

The Co-evolution of Land Use and Road Networks

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ABSTRACT

This paper explores the co-evolution of land use and transportation, which is a poorly understood field despite progress in studying each separately. Our study models the co-evolution of land use and transportation network as a bottom-up process by which re-location of activities and expansion of roads are driven by interdependent decisions of individual businesses, workers, and road owners according to simple decision rules. The model was kept simple to best illustrate collective spatial patterns of land use distribution without conflating factors. The sensitivity of these patterns is also discussed. A Simulator of Integrated Growth of Networks And Land-use (SIGNAL) is developed to implement these decentralized decision making processes, in which the Gini index and equivalent radius were computed to describe and track down the spatial patterns of space and network. Simulation experiments were conducted to explore the evolution of land use patterns in the context of the coevolution of land use and road networks. Experimental results demonstrate that initially flat land uses become more concentrated while initially concentrated land uses become less so, and they tend to converge on the same hierarchical distribution, suggesting that a stable hierarchical distribution of land use may emerge from different initial conditions. Experiments also reveal that the concentration of land use is reinforced by the differentiation of roads.

Key words: land use, road network, evolution, self-organization

INTRODUCTION

Transportation and land use are interdependent shaper of urban form, and both are constantly evolving. As cities have evolved in the first half of the 20th century, we saw a concentration of activities at the centers of American cities. As more highways are constructed since 1950s, however, road networks became more hierarchical (certainly in the pre-auto era most unpaved roads were equally slow; with paved highways and then freeways, some roads got much faster) and a flattening of the density gradient of land use (centers of cities are relatively less important) was observed. In a sense roads were improved to serve city centers, which then led to the decentralization of land uses. This paper aims to examine the co-evolution of transportation and land use, specifically, whether and to what extent the differentiation of roads leads to a more or less hierarchical distribution of activities.

While efforts have been made to investigate the evolution of transportation infrastructure and that of urban land use separately, few of them have examined the integrated development of transportation and urban space in an evolutionary way, leaving the co-evolution of transportation and land use still poorly understood. The investigation of the growth and transformation of transportation infrastructure dates back to 1960s, when a series of studies were conducted by geographers and transportation planners to replicate the changing topology and connectivity of road or rail networks (Garrison and Marble, 1962; Taaffe *et al.*, 1963; Morrill, 1965). The dynamics of transportation networks, however, was based on heuristic and intuitive rules in these studies, due to a lack of understanding on its inherent mechanisms at that time. In recent years, a limited number of attempts have been made to model the dynamics of transportation networks in a more realistic way. Yamins *et al.* (2003) presented a simulation of road growing dynamics on a land use lattice that generates global features observed in urban transportation infrastructure. Yerra and Levinson (2005) and Levinson and Yerra (2006) incorporated a simplified travel demand model to predict traffic flows on a surface transportation network, and introduced independent agents to invest (disinvest) in individual roads according to the revenue and cost associated with forecasted traffic. They demonstrated that a network could evolve into a hierarchical structure from either a random or a uniform state, even based on completely decentralized decisions of

autonomous roads. Previous studies, however, didn't integrate the dynamics of transportation networks with the development of urban space, with land use either ignored or taken as exogenous.

The evolution of urban space has been examined by another stream of studies. The pioneering work by von Thünen (1910) presented a single-center city surrounded by agricultural land and predicted the rent and land use distribution for competing socio-economic groups. Christaller (1933) introduced central place theory and demonstrated that a hierarchy of central places will emerge on a homogenous plain to serve the surrounding market while minimizing transportation costs. von Thünen and Christaller's work paves the way for subsequent studies in urban economics and regional science concerning the distribution of activities over urban space. From a dynamic perspective, Fujita et al. (1999) synthesize theoretical work since the 1990s on where economic activities occur and why. Krugman (1996) explores the phenomenon of self-organization in urban space. He develops an edge city model to demonstrate how interdependent location decisions of businesses within a metropolitan area could lead to a polycentric pattern under the tension between centripetal and centrifugal forces. Based on these theoretical investigations, a host of empirical integrated transportation and land use models have been developed to forecast land use development while considering transportation as an important factor. One of the first that gained substantive interest was the Lowry model (Lowry, 1963). Since 1980s, many integrated models have been applied in real cities and some have been developed into commercial packages. Examples include START (Bates *et al.*, 1991), LILT (Mackett, 1983, 1990, 1991), and URBANSIM (Alberi and Waddell, 2000; Waddell, 2002). A comprehensive review of these integrated models has been provided by Timmermans (2003). In most of these models, the dynamics of urban space has been played out as the outcome of the location decisions made by residents and businesses, in which both accessibility to employment and accessibility to population play an essential role (Hansen, 1959; Guttenberg, 1960; Huff, 1963).

Although the concept of accessibility connects transportation with land use development, the change of transportation networks has seldom been considered in previous integrated transportation and land use models. A possible explanation is that these models are already complicated enough. They usually involve multiple modeling

approaches, incorporate numerous constraints and assumptions, and are estimated from empirical data, unavoidably leading to a comprehensive modeling framework including a wide variety of components. These models are so specific and complex that 1) they are difficult to replicate; 2) the relationships between components are entangled and implicit; 3) the emergent large-scale patterns in space and network are difficult to recognize and analyze.

In contrast to those complicated and all encompassing models that don't provide an explicit perspective, this paper models the integrated dynamics of land use and roads in as simple a way as possible that captures salient properties, enabling us to display and analyze the emergent hierarchy and agglomeration patterns of space and network on a large scale, as well as observe the interactions (reinforcement or counteraction) between the dynamics of roads and the development of land uses. The specific simplifications and assumptions made in our model specifications will be discussed later.

Extending Krugman (1996), Levinson and Yerra (2006), and Yerra and Levinson (2005), this paper models the co-evolution of land use and road network as a bottom-up, rather than a top-down process, by which interdependent location decisions of businesses (equivalently referred to as employment or jobs in this paper) and residents (also called population or workers or housing or resident workers) are incorporated, as well as investment decisions of autonomous roads based on predicted traffic on a network. Planners and engineers would argue that while market-based land use may be constrained by zoning and plans, transportation network investments are decisions that are now driven, or coordinated, by centralized organizations such as state departments of transportation or metropolitan planning organizations that make major investment decisions using a forecasting model and planning process to test and evaluate alternative scenarios. Local jurisdictions, of which there are many in some metropolitan areas, make investments on lower level roads. Certainly these organizations do affect new investment on links, but the decision to build or expand a link is also constrained by many facts on the ground, actual traffic on the link, competing parallel links, and complementary and upstream and downstream links, the costs of expansion, and limited budgets (Levinson and Karamalapati, 2003a,b). According to Krugman (1996), a self-organizing system of urban space and network will evolve into order and pattern, even based on simple, myopic, decentralized decisions of individual businesses and workers. If we can generate

convincing collective representations of land use and network structure without any centralized planning or direction, perhaps planning is not as important in shaping urban areas as it is sometimes credited.

The remainder of this paper is organized as follows: the next section introduces the simulation model developed for this study. Then the experiments are outlined, and results are presented and discussed. The concluding part summarizes the findings and suggests future directions for research.

MODEL FRAMEWORK

The Simulator of Integrated Growth of Network Growth and Land-use (SIGNAL) is developed in this study to simulate the co-evolution of land use and road networks. An overview and inter-connection of these models is illustrated in Figure 1. The components of the model include *travel demand*, *road investment*, *accessibility*, and *land use*.

[Insert Figure 1 here]

Travel demand models

The travel demand model converts population and employment data into traffic using the given network topology and determines the link flows by following the traditional planning steps of trip generation, trip distribution, and traffic assignment (for simplicity, a single mode is assumed) (Ortuzar and Willumsen, 2001).

A simplified *trip generation* model estimates the number of vehicle trips that originate from or are destined to a zone as a linear combination of the quantities of employment and population in this zone, without distinguishing trips by purpose:

$$O_i = \xi_1 E_i + \xi_2 P_i \quad (1)$$

$$D_i = \psi_1 E_i + \psi_2 P_i \quad (2)$$

Where O_i and D_i represent the number of trips that originate in or are destined

to Zone i respectively, while E_i and P_i are the employment (jobs) and population (resident workers) in this zone.

A doubly constrained gravity-based trip distribution model is adopted to match both trip generation and attraction of locations based on a negative exponential function that assumes the interactions of zones decreases with the travel time between them:

$$T_{ij} = K_i K_j O_i D_j e^{-\epsilon t_{ij}} \quad (3)$$

Where T_{ij} is number of trips from zone i to zone j ; K_i , K_j are balancing coefficients; O_i is the production of zone i ; D_j is the attraction of zone j . The parameters in this trip distribution model have been calibrated using the empirical data in the Twin Cities, (see Levinson *et al.* (2006) for details). The variable t_{ij} is the generalized travel cost from zone i to zone j calculated as:

$$t_{ij} = \begin{cases} \sum_a (\delta_{i,j}^a t_a) + t_{m,i} + t_{m,j} & i \neq j \\ t_{m,i} & i = j \end{cases} \quad (4)$$

Where $t_{m,i}$ and $t_{m,j}$ represent the generalized intra-zonal travel time in zones i and j , respectively. The generalized intra-zonal travel time captures a variety of costs incurred on trips that rise with land use intensity. It represents things like higher congestion levels, longer elevator waits in taller buildings, greater difficulty of finding parking, and taking longer to engage in parking that add to local travel time and travel cost in both zones. An intrazonal generalized time penalty acts as a surrogate for all of the above. Assuming a simple quadratic relationship between the generalized intra-zonal travel time and land use density in zone i , $t_{m,i}$ is calculated as:

$$t_{m,i} = t_m^0 \left[1 + \left(\frac{G_i}{G} \right)^2 \right] \quad (5)$$

Where t_m^0 is a specified base intra-zonal travel cost for all zones, G_i is the number of activities in zone i , while \bar{G} represents the average number of activities across all zones. In our case,

$$G_i = E_i + P_i \quad (6)$$

Where E_i and P_i represent the employment and population in zone i , respectively. They will be discussed later in the land use model.

The inter-zonal travel cost between zone i and zone j is computed as a summation of link travel cost along the shortest path from zone i to zone j , where t_a represent the generalized travel time that a vehicle spends on link a , while $\delta_{i,j}^a$ is a dummy variable equal to 1 if link a belongs to the shortest path from zone i to zone j and 0 otherwise. Dijkstra's Algorithm (Chachra *et al.* 1979) finds the shortest path from each node to all other nodes of the network. The generalized cost of travel time on link a is calculated by incorporating the monetary cost (toll) as an equivalence of time in addition to the actual travel time on this link (tolls are charged by the road agent):

$$t_a = \frac{l_a}{v_a} + \frac{R_a/\eta}{f_a} \quad (7)$$

Where l_a , v_a , f_a , and R_a respectively represent the length, average speed, traffic flow, and collected revenue of link a in a given time period. The parameter η represents the average value of time. The calculation of R_a will be discussed later.

A Stochastic User Equilibrium (SUE) is adopted in *traffic assignment* to predict route choices on a network according to perceived travel time, implementing Dial's Algorithm and Method of Successive Average (MSA) (Sheffi, 1985; Davis and Sanderson, 2002). Traffic assignment in a time period is based on the congested travel time resulted in the preceding time period, which makes the convergence in MSA much faster. The convergence rule in MSA specifies a maximal allowable link flow change equal to 0.5 (or a maximum of 100 iterations). A smaller maximal allowable flow change will result in a flow pattern that is closer to the equilibrium, but there is tradeoff between

the accuracy and run time. The parameters in the model have also been calibrated by Levinson *et al.* (2006).

Road investment models

Road investment models describe the economic decisions of individual roads as autonomous agents. These decisions in terms of tolling, spending, and investing are abstracted in simple equation forms, also assuming roads make myopic decisions without considering cooperating with others or saving for the future.

A *revenue* model determines the toll a road collects during a given time period, depending on the traffic that uses this road. To ensure two parallel and opposite one-way links a and b that connect two nodes are always maintained on the same conditions, we assume that a single agent operates both links as a whole. Let f_a and f_b respectively represent the flow traversing link a and link b for a given time period, the total revenue collected on both links by the agent can be calculated as:

$$R_{a+b} = \tau l_a (f_a + f_b) \quad (8)$$

Where τ is the regulated toll rate. Both links have the same length: $l_a = l_b$.

The *cost* to maintain links in their present usable conditions depends on link length, flow and speed. Suppose link a and link b are operated at the same free flow speed $v_{f,a} = v_{f,b}$, the overall spending of the agent operating links a and b is calculated as:

$$S_{a+b} = l_a v_{f,a}^{\sigma_2} (f_a^{\sigma_1} + f_b^{\sigma_1}) \quad (9)$$

Where the coefficients σ_1 and σ_2 are specified flow and speed powers in the equation.

An investment model assumes each agent spends all its available revenue at the end of a time period myopically, without saving it for the future. If the revenue exceeds the maintenance cost, remaining revenue will be invested to expand the capacity of subordinate links. In contrast, if the revenue is insufficient to cover the cost, link capacity will drop. This investment policy adopted by each agent can be expressed in a simplistic form as:

$$C_a^{k+1} = C_a^k \left(\frac{R_{a+b}^k}{S_{a+b}^k} \right)^\rho \quad (10)$$

Where $C_a = C_b$ is the capacity of link a and b , which changes with iteration (k), respectively, while ρ is a specified capacity reduction coefficient.

Zhang and Levinson (2005) estimated the relationship between the free flow speed of a link and its capacity in a log-linear model based on the empirical data in the Twin Cities. The log-linear relationship is adopted here to update the free flow speed (v_f) of a link after its capacity is changed:

$$v_{f,a} = \omega_1 + \omega_2 \ln(C_a) \quad (11)$$

where ω_1 and ω_2 are two coefficients in the log linear equation while C_a is the capacity of link a .

The relationship between the free flow speed and congested speed of a link is defined by the BPR function (Bureau of Public Roads, 1964) as:

$$v_{c,a} = v_{f,a} \left[1 + \alpha * \left(\frac{f_a}{C_a} \right)^\beta \right] \quad (12)$$

where α and β are the coefficients of the function. The values of the coefficients are assumed to be 0.15 and 4.0, respectively.

Accessibility and land use models

Accessibility reflects the desirability of a place by calculating the opportunities and activities which are available from this place via a road network but are also impeded by the travel cost on the network. Suppose an urban space is divided into J Traffic Analysis Zones (TAZs) or land use cells that contain both businesses (jobs) and residents (workers). The *accessibility* in each cell (to employment and population) is computed respectively using a negative exponential measure:

$$A_{i,E} = \sum_{j=1}^J E_j e^{-\theta t_{ij}} \quad (13)$$

$$A_{i,P} = \sum_{j=1}^J P_j e^{-\theta t_{ij}} \quad (14)$$

where $A_{i,E}$ is the accessibility to employment (jobs) from zone i while $A_{i,P}$ is the accessibility to population (workers). The coefficient θ indicates how fast the accessibility of a zone declines with the increase of travel time to the zone. This coefficient adopts the same value with the trip distribution coefficient ε , and its sensitivity is tested later.

A *land use* model is then developed to reflect how the distribution of population and employment respond to the accessibility patterns, while keeping the total population and total employment as constant. The land use model is simplified in the sense that accessibility to employment and accessibility to population are the only factors that affect the decision on locations made by businesses and workers. As accessibility is essential in the relationship between transportation and land use, other factors such as land price and administrative policies are excluded to keep this relationship succinct and clear, thus enabling simple accessibility-based rules to which independent location choices can be made. To be representative, our land use model contains both centripetal and centrifugal forces, that is, a force of attraction (e.g. economies of agglomeration) and a force of repulsion (a desire on the workers part for spatial separation, keeping all activities from locating at a single point). We assume housing (population) wants to be near employment, but far from other houses (to maximize available space and to avoid potential competitors for employment), while businesses (employment) wants to be accessible both to other businesses and to people (who are their suppliers of labor and customers). The following stylized models are developed to track the dynamics of population and employment based on independent decisions of businesses with regard to their locations.

Equations (15) and (16) estimate the desirability (potential) of a zone to attract employment and population, respectively.

$$U_{i,E} = A_{i,E}^{\lambda_1} A_{i,P}^{\lambda_2} \quad (15)$$

$$U_{i,P} = A_{i,E}^{\lambda_3} A_{i,P}^{\lambda_4} \quad (16)$$

where λ_1 , λ_2 , λ_3 , and λ_4 are coefficients that indicate the positive or negative relationship between accessibility and land uses. Note that both accessibility to employment and accessibility to population reinforce the employment desirability of a

zone, indicating only a centripetal force exists in shaping the pattern of employment (though intrazonal transportation costs do increase with density). On the other hand, accessibility to employment reinforces while accessibility to population counteracts the population desirability of a zone. Thus we have $\lambda_1, \lambda_2, \lambda_3 > 0$ and $\lambda_4 < 0$. A recent empirical study by El-Geneidy and Levinson (2006) corroborates our assumptions. Based on 44,429 home sale records for the year of 2004 in the Twin Cities metropolitan region, a hedonic model discloses the connection between single-family residence property values and accessibility to jobs and resident workers, with other factors controlled. Accessibility to jobs did show a statistically significant positive effect on home sale values, while accessibility to workers did show a statistically significant negative effect. Furthermore, their coefficients are approximately equal in the model (though having opposite signs), implying the centripetal force and the centrifugal force on residence location are equally strong. According to their findings, this study further assumes $\lambda_3 = -\lambda_4$.

Employment and population are then reallocated across zones at time period $k+1$ according to Equations (17) and (18), basically in proportion to the desirability of each zone at the preceding time period k , except for the parameter μ introduced to indicate the reluctance for jobs and workers to move away from the original location. For simplicity, the totals of employment and population are held constant over time.

$$E_i^{k+1} = \sum_j \left\{ E_j^k \frac{(U_{i,E}^k)^\mu}{\sum_s (U_{s,E}^k)^\mu} \right\} \quad (17)$$

$$P_i^{k+1} = \sum_j \left\{ P_j^k \frac{(U_{i,P}^k)^\mu}{\sum_s (U_{s,P}^k)^\mu} \right\} \quad (18)$$

where $\mu = \begin{cases} 1, & \text{if } i = j \\ < 1, & \text{if } i \neq j \end{cases}$, indicating jobs and workers prefer staying in the original

zone to moving to the other zones.

After investing (or disinvesting) in each link in the network, computing zonal accessibility and potential, and relocating land uses, the time period is incremented and

the whole process is repeated. In this study one time period represents a year as the average daily traffic on the network is predicted and converted to yearly traffic for road investment models.

SIMULATION EXPERIMENTS

The research question is the degree to which the dynamics of transportation networks is reinforcing or counteracting hierarchies of land use. It is posited that this depends on initial land use and network conditions. Initially flat land uses become more concentrated, and initially concentrated land uses become less so when road networks are allowed to vary rather than remain constant. That is, the gradient of land use reinforces to a point, and counteracts beyond some point.

Two sets of experiments are conducted. The first fixes the road network, and explores how the land use evolves in response to the fixed network. The second allows both the network and the land use to evolve simultaneously in response to accessibility to population and employment.

Simulation experiments were conducted in a hypothetical metropolitan area where both the population and employment are distributed over a two-dimensional grid. For simplicity, the experiments here are conducted over a square planar surface, stretching 20 km in both dimensions, divided into a 20X20 grid lattice of land use cells (400 zones). Each zone occupies one square kilometer of land. A total of 400,000 people are living in this city, which is equivalent to an average of 1,000 residents in each zone. Total employment equals 400,000 as well (and each resident holds a job). Two-way roads connect the centroids of each pair of adjacent zones, thus forming a 20X20 grid of road network as well, comprising 400 nodes and 1,520 links.

Each set of experiments was tested under two different sets of initial conditions. Both sets of initial conditions specify a uniform network in which the same initial conditions are specified for all the links except for their locations: each link is 1km in length with a free flow speed of 80 km/h, and a capacity of 800 veh/h. The first specifies uniform land uses with both population and employment of each zone equal to 1,000; the second assumes an uniform distribution for population but a bell-shaped distribution for employment so that zonal employment decreases negative-exponentially as the distance

from the center of the hypothetical land increases. The experiments are outlined in Table 1.

[Insert Table 1 here]

Table 2 lists parameters and their values for our experiments. As explained in Table 2, the toll rate and value of time are adopted from empirical estimates; so are the coefficients that define the log-linear relationship between link capacity and free flow speed (Zhang and Levinson, 2005). Among those parameters that are arbitrarily specified for the models, some of them were tested using sensitivity analysis, which will be discussed later.

[Insert Table 2 here]

A series of measures of collective properties for space and network are developed to track the patterns in the experiments. The Gini index is adopted in this study to indicate the degree of spatialglomeration for land use and network infrastructure. The Gini index has been widely adopted as a measure of spatial concentration (Krugman, 1991; Chatterjee, 2002). Chatterjee (2003) elaborates the computation of the Gini index based on the Lorenz Curve.

The Gini index of land use (employment or population) is computed in this study to reflect how evenly land uses are distributed on the hypothetical space. The index is a number from zero to one, which is equal to zero when employment or population is uniformly located across all zones, while close to one when all employment or population is located in one zone. The more unevenly land use is distributed, the higher value the index is.

Similarly, the Gini index of road capacity is computed to reflect how evenly roads are developed. The index is equal to zero when all roads have the same capacity while it becomes higher when a larger portion of total capacities are occupied by a smaller number of roads.

In analogy with kinematics, measures of the moment of inertia (I) and the equivalent radius (r) are computed to reflect the spatial clustering patterns of land use and network infrastructure.

The moment of inertia for the spatial distribution of employment is computed as:

$$I = \sum_{j=1}^n E_j d_j^2 \quad (19)$$

where E_j represents the employment of Zone j while d_j is the distance between the centroid of this zone and the center of the hypothetical metropolitan area.

The equivalent radius is then computed as:

$$r = \sqrt{\frac{I}{\sum_{j=1}^n E_j}} \quad (20)$$

The equivalent radius r essentially reflects how far away employment is distributed from the center of a region. A radius of zero indicates all employment is clustering in the center of the region while a larger radius indicates employment is located farther away from the center.

Similarly the equivalent radius can also be computed for the spatial distribution of population as well as road capacity.

RESULTS

The evolving spatial patterns of land use and network were analyzed by plotting the measures of Gini index and equivalent radius for employment, population, and link capacity on a time horizon. Each experiment was executed for 100 iterations. Since all the spatial patterns are stabilized within 50 iterations, the measures are plotted every other iteration for 50 iterations. The plots are summarized in Figure 2 (i)-(iv).

Each plot displays four fluctuations from uniform and concentrated initial land uses with and without road dynamics, that is, Experiments 1-4. Plots 2(i) and 2(ii) demonstrate how spatial patterns of employment distribution evolve over time from the perspectives of agglomeration (reflected by the Gini index) and centralization (reflected by equivalent radius), respectively. As can be seen, starting from uniformly distributed

land uses in Experiments 1 and 2, the Gini index is increasing while the radius is dropping, showing a strong trend of agglomeration and centralization of employment. On the other hand, the Gini index is dropping while the radius is increasing in Experiments 3 and 4, showing the initially concentrated employment is spreading out over time. Over 50 iterations the spatial patterns are stabilized as the curves become flat. More interestingly, whether starting from an uniform or concentrated state, the distribution of land use tends to converge on the same Gini index and radius (Experiments 1 and 3 converge on a Gini index of 0.093 and a radius of 7.718 km, while 2 and 4 on a Gini index of 0.178 and a radius of 7.319 km), indicating a stable hierarchy of employment distribution may emerge from different initial conditions. Experiments allowing road dynamics (2 and 4) generate a consistently higher Gini index and lower radius than their counterparts with a fixed road network, suggesting investment on roads (from an initial uniform state) reinforces the concentration and centralization of employment.

The evolution of population distribution, however, works out differently. As shown in Plot 2(iii), since all the experiments start from an initially flat distribution of population, the centripetal force dominates at the beginning and the Gini index increases dramatically. While people are clustering and moving toward the region center, however, the centrifugal force outcompetes the centripetal force and the Gini index starts to drop after a turning point. The population distributions of Experiments 1 and 3 are eventually stabilized on a Gini index of 0.027, while those of Experiments 2 and 4, which allow road dynamics, are stabilized on a higher level of 0.051. The fluctuations of equivalent radius for population, displayed in Plot 2(iv), reflect the same dynamics process of population distribution.

The observation that initially flat land uses become more concentrated while initially concentrated land uses become less so, and they tend to converge on the same hierarchical distribution suggests a stable hierarchical distribution of land use that may emerge from different initial conditions. This finding can be further corroborated by the snapshots of employment distribution patterns shown in Figure 3 (i)-(vi). According to the relative value of employment, zones are divided in Figure 3 into 5 hierarchies and displayed in different colors. Note that the total employment in the hypothetical region is fixed. Figures 3(i), 3(iii), and 3(v) display the spatial patterns of Experiment 2 with flat

initial employment distribution at iteration 0, iteration 5 and iteration 50, respectively, while Figures 3(ii), 3(iv), and 3(vi) display the spatial patterns of Experiment 4 with concentrated initial employment distribution. As can be seen, although the two experiments started from differential initial conditions (as shown in Figures 3(i) versus 3(ii)), and generated different spatial patterns at the beginning (3(iii) versus 3(iv)), they eventually evolved into the same pattern (3(v) versus 3(vi)), suggesting a stable hierarchical distribution of land use emerges regardless of the initial land use conditions.

Experimental results also show that the hierarchical distribution of land use is reinforced when the road network is allowed to vary rather than remain constant, indicated by a consistently higher Gini index and consistently lower equivalent radius in the former case, which Experiment 4 also demonstrates that the initial concentrated gradient of land use is flattened as roads are expanded from an undifferentiated and relatively slow road network (the average link capacity is increased from 800 veh/hour to around 1,900 veh/hour over 50 iterations), which mirrors development in the United States and other advanced countries during the twentieth century when the increasing differentiation and development of roads was accompanied with a flattening of the land use density gradient.

SENSITIVITY

Changing the specified values of the parameters in the models of road dynamics and land use dynamics may affect the emergent spatial patterns significantly. The sensitivity of these parameters is thus examined as follows.

For road dynamics, the specified flow power δ_1 and speed power δ_2 (0.0 and 1.0) in our road cost model simplify the road network dynamics model such that equilibrium is reached when the volume equals the capacity on each link. The parameter ρ in the investment model doesn't affect the equilibrium state, but it defines how fast road investment responds to road conditions, thus affecting the speed of reaching equilibrium.

The parameters in the land use model, including the accessibility reduction factor θ , the coefficients in the zonal desirability model ($\lambda_l - \lambda_d$), and the reluctance factor in the land use reallocation model (μ), may affect the emergent spatial patterns as well. The accessibility reduction factor θ in Equations (13) and (14) determines how fast the

accessibility of a place declines with the increase of (generalized) travel cost to that place, reflecting the extent to which the change of travel time can affect the location of land use. The coefficients λ_1 - λ_4 determines the power of centripetal and centrifugal forces in location decisions with related to accessibility to jobs and accessibility to workers. The reluctance factor μ indicates the willingness of workers and jobs to stay in the original location.

Different values for four parameters ρ , θ , λ_3 , and μ were tested in Experiment 3 with flat initial land uses and allowing both network and land uses to vary, and the results are summarized in Figure 4. To be concise, only the Gini index of employment distribution is plotted.

As can be seen in Plot 4(i), while the spatial distribution of employment evolved into the same pattern with different values of ρ , the speed of reaching equilibrium varies. A higher value of ρ indicates a faster convergence of land use dynamics. As shown in Plot 4(ii), the decrease of θ basically exaggerates and quickens the concentration of employment because it puts more weight on the reinforcement effect associated with road dynamics. Plot 4(iii) displays the fluctuations of the Gini index with different values of λ_3 . Note that λ_4 changes accordingly with λ_3 such that λ_4 is always equal to $-\lambda_3$. The increase of λ_3 reinforces the agglomeration, while the increase of λ_4 (in absolute value) enhances the centrifugal force. Jointly their changes didn't affect the resultant spatial pattern significantly. Plot 4(iv) tests five different values of the reluctance factor μ . As can be seen, the resultant spatial pattern is very sensitive to this coefficient. Note that the change of μ affects the distribution of employment and that of population differently. With a higher value of μ (lower moving reluctance), the employment distribution will become more concentrated, while the population distribution could become less so (because of the reinforced centrifugal power). A less concentrated population distribution may in turn counteract the agglomeration of employment. The sensitive analysis discloses that a higher value of μ counteracts the agglomeration of employment below a turning point of 0.85, and reinforces that above the turning point.

CONCLUSIONS

This study models the co-evolution of land use and transportation network as a bottom-up process by which the re-location of activities and expansion of roads are driven by interdependent decisions of individual businesses, workers, and road agents according to simple decision rules. The model was kept simple so that collective spatial patterns of land use distribution can be displayed and analyzed without multiple conflating factors, while the sensitivity of these patterns were also discussed. The Gini index and equivalent radius were adopted to track down the evolution of spatial patterns.

This paper in particular examines the evolution of urban land use under the context of the co-evolution of network and land use. Simulation experiments suggest that there may exist an inherently stable hierarchical distribution of employment and residence so that initially flat land uses become more concentrated and concentrated network become less concentrated. Experimental results also demonstrate that the agglomeration and centralization of employment and residence is reinforced by the dynamics of the underlying road network under the tension of pushing and pulling forces. The differentiation of the road network makes the land uses more concentrated than it otherwise would be. Since it has been replicated in a self-organizing process based on completely decentralized decisions in this study, this reinforcement phenomenon is suggested to be an emergent property of the co-evolution of land use and road network.

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TABLES AND FIGURES

Table 1. Specification of experiments

No.	Initial conditions			Dynamics	
	Link capacity	Employment	Population	Roads	Land uses
1	Uniform	Uniform	Uniform	Fixed	Evolving
2	Uniform	Uniform	Uniform	Evolving	Evolving
3	Uniform	Concentrated	Uniform	Fixed	Evolving
4	Uniform	Concentrated	Uniform	Evolving	Evolving

Table 2. Model parameters

Parameter	Description	Citation	Value	Source
$\xi_1, \xi_2,$ ψ_1, ψ_2	Coefficients in trip generation and attraction	Eq.(1)	0.5, 1.0, 1.0, 0.5	Specified
ε	Trip distribution coefficient	Eq. (3)	0.048/min	Empirical calibration
t_m^0	Base intra-zonal travel time	Eq. (5)	10 min	Empirical estimate
η	Value of time	Eq. (7)	\$10 /h	Empirical estimate
τ	Toll rate	Eq.(8)	\$1.0/ veh.km	Empirical estimate
σ_1, σ_2	Coefficients in cost model	Eq.(9)	0, 1.0	Specified
ρ	Capacity reduction factor	Eq.(10)	0.1	Specified*
ω_1, ω_2	Coefficients in the <i>capacity-freeflow speed</i> loglinear function	Eq.(11)	-30.6, 9.8	Empirical calibration
α, β	Coefficients in BPR function	Eq.(12)	0.15, 4.0	Empirical calibration
θ	Reduction factor in accessibility model	Eq.(13), Eq.(14)	0.048/min	Specified*
$\lambda_1, \lambda_2,$ λ_3, λ_4	Coefficients in zonal desirability model	Eq.(15), Eq.(16)	1.0, 1.0, 0.9, -0.9	Specified*
μ	Reluctance to move	Eq.(17), Eq.(18)	0.80	Specified*

* Analyses were conducted on the sensitivity of asterisked parameters

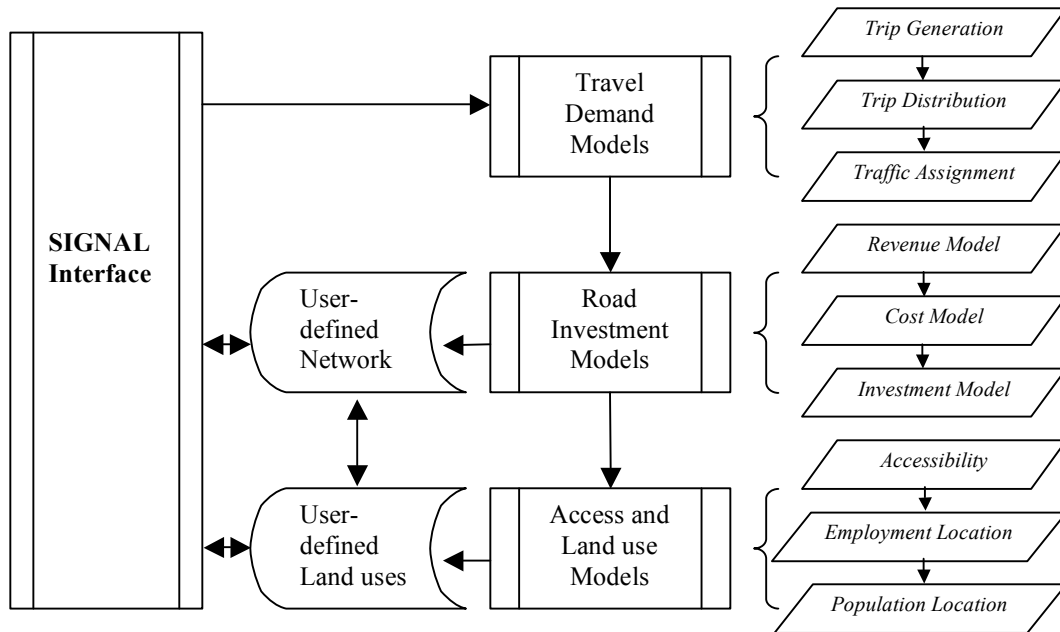
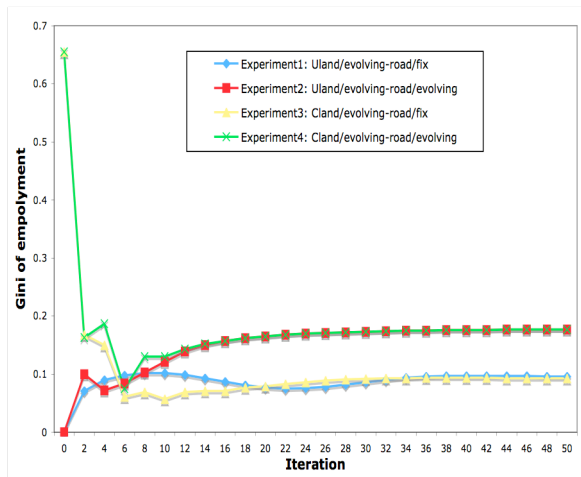
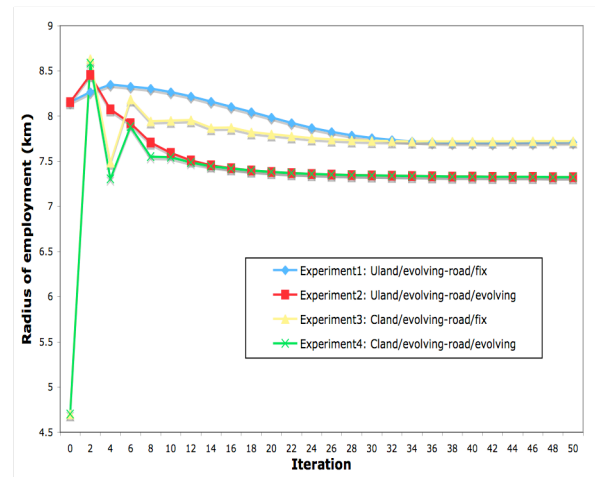


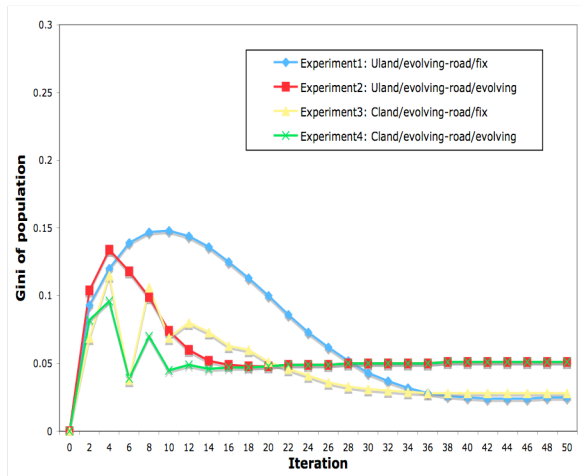
Figure 1. Overview of the SIGNAL model.



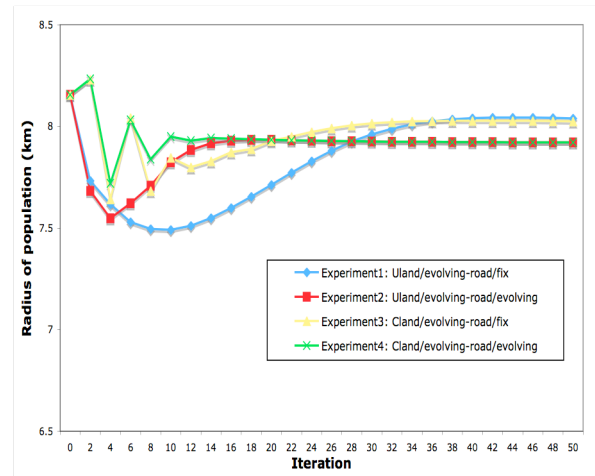
(i) Gini index for employment



(ii) Equivalent Radius for employment

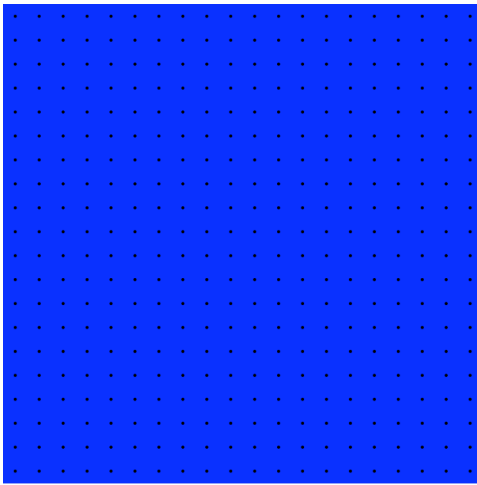


(iii) Gini index for population

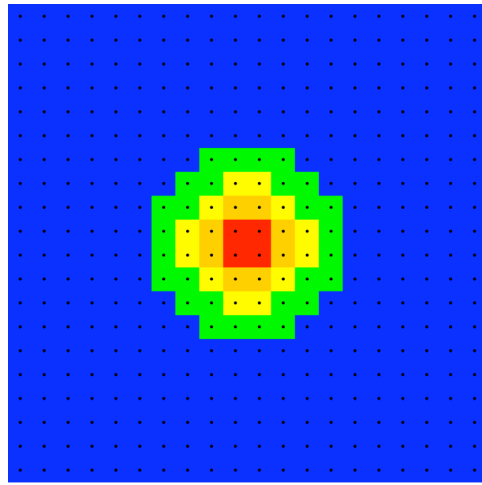


(iv) Equivalent Radius for population

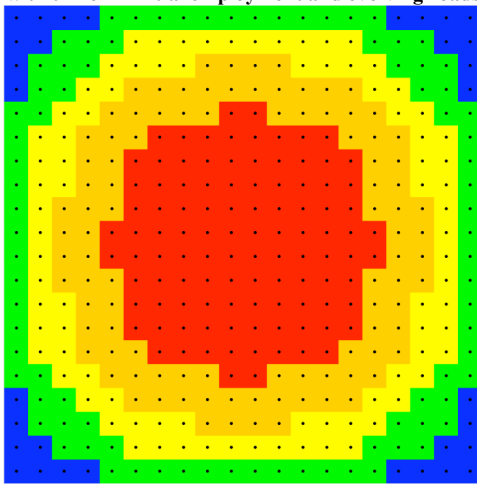
Figure 2. Measures of land use patterns



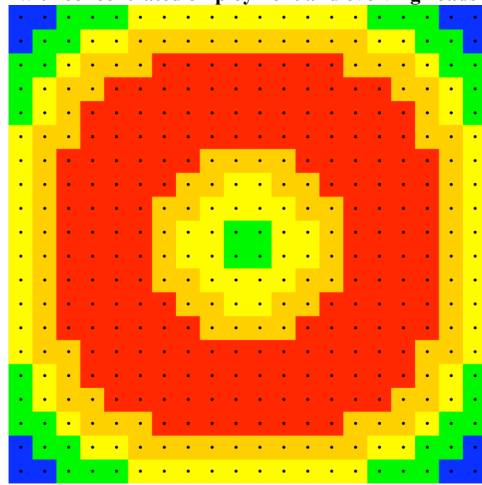
(i) Experiment 2: Initial distribution of employment with uniform initial employment and evolving roads



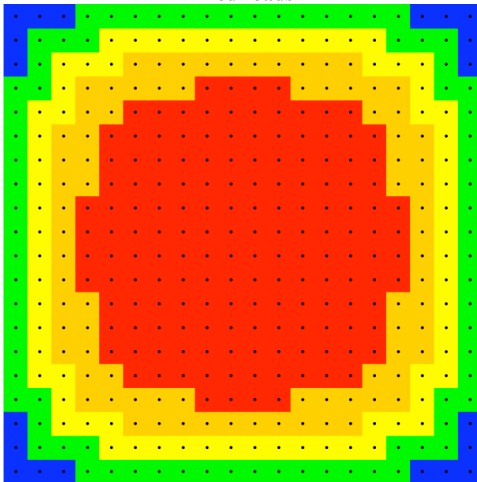
(ii) Experiment 4: Initial distribution of employment with concentrated employment and evolving roads



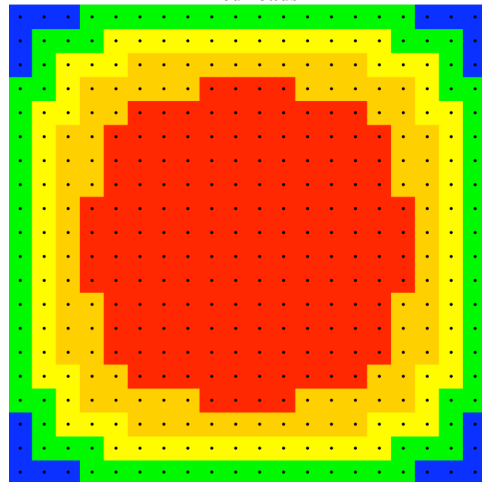
(iii) Experiment 2: Distribution of population at iteration 5 with uniform initial employment and fixed roads



(iv) Experiment 4: Distribution of employment at iteration 5 with concentrated initial employment and fixed roads

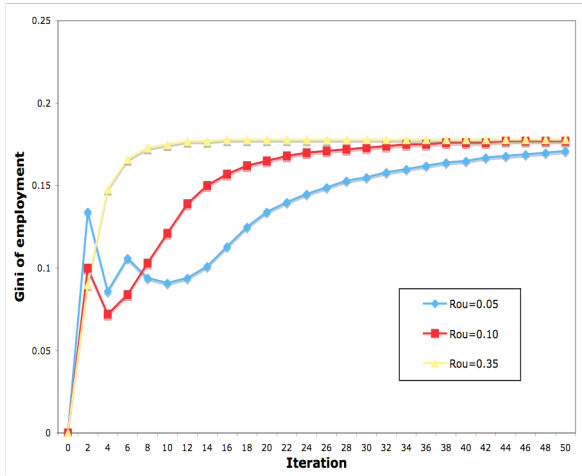


(v) Experiment 2: Distribution of employment at iteration 50 with uniform initial employment and evolving roads

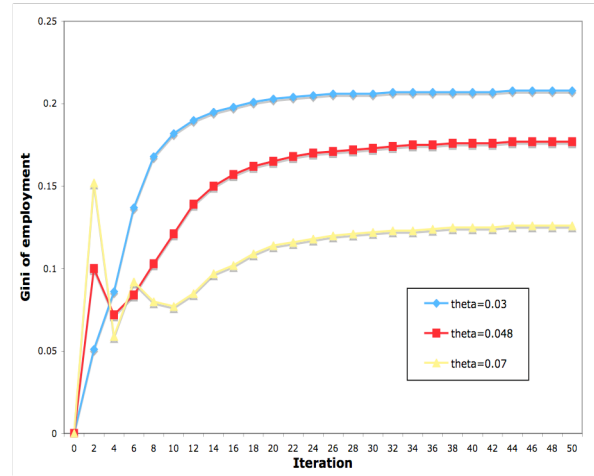


(vi) Experiment 4: Distribution of employment at iteration 50 with concentrated initial employment and evolving roads

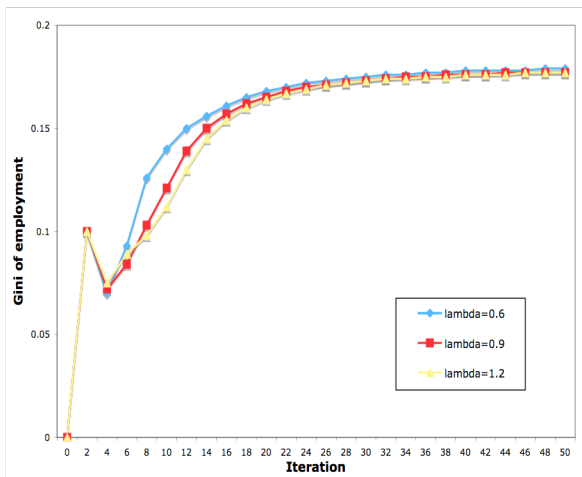
Figure 3. Initial and emergent land use patterns



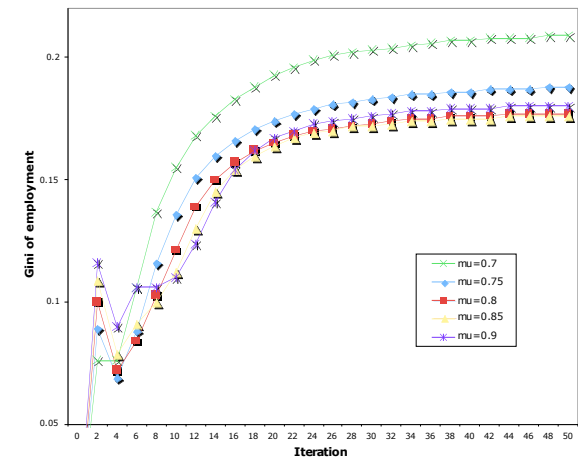
(i) Sensitivity Analysis of rho: Gini



(ii) Sensitivity Analysis of theta: Gini



(iii) Sensitivity Analysis of lambda 3: Gini



(iv) Sensitivity Analysis of mu: Gini

Figure 7. Sensitive analyses for four parameters