17 The Economics of Transportation Network Growth

Lei Zhang

Department of Civil Engineering
University of Minnesota (U.S.A.)

David Levinson

Department of Civil Engineering
University of Minnesota (U.S.A.)

17.1 Introduction

A number of factors influence the efficiency, productivity, and welfare of transportation networks. Travel demand, user costs, and facility supply costs equilibrate on various time scales under a set of pricing (taxes and tolls), investment and ownership policies. Two types of equilibria exist in a transportation network, short-run traffic equilibrium and long-run supply-demand equilibrium. The phenomenon of traffic equilibrium is explored with a fixed transportation network where the capacity of links is given. Even though investment- and ownership-related policies are not of major concern for studies of traffic equilibrium, it is still a complex problem due to network congestion effects, variations of pricing rules, and multidimensionality of user choices. In order to understand the long-run supply-demand equilibrium in a transportation network, one has to consider all of the above-mentioned factors in a coherent analytical framework. We refer to this research problem as the transportation *network growth problem*, because the network evolves and link capacity is not fixed in the long run.

The growth (and decline) of transportation networks obviously affects the social and economic activities that a region can support, yet the dynamics of how such growth occurs is one of the least understood areas in transportation, geography, urban economics, and regional science. The growth of the transportation network is determined by the total amount of investment and the investment rule, both of which could change over time. What has become known as the *network design problem* in the transportation literature simplifies the *network growth problem* in three aspects: (1) investment decisions are considered independent of pricing rules and ownership structures; (2) only the optimal investment rule is considered; (3) inter-dependencies of sequential investment decisions are ignored. In

reality, the budget is typically determined by the revenue generated from the pricing policy and inter-agency negotiations. Various practical investment rules have been adopted by public or private decision-makers with different goals in mind, that are not necessarily socially optimal. Historical dependency is also an important property of network growth. Economic studies on transportation network growth should recognize these facts. A salient feature of the network growth problem, defined in this chapter, is that it considers the growth of transportation networks as endogenous, in contrast with current transportation planning practice that strives to exogenously direct that growth. In other words, transportation network growth is not entirely an artifact of design, but driven by various market forces present in the network.

Today's decisions both depend on expectations of tomorrow, and constrain tomorrow's choices. Understanding how markets and policies translate into facilities on the ground is essential for both scientific understanding and improving forecasting, planning, policy-making, and evaluation. An improved understanding of long-term network dynamics should lead to better planning and design of transportation networks to exploit network economies and externalities. The challenge for solving the network growth problem is that travel demand, cost structures, and all relevant policies must be modeled with accuracy and sensitivity. This chapter is therefore exploratory in nature, investigating these modeling needs and possible solutions. Another purpose of this chapter is to demonstrate how a network growth model can improve transportation planning in ways short-run network models cannot achieve.

Most previous studies have considered network pricing, investment, and ownership structures separately, which are reviewed in the following section. The next section considers choices of prices, capacity, and ownership simultaneously on small parallel, serial, and parallel-serial networks, and develops an analytical network model. Section 17.4 of this chapter discusses properties of long-run network equilibria with different network layouts and ownership regimes, and the implications on network efficiency. Section 17.5 concludes the chapter with some critiques on the analytical model and suggestions for future research.

17.2 Literature Review

Transportation economists have long been investigating various road pricing policies for optimal allocation of scarce road resources, primarily from a theoretical framework (Dupuit 1844, Pigou 1920, Knight 1924, Mohring and Harwitz 1962, Vickery 1963, Walters 1968, Small 1992, Arnott *et al.* 1993, Button and Verhoef 1998, Gomez-Ibanez 1999, de Palma and Lindsey 2002, Verhoef 2002). 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. An important finding, due to Mohring and Harwitz (1962), states that the revenue generated from the optimal pricing scheme is just sufficient to finance the optimal level of capacity under certain conditions. A series of stud-

ies have examined the validity of this “self-financing rule”, which are summarized by Verhoef and Rouwendal (2004). However, the theoretical analyses are typically performed under a strict set of economic conditions which, in some cases, hardly correspond with reality. Some have concerns that the revenue collected from short-run marginal cost pricing schemes may either significantly exceed or fall short of long-run cost of facility supply for reasons with regard to economies of scale and non-optimality of existing road capacity (Walters 1968, Gwilliam 1997). While the majority of road pricing literature considers a network of parallel roads, several studies examine revenue choices on a serial network managed by multiple jurisdictions (Levinson 1999, Levinson 2000).

While pricing policies are typically proposed with the goal of improving short-run network efficiency, studies on investment principles are generally concerned with long-run efficiency assuming *a priori* the pricing policy (Wohl and Hendrickson 1984). Previous research on the network design problem (NDP) seeks to find the optimal network that serves a certain travel demand, or the optimal network enhancement given a budget constraint (Boyce *et al.* 1974, LeBlanc 1975, Poorzahedy and Turnquist 1982, Yang and Bell 1998, Meng *et al.* 2001). However, these studies, focusing on investment only, do not address the conflict between long-run economic efficiency and financial feasibility in reality. Benefit-cost analysis has been extensively used in practice for strategic planning. Decision-makers have also developed practical investment rules dealing with problems of concern, most notably congestion, such as bottleneck removal and bottleneck bypassing (Zhang and Levinson 2005).

Another related issue is transportation commercialization and privatization. Gomez-Ibanez and Meyer (1993) have reviewed transportation privatization at an empirical level, though the cases of roadway privatization are few and not entirely successful. It is unlikely that even if roadways were privatized, that their price structure would be left entirely to the private sector. Roth (1996) reviewed positive aspects of road commercialization and privatization, and proposed a framework for creating a market economy of roads. In many ways, roadways are natural monopolies, as their provision and use has a declining average cost (aside from congestion effects). The relative advantages and disadvantages of various ownership regimes may also depend on the type of regulation (Kahn 1988, Train 1991).

Most previous economic studies consider the aforementioned three policy aspects (pricing, investment and ownership) of transportation network growth separately with a few exceptions. Keeler and Small (1977) developed a theoretical model to examine optimal peak-load pricing and investment on urban expressways. Verhoef and Rouwendal (2004) recently revisited this topic with additional considerations of second-best pricing policies. Several studies consider alternative ownership regimes and toll choices on a small network with one OD pair and two or more alternative routes (DeVany and Saving 1980, de Palma 1992, Viton 1995, Verhoef *et al.* 1996, de Palma and Lindsey 2000). No previous study has consider pricing, investment and ownership issues jointly on hypothetical or real-world networks.

There are also different methodological tools which could be used to model transportation network growth. Following the seminal work by Pigou (1920) and

Knight (1924), most economic studies on road pricing and financing adopt a theoretical framework and base the analysis on small hypothetical networks, which may be labeled as small network (equilibrium) models. Models of the transportation network as a physical system have been well developed in the transportation literature (Sheffi 1985). When there are multiple agents making pricing and investment decisions (e.g. private roads competing with public roads), an economic network arises which considers coordination and competition between decision-makers. Johansson *et al.* (1994) describe various economic networks from an empirical viewpoint, while Nagurney (1993) provides a computational framework, which links analysis of economic networks (supplier-customer relationships) with algorithms developed for the analysis of physical networks. Economides (1996) compares the economic structure of networks with vertically related industries. Economic systems with multiple decision-making agents may not contain a neat equilibrium solution. Game theory (Von Neumann and Morgenstern 1944, de Palma 1992) provides an alternative means for capturing the interactions between agents in deciding prices and investments. However, game theory assumes a certain amount of knowledge and information available to the players. A modeling approach using cellular automata (Langton 1989) suggests specifying simple rules and allowing the system to evolve. The transportation system is, in Sussman's (2000) word, a complex, large, integrated, and open system. Modeling tools developed for analyzing complex systems, such as agent-based techniques (von Neumann 1966, Zhang and Levinson 2004a), may also be used to model transportation network growth.

17.3 An Analytical Model of Pricing, Capacity Choice and Ownership Structure

17.3.1 Demand Side: Models of Road Users

Users in the transportation systems make a number of spatial and temporal choices that affect travel demand: residential and job locations, vehicle ownership, activity location, activity participation, timing, duration, trip chaining, travel mode, and routes. Traditionally, these choices are modeled in a sequential manner with trips as the basic analysis units, while integrated models have also received significant research interest (Boyce 2002). New activity-based approaches have also emerged since major breakthrough in behavioral geography in the 1970s (Hagerstrand 1970) and have also been applied to aid transportation planning (Pas 1985, Kitamura 1988, Jones 1990, Axhausen and Gärling 1992). In transportation economics studies, the problem of road pricing has been traditionally set up for simplicity with route choice and origin-destination travel frequency choice being the only two demand dimensions. Recently, several studies also consider departure time choice, employing Vichrey's (1969) bottleneck model (Bernstein and Muller 1993, Braid 1996, Liu and McDonald 1999, de Palma and Lindsey 2000). Verhoef and Rouwendal (2004) developed an analytical model with vehicle ownership as

one of the endogenous variables. The analysis in this chapter considers departure time, route, and trip frequency choices with a flat toll, optimal capacity choices, and alternative ownership regimes. Although the assumption of flat toll corresponds to the current practice, it underestimates the effectiveness of road pricing with dynamic tolls varying with traffic conditions (de Palma and Lindsey 2000). The following sections in this chapter will discuss limitations of the analytical models.

Departure Time Choice

Vickrey (1969) derives the departure time equilibrium with flat tolls and the duration of the departure period (i^0 , i^e) is determined by the total number of users or total flow (f) and road capacity (F):

$$i^e - i^0 = f / F \quad (17.1)$$

Total travel cost (U) excluding toll (τ) for each user is comprised of three parts: free-flow travel cost ($\gamma \cdot T^*$), queuing delay (D^q), and schedule delay (D^s). A summary of notation is given in the appendix. Throughout this chapter, superscripts are indexes and subscripts denote first-order (partial) derivatives.

$$U = \gamma \cdot T^* + D^q + D^s \quad (17.2)$$

Let i^* and i denote the desired and actual arrival times respectively, where i^* is further assumed to be the same for all users. A piece-wise linear schedule delay cost function is then specified where α and β are coefficients.

$$D^s(i - i^*) = \alpha \cdot \text{Max}(0, i^* - i) + \beta \cdot \text{Max}(0, i - i^*) \quad (17.3)$$

At the departure time equilibrium, all drivers using the same route should experience the same total travel cost (U^*) whenever they depart. It is convenient to consider the earliest driver and the latest drivers as their queuing delays are both zero.

$$U = \gamma \cdot T^* + D^s(i^0 + T^* - i^*) = \gamma \cdot T^* + D^s(i^e + T^* - i^*) \quad (17.4)$$

Solve Eq. system 17.1, 17.3 and 17.4 and the following expression of travel cost under departure time equilibrium is derived:

$$U = \gamma \cdot T^* + \frac{\alpha \cdot \beta}{\alpha + \beta} \cdot \frac{f}{F} \quad (17.5)$$

The second term of Eq. 17.5 is the sum of queuing cost and schedule delay cost under departure time equilibrium, which is proportional to total number of users and inversely proportional to road capacity. In contrast, the classic BPR function raises the ratio of f/F to the power of four (BPR 1964). It is possible to use empirically derived schedule delay functions, such as the one developed in Small (1982), to specify the coefficients in Eq. 17.5. There is also a more fundamental difference between Eq. 17.5 and the BPR function. The BPR flow-travel-time function is of-

ten regarded as a supply side equation in transportation economics, while Eq. 17.5 is derived from user departure time choices and a given road capacity.

Route Choice and Trip Frequency Choice

Three small networks are considered in this study so that the equilibrium network properties can be examined for parallel, serial, and parallel-serial networks (see Figure 17.1). Different analytical route choice models exist with various assumptions about route choice behavior and are summarized in Sheffi (1985). Wardrop's (1952) first equilibrium principle states that all used routes between each OD pair have the same travel cost which is lower than costs of all unused routes connecting the OD pair. This route assignment criterion assumes that users have perfect knowledge about the network and can always identify the best route however defined. Although it is behaviorally questionable, the Wardrop principle, or the deterministic user equilibrium condition, is still the most widely used route choice protocol for its simplicity. Let C denote the total travel cost including toll, and q^{12} the total number of users between origin-destination pair 1-2. For the parallel network (Figure 17.1a), the Wardrop route choice equilibrium conditions are:

$$U^A + \tau^A = U^B + \tau^B = C^{12} \quad (17.6-1)$$

$$f^A + f^B = q^{12} \quad (17.6-2)$$

By assuming a demand curve to describe trip frequency choices, we also have the following equilibrium demand expression, where $P(\cdot)$ is the inverse demand function:

$$P(q^{12}) = C^{12} \quad (17.6-3)$$

Similar route choice equilibrium conditions and equilibrium demand expressions can be derived for the serial network (Figure 17.1b):

$$q^{12} + q^{13} = f^A \quad (17.7-1)$$

$$q^{23} + q^{13} = f^B \quad (17.7-2)$$

$$P^{12}(q^{12}) = C^{12} = U^A + \tau^A \quad (17.7-3)$$

$$P^{23}(q^{23}) = C^{23} = U^B + \tau^B \quad (17.7-4)$$

$$P^{13}(q^{13}) = C^{12} + C^{23} \quad (17.7-5)$$

and for the parallel-serial network (Figure 17.1c):

$$q^{12} + q^{13} = f^A + f^B \quad (17.8-1)$$

$$q^{23} + q^{13} = f^C \quad (17.8-2)$$

$$P^{12}(q^{12}) = C^{12} = U^A + \tau^A = U^B + \tau^B \quad (17.8-3)$$

$$P^{23}(q^{23}) = C^{23} = U^C + \tau^C \quad (17.8-4)$$

$$P^{13}(q^{13}) = C^{12} + C^{23} \quad (17.8-5)$$

It is assumed that there is no OD substitutional effects, i.e. demand functions for different OD pairs are independent of each other.

Fig. 17.1. Three stylized networks

17.3.2 Supply Side: Road Provision Cost

The cost of supplying road capacity usually involves land acquisition, construction, and maintenance cost (Keeler and Small 1977, Zhang and Levinson 2005). Several empirical studies have tested if constant returns to scale characterize the road supply cost function for its theoretical importance (Keeler and Small 1977, Krause 1981, Small *et al.* 1989, Levinson and Gillen 1998, Small 1999, Levinson and Yerra 2002, Levinson and Karamalaputi 2003). It is fair to conclude from these studies that the overall empirical evidence does not strongly disagree with the proposition that road supply cost exhibits approximately constant returns to scale. However, it should be kept in mind that a small deviation from constant returns to scale in either direction may have significant practical importance in terms

of financial feasibility. The approach herein is that a cost function with constant returns to scale is taken as a base case and then sensitivity analysis with increasing and decreasing returns to scale is conducted. With constant returns to scale, the average amortized cost of providing a unit of capacity (S) is simply a constant:

$$S \equiv S^* \quad (17.9)$$

This simple average cost function does not differentiate between various components of road supply costs. It also implies that capacity expansion can be considered continuous.

17.3.3 Ownership and Policies: Models of Road Providers

Two types of road owners are considered, public and private. Each road owner sets prices and chooses capacity to build based on a pre-determined goal. It is assumed that private road authorities maximize profit, and public road authorities maximize social welfare without budget constraint or discounting. But it should be pointed out that how well these assumed objectives correspond the real objectives pursued by road owners in a real world fraught with principal-agent problems is still an open question.

The general welfare function for a network growth process over a period of time is:

$$W = \sum_t \left\{ \sum_b \left(\int_0^{q_b} P(q) dq \right) - \sum_a C(f^{a,t}, F^{a,t}) \cdot f^{a,t} + \sum_a \tau^{a,t} f^{a,t} - \sum_a S \cdot \Delta F^{a,t} \right\} \quad (17.10)$$

Where t , b , q , a are indices of years, OD pairs, users of an OD pair, and roads respectively, and delta indicates capacity changes. For the analytical models developed in this section, the time index is not meaningful and dropped because only the equilibrium network is considered and the equilibrating process is ignored in all equilibrium analyses. An evolutionary approach is necessary to take into account the growth process in addition to the final network. The first term is users' willingness to pay, and the second term is user cost including toll, and their difference is consumers' surplus. The third term is total revenue for the facility provider, and the last term is facility provision cost, and their difference is suppliers' surplus or profit. A private road company simply maximizes total profits that are produced from all roads it owns:

$$\pi = \sum_a \tau^a f^a - \sum_a S^a F^a \quad (17.11)$$

Since there are two roads for the parallel and the serial network, we have seven possible ownership regimes:

Free-Free: Welfare maximization with no-toll constraints on both routes and only capacity is optimized;

Public: Unconstrained welfare maximization in which capacity and toll are optimized simultaneously;

Private: Profit-maximization in which a monopoly apply profit-maximizing tolls and capacities on both routes;

Private-Private: A duopoly situation where each of the two companies builds, owns, and operates one road to maximize its profit;

Public-Free: Welfare maximization with no-toll constraint on one route – the public agency optimizes capacity on both roads and toll on only one road;

Private-Free: A monopoly builds and operates one of the two roads to maximize profit by setting appropriate toll and capacity while a public agency builds optimal capacity on the other non-toll road.

Public-Private: Same as the Private-Free case except that the public agency optimizes both capacity and toll on the public road.

The scenario with the parallel-serial network has somewhat more complicated possible ownership regimes. In fact, several ownership regimes on this network are special cases of the serial network when roads A and B are owned by the same agency and have the same travel cost function. We consider two interesting ownership regimes on the parallel-serial network in order to explore market properties with private roads, which will be discussed in the next section.

If we define W_1 as the welfare of the *Free-Free* scenario, and W_2 the *Public* scenario. A measure of efficiency (e) for the each ownership regimes (R), with larger e indicating superior efficiency, can be calculated based on its welfare (W_R):

$$e_R = (W_R - W_1) / (W_2 - W_1) \quad (17.12)$$

17.3.4 A Numerical Example

Although the expression of the optimal prices can be derived in closed form as functions of road capacity, a closed-form expression of the optimal road capacity is not always available as shown in the next section. Therefore, a numerical model is constructed for the three stylized networks so that more useful insight can be obtained from the analysis. However, we do not intend to replicate any real-world decision scenarios with this example.

Inverse demand function for the parallel network

$$P = 20 - f / 1000$$

Inverse demand function for the serial network

$$P^{12} = 20 - f / 1000$$

$$P^{23} = 20 - f / 1000$$

$$P^{13} = 40 - f / 1000$$

Average construction cost function (same for all links)

$$S = 5 \quad (\text{constant return to scale})$$

$$S = 5F^{0.1} \quad (\text{increasing return to scale})$$

$$S = 5F^{-0.1} \quad (\text{decreasing return to scale})$$

Travel cost function excluding toll (same for all links):

$$U = 5 + 4 \frac{f}{F}$$

Homogenous user group

Free-flow travel time is valued at \$10 per hour for all users. Assuming away user heterogeneity and the possibility of product differentiation could cause underestimation of the benefit of road pricing, as shown by several previous studies (Arnott *et al.* 1992, Schmanske 1993, Small and Yan 2001).

The task of finding an equilibrium toll and capacity is a nonlinear programming problem for ownership regimes with only one authority managing all roads (cases Free-Free, Private, Public, and Public-Free for all networks), or for regimes with two road authorities on a symmetric network (case Private-Private on the parallel or the serial network) and a game theoretical problem for regimes with two road authorities having different objectives (e.g. cases Public-Private, Private-Free on all networks, and case Private-Private on the Parallel-Serial network). Various studies have developed algorithms to solve one or more of those cases, or to solve equilibrium toll only with fixed capacity (de Palma 1992, de Palma and Lindsey 2000, Verhoef 2002, among many others). The solution algorithm adopted for this study is as follows. For the nonlinear programming problem with the objective function defined by either Eq. 17.10 or 17.11, and with toll and capacity as decision variables, we take advantage of the equality constraints defined by Eq. 17.5 to 17.9 depending on the network in question, and solve for the Lagrangian stationary point. Non-negativity constraints are then checked at those stationary points. For the game-theoretical problem, we derive the pure strategy Nash equilibrium necessary conditions (i.e. first-order necessary conditions) based on the objective functions of players (Eq. 17.10 or 17.11 or both), and form a system of linear and non-linear equations by combining the first order conditions with user equilibrium conditions (Eqs. 17.5 to 17.9). The solution to this equations system is also a stationary point for the problem. If there are multiple stationary points (this only occurs for the parallel-serial network), a brute-force method is applied evaluating objective functions at all stationary points and identifying the true solution. The exhaustive search is acceptable with at most six decision variables on the three small networks being examined in this study. Applications to larger networks should pursue more efficient search algorithms. Provided in de Palma and Lindsey (2000) is the detailed solution procedures for a simpler case with only toll as the decision variable on a parallel network. Interested readers can refer to their paper for some mathematical details. When capacity choices are also considered, the equation systems will also include first order derivatives with respect to capacity,

which are nonlinear in nature. Extending de Palma and Lindsey's (2000) solution method to include capacity choices on the three small networks requires solving a non-linear system of as many as twenty-four equations.

17.4 Equilibrium Toll and Capacity under Various Ownership Regimes

Although in most cases equilibrium tolls can be expressed as simple functions of equilibrium capacity, the closed-form solutions for tolls and capacity are either too complicated for one to draw meaningful policy insights or not available at all. Therefore, we will only analyze the expressions of equilibrium tolls as functions of capacity (called *toll equations* for the remainder of this chapter), and refer to the numerical solutions for equilibrium capacity to discuss policy implications.

17.4.1 Parallel Network

The toll equations for the parallel network have been previously derived in several previous studies (Verhoef et al. 1996, de Palma and Lindsey 2000) for most aforementioned ownership regimes, and some of them are presented in our notation for discussion below and for comparison with the equilibrium tolls on the serial network. Table 17.1 summarizes toll equations for both networks.

A private monopoly controlling both alternatives between the origin-destination pair always levies tolls higher than the marginal cost ($f \cdot U_j$). In the duopoly (Private-Private) case, the toll is always lower than that in the monopoly case for both roads. The duopoly toll on a road is higher if the demand elasticity is lower (i.e. larger c^j), and if the alternative road is more prone to congestion (i.e. larger U_j). The properties of the duopoly toll also hold for the Private-Free and Public-Private case. A public agency will set the toll on one road higher (lower) than the marginal cost if the toll on the alternative road is higher (lower) than the marginal cost (Public-Free, and Public-Private). In other words, in a second best situation with an untolled alternative (Public-Free), the optimal toll on the toll road should be somewhat lower than the true marginal cost. Also, the optimal toll should be even lower in order to avoid over-usage on the untolled alternative if the untolled alternative is more susceptible to congestion (i.e. larger U_j).

The solutions of optimal toll, optimal capacity, volume-capacity ratio, profit, and welfare are summarized in Table 17.2a for the parallel network. It should be noted that the volume-capacity ratio here is an indicator of the extent of bottleneck queuing congestion. This ratio should always be larger than one because a bottleneck model is used. Otherwise, the bottleneck is underutilized. The base case (Free-Free with capacity optimization only) assumes that the construction expenditure comes from other revenue resources and is not paid by the road users. This is why changes in consumers' surplus in all other scenarios are negative. In the numerical example, users must at least contribute 68% of total construction cost in

the base case scenario so that they would support welfare-maximization pricing and investment policies. They would always oppose any form of privatization unless a sufficient portion of the toll profit is appropriately redistributed. Thanks to the assumption of constant returns to scale in the road supply cost function, the public agency can operate at a balanced budget when the levels of toll and capacity are both at the optimum. This will not be the case when there are increasing or decreasing returns to scale, as we shall see in the sensitivity analysis later in this chapter.

Since the public agency and the private sector have different objectives, they also adopted quite different levels of tolls and capacity. In all cases, the private sector significantly under-built capacity while charging much higher tolls than optimal, even though the extent of queuing is the same for the social optimal Public case and the private Monopoly case. This result, based on the numerical example, demonstrates that, although severe congestion on untolled roads may be an indicator of inefficiency (Free-Free, and Private-Free), the level of congestion is in general not a very good measure of system performance. One can find other examples by comparing the volume-capacity ratio between some other cases. Of the last five columns in Table 17.2, the Public-Private ownership regime is the most efficient, followed by private Duopoly, private Monopoly, and Public-Free. The Private-Free case is even worse than the base case (Free-Free). One conclusion from these results is that if road pricing is pursued on several alternative roads, it is better for efficiency purposes to levy tolls on all alternatives no matter what ownership structure is present. However, untolled alternatives maybe justified for equity purposes. If one compares capacity and VC ratios between scenarios Public and Public-Free, it is evident that a much larger number of users are priced off the roads when both roads are toll roads. Future studies should consider multiple user classes and possible product differentiation, and more seriously examine the equity issue, with toll and capacity choices under various ownership regimes. Finally, according to the computed rate of investment return (profit/construction cost), the private sector would most likely seek monopoly or duopoly status. The rate of return is abnormally high in this numerical example, but future studies applying similar analysis on real-world scenarios should be of interests to many parties.

17.4.2 Serial Network

While small parallel networks have been extensively studied by transportation economists for issues related to road pricing and ownership regimes, the serial network has received significantly less research interest. One reason is probably attributed to the fact that the parallel network is somewhat more relevant to the road pricing policy debates. However, any real-world network consists of both parallel roads and upstream/downstream roads.

Table 17.1 Toll Equations

Ownership	Parallel Network	Serial Network
Private	$c^1(f^A + f^B)$	$\frac{(c^2 + c^3)f^A - c^3 f^B}{c^4}$
$\tau_A = f^A U_{f_A}^A + ..$		
Private-Private	$\frac{U_{f_B}^B c^1}{U_{f_B}^B + c^1} f^A$	$\frac{(c^2 + c^3)f^A U_{f_B}^B + c^6 f^A}{(c^3 + c^4) + c^5 U_{f_B}^B}$
$\tau_A = f^A U_{f_A}^A + ..$		
Public-Free	$-\frac{c^1}{U_{f_B}^B + c^1} (f^B U_{f_B}^B)$	$\left[\frac{c^3}{(c^3 + c^4) + c^5 U_{f_B}^B} \right] (f^B U_{f_B}^B)$
$\tau_A = f^A U_{f_A}^A + ..$		
Private-Free	$\frac{U_{f_B}^B c^1}{U_{f_B}^B + c^1} f^A$	$\frac{(c^2 + c^3)f^A U_{f_B}^B + c^6 f^A}{(c^3 + c^4) + c^5 U_{f_B}^B}$
$\tau_A = f^A U_{f_A}^A + ..$		
Public-Private	$\frac{c^1}{U_{f_B}^B + c^1} (\tau^B - f^B U_{f_B}^B)$	$\left[\frac{c^3}{(c^3 + c^4) + c^5 U_{f_B}^B} \right] (f^B U_{f_B}^B - \tau^B)$
A-B		
$\tau_A = f^A U_{f_A}^A + ..$		
$\tau_B = f^B U_{f_B}^B + ..$	$\frac{U_{f_B}^B c^1}{U_{f_B}^B + c^1} f^B$	$\frac{(c^3 + c^4)f^B U_{f_A}^A + c^6 f^B}{(c^2 + c^3) + c^5 U_{f_A}^A}$

Note:

(1) Tolls for the Free-Free case are always zero, and for the Public case, always equal to the marginal cost $f U_f$.

(2) $c^1, \dots, c^6$ are constants defined below:

$$c^1 \equiv |P_f|; \quad c^2 \equiv |P_q^{12} P_q^{13}|; \quad c^3 \equiv |P_q^{12} P_q^{23}|; \quad c^4 \equiv |P_q^{13} P_q^{23}|;$$

$$c^5 \equiv \left| \sum_b P_q^b \right|; \quad c^6 \equiv \left| \prod_b P_q^b \right|$$

The toll Eq.s for the small serial network are slightly more complex than those for the parallel network (see Table 17.1), but some useful insights can still be drawn. Let us first examine the private monopoly scenario (Private). In this case, if road A has much lower flow than road B ($f^A < c^3 f^B / (c^2 + c^3)$), the profit-maximizing toll on road A would be lower than the marginal cost toll ($f^A \cdot U_{f_A}^A$), while the toll on road B would be higher than the marginal cost toll (the toll Eq. for road B can be obtained by exchanging superscripts of toll Eq. for road A due to network symme-

try). The monopoly can gain more profits on the high-flow overcharged road than the lost profits on the low-volume undercharged road. This result implies that a private road monopoly may attract more users to the high-volume trunk roads by charging low tolls on local connector roads. Similarly, in the airline industry, a carrier may be willing to provide cheap service on the secondary routes as long as they can charge high markups on the routes connecting hubs with much more passenger flow. However, if the amount of traffic on both upstream and downstream links is comparable, the profit-maximizing tolls on both roads will be higher than the marginal cost tolls. In the duopoly case (Private-Private), the toll is always higher than the welfare-maximizing toll. Furthermore, the duopoly toll is higher on one road if the upstream or downstream road is more congestible (i.e. larger U_j). It is interesting to compare second-best tolls in the parallel and serial networks (first row of the Public-Private case, or the Public-Free case). Whether the second-best toll is higher or lower than the first-best toll on one road depends on the relationship between the actual and first-best tolls on the other road in both networks, but in quite different ways. In the parallel network, the second-best toll and the actual toll on the other road should both be either higher or lower than the first-best toll. Whereas on the serial network, the second-best toll is higher (lower) than the first-best toll if the actual toll on the other road is lower (higher) than the first-best toll. One can easily see why it is a complex problem to determine the relationship between the second-best and the first-best tolls on a more complicated network. Verhoef (2002) offers a heuristic algorithm for finding second-best toll levels and toll points on a general network.

Table 17.2b provides numerical equilibrium solutions for the serial network. Again, the network under private ownership regimes would be significantly underbuilt compared to public ownership with or without optimal tolls. The toll levels are also consistently higher under private ownership regimes. Users would support marginal cost pricing only if they currently pay more than 76% of road construction cost. Even if all construction cost is currently borne by users, some redistribution would still be required to make them indifferent toward road privatization. To be exact, 66% of monopoly profit or 85% of duopoly profit needs to be redistributed.

Private roads compete with public roads by offering faster (small VC ratios) but more expensive services. Had the distribution of value of time among road users been considered, this phenomenon would be more apparent. One interesting finding is that the monopoly chooses a price (\$7.50) lower than the two duopoly roads (\$8.41), and is more efficient. This is reminiscent of the important result in vertical competition and integration due to Cournot (1738). In the serial network with vertically complimentary roads, a vertically-integrated monopoly actually faces a more elastic demand than two vertically-disintegrated duopolies. However, the incentive for the two firms to agglomerate almost does not exist according to the level of profits and rate of return. The most efficient ownership regime next to the social optimal benchmark is the Public-Free case, followed by Public-Private, Private Monopoly, Private-Free, and Private Duopoly. The private sector would prefer operating with a public complimentary road to operating with another private

road upstream or downstream as the rates of return suggest, which is different from the parallel network.

Table 17.2. Equilibrium solutions for the numerical example

17.2a: Parallel network

Ownership Route	Free-Free	Public	Private	Private-Private	Public-Free	Free-Private	Public-Private
A-Route B							
Toll A (\$/veh)	0	4.47	7.50	6.98	2.43	0	5.40
Toll B (\$/veh)	0	4.47	7.50	6.98	0	5.475	5.62
Capacity A (veh/hr)	2624	2708	1354	1316	3194	1480	2320
Capacity B (veh/hr)	2624	2708	1354	1316	2406	1228	2175
VC Ratio A (no unit)	1.62	1.12	1.12	1.21	1.16	2.49	1.14
VC Ratio B (no unit)	1.62	1.12	1.12	1.21	1.77	1.12	1.09
Profit A (\$)	-13120	0	4584	4528	-6983	-7399	2733
Profit B	-13120	0	4584	4528	-12030	1377	2437
Total Profit	-26240	0	9168	9056	-19013	-6022	5170
Rate of return A	—	—	68%	69%	—	—	—
Rate of return B	—	—	68%	69%	—	22%	22%
ΔCS	0	-17889	-31647	-31165	-4706	-23462	-23609
Δ Welfare (\$)	0	8351	3761	4131	2521	-3244	7801
Total Welfare (\$)	9989	18340	13750	14120	12510	6745	17790
Efficiency	0	1	0.45	0.49	0.30	-0.39	0.93

17.2b: Serial network

Ownership Route	Free-Free	Public	Private	Private-Private	Public-Free	Free-Private	Public-Private
A-Route B							
Toll A (\$/veh)	0	4.47	7.50	8.41	6.42	0	2.67
Toll B (\$/veh)	0	4.47	7.50	8.41	0	11.42	10.34
Capacity A (veh/hr)	19740	16250	8125	7405	16170	16220	14490
Capacity B (veh/hr)	19740	16250	8125	7405	18520	9349	8450
VC Ratio A (no unit)	1.42	1.12	1.12	1.02	1.12	1.22	1.12
VC Ratio B (no unit)	1.42	1.12	1.12	1.02	1.29	1.00	1.04
Profit A (\$)	-98700	0	27505	26420	35130	-81100	-29180
Profit B	-98700	0	27505	26420	-92580	59550	48990
Total Profit	-197400	0	55010	52840	-57450	-21550	19810
Rate of return A	—	—	68%	71%	—	—	—

Rate of return B	–	–	68%	71%	–	127%	116%
ΔCS	0	-151090	-233590	-242110	-106550	-162740	-195320
$\Delta \text{Welfare } (\$)$	0	46310	18820	8130	33400	13110	21890
Total Welfare (\$)	63690	110000	82510	71820	97090	76800	85580
Efficiency	0	1	0.41	0.18	0.72	0.28	0.47

It would be premature to make any recommendations on road commercialization and privatization based on the above results derived from a simple numerical example. But some insights are worth mentioning. First, the task of quantitatively evaluating the consequences of various forms of road privatization is an important yet difficult problem. Studies using different network layouts could draw different conclusions. The results in Table 17.2 exemplify this issue. A case-by-case examination maybe necessary. Since the analytical model does not scale very well in large networks, alternative modeling methods need to be pursued. Another issue has to do with deployment. Even though it is apparent that a new private toll road is socially desirable and profitable, the most socially desirable ownership arrangement could be different from the most profitable arrangement. Some sorts of constraints in terms of regulation policies or contracts need to be carefully forged.

17.4.3 Returns to Scale

The results presented above are all based on the assumption of constant returns to scale (CRS) in the road supply cost function. Cost functions with increasing (IRS) and decreasing returns to scale (DRS) are also specified and used to recalculate equilibrium tolls and capacity for the socially optimal case (Public) on both parallel and serial networks. Economic theory suggests that an IRS cost function causes a budget deficit and a DRS cost function leads to excessive revenue, as confirmed in Table 17.3. The main point of this sensitivity analysis is to demonstrate that a small deviation from CRS could cause significant budget-related problems, deficit or surplus, and large variations of the equilibrium network properties. It is anticipated that conclusive empirical evidence supporting any one of the three return-to-scale scenarios will not be available in the near future. Therefore, sensitivity analysis of this type should always be pursued in similar economic studies on road financing and ownership.

Table 17.3. Sensitivity analysis: Returns to scale of the construction cost function

	Parallel Network			Serial Network		
	CRS	IRS	DRS	CRS	IRS	DRS
Ownership: Public						
Ave. cons. cost fn. $\rightarrow$	S=5	S=5F ^{0.1}	S=5F ^{0.1}	S=5	S=5F ^{0.1}	S=5F ^{0.1}
Toll (\$/veh)	4.47	2.73	6.48	4.47	2.47	6.88
Capacity (veh/hr)	2708	7010	633	16250	48790	2149
VC Ratio (no unit)	1.12	0.68	1.62	1.12	0.62	1.72
Profit (\$)	0	-50560	1206	0	-16580	4628
Welfare (\$)	18340	42710	3305	110000	286700	9186

17.4.4 Parallel-Serial Network

For the three-road parallel-serial network, we only consider two scenarios, Private-Private, and Private-Private without capacity reduction (called Competition 1, and Competition 2 in the last two columns of Table 17.4). In scenario competition 1, company 1 operates road A and C, and company 2 wants to build a new alternative road B connecting OD pair 1-2. Scenario Competition 2 is similar to Competition 1 except that company 1 cannot reduce the capacity of roads A and C when company 2 decides to enter the market. The purpose of this analysis is to examine whether a new private company would have incentives to enter a market economy of roads where a monopoly dominates. In other words, we want to know what the degree of spatial monopoly is in a privatized road market.

Table 17.4. Numerical results: Parallel-serial network

Ownership	Welfare Max NoToll	Welfare Max.	Private Monopoly	Competition Scenario 1	Competition Scenario 2
Toll A (\$/veh/link)	0	4.47	7.50	5.70	5.79
Toll B (\$/veh/link)	0	4.47	7.50	5.70	5.47
Toll C (\$/veh/link)	0	4.47	7.50	8.40	8.36
Capacity A (veh/hr)	9870	8125	8125	6753	(Fix.)8125
Capacity B (veh/hr)	9870	8125	0	3784	3372
Capacity C (veh/hr)	19740	16250	8125	8125	(Fix.)8125
Flow on A (veh/hr)	13995	9085	8125	7550	8441
Flow on B (veh/hr)	13995	9085	0	4231	3770
Flow on C (veh/hr)	27990	18170	9084	9084	9243
Total Revenue (\$)	0	162500	136260	143472	146767
Comp. 1: A & C			136260	119347	126145
Comp. 2: B			0	24125	20622
Const. Cost (\$)	197400	162500	81250	93310	98110
Comp. 1: A & C			82150	74390	81250
Comp. 2: B			0	18920	16860
Total Profit (\$)	-197400	0	55010	50162	48587
Comp. 1: A & C			55010	44957	44830
Comp. 2: B			0	5205	3757
Rate of return 1	—	—	67%	60%	55%
Rate of return 2	—	—	—	28%	22%
Δ CS	0	-151090	-233590	-223002	-219907
Δ Welfare (\$)	0	46310	18820	24560	26080
Total Welfare (\$)	63690	110000	82510	88250	89770
Efficiency	0	1	0.41	0.53	0.56

Results suggest that new competition caused by the entry of company B significantly improves social welfare. After road B is built, the previous monopolist loses about 19% of profits and confronts a lowered rate of investment return. There is clearly a profit incentive for company 2 to enter the market with a rate of

return higher than 20%. However, company 1 still has larger market share between OD pair 1-2 than company 2. These findings suggest that a privatized road market maybe able to attract enough companies to sustain a socially desirable level of competition. However, further confirmation on real-world networks is necessary for policy recommendations.

Finally, in the numerical example, company 1 has no incentive to apply discriminative intersection control at node 2 that prevents traffic on link B from using link C to reach node 3. Such discrimination would only cause redistribution of local and through traffic on links A and B, but not affect the profit of company 1. This conclusion holds as long as the amount of the through traffic (demand from node 1 to 3) is less than the current equilibrium flow on link A. Of course, this would not be an issue at all if a regulator prohibits any types of discriminating traffic control plans.

17.5 Conclusions

The dynamics of transportation network growth previously have not attracted significant research attention and have not yet been very well understood by planners and economists. This lack of understanding is revealed time and again in the long-range planning efforts of metropolitan planning organizations (MPOs), where transportation network change is treated exclusively as the result of top-down decision-making. Changes to the transportation network are rather the result of numerous small decisions (and some large ones) by property owners, firms, developers, towns, cities, counties, state department of transportation districts, MPOs, and states in response to market conditions and policy initiatives. In the 1960s, several studies examined possible forces shaping transportation networks (Boyce 1963, Garrison and Marble 1965). Only recently has there been a revived small but growing interest in studying the growth of transportation networks (Levinson and Yerra 2002, Levinson and Karamalaputi 2003, Yamins *et al.* 2003, Zhang and Levinson 2003, Verhoef and Rouwendal 2004). An important intellectual merit of studies of the network growth problem is that they could improve and extend the understanding of how transportation networks grow and decline, and help theorize the intertwined process of the growth in travel demand and the growth of the transportation network. In practice, this improved understanding could illustrate how decisions made in one point of time affect future choice, and help guide planners and decision-makers desiring to shape the future.

Traditionally, transportation economists have approached network financing problems by first constructing tractable and transparent analytical models on small networks like the one described in section 17.3 of this chapter and then with some insights gained from the analytical models developing models and algorithms applicable to large-scale realistic networks. Such a method is also suitable for studies of transportation network growth, as the analytical model has several inherent limitations. Models involving analytical equilibrium analysis evaluate the desirability of alternative policies based on the performance of the final equilibrium

network only, ignoring the equilibrating process. It is now well known that in complex systems, historical dependency or path dependency is a major property. A small change of the system state at a time may profoundly impact the future network growth path. Another drawback of the analytical model described in section 17.3 lies in its inapplicability to large networks. Even for network economics problems with a static network for which pure mathematical programming models could be formulated for real-world scenarios, there is often the lack of efficient and reliable solution algorithms. As a result, various simplifying assumptions are required to make the problem tractable, while necessary validation of the assumptions is not seriously pursued. This problem will also be evident if analytical models of network growth are formulated for large dynamic networks.

Two approaches seem to be appropriate for exploring regularities in transportation network growth processes, with the observation that network growth stems from the behaviors of and interactions between a large number of heterogeneous agents (users, various levels of government, private roads etc.) having different goals and limited information. The expansion and contraction of a network could be modeled as the outcome of an evolutionary game played by those agents. The complexity in a transportation network also suggests an agent-based simulation approach, which has been pursued in several exploratory studies (Zhang and Levinson 2003, Zhang and Levinson 2004b). Future research may apply these methods to study the network growth problem and its planning implications.

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Appendix: Notation

a	index of link
b	index of OD pairs
C	generalized travel cost on a link
E	revenue
f	number of users on a link
F	capacity
$K(.)$	expansion cost function (for dynamic analysis only)
$M(.)$	maintenance cost function (for dynamic analysis only)
$P(.)$	inverse OD demand function that is continuously differentiable and $p_x(x) > 0$
q	number of users between an OD pair
$S(.)$	average amortized cost of supplying a unit capacity (for static analysis only)
r	interest rate

t	index of pricing cycles
T	travel time: $T(f/F)$
T^*	free-flow travel time
U	average user operating cost $U = \gamma T = U(f/F)$
α	schedule early cost
β	schedule delay cost
γ	value of travel time savings
τ	toll
π	profit