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Pricing, Investment, and Network Equilibrium

Lei Zhang[1] and David Levinson[2]

1. Ph.D. Candidate
Department of Civil Engineering
University of Minnesota
500 Pillsbury Drive SE
Minneapolis, MN 55455
V: 612-626-0024 F: 612-626-7750
zhan0294@tc.umn.edu

2. Assistant 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

Despite rapidly emerging innovative road pricing and investment principles, the development of a long run network dynamics model for necessary policy evaluation is still lagging. This research endeavors to fill this gap and models the impacts of road financing policies throughout the network equilibration process. The manner in which pricing and investment jointly shape network equilibrium is particularly important and explored in this study. The interactions among travel demand, road supply, revenue mechanisms and investment rules are modeled at the link level in a network growth simulator. After assessing several measures of effectiveness, the proposed network growth model is able to evaluate the short- and long-run impacts of a broad spectrum of road pricing and investment policies on large-scale road networks, which can provide valuable information to decision-makers such as the implications of various policy scenarios on social welfare, financial situation of road authorities and potential implementation problems. Some issues hard to address in theoretical analysis can be examined in the agent-based simulation model. As a demonstration, we apply the network growth model to assess marginal and average pricing scenarios on a sample network. Even this relatively simple application provides new insights into issues around road pricing that have not previously been seriously considered. For instance, the results disclose a potential problem of over-investment when the marginal cost pricing scheme is adopted in conjunction with a myopic profit-neutral investment policy.

Key words: Transportation network equilibrium; Road growth; Pricing; Congestion toll; Investment; Transport policy analysis.

1. Introduction

Transportation economists have long promoted marginal-cost road pricing because it can lead to socially optimal allocation of scarce road resources (Dupuit 1844, Pigou 1920, Knight 1924, Mohring and Harwitz 1962, Vickery 1963). The economic theory also suggests that the optimal level of road investment is to expand a road to the point that the cost of one additional unit of capacity just equals the benefits it brings. However, the theoretical analyses are typical performed under a strict set of economic conditions which hardly correspond with reality (Wohl and Hendrickson 1984). Therefore, implementation of the theoretically optimal pricing and investment policies face a number of practical problems. First, many have concerns that the revenue collected under those policies may either significantly exceed or fall short of long-run cost for reasons with regard to economies of scale and non-optimality of existing road capacity (Walters 1968, Gwilliam 1997). Second, it is extremely difficult to actually compute marginal costs and benefits in a road system with the presence of enormous network effects (i.e. complementarity and substitution between roads) (Yang and Huang 1998). Even if the computation becomes possible as technology progresses, implementation of a perfectly differentiated marginal cost pricing scheme is practically impossible. Third, the optimal pricing and investment policies require toll collection facilities on all roads if implemented. However, toll collection costs and the incremental nature of the deployment process must be considered in practice (Hensher 1991, Levinson and Chang 2003). This gives rise to many "second-best" policies in which only a subset of roads are priced. Fourth, there is also the issue of optimal ownership structure. The various levels of government involved in road provision and management may not behave as benevolent welfare maximizers as traditional economic theory assumes. Commercialized or even privatized roads competing in a free market may provide a better ownership structure for efficient pricing and investment policies (Gomez-Ibanez and Meyer 1993, Roth 1996, Winston and Shirley 1998). Finally, a change in policy almost always creates winners and losers. Road financing is no exception. Equity concerns, especially when the amount of benefit and/or cost transfers is obvious and large, may force the government to step in and a direct implementation of the most efficient policy is unlikely.

The conclusion drawn from the above observations should not be that road pricing and toll financing are unlikely to gain real momentum due to those unresolved issues. In view of the substantial benefits of optimal road pricing and investment policies and the problems associated with the fuel taxes, there should remain interest among policy-makers. Rather, the real implication is that a number of practical road pricing and financing policies will become available and compete one another. Each one is backed by the basic economic theory but adjusted one way or another to address practical issues. In fact, researchers have already put forward several alternative revenue mechanisms. When cost recovery is of importance, a Ramsey-type pricing policy or practical price differentiation has been considered (Gomez-Ibanez 1999). Link-based marginal congestion cost pricing has been used to approximate real network-wide marginal cost pricing (Mohring 1999, Safirova and Gillingham 2003). Various "second-best" pricing alternatives have been proposed and some already deployed, such as a single toll road, cordon toll and destination toll operationalized through parking surcharges (Li 2002, Hyman and Mayhew 2002, Sullivan *et al.* 2000, Burris and Hannay 2003). When revenue redistribution is controversial, minimum-revenue pricing strategies are especially valuable (Dial 1999). As equity becomes the central focus, a Pareto-improving pricing policy is desirable (Small 1992, Daganzo 1995, Kockelman and Kalmanje 2004). Those in favor of road privatization suggest that society may be better off when roads are managed, financed and even owned by the private sector. It is conceivable that the current transportation decision-makers may quickly find themselves in a situation where they are presented several appealing pricing and/or financing alternatives for them to decide which one to implement. In fact, government agencies collecting and distributing fuel tax revenues have been facing the choice problem of when, where and how to spend money on road networks. The emergence of innovative pricing and financing schemes adds dimensions and complexity to the problem. Clearly, an evaluation tool capable of assessing a variety of policy alternatives and regulatory actions is in order.

2. Research Objectives

Despite the rapid emergence of various proposals for road pricing, financing, and ownership arrangements, the development of a network model for necessary policy evaluation is still lagging. *This research endeavors to fill this gap and models long-term impacts of road pricing and financing policies.* The way pricing and investment jointly shape long-run network equilibrium is of particular importance, and explored in this study. This objective contrasts with the goal of identifying the "best" policy alternative in previous economic studies. The model to be developed is able to test if, in real-world road networks, various proposed pricing and investment policies could live up to the expectations as established in abstract theoretical analyses. The research efforts presented in the following sections should also be distinguished from benefit cost analysis which is typically conducted to facilitate investment decision-making of individual projects. Of high interest in this study is the long-term *system* performance under a set of system-wide fundamental pricing and investment principles. A salient feature of the proposed model is the consideration of network growth over time.

The following section identifies a set of desirable properties for general network policy evaluation tools. Section 4 outlines our modeling framework and describes each model component in detail. The proposed network growth simulator is then calibrated using data in the Twin Cities (Minneapolis and St. Paul, Minnesota). Several existing and proposed road pricing and investment polices are also modeled in Section 5. In order to demonstrate the ability of the network growth model as a policy analysis tool, it is combined with the policy models, and applied to a sample network. In particular, long-run impacts of the marginal cost pricing scheme, when adopted in conjunction with a profit-neutral investment rule, are assessed in Section 6 by several measures of network effectiveness. Conclusions are delivered at the end of the manuscript.

3. What is a Good Model for Road Network Policy Analysis?

A number of desirable model capabilities should be pursued when developing a policy evaluation tool for road financing, seven of which are identified below. It should be noted that these criteria might compete one another. For instance, sensitivity of a model to a specific policy in question may be improved by including more sophisticated behavioral or mechanical modules. However, such an expansion would almost always invite additional doubts about model accuracy, and increase difficulties for implementation on large-scale networks. The order of the listed criteria does not represent their priorities, which should be judged on a case-by-case basis. Of course, an acceptable policy evaluation tool should always produce replicable results. This and other rather obvious criteria are not discussed below for brevity.

Ability to assess sub-optimal policies

For various political (e.g. policy stability, equity consideration) and practical (e.g. indivisibility of road construction, computational complexity) issues, very often the theoretically optimal policy cannot be directly implemented. For instance, needs assessment and benefit cost analysis are often cited as the two most common road investment rules but neither guarantees optimality in the long run. Ideally, even the theoretically optimal policy should be evaluated on realistic road networks before implementation because all theories have limitations.

Ability to assess alternative ownership structures

Road commercialization and privatization have been considered by some as being able to provide ownership structures that foster more efficient pricing and investment rules. To become capable of assessing policies that involve alternative ownership structures such as deregulation and privatization, it is essential for the evaluation tool to accommodate behavioral models of road owners, either government agencies or private sector investors.

Inclusion of long-run road network dynamics

In order to fully assess the consequences of road pricing and investment policies, a thorough understanding of long-run network dynamics is necessary. Previous studies of transportation system dynamics focus on traffic equilibrium, and usually assume a fixed transportation network. However, the growth (and decline) of a road network must be explicitly considered in the evaluation tool for analysis of road pricing and investment policies.

Applicability to large realistic road networks

Road networks are complex systems. There may not be a "one-size-fits-all" pricing and investment policy. It is thus important to evaluate alternative proposals on a case-by-case basis. Decision-makers are more willing to accept a policy change if they can identify the benefits it can bring to the road network they manage. This requires the evaluation tool to be applicable to a variety of real-world road networks. A set of measures of effectiveness should also be incorporated to quantify the impacts of alternative policies.

Description of the complete equilibration process

A typical economic evaluation study usually compares the equilibria of alternative scenarios. However, this approach ignores how long it takes to achieve the equilibria and what happens during the equilibration process. A short reflection would convince us that it might take a very long time for a road network to finally achieve equilibrium under a specific pricing/investment policy package. In such a situation, a good evaluation tool should also monitor network performance over time and identify any potential problem during the equilibration process. This suggests an evolutionary approach.

Ability to show impacts on different user groups

This is especially valuable for an evaluation tool designed for policy analysis. The distribution of benefits and costs resulting from a policy change in road networks has important equity implications among users with different socioeconomic characteristics, such as income and geographical location.

Accuracy

The soundness of a policy evaluation tool relies to a large extent on the accuracy of its demand and cost models. In the case of road networks, travelers' behavior adjustments, as well as the spatial demand dependencies between complementary and competing roads, are especially important. Cost comes from road construction, maintenance, management, and user spending (travel time and vehicle-related expenditures). If accurate demand or cost information is not available, the evaluation tool should allow sensitivity analysis.

4. Model

This section develops a microscopic network growth model, which satisfies most criteria identified in the previous section, and therefore could be applied to evaluate a broad spectrum of road pricing and investment policies. Limitations of the proposed model are also discussed.

The network growth model brings together all relevant agents and their interactions to simulate road expansion and contraction. The complexity of the whole transportation system in a region can not be described fully by the proposed network growth model and therefore it has certain limitations. Economic growth is taken as exogenous because transportation infrastructure is not the only factor that drives economic growth. It has long been known that transportation service and land use influence each other through iterative changes in accessibility and travel demand. However, land use dynamics are also treated as exogenous in the following network analysis because we do not yet have adequate models to explain change in land use. Attention is focused on road network growth, a process with enough complicated and unknown dynamics to start. These limitations can be removed in future research. The dynamics of other factors involved such as travel behavior, road maintenance and expansion costs, network revenue, investment rules, road expansion and degeneration, are considered as endogenous.

An overview of model components and their interconnectivity is shown in Figure 1. A travel demand model predicts link-level flows based on the road network, land use patterns, socio-economic and demographic information. Based on the demand forecasting results, revenues and costs are calculated for links. An investment module then operates and causes annual supply changes, producing an updated network. The modeling process does not have to iterate annually, and other updating intervals can also be used. But yearly supply changes correspond to budgets which are typically decided each fiscal year. The road network is represented by a directed graph that connects nodes with directional arcs (links). The standard notation convention for directed graphs is adopted for the following presentation on the details of mathematical formulations of the sub-models.

<Figure 1>

4.1 Travel demand

A traditional four-step forecasting model is used to predict travel demand at the link level, taking as exogenous land use, socio-economical variables, and the existing network. 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 (Haynes and Fotheringham 1984).

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

where:

q_{rs}^{i}	demand from origin zone *r* to destination zone *s* in year *i*
O_r	number of trips produced from zone *r*
D_s	number of trips destined for zone *s*
m_r, n_s	coefficients in the gravity model
t_{rs}^{i}	generalized travel cost of traveling from zone *r* to *s*
d(.)	travel cost impedance function in the gravity model; $d(t_{rs}^{i}) = e^{-\gamma \cdot t_{rs}^{i}}$
γ	coefficient in the impedance function

The resulting OD table is loaded onto the current year transportation network through the origin-based user equilibrium traffic assignment algorithm (OBA) developed by Bar-Gera and Boyce (2003). The generalized link cost function comprises two parts, a travel time component and a vehicle toll. The travel time component uses the BPR (Bureau of Public Roads 1964) functional form.

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

where:

t_a^{i}	generalized travel cost on link *a* in year *i*
λ	value of travel time constant (dollar/hr)
v_a^{i}	free-flow speed of link *a* (km/hr) in year *i*
F_a^{i}	capacity of link *a* in year *i* (veh/hr)
l_a	the length of link *a* (constant) (km)
f_a^{i}	average hourly flow on link *a* in year *i* (veh/hr)
_1-2	coefficients of the BPR travel time function
τ_a^{i}	link toll per vehicle (dollar, determined by pricing policy)

In the traffic assignment step, if the relative excess travel cost is less than 0.001, the Wardrop user equilibrium (Wardrop 1952) is considered to be satisfied. The travel demand model specified herein does not consider mode choice and multiple user classes, which limits the ability of the whole network growth model. For instance, substitutional effects between road and transit networks are neglected. Also impacts of a particular policy can not be distinguished among various user groups. Those limitations could be removed with a multi-modal multiple-user-class travel demand model.

4.2 Price and revenue

Revenue is collected at the link level by vehicle toll. The annual revenue is simply the product of the toll and annual flow. The amount of the toll depends on the pricing policy specified. Two pricing policies based on marginal and average costs respectively will be described and specified in the next section for subsequent evaluation purposes.

$$E_a^i = \tau_a^i \cdot (\psi \cdot f_a^i) \quad (3)$$

where:

E_a^i	revenue (earnings) of link *a* in year *i* (dollar)
ψ	coefficient to scale average hourly flow to annual flow

4.3 Maintenance cost

Empirical evidence (Paterson and Archondo-Callo 1991) shows that the cost of maintaining and operating roads are only partially (30% and 46% respectively) related to the traffic volume on the road. Some maintenance expenditures are fixed and irrespective of traffic. Non-linear increases in maintenance costs with respect to traffic volume have also been observed. Traffic loading characteristics obviously also affect costs for pavement resurfacing. A simplified link maintenance cost function is specified with three determining factors: link length, capacity, and volume. Therefore, all maintenance costs unrelated to traffic are attributed to capacity in this model.

$$M_a^i = \mu \cdot (l_a)^{\alpha_1} (F_a^i)^{\alpha_2} (f_a^i)^{\alpha_3} \quad (4)$$

where

M_a^i	cost of maintaining link *a* at its present condition in year *i* (dollar)
μ	scale parameter
α_{1-3}	coefficients indicating economies or diseconomies of scale

4.4 Construction cost

The cost of road construction depends on many factors – lane-miles of construction, road hierarchy (road types, e.g. interstate highway, state highway), land acquisition cost, degree of urbanization, terrain, and elevated sections (e.g. interchanges, bridges). Keeler and Small

(1977) developed a construction cost model with only two variables, lane-miles of construction and urbanization. Their model explains about 52 percent of total cost variation. A regression model developed for construction projects in the Twin Cities is able to explain 77 percent of cost variation with two additional variable, road hierarchy and duration of construction (Levinson and Karamalaputi 2003). A three-variable function is specified for road construction cost. In this function, it is more expensive to construct a road that is longer, has a high existing capacity (hierarchy), and needs a larger capacity increase.

$$K_a^i = \phi \cdot (l_a)^{\sigma_1} \cdot (F_a^i)^{\sigma_2} \cdot (F_a^{i+1} - F_a^i)^{\sigma_3} \quad (5)$$

where

K_a^i	cost of expanding link *a* in year *i* (dollar)
_	scale parameter
_*1-3*	coefficients indicating economies or diseconomies of scale

Some consider road construction as discrete, highly indivisible, and lumpy investments while others argue that capacity improvements are usually less lumpy than they seem. There exists evidence supporting both arguments. A road can only be built with or expanded by a discrete number of lanes. However, incremental capacity improvements can also be achieved by improving management efficiencies, widening shoulders, and resurfacing pavement. The continuous function specified in Equation 5 is used in this analysis. However, it is also possible to use this function to calculate the cost of construction required to add one or two more lanes once a relationship between capacity and number-of-lanes is established empirically.

4.5 Investment rule

The investment model takes revenues and costs on all links as inputs, and determines how revenues are distributed to maintain and expand the network. If the amount of revenue distributed to a link is not sufficient to defray its maintenance cost, capacity of the link will decrease in the next iteration. Revenues may also be used to expand some links in the network depending on the investment policy. An investment rule may seek maximum social welfare, maximum profit, or minimum profit as determined by the organizational structure (public, private, government hierarchies etc.) in the road network. For instance, a profit-neutral investment policy dictates that all revenues collected every year be re-invested into the network. This specific rule actually is probably very close to the decision-making process of various levels of real-world road owners operating on a pre-determined budget and dedicated road funds. A profit-neutral investment rule under decentralized road management is actually very simple and myopic: every link spends all the revenue it collects in the current iteration (thus zero profit for the link); its capacity increases (decreases) if the revenue exceeds (falls short of) the required maintenance cost. One may also model other types of investment policies depending on the particular evaluation needs. The amount of capacity changes can always be determined by the construction cost function. A capacity change on a link is usually associated with a concurrent change in free-flow speed. Vehicles are in general able to travel faster on wider roads. A log-linear function is specified to capture the correlation of capacity and speed.

$$v_a^{i+1} = \omega_1 + \omega_2 \cdot \ln(F_a^{i+1}) \tag{6}$$

With updated link capacity and free-flow speed, some factors influencing travel behavior such as link travel time and toll level will change. Theses supply shifts, combined with preference, economic growth and demographic changes, give rise to the emergence of a new demand pattern in the next iteration.

So far, a complete cycle of the network evolution process has been modeled. This cycle repeats itself year after year. Simulation of these cycles can reveal various emergent properties of transportation network growth in the short and long run. Under centralized control, the network achieves long-run supply-demand equilibrium if the total revenue is equal to the total required maintenance cost. With autonomous links, the equilibrium is achieved when the revenue is equal to the maintenance cost on each link. In both cases, there is no excess revenue available for further capital expansion at equilibrium.

4.6 Estimation of model parameters

The exact value of the parameters in the network dynamics model certainly depends on the road network in question. This section discusses in general the empirical data required for model estimation and their likely sources, and in particular the derivation of a complete set of parameter estimates for the road network in the Twin Cities metro area. As mentioned earlier, the equation determining the amount of toll on a road should be derived from the specific pricing policy. Similarly, the investment rule should also be specified in accordance with the investment policy being evaluated, and no calibration or validation is required.

The first set of data for the execution of the network dynamics model is the initial network status, including capacity, length, free-flow speed, and tolls (if any) for all links and their connectivity. Changes in land use, demographics and regional economy are assumed to be exogenous, and therefore should be obtained from corresponding forecasting models.

Travel demand forecasting has become a fairly standard planning exercise over the years. Most metropolitan areas update their travel demand models, mostly four-step models, every five or ten years. The parameters related to travel demand, such as _ in the gravity model should be available from metropolitan planning organizations. In the Twin Cities, the value of _ is around 0.1.

Keeler and Small (1977) estimated a simple linear model of road maintenance costs using project-level data. In their specification, maintenance cost is a function of vehicle miles of travel. Heggie (1995) calculated maintenance costs based on both vehicle-kilometers of travel and roads hierarchy. Paterson and Archondo-Callao (1991) show that only about 46% of total maintenance costs are traffic-related while the remaining 54% are fixed costs. Clearly, road-specific data would enable most accurate estimation of maintenance cost. There is evidence of substantial economies of scale in maintenance cost as traffic volume increases. Maintenance cost per vehicle-kilometer of travel is much lower on a high-volume road. This suggests that α_3 is between 0 and 1, and probably just slightly larger than 0. While it is conceivable that higher-level roads, such as an interstate highway, are more expansive to maintain than lower-level roads, such as an arterial street, even if they carry the same amount of traffic ($\alpha_2 > 0$), no previous study has exactly estimated α_2. It is assumed that there are diseconomies of scale in road maintenance as the capacity of the road increases ($\alpha_2 > 1$).

For the estimation of the road expansion cost function, data at the project level is again the most desirable. Several previous studies on economies of scale in road construction use lane-kilometers of expansion as a predictor, effectively assuming $\_{1} = \_{3}$ (Keeler and Small 1977, Kraus 1981, Meyer *et al.* 1965). Construction projects of all sizes are combined and therefore it is not surprising most of them find near-constant returns to scale ($\_{1} = \_{3} = 1$). A recent study (Levinson and Karamalaputi 2003) using data of 110 projects in the Twin Cities show significant increasing returns to scale (_$_1$ = _$_3$ = 0.5) after controlling for road hierarchy. Using the same data set, the authors find constant returns to scale without controlling for road hierarchy. It should be more expensive to expand a road already having high capacity due to exponentially increasing land acquisition costs. Therefore, _$_2$ > 1 should be a plausible assumption. These observations suggest that _$_1$ = _$_3$ = 1 seem to be the so-far most reliable estimates for the road expansion cost function, and that there is a need for further studies on cost functions (e.g. a function that considers second order effects, factor prices, and land acquisition cost). The cost data in the Twin Cities were collected from the Transportation Improvement Program managed by the Metropolitan Council.

The database developed by the Metropolitan Council for the regional transportation planning model also includes capacity, free-flow speed, and number of lanes for more than 10,000 road segments in the Twin Cities. These data are used to estimate the capacity-speed function (Equation 6). Both coefficients are statistically significant at level 0.05, and the R^2 of the regression model is 0.7. The predicted values of the dependent variables are plotted against observed data in Figure 2. The complete set of model parameters estimated or assumed for the Twin Cities road network is summarized in Table 1.

<Figure 2>

<Table 1>

5. Using the Network Growth Model for Policy Analysis

The proposed model is able to consider short- and long-run network dynamics on a general road network. Its simulation nature allows for systematic comparison of any number of pricing, investment, and combined policies. It is also possible to assess various ways of implementing a specific policy. For instance, marginal cost pricing may be imposed on all roads or on congested roads only. The model can point out potential short- and/or long-term practical problems, and quantify overall welfare changes taking into account all identifiable costs. Model execution time is largely determined by the traffic assignment procedure, the implantation of which on a large-scale network is in general acceptable. For instance, the

OBA algorithm can solve for traffic equilibrium on the Twin Cities road network (1200 zones, 7976 nodes and 20914 links) within twenty minutes on a typical personal computer.

The network dynamics model also incorporates substitutional and complementary effects in a general network by using a standard travel demand model. This distinguishes it from previous economic analyses that ignore network effects altogether. Some abstract studies in transportation network equilibrium (e.g. Yang and Huang 1998, Hearn and Yildirim 2002) do consider network effects and their impacts on the marginal cost pricing scheme. However, they do not provide a general policy analysis tool (defined by the seven criteria in Section 3) and the computational complexity involved tend to prohibit applications on large realistic road networks.

A very interesting and important capability of the proposed model arises from the embedded agent-based structure. Each road can be treated as an autonomous agent that determines for itself price, investment, and the level of coalition with other roads. This opens many opportunities to model profit-maximizing behaviors in a decentralized road network. Game theory has been used to study pricing strategies of a private road in competition with another parallel private or public road. However, as network size gets larger, it is almost impossible to determine payoff matrices due to complicated network effects, undermining the suitability of an analytical game theoretical approach for analyzing the behavior of autonomous roads. In contrast, the agent-based simulation framework manifested in the proposed network dynamics model overcomes this problem and can be used to address important research questions regarding road commercialization and privatization.

For the network growth model to become an operational policy analysis tool, a set of evaluation criteria must be established for comparison among policy alternatives. The following sub-section describes several measures of network effectiveness. Section 5.2 demonstrates the model capability using an example.

5.1 Measures of network effectiveness

The network growth model provides the following information for each year in the evolutionary process: population and activities at the zone level; demand, travel time, and generalized travel cost at the OD level; flow, capacity, speed, travel time, and toll at the link level. They are used to develop several measures of effectiveness (MOEs) for the evaluation of network performance with alternative pricing and investment policies over time. Total vehicle hours traveled (*H*) and total vehicle kilometers traveled (*L*) are fairly standard network MOEs. The change in consumers' surplus (*U*) between year 0 and year *i* is approximated by the rule of half.

$$U^{0-i} = \sum_r \sum_s \frac{1}{2}(q_{rs}^i + q_{rs}^0) \cdot (t_{rs}^0 - t_{rs}^i) \tag{7}$$

Total net social benefit (*W*) is the sum of changes in consumers' surplus, plus total network revenue minus total construction and maintenance costs. Toll revenue is a transfer, and therefore the second term needs to be included to cancel it out because tolls are also used in deriving changes in consumers' surplus.

$$W^{0-i} = U^{0-i} + \sum_i \sum_a E_a^i - \sum_i \sum_a \left(M_a^i + K_a^i\right) \tag{8}$$

Ideally, costs of accidents, energy, pollution and noise should also be included in the computation of net social benefit. However, evaluation of these costs is a complex exercise and existing methods sometimes depend on rather subjective assumptions. Those who are interested in environmental impacts and other social issues should find it straightforward to attach any pollution or accident models to the proposed network dynamics model, and conduct performance related analyses.

Accessibility to activities for residents in zone *r* (A_r) is defined below. It states that the accessibility of a traffic zone is the sum of the products of activities in each destination zone and the travel impedance from the current zone to the destination zone.

$$A_r^i = \sum_s D_s^i \cdot d(t_{rs}^i) \tag{9}$$

Productivity (*P*, km/dollar) is defined as vehicle kilometers of travel divided by total inputs to the system. The inputs include travel costs borne by users (excluding tolls which are transfers), maintenance and expansion costs borne by road authorities. This productivity measure may also be interpreted as the inverse of the full cost per kilometer of travel in the road network.

$$P^i = \frac{L}{\lambda \cdot H + \sum_a (M_a^i + K_a^i)} \tag{10}$$

It has also been a concern that in a privatized road network where toll revenue is the primary financing source, equity may be jeopardized. The Gini coefficient is used to measure the geographical inequity of accessibility among different network zones, which falls between 0 (perfectly equitable) and 1 (perfectly inequitable).

$$G = \frac{\sum_r \sum_s |A_r - A_s|}{2N \sum_r A_r} \tag{11}$$

5.2 An example – Evaluating two pricing schemes

Appropriate prices are important for efficient allocation of resources. A specific pricing strategy may carry the goal of unconstrained social welfare maximization, constrained social welfare maximization, and profit maximization depending on the organizational structure. Two pricing schemes are described below and later evaluated using the proposed model.

Marginal cost pricing

A pricing scheme based on the marginal cost of road use maximizes social welfare in the short run in the first-best situation. Marginal cost of road use is comprised of congestion costs equal to the additional delay costs imposed on other drivers by one additional vehicle, marginal variable road maintenance costs borne by the road authority, marginal vehicle operating costs borne by the driver, and marginal social costs. If the current road capacity is optimal, short-run marginal cost equals long-run marginal cost under certain conditions (Mohring and Harwitz 1962). Implementation of marginal cost pricing on a general network has encountered several problems. Toll collection costs would be high if all roads are priced at marginal costs. If marginal cost pricing is adopted for a congested network, the amount of immediate toll increase will be large. It also turns out to be extremely difficult to estimate the real marginal cost of an additional trip on a specific road due to network effects. A simplified but practically appealing link-based policy for marginal congestion cost pricing states that the amount of user charge on a link equals the delay costs a driver imposes on all other drivers using the same link:

$$\tau_a^i = f_a^i \cdot \lambda \cdot \frac{l_a}{v_a^i} \cdot \theta_1 \left[\left(\frac{f_a^i}{F_a^i} \right)^{\theta_2} - \left(\frac{f_a^i - 1}{F_a^i} \right)^{\theta_2} \right] \tag{12}$$

Mohring (1999) used this link-by-link method to compute marginal congestion costs on the Twin Cities road network. It should be mentioned that Safirova and Gillingham (2003) found network effects are significant in the Washington DC area road network, and concluded the link-based method may not be appropriate for designing finer geographically differentiated congestion tolls. Evaluation of finer pricing strategies based on better approximation of true marginal congestion costs could also be accommodated in the proposed network dynamics model. In that case, user charges may have to be determined by a numerical procedure instead of a closed-form equation.

Fuel taxes or Distance-based user charges

Toll financing has been adopted on few highways in the US, where road improvement funds primarily come from fuel taxes. If the variation of vehicle fuel efficiency is neglected, fuel taxes essentially charge users based on total vehicle-kilometers of travel without taking into account when and where trips occur. This average-cost pricing scheme can be modeled with a simple function of link toll. The constant term ($\_{1}$) is determined by the amount of surcharge per gallon of fuel and later normalized to unity in the simulation.

$$\tau_a^i = \rho_1 \cdot l_a \tag{13}$$

In evaluating these two pricing schemes, it is necessary to assume the same investment policy for both scenarios. The straightforward but myopic profit-neutral investment rule explained in Section 4.5 is selected to help form two complete network policy scenarios. In some other cases, one may need to assess totally different policy packages without any common element. While the network growth model allows comparison of the two pricing policies on any realistic road network, a relatively small but very regular ten-by-ten grid network (100 zones, 100 nodes and 360 links) is used in this demonstration example (see Figure 3), partly for simplicity and partly for the concern that certain network growth patterns may not be obvious on a complex large network. The same initial network condition is specified for both scenarios. All links in the grid network are four kilometers in length and have an initial capacity of 735 vehicles per hour (This value corresponds to a one-lane road according to the regression analysis using the capacity and number-of-lane data in the Twin Cities). The initial network is heavily congested with an average volume capacity ratio of 0.8 because congestion pricing, as well as other innovative road financing policies, are usually not considered for uncongested networks. The initial land use is uniform among all 100 network zones with ten thousand trips originating and destined for each zone respectively.

<Figure 3>

6. Evaluation Results

On the grid network, both simulation runs take less than two minutes before the network achieves equilibrium after about one hundred iterations. However, the most significant capacity changes occur during the first thirty iterations. Various measures of effectiveness for the whole network are calculated for each iteration and plotted in Figure 4, including vehicle hours traveled, vehicle kilometers traveled, average network speed, accessibility, productivity, revenue, consumers' surplus and equity. It should be pointed out that the net social benefit in the long run equals the change in consumers' surplus because all revenue collected are used for road maintenance and construction under a profit-neutral investment policy. If a short-run perspective is taken, net social benefit at each point of time should be the sum of revenue and the change in consumers' surplus minus maintenance costs, as road expansion decisions are not considered in the short run.

<Figure 4>

The road network seems to exhibit better mobility measures if marginal cost prices are implemented in both the short and long run. With prices set at marginal congestion costs, users are able to spend less time to travel more at higher speeds. These results are expected because on average, marginal cost prices are higher than average cost tolls for automobile travel. More toll revenues are then transferred into more road expansion projects and higher road capacities. However, the mobility measures only tell part of the whole story.

An examination of the accessibility and productivity measures disclose more information as they incorporate both travel time and toll. Actually, users will enjoy a bit more accessibility if average cost prices are implemented. Although the network financed by marginal cost tolls provides some travel time benefits, shorter travel times are clearly counteracted by higher tolls. Productivity is higher with marginal cost prices during the first twenty iterations. However, average cost pricing catches up very quickly and there is not much difference in productivity over the long run. At the equilibrium under the average cost pricing scheme, the productivity for the whole network is about 4.7 km/dollar, which translates into an estimated full cost of about 0.21 dollar/km. Since vehicle operating costs, fuel consumption, and external social costs are not included in the network dynamics model, this is lower than the value derived by some other studies using econometric methods (e.g. 0.34 dollar/km in Levinson and Gillen 1997).

As mentioned above, the initial road network is heavily congested with an average speed of about 10km/hour. It is not surprising that the results show very high network revenue during the first ten iterations. During this period of time, roads are also expanded at a fast pace. Therefore, total revenue from congestion tolls drops significantly after the level of congestion decreases and the traffic equilibrium moves away from the exponentially increasing region of the marginal cost curve. Over the long run, congestion tolls still generate more revenue than average cost prices, which is expected as there are decreasing returns in congestion.

The result that probably would surprise many is that the implementation of marginal cost pricing causes slightly negative changes in consumers' surplus (in this case also the long-run net social benefit), while the average cost pricing scheme generates a very stable gain in consumers' surplus worth about two million US dollars every year. This does not conflict with the economic theory that marginal cost pricing is the most allocatively efficient in the short run. The short-run net social benefit should be the changes in consumers' surplus plus revenue. At every point of time, marginal cost pricing is still superior in the short run perspective, because the high positive revenue is more than sufficient to compensate for the slightly negative changes in consumers' surplus and the extra can still be larger than the benefit from average cost pricing. The long-run inferiority of the scenario with marginal cost pricing actually should be attributed to the investment rule adopted, which is profit-neutral in that all toll revenues are used for road expansion (except the portion appropriated for maintenance). The combination of a marginal cost pricing scheme and a profit-neutral investment rule on a congested network clearly has caused over-investment on the sample network. Toll revenue just covers investment only if the road capacity is currently optimal (constant returns to scale in construction have already been assumed in the construction cost function; see equation 5). Excess revenue will be generated in a congested network with marginal cost pricing, while the opposite will occur on roads that are almost empty. From the perspective of economic efficiency, the excess revenue should not be re-invested in the road network beyond the optimal capacity point. However, if over-investment does occur especially when the revenue is managed by a public agency that has various incentives to be profit neutral, users of the road network may be worse off, as we see in the simulation example. In light of this finding, redistribution of excess toll revenue back to negatively affected drivers may not only improve equity, but prevent long-run efficiency loss as well. The problem of over-investment should be less serious when revenues are spent based on market principles. These results also depend on the road network in question. The initial network contains only congested roads. However, in a realistic network, some roads are congested while others underutilized. The actual amount of excess revenue may not be as large as what is observed in these simulation experiments.

Equity issues have often been raised when marginal cost pricing is discussed. Equity has several dimensions. Horizontal equity requires that people with equal income or ability be treated equally, while vertical equity implies policies should be in favor of those with lower income or less ability. Equity may also be defined with respect to space or time. The Gini coefficient defined in Section 5.1 is a spatial equity measure which examines the degree of accessibility inequity among users located in different geographical regions. The results suggest that the network is more equitable with the average cost pricing scheme. The equity implications of the marginal cost pricing policy are especially poor when the network operates at a heavily congested state. Income equity is at least equally important for analysis of pricing policies. However, the network dynamics model as specified in Section 4 does not distinguish users by income levels. Future research should extend the ability of the network model. Some travel demand models categorize users into a finite number of classes according to certain user attributes (e.g. income) and can be used to replace the single-class demand model.

6. Conclusions

Traditionally, transportation networks have been assumed to be static or predetermined in analysis of urban areas. Predicting the growth of transportation networks is difficult because it requires us to consider both the nature of several sub-processes in network dynamics (e.g. road maintenance and construction) and the behavior of all agents involved (e.g. travelers, road owners and managers). Nevertheless, this study demonstrates that it is possible to develop a network growth model at the microscopic level, and such a model could improve our understanding about how pricing and investment policies determine long-run road network equilibrium.

At present, policy debates related to road pricing and investment principles are often restricted to the identification of pros and cons of alternative policy scenarios, while quantification of long-term consequences is usually unavailable. There are also controversies about the appropriate implementation agenda. Though these issues are hard to address satisfactorily in theoretical analysis, they can be examined straightforwardly using agent-based simulation. The network growth model has been successfully applied to assess two pricing policies on a sample network. Even this relatively simple example provides important new insights into issues around road pricing that have not previously been seriously considered, such as the potential problem of over-investment when the marginal cost pricing scheme is adopted in conjunction with a myopic profit-minimizing investment policy.

Calibration of the network dynamics model does not require significant new data collection tasks for road authorities. Travel demand models are fairly standard in most urban areas. Modeling candidate pricing or investment policies should also be straightforward. Most road agencies keep records of previous construction and maintenance activities, which can be used to estimate the maintenance and construction cost functions. Execution of the network simulation can be done within a reasonable amount of time. Compared to the capability and potential benefits of the network growth model, the cost of developing and maintaining it should be acceptable. We therefore highly recommend that major transportation agencies establish such a simulation model for their own road networks, so that decisions can more often be made with a long-term and system-wide vision.

The proposed policy evaluation tool certainly has some limitations at its birthing stage, which have been mentioned in various places in the manuscript. Some of them are repeated here because they point directions for future research. First, a completely agent-based network growth model would require consideration of behavioral and interaction rules of individual travelers. Travel demand analysis is indeed moving towards a more disaggregate, behavior-centered paradigm with the rapid advancement of activity-based approaches (Carpenter and Jones 1983, Pas 1985, Kitamura 1988, Ettema and Timmermans 1997, McNally and Recker 2000) and the recent emergence of agent-based models (Zhang and Levinson 2003). Future research should incorporate disaggregate travel demand forecasting techniques into the network dynamics model to form a more coherent agent-based structure. Second, the network growth model may also be expanded by incorporating multiple travel modes, especially various transit options. This would allow planners to examine substitutional and complementary effects among various modes, and to evaluate a broader spectrum of transportation financing policies, e.g. various forms of cross-subsidies. Last but not least, transportation network dynamics should be ideally modeled interactively with network dynamics, whereas land use are assumed to change exogenously in this study.

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Table 1. Coefficients in the Network Growth Model

Parameter	Description	Value	Source
_	value of travel time constant ($/hr)	10	Empirical estimate in TC
θ_1 , θ_2	coefficients in the BPR function	0.15, 4	BPR recommended value
γ	coefficient in the gravity model	0.1	Empirical estimate in TC
ρ_1 ·_	Combined scale coefficient in revenue model (dollar·hr$^{\rho 3}$/km$^{\rho 2+\rho 3}$)	1	Scale parameter
μ	Scale coefficient in cost model (dollar·hr^{-2}/km^{-1})	20	Scale parameter
$\_{1}$	Power term of length in cost model	1	CRS of link length
$\_{2}$	Power term of capacity in cost model	1.25	IRS of capacity
$\_{3}$	Power term of flow in cost model	0	Ignore variable cost
$\_{1}$, $\_{2}$	Coefficient in the speed-capacity log-linear regression model	-30.6, 9.8	Empirical estimates based on Twin Cities data
_	Scale coefficient in cost model	1	Scale parameter
$\_{1}$	Power term of length in cost model	1	CRS of link length
$\_{2}$	Power term of capacity in cost model	1.25	IRS of capacity
$\_{3}$	Power term of _capacity in cost model	1	CRS in road construction

Note: CRS, DRS and IRS: constant, decreasing, and increasing returns to scale

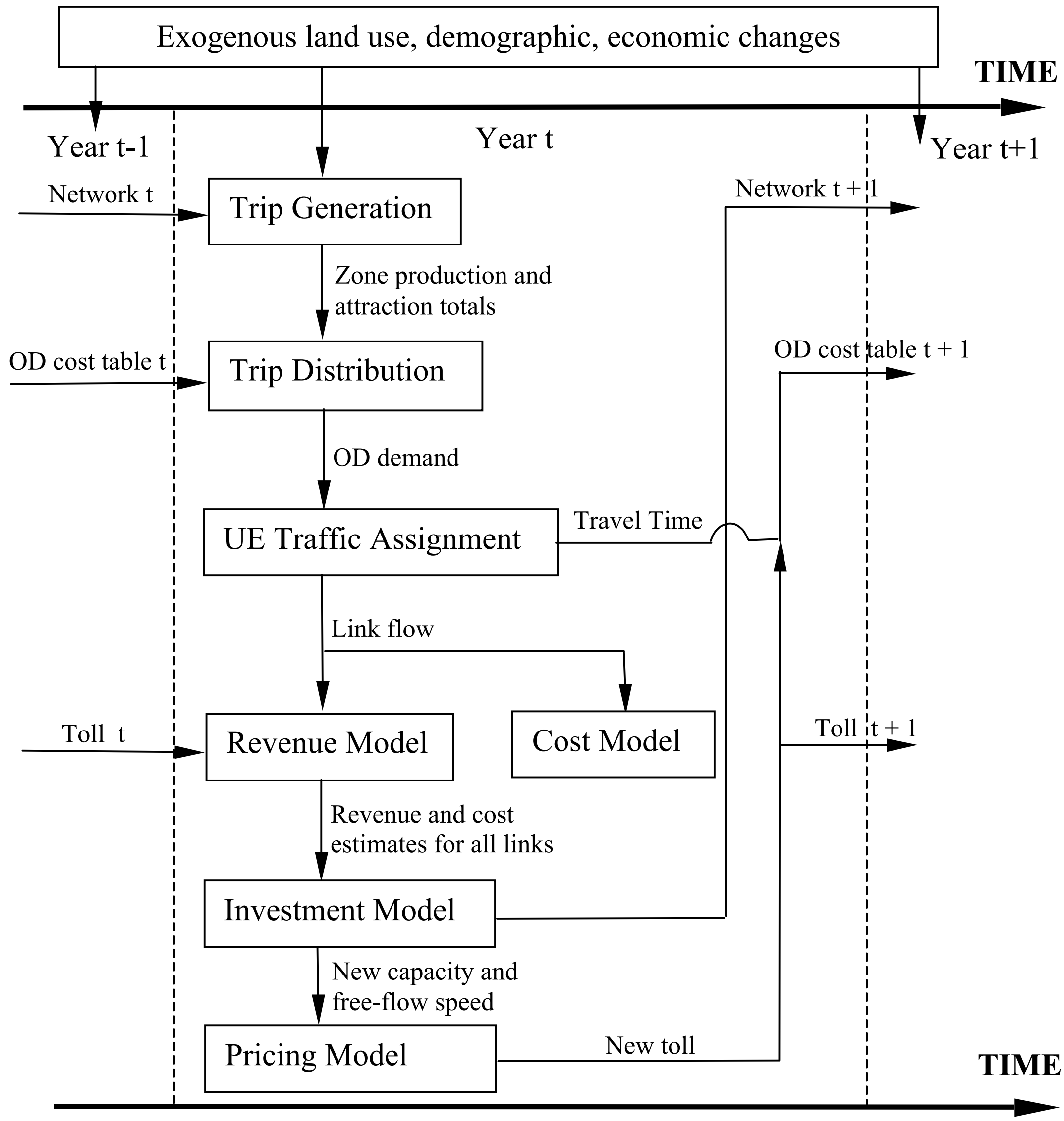

Figure 1. Flowchart of the Road Network Growth Model

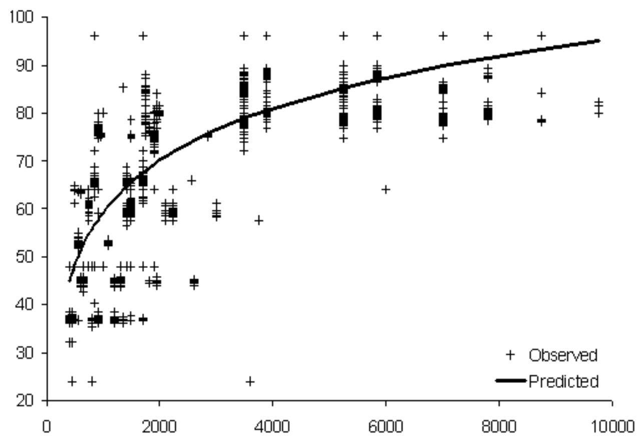

Figure 2. Relationship between Road Capacity and Free-Flow Speed

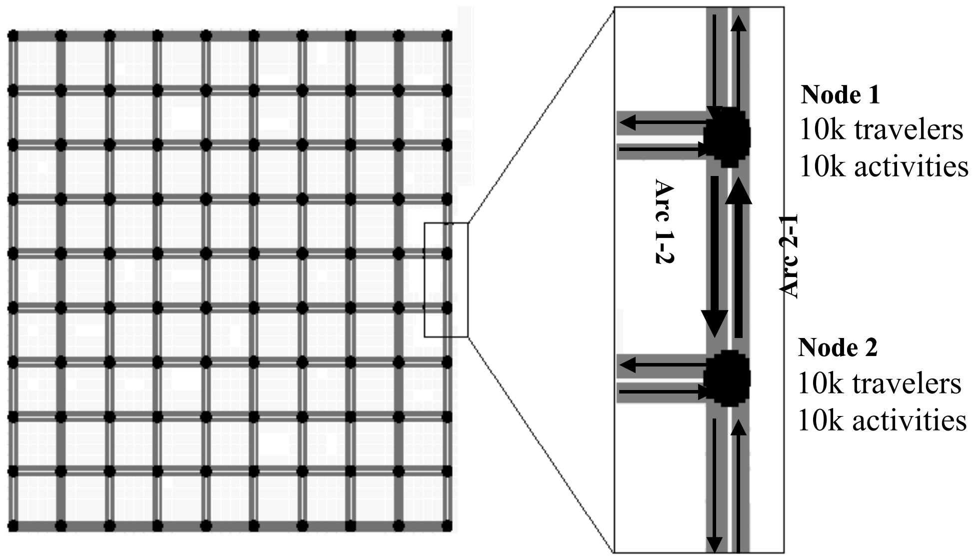

Figure 3. A 10-by-10 Grid Network with Uniform Distribution of Travelers and Activities

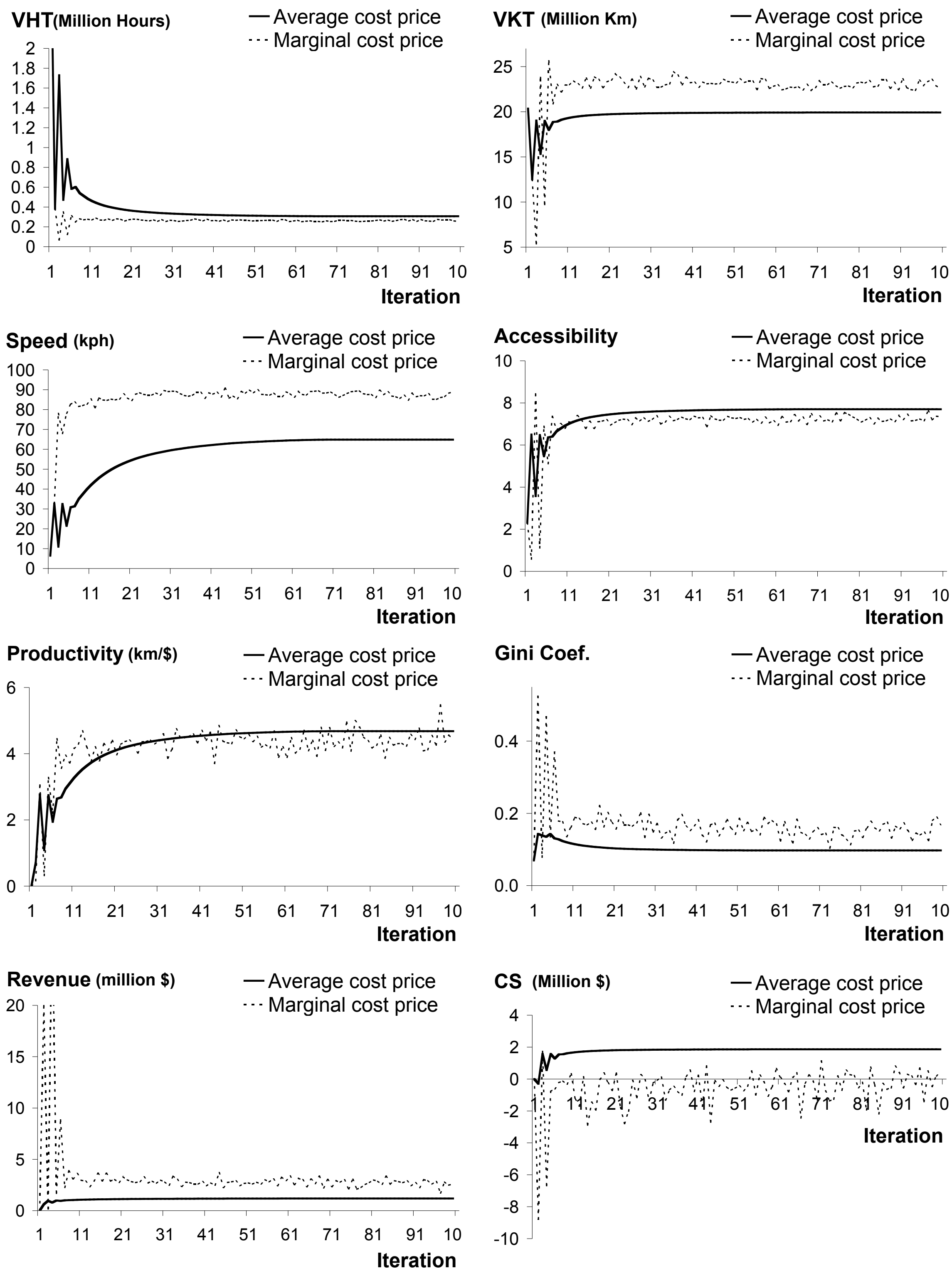

Figure 4. Network MOEs: Average Cost Pricing versus Marginal Cost Pricing