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Jurisdictional Control and Network Growth

Feng Xie · David Levinson

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Abstract Transport infrastructure evolves over time in a complex process as part of a dynamic and open system including travel demand, land use, as well as economic and political initiatives. As transport infrastructure changes, each traveler may adopt a new schedule, frequency, destination, mode, and/or route, and in the long term may change the location of their activities. These new behaviors create demand for a new round of modifications of infrastructure. In the long run, we observe the collective change in the capacity, service, connectivity, and connection patterns (topology) of networks. This paper examines how a fixed set of places incrementally gets connected as transport networks are constructed and upgraded over time. A simulator of network incremental connection (SONIC) is constructed to model the process of incremental connections and examines how networks evolve differently under centralized versus decentralized jurisdictional initiatives. Exploring the mechanism underlying this dynamic process can answer questions such as how urban networks have developed into various topologies, which network patterns are more efficient, and whether and how transport engineers, planners, and decision makers can guide the dynamics of land uses and infrastructure in a desired direction.

Keywords Network growth · Transport economics · Incremental connection · Jurisdictional control

F. Xie (✉) · D. Levinson
Department of Civil Engineering, University of Minnesota,
500 Pillsbury Drive SE, Minneapolis 55455, USA
e-mail: xiex0055@umn.edu

1 Introduction

The temporal growth of transport networks holds intrinsic interests for professionals and researchers. As early as the 1960s, geographers observed that the deployment and transformation of transportation networks followed a staged process and constructed a series of staged connection models to replicate this process (Lachene 1965; Pred 1966; Rimmer 1967; Taaffe et al. 1963). This research, however, had to deal with simple networks based on heuristics and intuition, and after an initial surge in activity, the field remained dormant over the following 40 years, due to the difficulty of modeling the complexity inherent in network growth problem.

This complexity arises from the many actors who design, construct, expand, control, manage, maintain, operate, and commercialize transport networks over the duration of decades. In particular, the development of all modes of transport, as observed by Taaffe et al. (1996), has been affected by a constantly shifting mix of private enterprise, on the one hand, and government initiatives at local, state, and national levels, on the other hand. Ownership ranges from governments, private investors, to public–private-partnership. Narrowing our focus to public ownership in transport development, centralized provision of transport infrastructure involves a single unitary government that is responsible for the financing, investment, maintenance, and operation of transport networks (e.g. roads), while a decentralized pattern involves autonomous local jurisdictions that build networks (roads) individually, or in coalitions, to connect to each other. In either case, central or local governments provide transport to maximize the aggregate benefit of their constituents. A broad literature of financial federalism has discussed the advantages and disadvantages associated with centralized versus decentralized provision of public goods (Epple and Nechyba 2004). In general, a centralized decision-making pattern has advantages in that it can effectively reduces conflicts between local jurisdictions arising from the intrinsic characteristics of infrastructure as natural spatial monopolies, such as the likelihood of free riders and spillovers, but a 'one size fits all' provision of infrastructure may fail to reflect local needs and thus undermine local interests, which may lead to the adoption of an alternative decentralized decision-making pattern. In reality, the two systems are intertwined and the trade-off between them profoundly shapes the physical structure of networks over time.

The trade-off between centralized versus decentralized provision of public goods has been the classic problem examined in political science and public economics both in theory (Besley and Coate 2003; Oates 1972) and in practice (Knight 2002). Specifically, the experience in road decentralization throughout the world has been examined (Humplick and Moini-Araghi 1996a,b). Transportation economists also consider ownership and investment choice in transportation networks (Gomez-Ibanez et al. 1999; Levinson 2002; Verhoef and Rouwendal 2004; Zhang and Levinson 2005a), although they had to limit their theoretic investigation on small, hypothetical networks, largely due to the computational complexity that arise from the optimization or game-theoretic approaches they adopted. The dynamic impact of ownership structure in shaping transport networks has not been examined.

In the past decade, a marked revival of the interests has been seen on the modeling and analysis of transportation network growth, especially aroused by the cornerstone findings made by Barabási (2002) in network science. Self-organization and agent-based simulation are also extensively introduced from natural science to model the growth of transportation networks while accounting for various economic initiatives and behavioral rules involved in this process (Helbing et al. 1997; Levinson and Yerra 2006; Xie and Levinson 2007; Yamins et al. 2003; Yerra and Levinson 2005). Levinson and Xie (2007) provided a comprehensive review of this literature. Among these studies, a few efforts have been made to model network growth while accounting for the role of heterogeneous political initiatives. Montes de Oca and Levinson (2006), based on a series of interviews with officials and engineers in the Twin Cities Metropolitan Area, Minnesota, revealed that different levels of jurisdictions (state, region, county) had developed different decision making processes in terms of funding allocation to road projects. Levinson et al. (2007) then incorporated these "stated" jurisdictional decision rules in a network growth model to forecast the Twin-Cities seven-county road network 30 years from now.

Extending these efforts, this paper examines in particular how a network evolves differently under centralized versus decentralized jurisdictional control during its early deployment phase, as the network expands and isolated places get connected incrementally. Given the complexity it involves, this study is not intended to be comprehensive. Instead, it focuses on providing a tool which represents the deployment of a network in a simulation environment, and demonstrates the capability of assessing policies under alternative jurisdictional controls quantitatively. A series of models have been encapsulated in this tool, which we refer to as SONIC (simulator of network incremental connection), to predict the decisions of travelers on destination and route choices on a daily basis, as well as the decisions of central or local jurisdictions with regard to their financing, investment, maintenance and operation policies in the long term.

This paper proceeds in the following form: the next section presents the definition of the incremental network growth problem. Models are then developed to represent strategic players and their decisions during network, which are followed by simulation experiments and results. The conclusions summarize the findings and suggest directions for future research.

2 An incremental connection problem

In this section, we first present the graphic definition of an incremental network growth problem. Strategic players that affect the deployment of a network are then presented, with their respective perspectives and behaviors explained.

2.1 The graphic definition

The incremental connection problem is proposed to represent the sequential deployment of a surface transport (road) network over space and time, which assumes the form of "link addition problems" that have been previously defined in transport geography (Harggett and Chorley 1969), in general, dealing with how links will be added among a set of fixed nodes to create an efficient network. Suppose we have the complete graph $G = \{V, L\}$ that comprises a finite set of potential vertices V and potential edges E. A set of established places is prespecified as $P \subseteq V$.

Established places could be connected in one continuous network or in separate subnetworks ($G_m = \{V_m, L_m\}, m = 0, 1, 2,$). A subnetwork holds the following three properties:

A subnetwork must be a subset of the compete graph G:

$$V_m \subseteq V, L_m \subseteq L \tag{1}$$

A pair of subnetworks shares no vertices or edge:

$$V_m \cap V_n = \emptyset \tag{2}$$

A subnetwork contains at least one established place (an isolated place without any connection can be viewed as a scalar subnetwork):

$$V_m \cap P \neq \emptyset \tag{3}$$

It is assumed that subnetworks are isolated in space with infinite transportation cost in between. An internal connection is defined as the connection made between two vertices that belong to one subgraph. On the other hand, if a connection is made between two vertices that belong to different subgraphs, it is referred to as an external connection. An internal or external connection represents a series of nodes and two-way links that consecutively connect along the geographical shortest-distance path in the complete graph. Figure 1 presents a graphic example for illustration. Based on the above specification, an incremental connection process is defined as:

- Step 0: Start with the complete graph G and a set of unconnected places that belong to separate subgraphs.
- Step 1: One internal or external connection is made at a time.
- Step 2: Two separate subgraphs merge when an external connection is made connecting them.
- Step 3: As the process goes on, a connected network of places and established links may eventually emerge. Steps 1 and 2 are repeated until the topology of the established network remains unchanged based on prespecified stopping criteria.

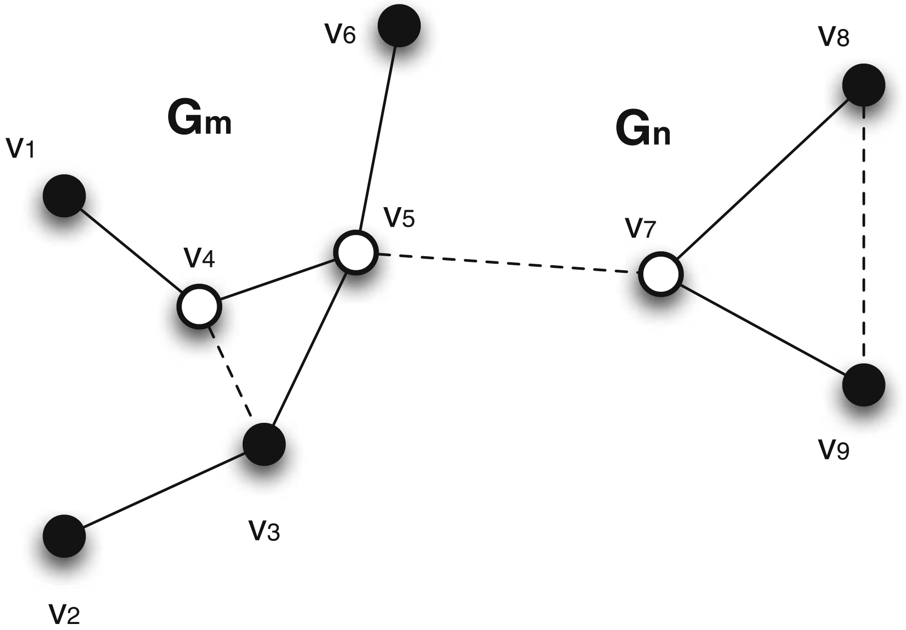

Fig. 1 A graphic example of external versus internal connections. *Solid lines* represent established links, *dashed lines* proposed connections, *dark dots* established places, and *white dots* intersections. Connections $v_3 - v_4$, $v_8 - v_9$ are internal connections while $v_5 - v_7$ is an external connection

2.2 Strategic players

Road infrastructure is provided and operated in a value chain which involves various groups of players, such as financiers, providers (represented by planners and engineers), and travelers. Thus the deployment course of a road network is played out as the outcome of the decisions made by these groups subject to their own interests. In order to represent the above defined network growth problem in the transport environment, key players in this process and their rationales are introduced as follows:

2.2.1 Travelers

To simplify the modeling, it is taken that travelers choose destinations following a gravity relationship, and choose routes that minimize their travel cost. The generalized travel cost includes travel time and monetary cost travelers pay for travel, such as fuel taxes and user tolls. A deterministic behavioral mechanism assumes travelers choose the least cost route from their origin to destination if they have perfect information regarding travel time over the entire network. To relax this assumption by including a random component in travelers' perception of travel time, this study assumes that travelers choose routes to minimize their perceived travel cost.

2.2.2 Providers

Road provision could be public or private, centralized or decentralized. This study, however, considers public roads provided by jurisdictional authorities only, which was the common practice during the twentieth century for roads in the USA. Note also that although a mixed ownership of public roads at local and central levels is common, this study treats centralized and decentralized road provision separately.

Ideally, a jurisdiction seeks to maximize the aggregate welfare of its local residents (Levinson 2002). Although tolls or taxes may be levied for using its roads as a means of financing, it is assumed that the central jurisdiction does not intend to maximize its toll revenue, because user tolls or taxes increase the access cost to properties, therefore reducing windfall gains in land values for road provision, and the end effect on overall welfare would be the same (Mohring and Harwitz 1962). Instead, it is assumed that the central agency provides and manages public roads aiming to maximize its land value (indicated by aggregate accessibility of the region), as road investment leads to the reduction of access cost to properties, and to increased aggregate accessibility and accrued land value in the long run.

A local authority maximizes the welfare of its own residents. The local agent builds roads for its own residents. Those roads however could be used by travelers from other jurisdictions. To reduce the free-rider effect, it is reasonable to expect that local agents will charge user tolls on the roads they own and adjust toll rates according to the fluctuation of the demand. Therefore, it is assumed in this research a local jurisdiction builds and operates roads to increase both toll revenue and the aggregate accessibility of local residents. To make matters more complicated, when more than one local jurisdiction participates in the project, negotiation regarding how construction cost and revenue associated with a road project will be split may be required. It is also assumed that whether a road project is built by a single local jurisdiction or by the joint venture of several, the road project will be managed and maintained as a whole by a project operator who represents the owner(s).

2.2.3 Central bank

A bank agent is involved when jurisdictions need to save the surplus of toll revenue for future investment or borrow money from future for present spending. The bank pays interests for the savings and provides loads at an interest rate. The bank prioritizes road construction projects with funding needs trading off risk for reward. For simplicity of this study, we assume a central bank agent and no spread between the rate for savings and the rate for lending.

3 Model specification

In this section, simulation models are constructed to predict the strategic decisions made by major players during network growth. An integration of

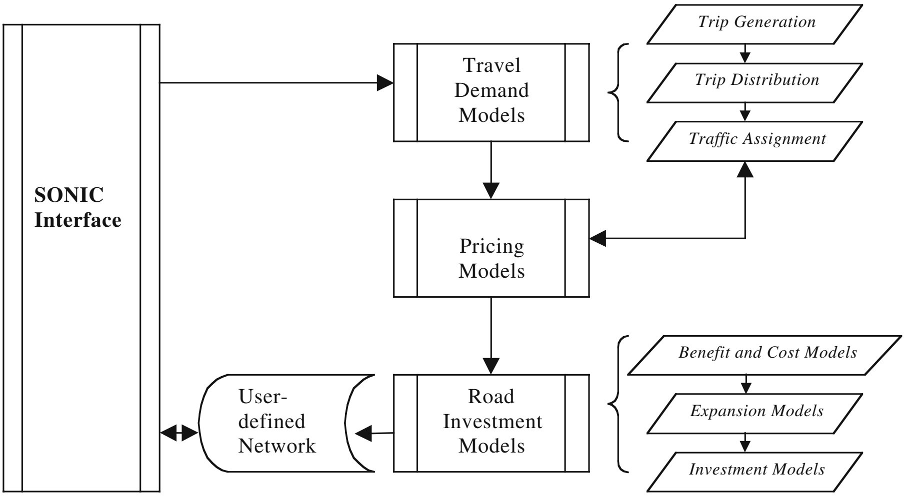

Fig. 2 Framework of the SONIC models

these component models implements the above defined incremental network growth process which creates a network link-by-link to connect a pre-specified set of established places. As illustrated in the flowchart of Fig. 2, travel demand models predict daily traffic across individual links on a given network; toll rates on roads are set and adjusted in the pricing models on a daily basis while toll revenue annually accrues to central or local jurisdictions. Expansion models expand existing congested roads, while new construction models choose one and only one new connection at a time (if any) for construction. After road investments are made, the time period is incremented and the whole process is repeated (in this study one time period represents a year as the morning peak hour traffic is predicted and converted to yearly traffic for investment models). The process is terminated when neither expansion nor new construction occurs or up to a maximum of 50 iterations.

Note that the model is simplified in that spatial activities are distributed among a given set of places and remain fixed over time. Additionally, spatial accessibility is priced at a constant rate associated with accrued land value. Agents such as employers, resident workers, and landowners would have come into play if the mutual effects between land use and transport are considered in a broader context. In this regard, parallel research by (Levinson et al. 2007) that simulates the co-evolution of land use and transport networks complements this study.

3.1 Notation

Variables and coefficients that will appear in the remainder of this paper are summarized in Tables 1 and 2, respectively.

Table 1 List of variables

Variable	Description	Variable	Description
A_i	Accessibility to jobs of place *i*	m, n	Index of subgraph
a	Index of link	N	Planning horizon in year
B	Net social benefit	O_i	Trip generation of Zone *i*
C_a	Link capacity	P	Set of places
c, d	Ownership (centralized, decentralized)	p, q	Index of road project
D_i	Trip attraction of place *i*	Q^*	Threshold volume capacity ratio
E_e	Construction cost, expansion projects	R_p	Collected revenue of road project *p*
E_n	Construction cost, new projects	r_s, r_l	interest rates for saving and loan
f_a	The flow of link *a*	s_a	Free flow speed of link *a*
G	The complete graph	$T_i j$	Number of trips from place *i* to place *j*
G_m	Subgraph	$t, \tilde{t}$	Actual travel time, generalized travel cost
H	Benefit–cost ratio	t_0	Intra-place travel time
i, j	Index of place	U_i	Land use of place *i*
J_i	Number of jobs in place *i*	V	Set of vertices
K	Balancing variables in trip distribution	v	Index of vertices
k	Index of iteration	W_i	Number of resident workers in place i
l_a	The length of link *a*	Y_a	Travelers willingness to pay on link *a*
L	Set of links	Z	Current balance

Table 2 List of parameters

Parameter	Description
ξ_0, ξ_1, ξ_2	Coefficients in trip generation
$\sigma_0, \sigma_1, \sigma_2$	Coefficients in trip attraction
ω_1, ω_2	Coefficients in empirical capacity-speed relation
υ	Value of time
θ	Spatial interaction coefficient
μ	Expansion share of investment budget
κ	MSA convergence threshold
ρ_1, ρ_2	Toll rate adjustments under decentralized control
$\beta_0, \beta_1, \beta_2$	Coefficients in empirical construction cost models
ϕ	Coefficient that coverts peak hour traffic to daily traffic
χ_p^I	Ownership share of place *i* in project *p*
δ_a^p	Dummy variable denoting if link *a* belongs to project *p*
δ_a^{ij}	Dummy denoting if link *a* is on the least-cost path from place *i* to *j*
π	Value of accessibility to jobs
λ_a	Proportion of resident-travelers on link *a*
ε	Constant

3.2 Travel demand models

The travel demand model predicts travel needs between origins and destinations associated with spatial activities, travelers destination, mode and route choices, and predicts aggregate traffic on a given network topology. The travel demand models for this study follow the classic four-step planning process (de Dios Ortuzar and Willumsen 2001) including trip generation, trip distribution, and traffic assignment while skipping modal choice by assuming a single mode of trips. Since the subject network in the incremental network growth problem changes over time and is fragmental at the beginning, travel demand forecasting is conducted for each subgraph at each time period.

This study includes only two types of land use activities: population and employment. The trip generation and attraction of a place is simply estimated as a linear combination of the quantities of employment and population in this place, without distinguishing trips by purpose:

$$O_i = \xi_0 + \xi_1 J_i + \xi_2 W_i \quad (4)$$

$$D_i = \sigma_0 + \sigma_1 J_i + \sigma_2 W_i \quad (5)$$

A doubly constrained trip distribution model is implemented to predict the travel demand between a pair of origin and destination places. The interaction between places assumes a gravity-type negative exponential form:

$$T_{ij} = K_i K_j O_i D_j e^{-\theta \tilde{t}_{ij}} \quad (6)$$

The generalized travel cost from origin to destination is calculated along the least-cost route as:

$$\tilde{t}_{ij} = \begin{cases} \sum_a \delta_a^{ij} (t_a + \tau_a/\upsilon) + 2t_0 & i \neq j \\ t_0 & i = j \end{cases} \quad (7)$$

Traffic assignment adopts the basic procedure of a stochastic user equilibrium (SUE; Sheffi 1985), while also including tolls. Suppose, in an extremely decentralized pricing strategy, road operators set a toll on each subordinate link and adjust the toll rate dependent on through traffic ($\tau_a = \tau_a(f_a)$). When equilibrium is reached, neither travelers nor road operators would deviate their decisions unilaterally. A revised method of successive average (MSA) procedure is then proposed as follows to pursue this equilibrium:

- Step 0: Perform a stochastic network loading procedure based on $\{\tilde{t}_a^0 = t_a^0 + \tau_a^0/\upsilon\}$, the set of initial generalized travel times from the resultant generalized travel times of the preceding time period, which generate a set of link flows $\{f_a^1\}$. Set n:=1
- Step 1: Update toll on each link $\tau_a^n = \tau_a(f_a^n), \forall a$.
- Step 2: update link travel time on each link $t_a^n = t_a(f_a^n), \forall a$.
- Step 3: Perform a stochastic network loading procedure based on the current set of generalized link travel times $\{\tilde{t}_a^n = t_a^n + \tau_a^n/\upsilon\}$, which generates an auxiliary link flow pattern $\{\hat{f}_a^n\}$.
- Step 4: $f_a^{n+1} = f_a^n + (1/n)(\hat{f}_a^n - f_a^n)$
- Step 5: Stop upon convergence or set n:=n+1 and go to Step 1.

This study sets the convergence rule with a maximal allowable link flow change between two consecutive network loadings and implements it within a maximum of 150 iterations:

$$\left| f_a^{n+1} - f_a^n \right| < \kappa, \forall a \tag{8}$$

Powell and Sheffi (1982) have proven that the convergence of MSA for SUE is ensured only if $\tilde{t}_a(f_a)$ and $d\tilde{t}_a(f_a)/df_a$ are strictly positive and bounded for feasible values of f_a. Without a toll the conditions are commonly met in practice, for instance, with the fourth power US BPR curve (Bureau of Public Roads 1964):

$$t_a = (l_a/s_a)(1 + 0.15(f_a/C_a)^{4.0}) \tag{9}$$

The setting of toll rate will be discussed in more details in the pricing models.

3.3 Pricing models

Charging for the service of road transport provides road suppliers a source of income as well as a means of recovering road investment. Suppose the travel demand on a link depends solely on its flow and the inverse demand curve is indicated by $Y_a(f)$. Suppose the proportion of trips made by local residents at a given point of time is λ_a, and then the volume of trips made by residents is $\lambda_a f_a$ while that by non-residents is $(1 - \lambda_a) f_a$. Let's assume λ_a is fixed over a small change of flow or toll rate. For a jurisdiction that controls this link, its net social benefit from the link can be written as:

$$B = \lambda_a \int_0^{f_a} (Y_a(f) - t_a - \tau_a) df + f_a \tau_a \tag{10}$$

Note that while the toll is imposed without discriminating between resident and non-resident travelers, the toll revenue from residents is viewed as a transfer within the jurisdiction, which is not included in the net social benefit. To maximize the benefit, set the first derivative of Eq. (10) with regard to λ_a at zero which then yields:

$$Y_a(f_a) = t_a(f_a) + \frac{\partial t_a(f_a)}{\partial f_a} f_a - \frac{1-\lambda_a}{\lambda_a}(\tau_a(f_a) + \frac{\partial \tau_a(f_a)}{\partial f_a} f_a) \tag{11}$$

The left-hand side of the equation represents the marginal benefit of producing an extra trip while the right-hand side represents the marginal cost, which includes the average travel cost per trip, the change in the average cost, and the change in the toll rate from serving an additional trip. In order to maximize the net social benefit, we need to set a toll such that:

$$\tau_a(f_a) = \frac{\partial t_a(f_a)}{\partial f_a} f_a - \frac{1-\lambda_a}{\lambda_a}(\tau_a(f_a) + \frac{\partial \tau_a(f_a)}{\partial f_a} f_a) \tag{12}$$

In another form:

$$\tau_a(f_a) + (1-\lambda_a)\frac{\partial \tau_a(f_a)}{\partial f_a} f_a - \lambda_a \frac{\partial t_a(f_a)}{\partial f_a} f_a = 0 \tag{13}$$

This is a partial differential equation. If $t_a(f_a)$ is specified as a BPR function as in Eq. (9), the solution to this equation is then given by:

$$\tau_a(f_a) = \frac{0.6\lambda_a}{5-4\lambda_a}(l_a/s_a)(f_a/C_a)^{4.0} + \varepsilon f_a^{-\frac{1}{1-\lambda_a}} \tag{14}$$

Unfortunately, the solution is not unique due to the unspecified constant ε. When $\lambda_a = 1$, that is all the travelers are local (it applies to the centralized jurisdictional control), the toll rate is set at marginal travel cost:

$$\begin{aligned} \tau_a(f_a) &= \frac{\partial t_a(f_a)}{\partial f_a} f_a \\ &= \frac{\partial \left((l_a/s_a)(1+0.15(f_a/C_a)^{4.0})\right)}{\partial f_a} f_a = 0.6(l_a/s_a)(f_a/C_a)^{4.0} \end{aligned} \tag{15}$$

Although fuel tax is still the most common practice throughout the USA, marginal cost pricing has been the subject of academic interest for decades as the first-best optimal pricing strategy in theory (Gomez-Ibanez et al. 1999; Mohring and Harwitz 1962), and started to gain popularity among practitioners in recent years. The above equation represents the marginal-cost pricing function that has been derived in the one-link static scenario under centralized jurisdictional control. Note that in the short run, the free flow speed and capacity are fixed and the toll rate is adjusted solely depending on through traffic.

When $\lambda_a = 0$, the solution becomes:

$$\tau_a(f_a) = -\frac{\partial \tau_a(f_a)}{\partial f_a} f_a \tag{16}$$

This is the toll rate that maximizes toll revenue ($\tau_a f_a$) when all the travelers are non-residents, which is the case when the road operator is private. Note that it is assumed $\frac{\partial \tau_a(f_a)}{\partial f_a} < 0$, indicating that the toll rate decreases as the volume of trips increases.

The complexity of road pricing, however, goes beyond the one-link static model. Considering network effects, the demand on a link depends not only on the travel cost of this link, but also on the costs of other links, which becomes too complex to be specified as an equation. In practice, Anderson and Mohring (1997) computed marginal congestion costs on the road network of the Twin Cities area using a link-by-link method, accordingly proposing a marginal congestion pricing policy, based on the assumption that marginal congestion costs for each link could be used as substitutes for the true system-wide marginal congestion costs. Safirova et al. (2007) compared marginal congestion costs computed link-by-link with measures taking into account network effects, finding that while network effects are not significant in the aggregate, marginal cost measured on a single link does not accurately predict the actual congestion cost on that link.

Following Anderson and Mohring (1997), we adopt a link-by-link marginal cost pricing policy under centralized jurisdictional control, in which the central authority sets the marginal-cost price described in Eq. (15) as if each road is operated in the one-link static environment. In this case, the generalized travel time on a link can be written as:

$$\begin{aligned} \tilde{t}_a &= t_a + \tau_a^c/\upsilon \\ &= (l_a/s_a)(1 + (0.15 + 0.6\upsilon^{-1})(f_a/C_a)^{4.0}) \end{aligned} \tag{17}$$

According to Powell and Sheffi (1982), the necessary conditions for the convergence of MSA in traffic assignment are satisfied.

Under decentralized jurisdictional control, it is assumed links are operated individually by road operators. Due to the imperfect and incomplete information involved in the process, a heuristic price-probing method is proposed to predict individual links toll setting behaviors. (Bayesian Nash equilibrium may be found analytically when there are several links setting their toll rates, but the game theoretic problem becomes almost unsolvable for a real-size network). The following implementation procedure is presented, which is then embedded in the toll-updating step of the aforementioned revised MSA algorithm to pursue equilibrium:

- Step 0: The initial toll rate is estimated using marginal-cost price with the flow adopted from the preceding time period (use estimated flow for a new link).
- Step 1: In the second MSA iteration, each link attempts to increase their toll rate by ρ_1, as the operator knows the price should be somewhere between the marginal cost price and the higher profit-maximizing price but does not know what the exact increase should be.
- Step 2: In iteration n, the toll rate is updated based on the information derived from previous iterations:

- Step 2.1: The proportion of resident-travelers (λ_a^n) is updated after each network loading. Since it is assumed that the operator of a link represents a joint venture of the places that own this link, travelers from each owner/place are weighted according to its respective share and summed up to the quantity of resident travelers.
- Step 2.2: the change of net social benefit (ΔB_a^{n-1}) from iteration $n-2$ to $n-1$ is estimated. As the travel demand changes in response to the increase or decrease in the generalized travel time, with relatively small changes in cost, the change of consumer surplus can be approximated using the "rule of 1/2" (Neuberger 1971; Xie and Levinson 2007) as:

$$\Delta CS_a^{n-1} = 0.5\left(\tilde{t}_a^{n-2} - \tilde{t}_a^{n-1}\right)\left(f_a^{n-1} + f_a^{n-2}\right) \tag{18}$$

Since the operator is concerned with consumers surplus from resident-travelers plus toll revenue from non-residents, the change of social benefit can then be estimated as:

$$\Delta B_a^{n-1} = 0.5\left(\tilde{t}_a^{n-1} - \tilde{t}_a^{n-2}\right)\left(\lambda_a^{n-1} f_a^{n-1} + \lambda_a^{n-2} f_a^{n-2}\right) + f_a^{n-1}\tau_a^{n-1} - f_a^{n-2}\tau_a^{n-2} \tag{19}$$

- Step 2.3: a link changes its toll rate by $\Delta\tau_a^n = \tau_a^n - \tau_a^{n-1}$ according to the following myopic rules:
If $\Delta B_a^{n-1} = 0$, the operator would expect its benefit may be at a local maximum, so the toll rate remains unchanged ($\Delta\tau_a^n = 0$);
If $\Delta B_a^{n-1} > 0$, then $\Delta\tau_a^n > 0$, meaning if the net social benefit increased during the last iteration, the operator would keep the direction of toll adjustment. Suppose in this case it will adopt a conservative pricing policy which increases its toll at a decreasing rate ($0 < \rho_2 < 1$) in order to approach a local maximum:

$$\Delta\tau_a^n = \rho_2 \Delta\tau_a^{n-1} \tag{20}$$

If $\Delta B_a^{n-1} < 0$, then $\Delta\tau_a^n < 0$, meaning if the net social benefit decreased, the operator would change the direction of toll adjustment.
If $\Delta B_a^{n-1} < 0$ and $\Delta B_a^{n-2} > 0$, the operator would expect a local maxima that lies somewhere in between, so a toll could be set as:

$$\Delta\tau_a^n = -\Delta\tau_a^{n-1}\left|\Delta B_a^{n-1}\right| / \left(\left|\Delta B_a^{n-1}\right| + \left|\Delta B_a^{n-2}\right|\right) \tag{21}$$

If $\Delta B_a^{n-1} < 0$ and $\Delta B_a^{n-2} < 0$, the benefit has decreased since iteration n-2, so the operator would adjust the toll further back beyond τ_a^{n-2}.

$$\Delta\tau_a^n = -\Delta\tau_a^{n-1}\left(\left|\Delta B_a^{n-1}\right| + \left|\Delta B_a^{n-2}\right|\right) / \left|\Delta B_a^{n-1}\right| \tag{22}$$

3.4 Investment models

The implementation of road investment is illustrated in Fig. 3. It is assumed agents under centralized or decentralized scenarios make investment decisions based on benefit–cost analysis. For each time period, projects with the highest benefit–cost ratios will be built first until the budget (estimated from toll

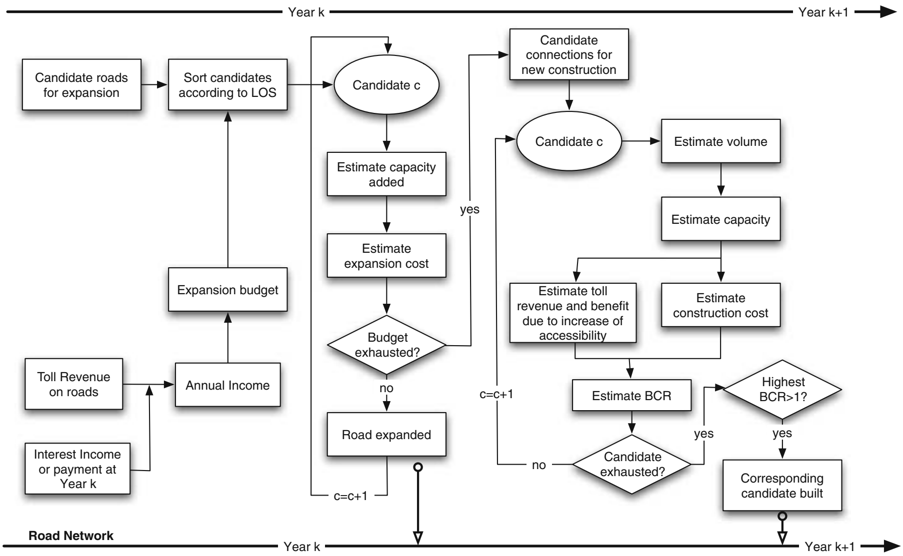

Fig. 3 Implementation of road investment process

revenue) is exhausted. Based on estimated benefit–cost ratios, an intelligent agent should be able to rank expansion versus new construction projects in terms of their funding priorities. For the purpose of simplicity, however, this study separates an expansion budget from a given portion (μ) of annual income. The component models of revenue, benefit, cost, expansion, and new construction in this process are explained in turn as follows:

3.4.1 Toll revenue

A central authority collects toll revenue from all its roads. Suppose public roads are built and managed in projects, the annual income of a central agent can be calculated as:

$$R^c = \sum_p R_p^c = \sum_p \sum_a \left(365\phi\delta_a^p \tau_a^c f_a\right) \tag{23}$$

Under decentralized control, on the other hand, a road operator collects toll revenue from its subordinate links and the remaining revenue after necessary road expansion eventually accrues to the balance of the owner(s).

$$R_p^d = \sum_a \left(365\phi\delta_a^p \tau_a^d f_a\right) \tag{24}$$

3.4.2 Benefit

In the centralized case, the central government's benefit associated with road investment is estimated by the increase of property value throughout the region due to improved accessibility, while under decentralized control, each place's benefit comes both from the increased value of local properties and from projected toll revenue from non-residents. Toll collected from a jurisdiction's local residents are simply considered transfers, and are dropped from the benefit calculations for both centralized and decentralized cases.

Accessibility to jobs reflects the desirability of a place by calculating jobs opportunities that are available from this place via a road network but are also impeded by the travel cost on the network. The accessibility to jobs is computed in this study using a gravity-type measure:

$$A_i = W_i \sum_j J_j e^{-\theta \tilde{t}_{ij}} \tag{25}$$

As discussed before, it is assumed the land value of a place is estimated by pricing spatial accessibility at a constant rate according to:

$$U_i = \pi A_i \tag{26}$$

The monetary value of a unit of gravity-type spatial accessibility to jobs is estimated in a recent empirical study by El-Geneidy and Levinson (2006) based on 44,429 home sale records for the year of 2004 in the Twin Cities metropolitan region. A hedonic model discloses the relation between single-family residence property values and accessibilities to jobs and to residents with other factors controlled. In essence the capitalized value of access in home prices reflects the value of time saved in the long run.

3.4.3 Cost

Cost functions estimate the monetary cost of proposed expansion or new construction (spending on maintenance is neglected for simplicity). Our expansion and new construction models adopt an empirical cost function estimated by Levinson and Karamalaputi (2003), also assuming that any project can be completed within one year.

$$Ln(E_{e,p}) = \beta_0 + \beta_1 Ln\left(\sum_a \delta_a^p l_a \Delta C_a\right) \tag{27}$$

$$Ln(E_{n,p}) = \beta_1 Ln\left(\sum_a \delta_a^p l_a \Delta C_a\right) + \beta_2 \tag{28}$$

Note that the costs above are measured in thousands of dollars. After the costs of expansion and new construction are appropriated from, remaining annual income accrues to a jurisdiction's current balance. The balance of a central jurisdiction at the beginning of iteration k+1 is calculated as follows:

$$Z^{c,k+1} = Z^{c,k}(1+r) + R^{c,k} - E_e^k - E_n^k$$
$$Where:\ r = \begin{cases} r_s, \ if\ Z^{c,k} > 0 \\ r_l, \ if\ Z^{c,k} < 0 \end{cases} \tag{29}$$

In the decentralized scenario, the toll revenue and expansion cost of a project is split between owner jurisdictions according to their shares (how to determine the shares will be discussed later):

$$Z_i^{d,k+1} = Z_i^{d,k}(1+r) + \sum_p \left(\chi_p^i \left(365\phi R_p^{d,k} - E_{e,p}^k\right)\right) - \sum_q (\chi_q^i E_{n,q}^k)$$
$$Where: \ r = \begin{cases} r_s, \ if \ Z_i^{d,k} > 0 \\ r_l, \ if \ Z_i^{d,k} < 0 \end{cases} \tag{30}$$

3.4.4 Expansion

A central agent or decentralized project operator selects expansion projects and determines the amount of capacity addition by following the procedure below:

- Step 0: Links with their volume–capacity ratios above a threshold ($Q*$) constitute a set of candidates for expansion.
- Step 1: Sort candidate links based on volume–capacity ratios from high to low
- Step 2: Expand the first link among remaining candidates by the amount of

$$\Delta C_a = f_a/Q^* - C_a \tag{31}$$

.
- Step 3: Deduct the expansion cost ($E_e(\Delta C_a)$) from the expansion budget.
- Step 4: If expansion budget has not been exhausted and there are remaining candidates, go to Step 2; otherwise stop.

3.4.5 New construction

As the most essential part of the incremental network growth problem, the process of constructing new roads is implemented in the following procedure:

First, find candidate projects of internal and external connections. A candidate project is identified if and only if no links have been established between a pair of established nodes along the geographical shortest path. To illustrate, three candidate projects are identified in Fig. 1 corresponding to connections $v_3 - v_4$, $v_5 - v_7$, and $v_8 - v_9$. Although v_4 and v_7 are not fully connected by established links along the geographical shortest path, the connection between them is not identified as a candidate project because it contains an established link $v_4 - v_5$. If two established nodes are already connected, but not along the geographical shortest path, and if the total length of the proposed connection (along the geographical shortest path) is either less than 2 km or less than 25% shorter than that of the current connection (along the least-cost route), the corresponding project will be eliminated from consideration because it is expected that in this case expanding the current connection would be more efficient as compared to building a new connection, as no additional land acquisition cost will be involved. For example, proposed connection $v_4 - v_5$

may be eliminated if the distance between v_4 and v_5 is 2 km or 25% shorter than that of the current connection $v_3 - v_5 - v_4$.

Second, estimate traffic volumes for a candidate project. The difficulty of this step lies in the trade-off between the accuracy of volume estimation and the running time required for evaluating a range of candidate projects. For an internal connection, for example $v_3 - v_4$ in Fig. 1, we add into G_m two hypothetical links that connect $v_3 - v_4$ in opposite directions (despite that a hypothetical link may represent a series of links in the complete graph), with a length of the geographically shortest distance between $v_3 - v_4$, and a proposed capacity of 400 vehicle/h (in this study it is equivalent to one lane). A stochastic network loading is then performed once and the loaded traffic on the two hypothetical links is used to approximate the equilibrium flows (the accuracy could be improved by iterating this step with the estimated volume, but again, it depends on the trade-off between the accuracy and the running time).

The flow estimation for an external connection follows the same procedure except that a network loading is not necessary, because the hypothetical links serve as the only connections between G_m and G_n. Thus the flow on the hypothetical link from G_m to G_n can be estimated as:

$$\hat{f} = \sum_{p_i \in G_m, p_j \in G_n} \hat{T}_{ij} \tag{32}$$

Third, estimate benefits from a candidate project. The increase in accessibility from a place is estimated as:

$$\Delta A = \sum_i W_i \sum_j J_j \left(e^{-\theta \widehat{\overline{t_{ij}}}} - e^{-\theta \overline{t_{ij}}} \right) \tag{33}$$

For a project under centralized control, the gains in land use due to increased accessibility in all the places will be summed up while for a project under decentralized control, a local jurisdiction considers only the increased value of local properties. A local jurisdiction also considers the estimated toll revenue from non-residents as benefits.

Fourth, estimate new construction cost for a candidate project. To increase realism with the presence of lumpy investments, suppose a link is designed in discrete lanes, and each lane represents a capacity of 400 veh/hr. The least number of lanes will be chosen such as:

$$C_a > \hat{f}_a / Q^* \tag{34}$$

The cost of constructing this amount of capacity will be estimated accordingly.

Fifth, select one project for investment. For a central agent, only candidate projects with a benefit–cost ratio above one will be considered, among which the candidate with the highest benefit–cost ratio will be built with proposed capacities on opposite directions. Up to one new road will be constructed according to the definition of incremental connection problem. The benefit–cost ratio of a candidate project is estimated as:

$$H_p^c = \pi \Delta A_p^c / E_{n,p} \tag{35}$$

Under decentralized control, matters become more complicated as more than one place maybe eligible to participate in a construction project. Given the complexity this process involves, heuristic assumptions are included in the implementation procedure. To approximate the border effect and spatial monopoly effect, we assume a place is eligible if this place is an end node of the proposed connection, or if it is the (full or partial) owner of a link that is directly connected to either end node when the end node is not a place. It is also assumed that the toll revenue and construction cost of a project will be split among participating jurisdictions in proportion to the projected traffic they will generate on the proposed links. To build the internal connection $v_3 - v_4$ in Fig. 1, for example, eligible places include v_3 and the owner places of links $v_1 - v_4$ and $v_5 - v_4$ (as v_4 is not a place). Additionally, each participating place will estimate the proportion of resident travelers on the proposed connection, and considers toll revenue only from non-resident travelers as its benefit. Suppose the planning horizon of a road project is N years, the estimated proportion of resident-travelers from place i on road p is λ_p^i, each place then estimates the benefit–cost ratio for each project as follows:

$$H_i^p = \left(\pi \Delta A_i^p + \left(1 - \lambda_p^i\right) \chi_p^i R_p^d N\right) / \chi_p^i E_{n,p} \tag{36}$$

A participating place will quit a project if its estimated benefit–cost ratio is below one. When a place quits, the benefit–cost ratios of the remaining participating places need to be re-estimated since the split of toll revenue and construction cost changes. Eventually, a list of candidate projects is developed with each participating place in each project having a benefit–cost ratio above one. Each place then ranks candidate projects according to its own benefit–cost ratio. A place would build the most cost-effective projects first, but it also compromises its own priorities to reach possible cooperation with other places, because each participant has equal right to veto a project. In this case, negotiation between participating places is in order. A project selection procedure implements this process as follows:

- Step 0: For any time period, starting from n=1.
- Step 1: For a list of candidate projects, each eligible place considers only the top n candidate projects ranked by its own benefit–cost ratios.
- Step 2: If any participating place of a candidate project ranks this project beyond its top n candidate list, this project will be eliminated.
- Step 3: If no qualifying project is found, $n := n + 1$ and go to Step 1; if n reaches a threshold (say ten), the whole process is terminated with no project built; otherwise go to Step 4.
- Step 4: A qualifying project can be self-financed if the current balance of each participating place can cover its share of construction cost. Among

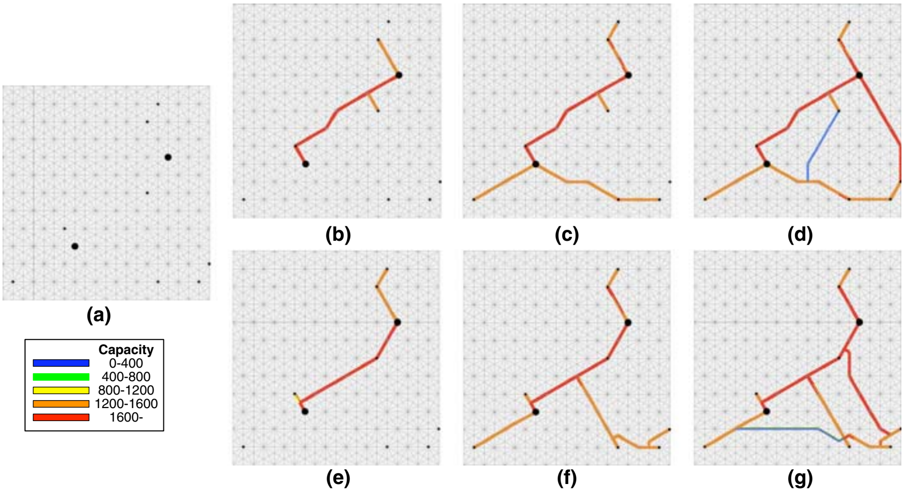

Fig. 4 Snapshots of incremental network growth (**a**) the initial network; (**b**) Experiment A, iteration 4 (**c**) Experiment A, iteration 8 (**d**) Experiment A, iteration 12 versus (**e**) Experiment B, iteration 4 (**f**) Experiment B, iteration 8 (**g**) Experiment B, iteration 12

the qualifying projects that can be self-financed, the one with the lowest financial risk (indicated by the ratio of anticipated toll revenue to construction cost) will be built. If no qualifying project can be self-financed, a loan is involved. The bank agent will instead minimize its own financial risk by selecting the qualifying project with the lowest ratio of projected toll revenue to the total amount of loans.

4 Simulation experiments

The model of incremental network connection is tested with a specified initial set of established places on a hexagonal complete graph[1] in two experiments: Experiment A is executed under centralized jurisdictional control in which a central government agent builds and manages all the roads, while Experiment B implements decentralized jurisdictional control under which local jurisdictions build and operate roads projects on their own. The distance between two neighboring hexagon centers is $\sqrt{3}/3$ km. Hexagon centers represent the possible locations of places, from which ten locations are randomly selected. Two of them are specified as bigger places each with 50,000 residents and 50,000 jobs, while the remaining eight ones are much smaller each with 5,000 residents and 5,000 jobs. The initial set of places is illustrated in Fig. 4(a),

[1]The hexagonal graph is created following Hargett (1966), in which vertices and edges represent the possible location of established nodes (places or intersections) and established links (segments of roads), respectively.

in which dark dots represent established places while gray dots and lines represent potential nodes and links.

Table 3 lists model coefficients and their specified values for the experiments. While it is intended for providing a practical tool of assessing policies under alternative jurisdictional controls, the present version of the model is not calibrated, and tests a number of arbitrarily specified parameters. In this regard the following comparison of the measures of effectiveness (MOEs) under centralized versus decentralized control provides more of a demonstration. The current simulation model, however, enables us to predict the deployment course of a road network in a sequential process, and evaluate how network development could be affected by the pricing and investment policies under different types of jurisdictional control.

In Experiment A the new construction ends after 11 years and expansion continues until the simulation is terminated at the end of the 50th year. The first nine connections are external connections while the last two are internal connections. Eventually the annual travel demand on the established network reaches a total travel time of 50.1 billion vehicle hours or a total distance of 291 million vehicle kilometers. As shown in Fig. 5, a test compares the predicted volumes (given in the investment models) on the consecutive new connections added during the first 11 consecutive years versus the assigned volumes (given in the travel demand models) on corresponding links in the next iteration when a proposed new connection has actually been incorporated in the established network. As can be seen, the new construction model works well in predicting the travel demand on a proposed new connection in the near future.

In Experiment B the new construction also occurs during the first 11 consecutive years, while the expansion continues until the end of the 50th year, when an annual travel time of 54.0 billion vehicle hours or a total distance of 299 million vehicle kilometers is consumed.

Figure 6 compares the resultant road investment in Experiments A and B. As can be seen, local jurisdictions invest more in road infrastructure than the central agent, with a little bit higher spending on new construction and much

Table 3 Specified values for simulation experiments

	Value	Source
N	25 years	Common practice
υ	\$10 /h	Common practice
r_s, r_l	0.03, 0.05	Specified
κ	0.5 veh	Specified convergence rule
t_0	1.0 min	Specified
ξ_0, ξ_1, ξ_2	0, 0.25, 0	Specified
$\sigma_0, \sigma_1, \sigma_2$	0, 0, 0.25	Specified
Q^*	0.95	Specified
ρ_1, ρ_2	0.2, 0.75	Behavioral assumptions on heuristic price probing
ω_1, ω_2	-30.6, 9.8	Empirical estimates by Zhang and Levinson (2005b)
θ	0.048/min	Empirical estimate by Levinson et al. (2007)
$\beta_0, \beta_1, \beta_2$	5.79, 0.50, 0.39	Empirical estimates by Levinson and Karamalaputi (2003)
ϕ	1/0.11	Adopted from Suwansirikul et al. (1987)
π	\$12.71	Empirical estimates by El-Geneidy and Levinson (2006)

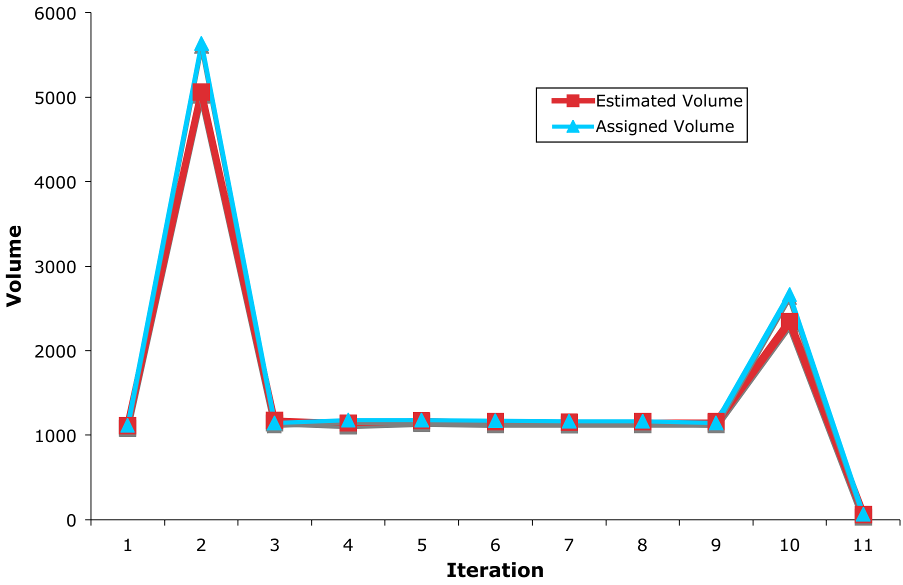

Fig. 5 Estimated versus assigned volumes on the new connections that appeared every iteration Experiment A. To be succinct, the volumes on only one direction of new connections are depicted

higher expansion expenditure. The road networks developed in the centralized and decentralized scenarios, however, eventually provide rather close spatial accessibility, which implies centralized road provision is more efficient than decentralized road provision if the central agent has perfect information on individual links and if the costs associated with bureaucracy, operation, and management are ignored.

The centralized pricing policies based on marginal cost pricing result in a deficit of 1.58 billion dollars at the end of the 50th year. Note that the empirical investment models specified in Eqs. (27) and (28) with β_1 smaller than 1.0 imply economy of scale in capacity. This agrees with the marginal cost pricing theory in that toll receipts will fall short of the facility costs if there are economies of scale in road provision (Gomez-Ibanez et al. 1999). Additionally, although jurisdictions may accurately predict the flow and toll revenue in the near future on a new connection at the time the investment decision is made, as more and more new roads are built in the long run, the demand on previously built roads may drop and the profitability of previous projects be undermined, which may lead to financial deficit on road infrastructure.

Local jurisdictions as a whole collect much less toll revenue than the central jurisdiction, despite the fact that they invested a lot more in road infrastructure and attracted more traffic, which results in a larger deficit (1.89 billion dollars) for them (though it would be expected that toll revenue will eventually cover all the investments as time goes on, since large-scale investment has been completed). Local jurisdictions collect less toll revenue probably because they impose a variable toll rate on individual links, and the links have to compete

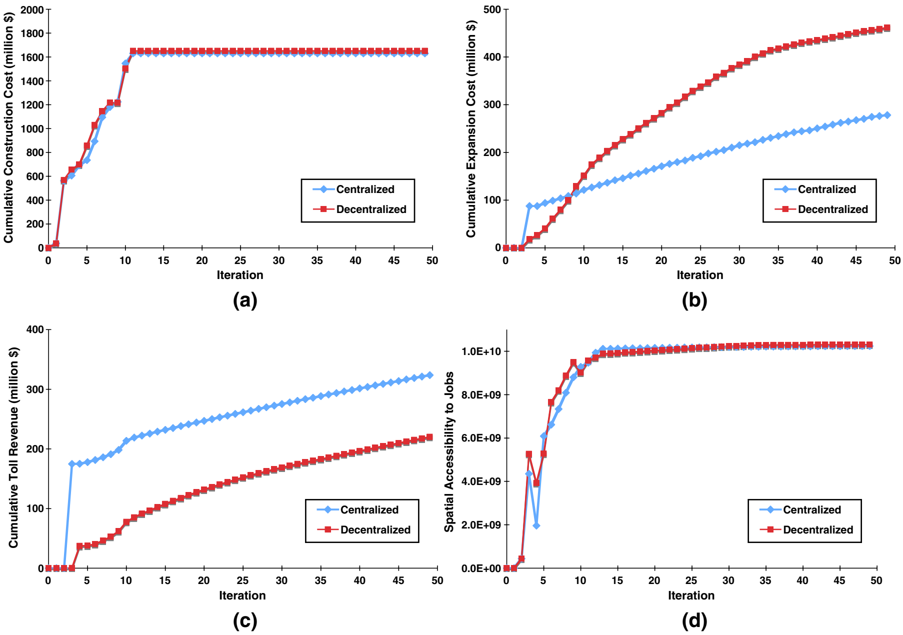

Fig. 6 Comparison of MOEs under centralized (Experiment A) vs. decentralized (Experiment B) control with regard to their (**a**) cumulative spending on new construction (**b**) cumulative spending on expansion, (**c**) cumulative toll revenues, and (**d**) resultant spatial accessibility

with each other on parallel routes for through traffic. Another observation worth noting is that local jurisdictions invest in new construction faster than the central agent, as can be seen in Graph 5a. This can be explained by the fact that when local jurisdictions evaluate a road project, they consider not only the increase of spatial accessibility, but also the future toll revenue from non-resident travelers as their benefits.

Starting from the same network shown in Fig. 4(a), the staged network growth under centralized and decentralized jurisdictional control is illustrated in Figs. 4(b)–(d) and in Figs. 4(e)–(g), respectively. As can be seen, the sequences of connections in both cases are similar: in the first four iterations, a central corridor is built between the two bigger places, forming the backbone of the road network; in the next four iterations, minor places in the corners are connected one by one; internal connections are then added in the last four iterations, which create rings and serve as shortcuts between places. The difference between the two scenarios lies in the fact that local jurisdictions, rather than directly connecting to other places, tend to connect to a node in the middle of a link so that the construction cost could be split among more involved places. Consequently, different network topologies are generated under centralized versus decentralized control. As can be seen, centralized control results in a network that connects places on a belt, on which roads are complementary to each other, while under decentralized control places on the south-east corner are connected to others via two parallel roads built by different groups of jurisdictions, which are more competitive in the network.

5 Concluding remarks

Road infrastructure evolves over time in a complex process as part of a dynamic and open system including travel demand, land use, as well as economic and political initiatives. This study implements the deployment of a road network as an endogenous process of incremental connections, played out in SONIC as the outcome of the decisions made by travelers with regard to destination and route choice in the short run, and by central or local public authorities with regard to road pricing and investment in the long run, from different political initiatives.

This study finds that equilibrium will be reached on a network between road operators and travelers if a link-by-link marginal-cost pricing policy is adopted in the centralized scenario. In the decentralized case, a heuristic pricing-probing measure is proposed for local jurisdictions to adjust the toll rate on each subordinate link in response to the variable demand, with uncertainty about other jurisdictions in the network environment. This strategy deserves investigation in terms of how autonomous road operator will actually adjust its toll rates upon the change of travel demand on a link with incomplete information on the competitor and cooperator links.

Simulation results disclose that both centralized and decentralized road provision result in a financial deficit. This finding agrees with the marginal-cost pricing theory in that toll receipts will fall short of the facility costs if there are economies of scale in road provision. The inefficiency in road investment may also be attributed to the myopia of an incremental investment process that relies intricately on a sequence of network growth decisions, even if jurisdictions pursue an optimal investment strategy at the point when the decision is made. Simulation results also show that local jurisdictions tend to make a larger investment on road infrastructure than a central jurisdiction, while collecting less toll revenues, suggesting centralized road provision is more efficient if the central authority has complete information on individual links and if the costs associated with its bureaucracy and management are ignored. In reality, the trade-off between the factors favoring centralization (such as economy of scale and economy of scope in road provision) versus those favoring localization (such as improved information on local markets) needs to be addressed.

SONIC has the potential to answer the questions such as how urban road networks have developed into various topologies, which network patterns are more efficient, and whether and how transport engineers, planners, and decision makers can guide the dynamics of land uses and infrastructure into their desired direction in a sequential process, especially providing a planning tool that allows us to test the consequence of different pricing and investment strategies under alternative jurisdictional ownership structures.

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