are responsible for pricing and investment strategies. The motivation of this study is two-fold. First, the question of which ownership structure, or industrial organization, is optimal for transportation networks has yet to be resolved. Despite several books devoted to this research issue, quantitative methods that translate ownership-related policy variables into short- and long-run network performance are lacking. Second, the U.S. and many other countries have recently seen a slowly but steadily increasing popularity of road pricing as an alternative to traditional fuel taxes. Not only is the private sector encouraged to finance new roads, this transition in revenue mechanism also makes it possible for lower-level government agencies and smaller jurisdictions to participate in network pricing and investment practice. The issue of optimal ownership is no longer a purely theoretical debate, but bears practical importance.

This research adopts an agent-based simulator of network dynamics to explore the implications of centralized and decentralized ownership on mobility and social welfare, as well as potential financial issues and regulatory needs. Components of the simulator: the travel demand model, cost functions, and key variables of pricing and investment strategies, are empirically estimated and validated. Results suggest that road network is a market with imperfect competition. While there is a significant performance lag between the optimal strategy and the current network financing practice in the U.S. (characterized by centralized control, fuel taxes, and budget-balancing investment), a completely decentralized network suffers from issues such as higher-than-optimal tolls and over-investment. For the decentralized ownership structure, appropriate regulation on pricing and investment practices is necessary. Further analysis based on simulation comparisons suggests that with appropriate price regulation, a decentralized road economy consisting of profit-seeking road owners could outperform the existing centralized control, achieve net social benefits close to the theoretical optimum, and distribute a high percentage of welfare gains to travelers. Decentralized control is especially valuable in rapidly changing environments because it promptly responds to travel demand. These results seem to favor the idea of privatizing or decentralizing road ownership on congested networks. Further tests on real-world transportation networks are necessary and should make an interesting future study.

Key words: Network economics, Modeling network dynamics, Road pricing, Transportation financing, Privatization.

1. Introduction

While recent research in transportation economics has focused on the optimal pricing and investment strategies for road networks, a more fundamental economic issue – road network ownership that defines pricing and investment objectives – remains inadequately understood. The apparently important problem of identifying the optimal ownership structure given certain network supply and demand characteristics has not found a satisfactory solution. The ownership of a road network could be public or private, centralized or decentralized, and evolves over time. The presumption that prevailing transportation problems such as congestion and inadequate financing can be best resolved in the public sector is unwarranted and may produce less effective policies. A potentially more productive approach is to carefully examine theoretically sound and practically feasible road network ownership structures, and to implement policies leading to the optimal one which for instance could be private-centralized (monopoly), private-decentralized (competitive market), public-centralized (e.g. decisions made at the federal level or by large jurisdictions only), public-decentralized (e.g. decisions relegated to smaller jurisdictions), or an arrangement in between these extreme situations.

The evolution of road network ownership can assume many forms such as privatization, nationalization, merging of decentralized road authorities, and separation of centralized road authorities. Although most roads in the U.S. are currently owned and operated by government agencies (state, county, and municipal governments), a recent trend in highway financing in the U.S. is characterized by the development of new private toll roads (e.g. SR-91, Dulles Greenway) and the takeover of existing state-owned roads through contacting to private vendors (e.g. Chicago Skyway, Indiana Turnpike). It is now widely recognized that the advance in toll collection technology, need for congestion reduction and environmental mitigation, increased substitution of alternative fuels for gasoline and the decline of gas tax revenue, and inadequate funding from traditional sources have made tolling an attractive alternative to taxes. This transition in revenue mechanism will likely cause a more decentralized ownership structure to emerge. Using tolls as the revenue mechanism, local jurisdictions would enjoy increased flexibility in setting prices for road usage. Private sector firms may invest in transportation facilities when the rate of return is sufficiently high and risks low. A better understanding of the economics of road network ownership is necessary to examine the full socio-economic consequence of the resulting more decentralized ownership structure.

The combination of private and competing toll roads would represent a comprehensive market-oriented approach to road transportation problems, but its impacts are unclear. There are competing views among economists regarding the proper scope of private sector involvement in road infrastructure. Some believe that roads have monopoly power because a link uniquely occupies space, and the use of alternative indirect roads is more costly to users in term of travel time. They have concerns that private roads may exercise their monopoly power and make socially undesirable pricing and investment decisions. Although theory suggests that excess profits will attract new entrants into a market, the cost of building a new road is high and the benefit likely low especially when a competitor already exists, indicating barriers to entry. Also, equity and safety concerns are not necessarily consistent with the profit-maximizing objective of private roads. On the other hand, there are defendable benefits of a decentralized private ownership structure. Compared to government agencies with political objectives, private roads may be more willing to adopt innovative pricing schemes. In other sectors of the economy, central control of pricing has proven itself less effective than decentralized control for serving customer demands in rapidly changing environments. Even though a market economy of private roads can result in high prices and excess profits in the short-run, these price and profit signals in the long run will attract capital and entrepreneurs to the transportation sector of the economy, which could provide an effective solution to the problem of inadequate funding. The incentives for the private sector to minimize costs and provide efficient levels of service through innovation may change the supply curve of the industry and therefore benefit users.

These potential benefits of private ownership, as well as the aforementioned issues with road privatization such as spatial monopoly, are well understood at the conceptual level. However, more rigorous studies of road network ownership using empirically-verified network economic models should be pursued, which will allow detailed quantitative analysis of the welfare impact of competing ownership regimes on specific road networks. This paper is driven by that vision and develops a quantitative method to explore the economics of road network ownership. The analysis consists of detailed examination and modeling of travel demand and road supply, as well as pricing and investment strategies adopted by public and private road authorities. A uniqueness in the modeling efforts lies in the consideration of the interdependencies between pricing and investment decisions as a transportation network evolves under public or private ownership: (1). Road tolls (taxes can be modeled as specific forms of toll) provide revenue for investment; (2). Previous tolls and toll revenue provide useful information about the proper level of future investment; (3). Investment results in new capacity therefore changes the "optimal" toll level. It is recognized that certain disadvantages of private ownership can be partially overcome by appropriate regulatory rules. This research also applies the proposed economic framework and models of road ownership to assess the effectiveness of regulatory policies in a private decentralized network.

In terms of methodology, this research builds on two previous studies [1, 2] in which an agent-based model of network evolution is developed for assessing network performance over time under different ownership structures. While several simplifying assumptions are made in these two previous studies, the analysis in this paper is based on more realistic profit-maximizing behavior of private roads. The impact of alternative ownership structures on welfare are simulated on a network with travel demand increasing over time, and with road toll and capacity shifting in response to pricing and investment decisions. The analysis of network evolution under this more realistic demand scenario is a significant departure from previous network equilibrium studies.

The intent of this research is not to be comprehensive. Instead, the merit of the paper resides in the definition of the road network ownership problem and its practical importance, the assembly of existing and new models to study this problem quantitatively, and the demonstration of the capabilities of the quantitative method on two test networks with distinct ownership structures: private-decentralized and public-centralized. In the decentralized market economy, all road links are competitive and independent with the objective of maximizing their own profits without regards for either social welfare or the profits of other links, though possibly subject to regulatory constraints. The comparison between the decentralized market-approach and the centralized government control has immediate policy implications in the U.S.

Section 2 reviews the most relevant literature in the areas of network economics, transportation privatization, road pricing, and industrial organization. Section 3 presents the network evolution model with emphasis on travel demand and road supply characteristics. Section 4 focuses on the pricing and investment strategies of public and private road owners. When component models in Sections 3 and 4 are combined, they are able to predict the evolution of a transportation network under specific ownership structures and provide detailed results regarding network performance, pricing dynamics, capacity growth, and social welfare over time. The modeling system also allows convenient addition of regulatory models for analyzing regulation policies. Section 5 implements the models on a test network with the aforementioned two ownership cases. Section 6 summarizes the results and discusses their policy implications. A simple price-ceiling regulation rule is also evaluated in this section for the case with private ownership. Conclusions are offered in Section 7.

2. Literature review

Previous studies on road ownership have been experiential, and based conclusions on consequences of privatization in other economics sectors [3] or on empirical observations of demand and cost characteristics of existing private roads [4]. Winston and Shirley [5] were able to quantify the welfare loss in urban transit systems due to inefficiencies inherent to public ownership, but did not provide a model for analyzing road ownership. The empirical evidence, existing situations, and political environment in many areas of the world suggest that the research question to answer is not “should all roads be privatized”, but “when, where, and how can the concept of private roads help solve urgent transportation problems”. This requires quantitative, valid, and flexible models of road ownership applicable in real-world networks. Such models would inevitably require the joint consideration of pricing and investment decisions by various types of road owners and their interactions on large networks and over a period of time. Several studies have examined the pricing dynamics between private toll roads and competing free-access roads [6-9]. de Palma and Leruth [10] and Yang *et al.* [11] considered price and capacity competition in congested networks. Levinson [12] examined price competition between serial monopolists with revenue stategies. Recently, Verhoef and Rouwendal [13] explored interrelations between pricing, capacity choice, and financing in transportation networks using a small network model. Zhang and Levinson [14] developed a mathematical model of transportation network evolution, and used the model to study pricing dynamics, capacity growth, and welfare impacts under various ownership structures on several stylized small networks. Their results suggest that the competition and complementarity among links in a road network significantly affect the pricing and investment decisions as well as the optimal network ownership structure. Profit-maximizing price and capacity are systematically biased from the socially optimal values. Public-private mixture appears to be a robust ownership arrangement in networks with various layouts. However, there is one drawback associated with the previous attempts to solve for the combined optimal pricing and investment choices analytically – the equation system or optimization program in these studies cannot be solved efficiently on large networks.

While the focus of this study is on the economic consequences of ownership structures and their corresponding pricing and investment strategies, the travel demand and travel time components of the model need to be specified [15-17]. The monetary costs of infrastructure provision, user operating costs, and social costs on highways as a function of flow have recently been estimated by several studies [18,19], and these costs will be considered by the links in profit maximizing and the prices they charge. These need to be integrated and solved in both traffic equilibrium [20] and long-term supply-demand equilibrium.

3. A Model of Network Evolution

Few researchers have considered the process of transportation network growth (or decline) at the microscopic level, although long-term transportation network dynamics are important for assessing alternative pricing policies, investment rules, and institutional structures. Analytical models of network growth [14] are not practical except under simple, idealized conditions, represented by very small networks and analyzed using the principles of transportation engineering, microeconomics, game theory, and industrial organization. Zhang and Levinson [1, 2] proposed a model of transportation network growth and demonstrated the feasibility of an agent-based simulation approach for transportation-related policy analysis. Their simulation model is extended in several ways in this study for assessing centralized and decentralized ownership.

An overview of model components and their interconnectivity is shown in Figure 1. Three aspects of the transportation system determine the path of network evolution: behavior, technology, and policy. A travel demand model captures collective consequences of travelers' behavior and predicts traffic flows on individual links based on the network from the previous year, and exogenous socio-economic and demographic information. On the policy side, a pricing strategy determines tolls, which both influence travel demand and generate a stream of revenue. Road owners, public or private, also adopt an investment policy to use this revenue at their discretion and based on their objectives. The revenue can be used to defray road maintenance cost, and/or to build new capacity, and/or to invest in other sectors of the economy. In order to achieve investment objectives, the cost structure of the system must be known. Existing technology determines maintenance and capacity expansion costs on specific facilities, which can be estimated from empirical data. After a set of investment decisions are made based on revenue and cost estimates, roads in the transportation network may grow with expanded capacity or degenerate (when not appropriately maintained). This supply-side change, combined with demand changes, causes the system to settle at a new short-term traffic equilibrium in the next time period. If total travel demand is fixed, the network may achieve a long-run supply-demand equilibrium when (1) no user can reduce travel cost by unilaterally changing route (the Wardrop's User Equilibrium condition); (2) no private road owner can increase profit by unilaterally changing road toll or capacity; (3) no public road authority can improve social welfare in its jurisdiction by unilaterally changing road toll or capacity. When travel demand constantly shifts (typically upwards in a growing economy), and technologies change, the network constantly evolves and no equilibrium can be observed, which is what happens in reality.

This section illustrates the demand and cost estimation procedures in the network model. Details of pricing and investment policies under alternative ownership structures are discussed in Section 4. The travel demand model follows a standard sequential procedure with zone-based generation structure, doubly-constrained gravity model of trip distribution, no modal choice (auto only), and user equilibrium traffic assignment.

3.1. Notation

A_r	accessibility of zone *r*
CS^{0-i}	change in consumers' surplus from year 0 to *i*
$d(.)$	cost impedance function in the gravity model; $d(t_{rs}^i) = e^{-\gamma \cdot t_{rs}^i}$
D_s	number of trips destined for zone *s*
DR_a^i	disposable revenue of link *a* in year *i* (dollar)
E_a^i	revenue (earnings) of link *a* in year *i* (dollar)
K_a^i	cost of expanding link *a* in year *i* (dollar)
f_a^i	average hourly flow on link *a* in year *i* (veh/hr)
F_a^i	capacity of link *a* in year *i* (veh/hr)
G	Gini coefficient of accessibility inequity
i	index of year
j, k	parameters in the decentralized pricing model
l_a	length of link *a* (constant) (km)
m_r, n_s	coefficients in the gravity model
M_a^i	cost of maintaining link *a* in year *i* (dollar)
O_r	number of trips produced from zone *r*
q_{rs}^i	demand from origin *r* to destination *s* in year *i*
t_a^i	generalized travel cost on link a in year *i*
t_{rs}^i	generalized travel cost from zone *r* to *s*
v_a^i	free-flow speed of link a (km/hr) in year *i*
α_{1-3}	coefficients indicating (dis)economies of scale
ϕ	scale parameter in expansion cost function
γ	coefficient in the impedance function
λ	value of travel time (dollar/hr)
θ_{1-2}	coefficients of the BPR travel time function
ρ_{1-2}	coefficients in the centralized pricing model

$\sigma_{1\text{-}3}$ coefficients in the expansion cost model

$\tau_a^{\,i}$ link toll per vehicle (dollar, see equation 4)

μ scale parameter in maintenance cost function

$\omega_{1\text{-}2}$ coefficients in the capacity-speed model

ψ coefficient to scale hourly flow to annual flow

3.2. Travel demand

A traditional four-step model is specified to estimate travel demand at the link level, taking exogenous land use, social-economical variables, and the existing network as inputs. Although the four-step model serves well for demonstration purposes in this paper, future studies should use more advanced travel demand models. For instance, combined travel demand models address inconsistencies in the sequential model by solving all steps in a coherent equilibrium [21]. Activity-based approaches [22] and agent-based micro-simulation [23] improve behavioral representation in travel demand models. A zone-based regression structure is used for trip generation. The origin-destination (OD) cost table obtained from the previous year traffic assignment is used for trip distribution in the current year based on a doubly constrained gravity model [24,25].

$$q_{rs}^{i} = m_r O_r n_s D_s \cdot d(t_{rs}^{i}) \tag{1}$$

The resulting OD table is loaded onto the current year transportation network through the origin-based user equilibrium traffic assignment algorithm (OBA) [26]. The generalized link cost function comprises two parts, a BPR travel time component and a vehicle toll.

$$t_a^i = \lambda \frac{l_a}{v_a^i}\left[1 + \theta_1 \left(f_a^i \big/ F_a^i \right)^{\theta_2}\right] + \tau_a^i \tag{2}$$

The OBA algorithm derives link flows at user equilibrium and generates a new OD cost table that will be used for trip distribution in the next year. This means in principal all of the demand could find new destinations each year, though in practice, once the system approaches equilibrium, the year to year changes are small. In the traffic assignment step, if the relative excess travel cost is less than 0.001, the Wardrop user equilibrium [27] is considered to be satisfied. Coefficients in the travel demand model are extracted from the Twin Cities metropolitan area planning models. They are empirically estimated and summarized in Table 1.

3.3. Cost functions

The functional forms of the cost functions are chosen based on project-level cost data collected in the Twin Cities metropolitan area in Minnesota. The same data set is also used to estimate and validate the coefficient in the cost functions. The link maintenance cost function (using a Cobb-Douglas functional form) has two determining factors: link length, and capacity. It costs more to maintain a link at its current level of service if the link is longer and carries heavier flow.

$$M_a^i = \mu \cdot (l_a)^{\alpha_1} (F_a^i)^{\alpha_2} \tag{3}$$

Link expansion cost is considered a function of link length, existing capacity, and additional capacity to be expanded. It is more expensive to expand a unit capacity on a link with higher existing capacity.

$$K_a^i = \phi \cdot (l_a)^{\sigma_1} \cdot (F_a^i)^{\sigma_2} \cdot (F_a^{i+1} - F_a^i)^{\sigma_3} \tag{4}$$

4. Pricing and Investment Policies

4.1. Centralized Public Control

Under centralized control, a government agency manages all roads, makes pricing decisions, and spends on road maintenance and construction based on a budget. This ownership scenario is constructed to replicate the existing road systems in U.S. urban areas. Therefore, marginal cost pricing is not assumed.

4.1.1. Pricing Policy: Average Cost Pricing

Under centralized control, users pay a distance-based toll for using the roads. This is similar to a fuel-tax except that the variation of fuel efficiency among vehicles is ignored. (Transaction costs of toll collection are assumed to be zero throughout).

$$\tau_a^i = \rho_1 \cdot (l_a)^{\rho_2} \tag{5}$$

This pricing equation essentially represents an average-cost-pricing practice. Cost per kilometer of travel is the same no matter where or when trips occur. Revenue from each link is then collected, which is simply the product of the toll and annual traffic flow on the link:

$$E_a^i = \tau_a^i \cdot (\psi \cdot f_a^i) \tag{6}$$

4.1.2. Investment Policy: Benefit-Cost Analysis and Budget Balancing

Revenue collected on all links is pooled together and a central government agency makes all investment decisions. It is assumed that the central government agency can adjust the distance-based toll (or fuel tax) so that total network revenue is always higher than the cost required to properly maintain all links in the network. The remaining revenue after the total maintenance cost is appropriated is spent to expand road capacity based on estimated benefit/cost ratios.

The maximum possible benefit/cost ratio (BC_{max}) of expanding each link, as well as the corresponding "optimal" amount of expansion, is computed based on the construction cost function and the following assumptions: (1) Traffic increases by three percent every year; (2) Interest rate is three percent; (3) Value of time is 10 dollars/hour for all users; (4) The planning horizon is 25 years; (5) Only local (on the same link) travel time benefits are considered. Total benefit of capacity expansion under these assumptions is the sum of discounted future monetized travel time savings over the planning horizon. The benefit/cost ratio than becomes a single-variable convex function of the amount of capacity increase, and solved. Revenue is used to expand the link with the highest BC_{max}. Then, the link with the next highest BC_{max} is expanded until the revenue is exhausted. This implies that at the end of each fiscal year, the centralized government agency in control of the road network has a balanced budged with no deficit or surplus. It is possible that this budget-balancing invest policy causes under- or over-investment, because the total amount of construction determined by the budget may exceed or fall short of the optimal amount of capacity improvement. Therefore, this investment policy under centralized control is most likely non-optimal. However, it describes current practice.

When roads are expanded, the capacity increase is usually associated with a concurrent change of free-flow speed. For instance, free-flow speed on higher-capacity roads such as divided arterials and freeways are higher than low-capacity roads. This positive correlation is estimated with speed and capacity data used by the Twin Cities Metropolitan Council in their regional planning models on more than ten thousand roadway sections. A log-linear model provided the best fit:

$$v_a^i = \omega_1 + \omega_2 \cdot \ln(F_a^i) \tag{7}$$

The assumption of a user group with uniform value of time may bias analysis of welfare implications. Several recent studies show that the ignoring user heterogeneity and the possibility of product differentiation underestimates the benefits of road pricing and decentralized control [28-30]. The network growth model described above needs to use a multi-class (or agent-based) travel demand model to account for variation of value of time, which should be pursued in future studies.

4.2. Decentralized Private Control

4.2.1. Pricing Policy: Short-Run Profit-Maximizing

When setting tolls, private roads under decentralized ownership take road capacity as given and seek to maximize their short-run profits in an imperfectly competitive market. Because travel demand is elastic with respect to price, the profit-maximizing toll is constrained by the market. Competing links (often parallel roads serving the same origin-destination pairs) also restrict the price that a link can charge. It is anticipated that each link will have an objective function for profit maximization. However, depending upon assumptions of whether the firm perfectly knows market demand, and how the firm treats the actions of competitors, the Nash equilibrium solution to the dynamic pricing game among private roads in a network may not be unique, or even exist.

Whether this system converges upon an equilibrium solution, and whether that solution is unique are both hard game-theoretic problems. This analysis does not take a game-theoretic approach to compute profit-maximizing prices, because any computable solution requires significant simplifying assumptions and unrealistic assumptions of the availability of information.

The incompleteness of information is profound in the market comprised of non-cooperative competing roads. The situation of incomplete information is further aggravated by the fact that the demand function on one link depends on its previous investment decisions and the pricing/investment decisions made by its competing and complimentary links. Once a link has found a toll that it can neither raise nor lower without losing profit, it will be tempted to keep it. It is assumed that with uncertainty on the future pricing and investment behavior of other links, a link focuses on the observed historical demand corresponding to its previous tolls. The collective influence of the behavior of other links can be viewed as represented by the demand curve on the link. Links deals with system dynamics and uncertainty by adjusting their prices iteratively based on updated information about link travel demand after each time period. This price-probing behavior for profit-maximization is depicted in Figure 2. In each iteration, a link estimates a demand curve based on observed flows and previous tolls in the previous k iterations (represented by crosses in the graph), and line-fitting methods. The k previous prices fall into a range $[P_{low}, P_{High}]$. The estimated demand curve can be extrapolated beyond this price range (dashed portion of the demand curve), but with increased uncertainty. This empirical demand curve is than used to find the optimal price P^*, which employs a standard quadratic optimization procedure. If $P^* \in [P_{low}, P_{High}]$, like in case A, it determines the toll for the next period. Otherwise (e.g. case B), when data suggest P^* is in a new price territory, the link will change price toward P^*_B only by a conservative step j to $P_{Low}(1-j)$.

This pricing rule assists private roads to maximize profit and keep the price changes smooth. It should be a plausible pricing rule when uncertainty about prices of other links and demand abound. When price regulation is present, the same pricing rule can be applied with a bound defined by the regulatory policy. A more intelligent link may realize that while it may have found a local maximum based on available information, because of the non-linearities comprising a complex network, it may not be at a global maximum. Furthermore other links may not be so firmly attached to their decision, and a periodic probing of the market landscape by testing alternative prices is likely. This too requires learning rules and should be explored in future studies.

4.2.2. Investment Rule: Long-Run Profit-Maximizing

For profit-maximizing links, capacity expansion allows them to charge higher tolls, attract more traffic, or both. When the resulting increased profit exceeds the expansion cost and maintenance cost in the life cycle, links will build more capacity. When disposable link revenue is not sufficient to make the investment and the estimated rate of return is higher than the interest rate, links can and should borrow from others. When the estimated rate of return is lower than the interest rate, links either save the toll revenue in a bank or invests it in other sectors. These investment options are made available in the simulation model with a bank agent. The bank agent pays interest for savings and lends money to links with profitable projects. The bank agent has an additional rule that only currently profitable links can get loans. This rule is added to ensure links under decentralized control have positive cash flow.

While the combined cost of road expansion for a link can be calculated from cost functions, the expected amount of profit in the planning horizon (also 25 years) cannot be estimated with much certainty as other links may also expand capacity and prices can change significantly during the planning horizon. It is assumed that a link estimates the amount of profit from road expansion using the following method:

(1) Assume traffic increases by three percent every year and the capacity and prices on other links remain unchanged;
(2) Compute travel time savings for users for a specific amount of capacity expansion (adding one more lane or two more lanes);
(3) Run a travel demand model; re-distribute and re-assign traffic with reduced travel time and unchanged toll; and calculate the amount of profit gain throughout the planning horizon due to increased traffic on the link, π_1;

(4) Convert an individual traveler's time saving on the link immediately after expansion to a monetary value; increase the toll on the link by exactly the same amount which should keep traffic flow unchanged; compute the profit gain throughout the planning horizon due to higher toll on the link, π_2;

(5) The final estimated profit gain is max (π_1, π_2)

The rationale behind this profit estimation procedure is as follows. The extra profit gain due to road expansion and new investment comes from one or both of these two sources: increased traffic and increased toll. The above method finds the profit gains when only one of the two sources is exploited while the other is kept unchanged. Exploiting both sources at once indicates a tradeoff. While the final profit gain in this more complex case is expected to be higher than π_1 or π_2, and it is theoretically possible to identify the optimal toll level and maximum expected profit gain through optimization, it is computationally intractable to implement the optimization method for all links in a large network. Therefore, the profit estimate from the proposed method is an underestimate. The assumption that competing links do not expand capacity is necessary unless a clear leader in the road expansion game can be identified and more strategic investment decisions can be computed, this may over-estimate the expected profit-gain. On the other hand, the assumption that complementary links do not expand likely underestimates profits.

Based on the discussion and analysis in this section, it is apparent that the combined globally optimal pricing and investment strategy for private roads in a decentralized road economy is very hard to determine due to uncertainty about future demand, others' strategies, and network effects. It is therefore reasonable to doubt the likelihood private roads will find the theoretically optimal investment level given the difficulty of that problem. The profit-maximizing pricing and investment strategies proposed in this section are hybrid strategies based on heuristic rules, learning, and optimization principles. The simulation results presented in later sections show that these hybrid strategies serve the profit-maximizing objective very well. For instance, private roads adopting the hybrid strategies on the test network are able to keep more than 75% of total welfare gains as their profits when there is no regulation.

4.3. Socially Optimal Pricing and Investment Policies

To better compare centralized and decentralized ownership structures, it is desirable to add to the comparison network performance with socially optimal pricing and investment policies. This optimal scenario provides the maximum possible welfare gains and serves as a benchmark. The theoretical best pricing policy in a first-best environment is marginal cost pricing, which is estimated by the link travel time savings when one user is removed from the link. It should be noted the true system-wide marginal cost of one additional trip on a link is different and can be higher or lower than the local link-level marginal cost (This is documented in [31]).

The capacity of a link is at optimum if the marginal cost of building one extra unit of capacity just equals the marginal benefit in a first-best scenario. In practical economic planning, the optimal capacity expansion project is often determined by benefit/cost analysis subject to budgetary constraints. The socially optimal investment policy defined herein is similar to the investment policy discussed in Section 4.1.2 except that budget balancing is no longer required. When there is still residual revenue after all capacity expansion projects with benefit/cost ratios larger than one are approved, this residual revenue is saved, instead of wasted on socially undesirable projects to eliminate any surplus. If there is insufficient revenue, it is borrowed from the future. When marginal cost pricing is adopted on a congested network, the occurrence of excessive revenue is quite possible.

5. Description of Simulation Experiments

In Sections 3 and 4, all components in the network evolution model illustrated in Figure 1 are described. When initial network data is provided, the model can predict its short- and long-run performance under various pricing, investment policies, and ownership structures. A long-term supply-demand equilibrium may be achieved when origin-destination demand curves are fixed (referred to as *fixed demand* hereafter) and when all equilibrium conditions mentioned at the beginning of Section 3 are satisfied. When demand curves shift over time (*variable demand* hereafter), equilibrium cannot be observed in the system and only a growth path is estimated. Measures of effectiveness collected from simulation experiments are valuable for policy evaluation. The question of whether a transportation network evolves better under centralized or decentralized control can be explored.

The network model can be applied to a realistic roadway network of any size. The computational load is primarily determined by the execution of travel demand models. The execution time is mainly affected by the convergence speed of the traffic assignment model. A ten-by-ten grid network (100 nodes and 360 links) is used in this study to explore consequences of alternative institutional structures. The same initial condition is specified for all simulation scenarios. All links in the grid network are 3.2 kilometers in length and have an initial capacity of 735 veh/h (This value corresponds to a one-lane road according to a regression analysis using the capacity and number-of-lane data in the Twin Cities regional planning model). The initial network is congested with an average volume/capacity ratio of 0.8. The initial land use is uniform among all 100 network zones with ten thousand trips originating and destined for each zone respectively. Although the use of a grid network loses to a real-world networks on realism and immediate applicability of results, it wins on ease of interpretation, elimination of conflating factors, and the ability to run a large number of scenarios for comparison within a reasonable amount of time.

Two sets of simulation experiments are conducted. The first set is under fixed demand. In all these simulation runs, long run network equilibria are identified. Consequences of all policy scenarios can be compared both over time and at the final equilibrium point. The second set of experiments incorporates variable demand. Results from these runs have more practical significance because total travel demand has continued to increase in the past, and will likely keep increasing in the foreseeable future. As noted previously, it is assumed in these simulation experiments that the total number of trips using the network increases at an annual rate of three percent.

6. Results

6.1. Fixed Demand

It should be emphasized again that in the fixed demand case, only the total number of trips generated in the network is fixed. However, these trips can redistribute among origin-destination pairs and take various routes. Therefore, demand curves for individual links are not stable and change over time. The long-term supply and demand in the grid network under all three scenarios (centralized, decentralized, and socially optimal) equilibrate after tolls and link capacity are adjusted. Figure 3 plots the equilibrium tolls and capacity in the fixed demand case. The marginal cost tolls are higher on links in the center of the grid as they attract more traffic and have higher levels of congestion than links on the edges. The socially optimal capacity distribution is quite flat. The uniform spatial demand (i.e. the same land use characteristics in all 100 zones) should be responsible for this result.

Under centralized control characterized by average cost pricing and budget-driven investment strategies, the grid network at equilibrium displays capacity significantly lower than the optimum. The average-cost-pricing policy such as the distance-based user charges or fuel taxes does not generate sufficient revenue for network growth. Furthermore, even the non-optimal capacity will not be used by travelers in an optimal fashion because tolls are much lower than marginal cost on congested links. These results under centralized control with the prevailing pricing and investment strategies corroborate speculation in many theoretical studies.

Quantitative analysis of network evolution under decentralized control has not been available previously. It is therefore interesting to examine the last two graphs in Figure 3. The profit-maximizing capacity is almost the same as the optimal capacity on the edges of the network, while over-investment can be observed near the center. The higher level of competition among the central links accounts for their higher-than-optimal capacity. When there exist a number of competing links, an improved level of service through capacity expansion should theoretically increase the market share of a particular link. In harsh non-cooperative competition, this leads these links in the game to build excess capacity from society's point of view. Some imperfection of the decentralized road economy can be identified in the equilibrium toll graph. First, the spatial monopoly power of some links is evident and most obvious on the links at the corners and on the edges where travelers have fewer choices for service. These links are able to maximize profit by charging very high tolls and avoid capacity expansion cost (and therefore maintenance cost in the long run), although the lower-than-average level of congestion on these links suggests low marginal cost. The story is exactly the opposite for the central links. Competition forces them to charge tolls close to the marginal congestion cost. It should be noted that due to over-investment on the central links, the marginal congestion cost on them is lower than the marginal congestion cost corresponding to the case with optimal capacity. In summary, the main issues with a completely decentralized road market are: (1) Some links exploit travelers with their spatial monopoly power; (2) Links facing harsh competition tend to invest in excessive capacity.

While Figure 3 provides a snapshot of network performance at equilibria, the curves in Figure 4 more completely plot key measures of network effectiveness over time. Analysis of the process leading to equilibrium provides an opportunity to examine strengths and potential issues of specific ownership structures, which is not available from equilibrium analysis. For the time being, the curves labeled "price ceiling" can be ignored. While the socially optimal and centralized control scenarios quickly achieve steady equilibria after a few years, the decentralized control case takes much long time to stabilize. Since the initial network is congested, in the socially optimal scenario, marginal congestion cost prices are high in the beginning years. However, the resulting abundance of revenue allows significant expansion of capacity to the optimal level within several years. The case with centralized control responds to demand slowly, but eventually achieves a net social benefit about 85% of the maximum possible. This slow response could be especially undesirable when overall demand increases rapidly, which we shall see in a later section. The issue of underbuilt capacity under centralized control is evident in the graph plotting the cumulative number of capacity expansion projects. Net social benefit consists of consumers' surplus and suppliers' surplus (or profit). Changes in consumers' surplus are computed using the rule of half [32]. Total revenue after amortized expansion and maintenance costs are subtracted provides an estimate of suppliers' surplus.

Initially, the pricing and investment behavior of private roads in a decentralized market economy are almost identical to the socially optimal case. They borrow from investors to expand capacity to a level close to what is socially optimal and maintain a relatively low price. However, they gradually learn the profit prospect of high tolls. High tolls bring significant profits that pay off loans. The residual profits are not immediately re-invested in the transportation system probably because the benefit of capacity expansion is not obvious at this stage. However, the consumers suffer from high tolls and network social benefit reduces to almost nil. Competition forces many links to reduce tolls, the average of which finally stabilizes around $3.50.

The discussion based on network performance at equilibrium and during the equilibration process reveals that both centralized and decentralized ownership structures have different sets of drawbacks. Often technological and political factors prevent the centralized government agencies from adopting socially optimal strategies. The following analysis focuses on economic solutions that can improve the welfare under decentralized control.

6.2. Decentralized Road Economy under Regulation

As mentioned in the previous discussion, performance of the private road market should improve if high tolls and over-investment are avoided. While the issue of over-investment on links facing harsh competition may be addressed if links are allowed to cooperate. However, that would cause a set of new issues on cooperative strategies and on consumer benefits. Price regulation, more specifically pricing ceiling regulation, seems to be a more effective action to eliminate socially undesirable high tolls. The following analysis explores the welfare implications of various ceiling prices on the network. Link cooperation and other forms of regulation, such as rate-of-return and fixed profit regulation, are more complicated and deserve a separate paper.

The impact of price-ceiling regulation on the tolls of private roads is straightforward. Short-run profit-maximization is now subject to a narrower toll range. The actual tolls on all links have to be lower than the ceiling price. However, there exists at least one optimal ceiling price. (If ceilings could vary by link, there would be multiple local optima for this problem, here a systemwide ceiling is imposed.) When the ceiling price is too high, the effect of price regulation is minimal. When it is too low, private roads may not be willing to expand a congested network to the optimal capacity level. This tradeoff is resolved by a number of agent-based simulation runs with different ceiling prices. Results are summarized in Figure 5.

Net social gain is a function of the ceiling price, and this function is unimodal with a single maximum. The optimal ceiling price is about $2.00 per km of travel With this ceiling price, the net social benefit is about 84% of the maximum possible, and rivals that under centralized control. What is more interesting is that, although the percentage of net social benefit attributable to consumers' surplus is relatively low under most ceiling prices, it is about 83% when the optimal ceiling price is adopted. If this result holds in a real world network, special efforts for redistribution of benefits from private roads to consumers are probably not even needed. Another observation is that profit is a multimodal function of the ceiling price with two local maximum points on the test network. This suggests that the profit-maximizing pricing problem for private roads in a market economy might also be complicated by the presence of multiple local optima. To achieve highest possible profit through pricing, private roads may need to probe the market periodically.

If one revisits Figure 4 and observes network performance over time with the optimal price ceiling regulation, it should be clear that the price ceiling regulation is very effective in damping tolls and preventing over-investment. While the price-damping effect is expected, the elimination of over-investment on the central links deserves some elaboration. Close examination of traffic distribution reveals that much lower tolls on corner and edge links cause the flow on central links to decrease compared to the scenario without price regulation. This flow decrease makes it no longer profitable for central links to expand capacity above the optimal level. The cumulative net social benefit in twenty or thirty years in a decentralized road economy actually exceeds that under centralized control.

6.3. Variable Demand

Traffic over most of the U.S. road network has been increasing ever since demand started to be documented. Traffic in most U.S. urban area is likely to continuously increase in the foreseeable future. From the practical point of view in transportation policy analysis, it is more important to evaluate network performance in this dynamic scenario than under fixed demand. Results of simulation experiments with variable demand are plotted in Figure 6. It should be noted that that like real-world networks, the simulated road network is not going to achieve an equilibrium in this case.

The problems associated with centralized control and average cost pricing in this dynamic scenario becomes more serious, namely sub-optimal prices and insufficient revenue for capacity expansion. Their undesirable consequences are more obvious when the level of total demand is higher. Net social benefit falls well behind that under decentralized control with price regulation or the socially optimal scenario over the long run.

Responsiveness of private roads to changing demand is a major benefit under decentralized control in this dynamic environment. Though earlier-than-optimal investment occurs at one point of time due to competition, total expansion activities are not far from the optimal level most of the time. Some price spikes can still be observed in the market economy. However, the average link toll with the optimal price ceiling regulation is nearer to optimal than the average-cost-pricing practice.

7. Conclusions

This research uses an agent-based simulation model to study welfare consequences of alternative ownership policies for transportation networks. The evolution of a transportation network composed of profit maximizing private roads in a market economy is examined. The paper is an attempt to jointly consider pricing schemes, investment strategies, and organizational structures in an integrated network model, which has not previously been seriously considered despite its obvious policy significance. Discussion of road privatization and its positive and negative consequences has long been conducted at the theoretical and conceptual level. The agent-based simulation system consists of a series of empirically developed demand, cost and policy models, provides a novel quantitative tool for policy analysis related to alternative ownership, and compliments conceptual analysis.

Results on a test network should encourage those in favor of a market-oriented approach to solving urban transportation problems. The goal of profit-maximization, the existence of spatial monopoly, spatial dependencies, and harsh competition could cause private roads in a market economy to adopt socially non-optimal tolls and capacity. However, a practical price-ceiling regulation appears to eliminate most perils of decentralized control. The advantages of decentralized control such as responsiveness to demand, financing flexibility, and competition seems to outweigh concerns about consumer benefits in the quantitative analysis. Roads in a market economy are also demonstrated particularly robust in rapidly changing environments where demand continues to increase. In comparison, centralized control with average-cost-pricing practice and budget-constrained investment rules, which currently prevails in the U.S., is restricted by its ability to raise sufficient revenue and to satisfy travelers' needs.

These conclusions need to be tested by future analysis on a real-world urban system, and future work in this regard has been planned. The agent-based simulation system and the analysis conducted on the test network are readily applicable to realistic networks of any size. The analysis herein does recommend a serious consideration of market-oriented approaches to prevailing urban transportation problems such as congestion.

One limitation of the research is that users are assumed to be homogenous with the same value of time. This could affect the results in two ways. Disregarding user heterogeneity prohibits analysis of equity impacts on users, and equity is an important part of social welfare. It also prevents product differentiation in the transportation network, and causes underestimation of total welfare in market economy. Another limitation is that cooperation among private roads is assumed away. Just as airline networks seem to have evolved into a hub and spoke hierarchy, a specific geometry may be optimal in a private road network. There may be advantages to both the private and social welfare if vertical integration of highly complementary links is allowed in the system. However the degree of complementarity for which integration serves both public and private interests remains to be determined. The questions of when and how a link seeks coalitions at the microscopic level and how road network evolves with changing industrial organization at the macroscopic level need to be answered. However, it would be interesting to see what kind of organizational structure will emerge in a market economy to take advantage of economies of scale in the network. This is left for future studies.

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List of Tables and Figures

Table 1. Model Coefficients

Parameter	Value	Source [1, 2]
λ	10	Empirical finding
θ_1 , θ_2	0.15, 4	BPR function
γ	0.1	Empirical finding
ρ_1, ψ, ϕ	1	Scale parameters
ρ_2	1	CRS of link length
ρ_3	0.75	DRS of level of service
μ	20	Scale parameter
α_1	1	CRS of link length
α_2	1.25	DRS of capacity
σ_1	0.5	Empirical finding
σ_2	1.25	Based on empirical findings
σ_3	1	CRS of additional capacity
ω_1, ω_2	-30.6, 9.8	Empirical estimates
k, j	5, 0.2	Link behavior assumption

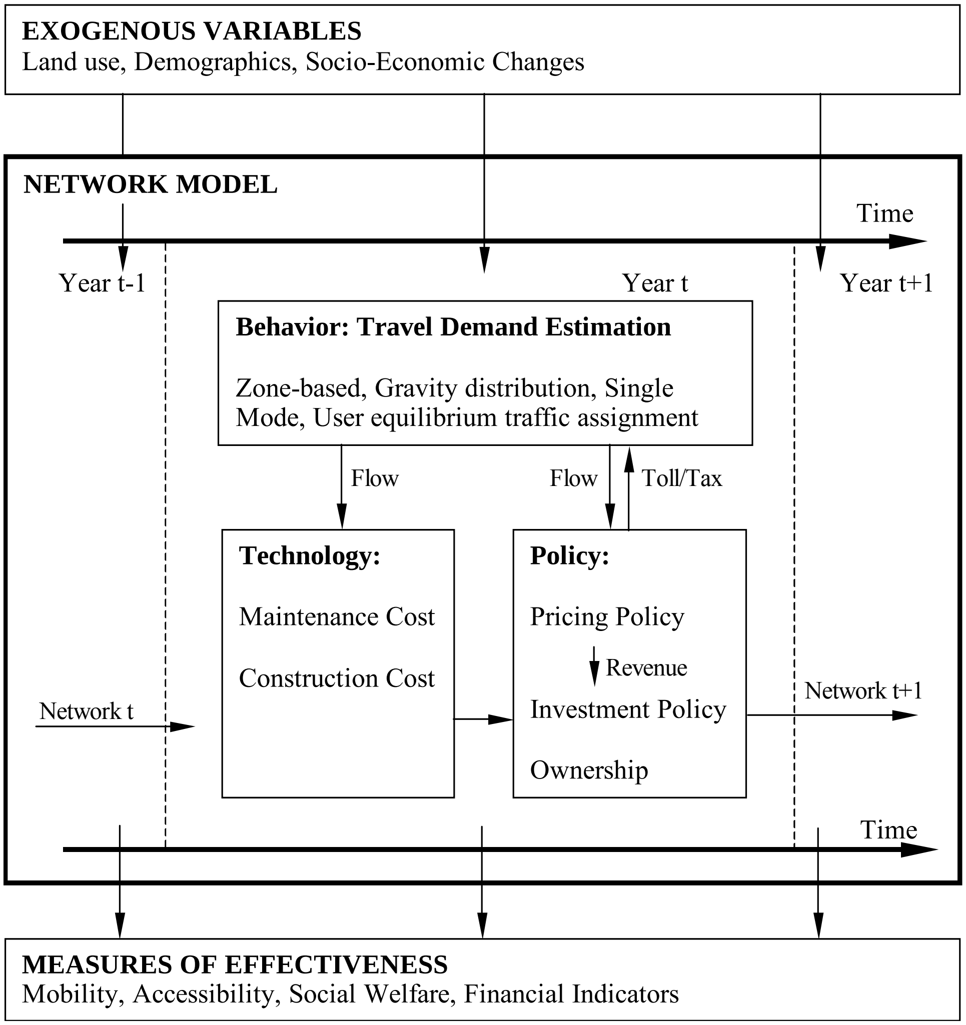

Figure 1. Flowchart of the Simulation Model

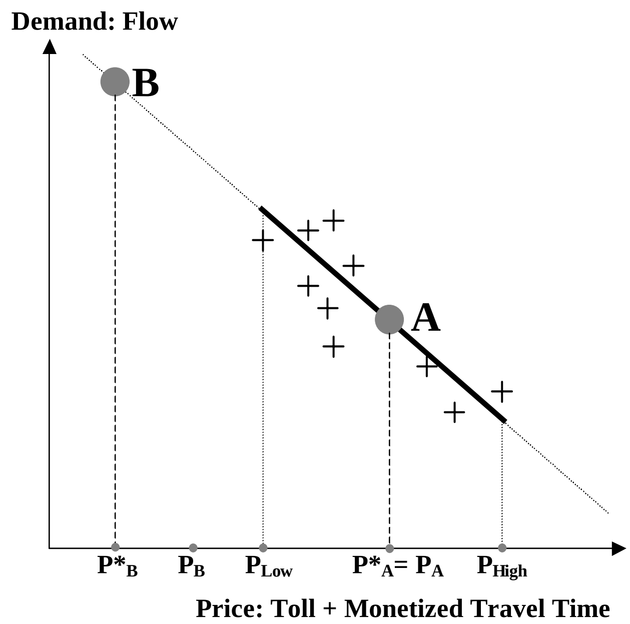

Figure 2. Profit-Maximizing Pricing under Uncertainty

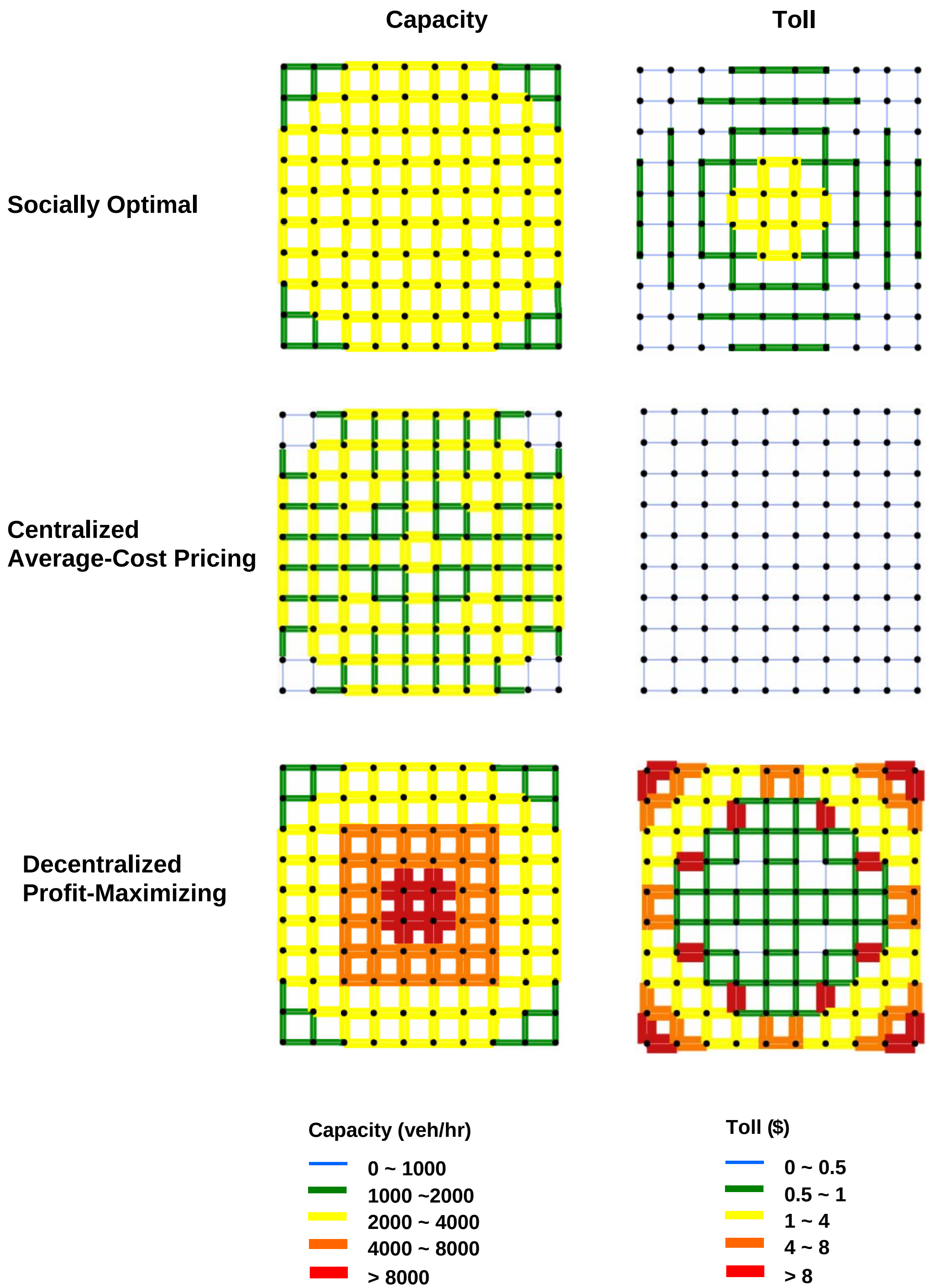

Figure 3. Equilibrium Tolls and Capacity

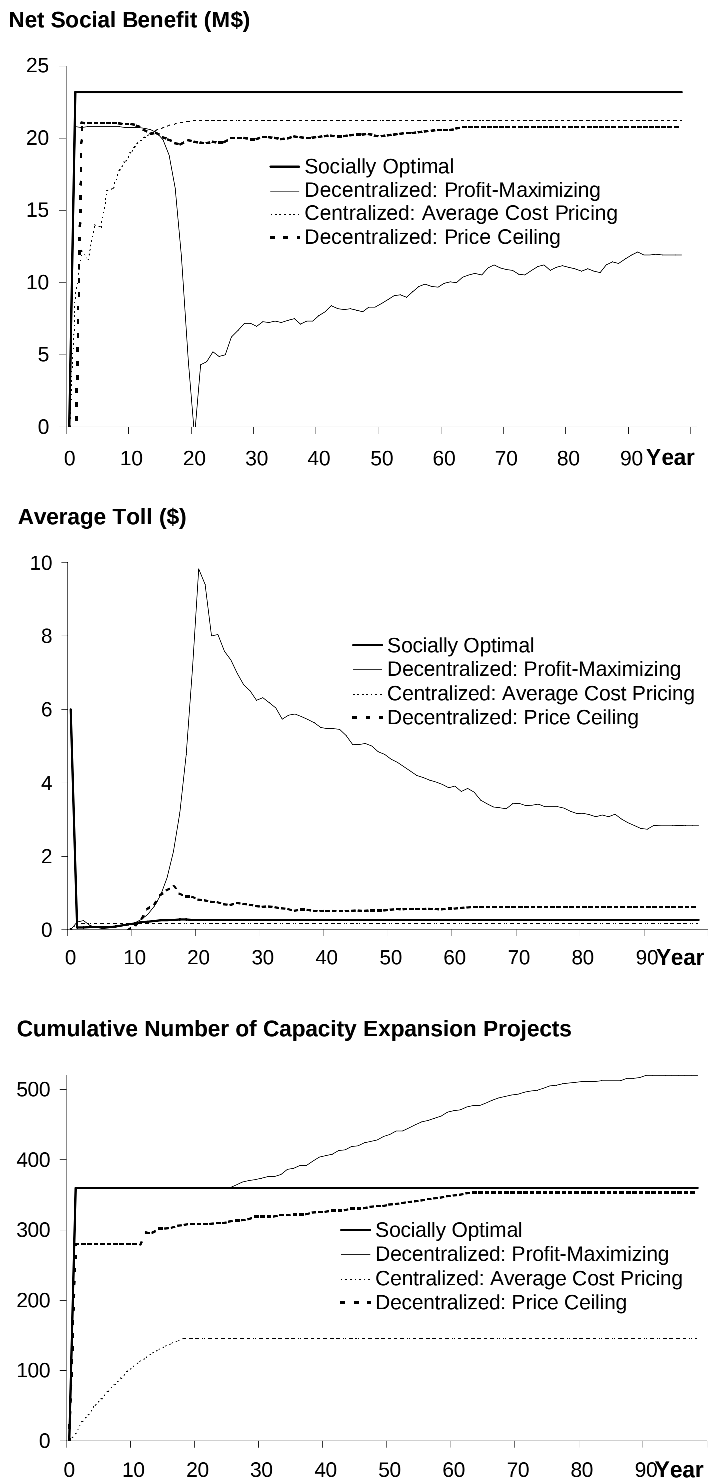

Figure 4. Network Performance Over Time under Various Policy Scenarios

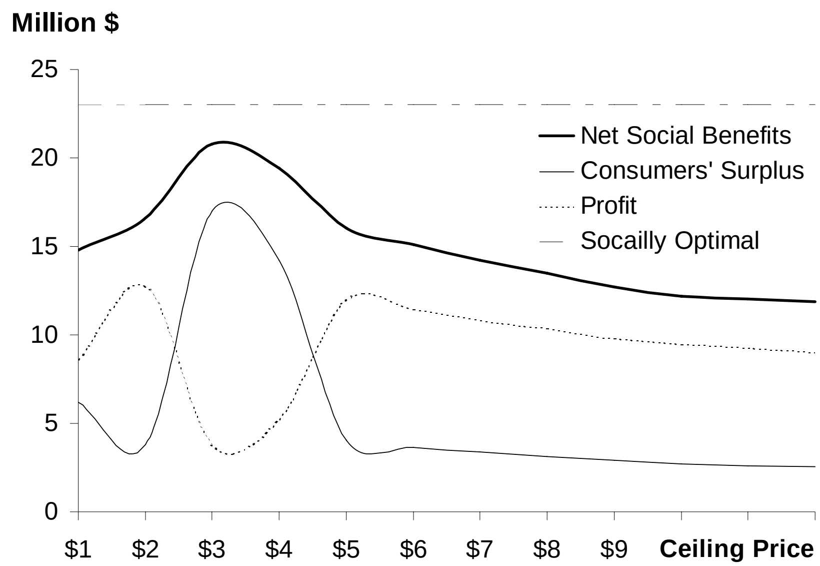

Figure 5. Determination of the Optimal Ceiling Price

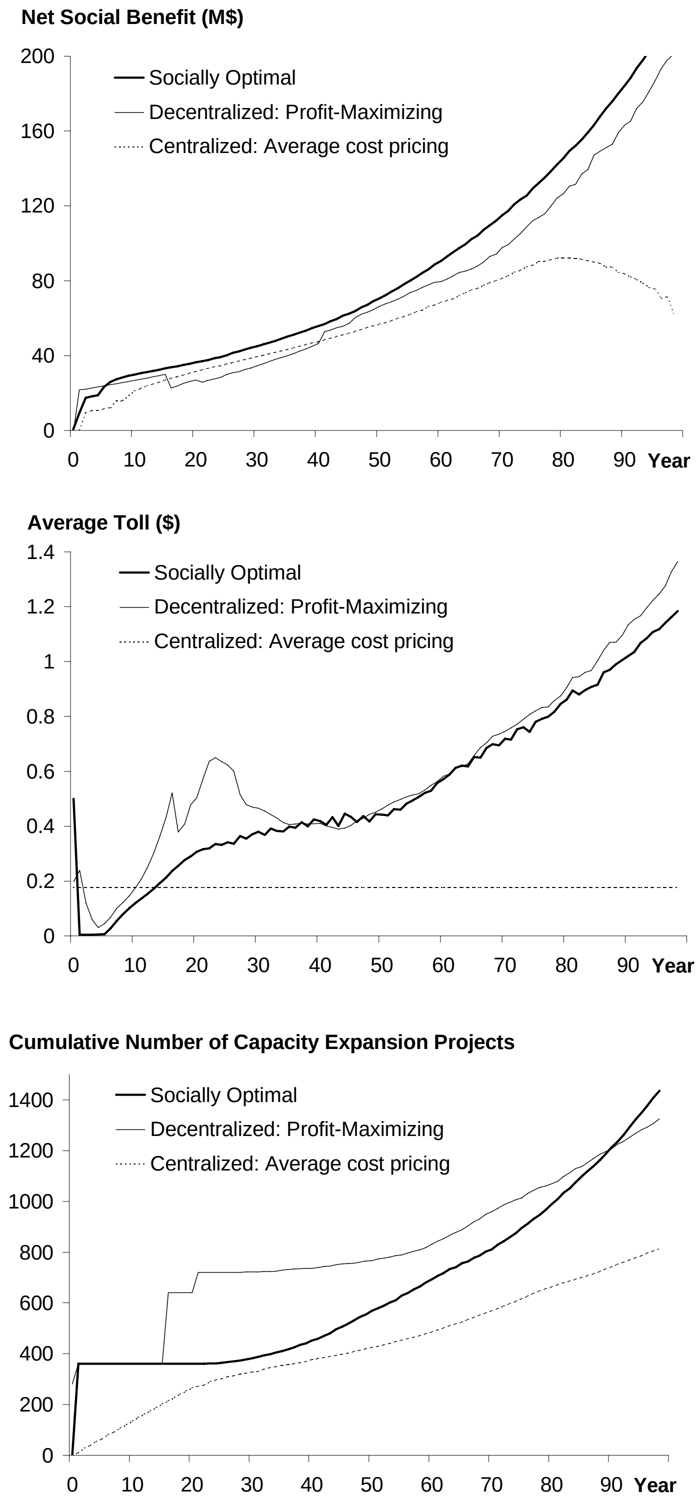

Figure 6. Network Performance Over Time with Increasing Travel Demand