Ann Reg Sci (1997) 31:39–56

The Annals of
Regional Science

The growth of city systems with high-speed railway systems

Kiyoshi Kobayashi[1], **Makoto Okumura**[2]

[1] Department of Civil Engineering, Kyoto University, Kyoto, 606-01 Japan
[2] Department of Environmental and Civil Engineering, Hiroshima University, Higashi-Hiroshima, 739 Japan

Received: May 1996 / Accepted: December 1996

Abstract. This paper proposes a dynamic multi-regional growth model with free mobility of capital and population. The economic system consists of multiple cities interconnected by high-speed railway systems with each city consisting of one production sector as well as residential land use. The railway systems provide production sectors of different cities with the opportunity of face-to-face communication for knowledge production. The model describes the dynamic interdependence between capital and knowledge accumulation, wage and land rent structures, urban patterns with endogenous city size and inter-city interactability. It is emphasized how differences in geographic and qualitative factors of high-speed railway systems may affect regional economic development. The model simulates the dynamic processes of economic development of city systems.

1. Introduction

Dynamic interdependency among the growth of city economies has been accelerated by world-wide economic integration. The arrangement of inter-city high-speed railway systems provides city economies with expanded opportunities of face-to-face communications for knowledge production. The short- and long-run effects of the high-speed railway systems upon city systems are very complex. The purpose of this study is to propose a multi-regional growth model to provide some insights into the dynamic impacts of high-speed railway systems upon the economic geography of city systems.

The growth aspects of our model are based on the multi-regional macro-economic one-sector growth model with perfect capital and population mobility, and perfect competition. So far, many efforts have been made to capture capital accumulation with free capital mobility in a two country setting (e.g., Wang 1990; Ikeda and Ono 1992; Zhang 1996). This framework has been extended by incorporating knowledge accumulation into dynamics (e.g. Zhang 1996). Our model exhibits the same orientation in the multi-regional setting. Knowledge is considered as non-rival, partially excludable goods (Romer 1986, 1990). The assumption is that, rather than being used up in the process of production, knowledge can be used many times over at little or no additional cost. Such knowledge is made available to other firms or individuals through the knowledge exchange processes that occur across spatial networks (Batten, Kobayashi, and Andersson 1989). An accessibility function, allowing for partial excludability, makes obvious the need for geographical control over knowledge transfer.

The second aspect of our model is to incorporate land into growth modeling. Land is considered as a factor for housing consumption. Following neoclassical urban economics, land is treated mainly for housing uses (e.g., Alonso 1964; Mills 1972; Zhang 1996). There has also been extensive literature concerned with economic mechanisms of urban growth (e.g., Richardson 1973; Smith 1975; Miyao 1981; Henderson 1985). Although this approach introduces factors such as dynamics of population, capital and knowledge to explain urban growth, it does not consider the endogenous formation of urban patterns. Recently, Zhang (1993) proposed a compact framework to combine the neoclassical growth model and the new urban economic model to explain urban dynamics with endogenous urban patterns, and capital and knowledge accumulation. In this paper, economic geography of city systems is explicitly introduced into Zhangian growth modeling to investigate the dynamic impacts of high-speed railway systems upon the development processes of city patterns, the accumulation of capital and knowledge in city systems, and the evolution of economic geography.

The high-speed railway systems, along with the other high-speed transportation systems like motorways and airways, provide city economies with expanded opportunities of inter-city face-to-face communications among the knowledge-handling labor force. In this paper, knowledge is assumed to be non-rival, partially excludable goods for the whole city system economy. This does not mean that each city has the same opportunity to learn from knowledge stocks. The quality of the railway systems is considered to affect how efficiently knowledge can be utilized to increase human capital levels. Hence, inter-city interactability should play a significant role in determining the knowledge diffusion processes. The quality of high-speed railway systems controls the accumulation processes of knowledge and capital stocks in each city on the network. Thus, the spatial topology of physical networks is decisive in determining regional disparities of income per capita and economic geography of city systems.

Irrespective of analytical complexity, the threeness or more of cities of the economy is considered. This assumption mainly comes from the analytical tenet of the current paper to explain endogenous formation of economic hub cities given the rapid railway systems. One cannot have a hub with only two locations. Transportation hubs are especially desirable places to locate the production of goods and services subject to increasing returns. The interaction between increasing returns in production leads to the endogenous formation of such transportation hubs. The transportation hub effect can be viewed as an alternative explanation of the regional differentiation (Krugman 1993a). This complication can only be made at the sacrifice of analytical tractability of the model. Instead of analytical rigorousness, the model simulates the dynamic processes of the systems.

The purpose of this study is to construct a multi-regional dynamic economic model with the scale effects of knowledge. The interaction between production, consumption, land use, capital accumulation, knowledge creation of different cities and inter-city interactability on high-speed railway systems is examined. The remainder of the paper is organized as follows; Sect. 2 defines a dynamic model of the city system economy with free mobility of population and capital and with inter-city knowledge spillover, Sect. 3 investigates some analytical properties of our model, Sect. 4 simulates the model to show dynamic processes of the system, and Sect. 5 concludes the study.

2. The model

An economic system consisting of n cities, indexed by $i=1, \ldots, n$, is considered, where cities are interconnected by a rapid railway system. The economy produces one fixed product bundle (a numéraire good) which can be either invested in firms to increase capital for production, or consumed by the population. Perfect competition is assumed to prevail in good markets both within each city and between cities, and commodities are traded without any barriers such as transport costs. The population is homogeneous. The people can freely move among cities but can live in only one city; multi-habitation as well as inter-city commuting are prohibited. The households achieve the same utility levels regardless of the locations in which they live.

Each city is geographically monocentric, and consists of two parts – the CBD and residential area. The city residents commute to the single CBD by intra-city railway systems. For simplicity, we assume that each CBD is a point and all production activities are concentrated in the CBD of the respective cities. Production agents employ capital, spatially distributed knowledge and the qualified labor force of the city. Knowledge is not directly applied to production processes, but affects the quality of human capital by improving productivity per capita. Knowledge has the characteristics of a partially excludable public good in the sense that any firm can use the knowledge of any other city while only incurring a transportation cost. Knowledge is assumed to be location specific; it cannot be transferred by human migration.

How material production, and capital and knowledge accumulation of each city is carried out when knowledge is a good flowing between cities without being used up, will now be examined. It is assumed that the labor force controls knowledge, which is accumulated in the form of human

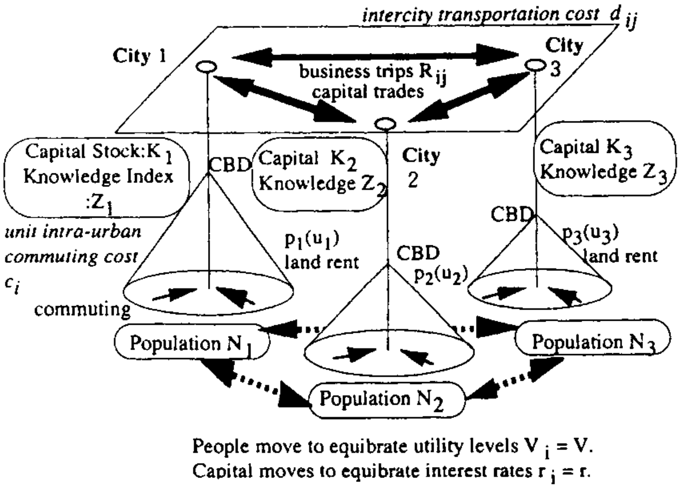

Fig. 1. The structure of the model

capital either through leaning-by-doing in production or by learning from face-to-face interactions with other firms. In other words, there are two sources of knowledge accumulation for labor force.

The economy develops the economy-wide perfectly competitive markets for products and capital. The capital capacity is assumed to be fully employed in the economy at each point in time. On the other hand, labor markets are localized in each city, and the local labor force is fully employed in their respective markets. The total population of the economy is given exogenously at any point in time. Products, population and capital are freely mobile between cities without any friction. The railway system is the means for knowledge diffusion among cities. It is endowed with the economy at the initial point in time without any costs (e.g. gifts from foreign countries), and then controls the growth processes of the city system throughout the various stages of development.

Figure 1 explains the basic structure of the model. The model comprises 1) the urban economics model to describe urban land use patterns of the respective cities, 2) the general equilibrium model to characterize the whole economy of the city system, and 3) the dynamic growth model to explain the accumulation of capital stocks and human capital resources (knowledge). This model has an advantage of simultaneously incorporating scale economy of agglomeration as well as external diseconomy raised by extended land-use. The size, land use patterns, and production capacities of respective cities, the so-called economic geography, are endogenous at each point of time given the spatial distribution of knowledge resources over the system, and the population and capital stocks of the whole economy. The railway system controls the accumulation processes of knowledge resources in each city.

2.1 The urban economic model

The general equilibrium model is presented to describe a static system of cities where all resources are ubiquitous and cities in the economy are situated on a flat plain where there is no agriculture. First, describe the respective city economy á la Alonso. Let it be temporally assumed that the capital stocks and population of each city are predetermined in some manner. In each city, land is owned collectively by all city residents through shares in a local land bank. The land bank pays out dividends to local residents which normally equals the average per capita land rent paid out. Further, for the simplicity of description, the following set of assumptions (Henderson 1985) is adopted: 1) the CBD is located at a central point of the city; 2) residential area is divided into land lots, whose areas are fixed to the same size regardless of locations; 3) commuting costs are paid by individual households; and 4) no agricultural land use is available. In other words, land price is zero on the edge of the city. These assumptions are useful to eliminate unnecessary complexity of the model without loss of generality in the following discussions.

Consider the representative household residing at a point with distance u_i from CBD of city i ($i=1, \ldots, M$). The utility function is regulated by both composite commodity consumption $x_i(u_i)$ and housing lot size $l_i(u_i)$, being fixed to $l_i(u_i)=1$. With a budget constraint, the composite commodity consumption is given by

$$x_i(u_i) = y_i - p_i(u_i) - c_i u_i \,, \tag{1}$$

where y_i is income, $p_i(u_i)$ is the land rent per fixed lot size at point u_i; and c_i is the cost of cummuting an unit distance and is constant everywhere in the city. The indirect utility function is supposed to be

$$V(u_i) = y_i - p_i(u_i) - c_i u_i \,. \tag{2}$$

Spatial equilibrium for identical households is characterized by $\partial V(u_i)/\partial u_i = 0$. From Eq. (2), it can be seen that increased transport costs with increased commuting distance are offset by reduced rents; thus we have $\partial p_i(u)/\partial u = -c_i$. From assumption (4), there holds $p_i(L_i) = C_0 - c_i L_i = 0$ at the edge of the city where $u_i=L_i$. Integrating the equation $\partial p_i(u)/\partial u = -c_i$, we have the land rent gradient:

$$p_i(u_i) = c_i(L_i - u_i) \,. \tag{3}$$

The utility level of the household at the city edge, $u_i=L_i$ is

$$V_i = y_i - c_i L_i \,. \tag{4}$$

Spatial equilibrium certifies that every household in the city can get the same utility levels as in Eq. (4) regardless of locations within the city.

Given the fixed lot size over the economy, the size of city i, N_i, can be defined by the area of urban land use. Thus,

$$N_i = \int_0^{L_i} 2\pi u_i \, d u_i = \pi L_i^2 \,. \tag{5}$$

By summing up individual consumption for composite commodity over the city population, the aggregate demand function can be described by

$$F_i = \int_0^{L_i} 2\pi u_i x_i(u_i) \, d u_i = N_i \left(y_i - c_i \pi^{-1/2} N_i^{1/2}\right) . \tag{6}$$

The aggregated land rents and transportation costs over population in city i are given by

$$P_i = \int_0^{L_i} 2\pi u_i p_i(u_i) \, d u_i = \frac{1}{3} c_i \pi^{-1/2} N_i^{3/2} \,, \tag{7}$$

$$T_i = \int_0^{L_i} 2\pi c_i u_i^2 \, d u_i = \frac{2}{3} c_i \pi^{-1/2} N_i^{3/2} \,, \tag{8}$$

respectively. Thus, land use patterns of respective cities are uniquely determined given y_i, N_i, c_i. The equilibrium utility levels of the representative household can be fully characterized by these parameters:

$$V_i = y_i - c_i \pi^{-1/2} N_i^{1/2} \,. \tag{9}$$

To determine income levels in this equation the production sector of the city economy is examined.

It is assumed that city people of a particular city are identical with respect to applied knowledge capacity, though the qualification levels of the labor force can be differentiated across city economies. This means that when laborers migrate between cities, they can instantaneously acquire the whole knowledge stocked in the destination city, and abandon all old knowledge in the origin city. To describe the qualification levels of the labor force, we introduce a knowledge index, Z_i, of the labor force of city i. The knowledge index is an aggregated measure of the applied knowledge of the labor force. It is determined by the average quality of local human networks, working skills and other aspects of the human capital of the population of the city under consideration. The qualified labor force of the ith city is defined by $Z_i N_i$. Thus, the qualified labor force is determined by the product of quantitative labor force and the knowledge index (Zhang 1996). This idea is very akin to the labor-augmenting technological progress (Robinson 1938; Uzawa 1961) because knowledge is supposed to raise output in the same way as an increase in the stock of labor.

Production of city i is described by the constant-return-to-scale technology for K_i, N_i and R_{ij}:

$$Y_i = K_i^a (Z_i N_i)^\beta \left\{ \sum_{j \neq i} Z_j N_j \left(\frac{R_{ij}}{Z_j N_j} \right)^\xi \right\}^\gamma , \tag{10}$$

where Y_i is total output; K_i is capital stocks; Z_i is the knowledge index; R_{ij} is the number of face-to-face communications between city i and j, and a, β, $\gamma(>0)$, $1>\xi>0$ are parameters satisfying $a+\beta+\gamma\xi=1$. The production sectors of respective cities control K_i, N_i and R_{ij} to maximize their profits, while the knowledge stocks of other cities Z_iN_i are exogenously given to the firms' decision making. The production function (10) implies that the cities have the identical production technology, but different accessibility to knowledge resources. It is conceptually possible to interpret Z_i as a human capital index and thus extend the analysis to include dynamics of human capital accumulation (e.g., Romer 1986, 1990; Lucas 1988).

The function does not directly include the agglomeration economy term as one of its components as commonly adopted in previous literature (Henderson 1985). Instead, the function describes the public-goods-like character of knowledge resources. The intercity communications via high-speed railway systems are major variables for production technology (Mun 1993). The frequencies of interaction among cities are endogenous in the model.

It is assumed that with each city factor demands for production are determined by perfect competition. The marginal products of the capital, labor force and the frequency of face-to-face communications are respectively equalized to capital rent, r_i, wage rent, ω_i and transportation costs. These conditions are given by

$$\begin{aligned} r_i &= \frac{a\, Y_i}{K_i} , \\ \omega_i &= \beta \frac{Y_i}{N_i} , \\ d_{ij} &= \gamma \xi\, Y_i \frac{Z_j N_j d_{ij}^{-\frac{\xi}{1-\xi}}}{R_{ij} \sum_{k \neq i} Z_k N_k d_{ik}^{-\frac{\xi}{1-\xi}}} . \end{aligned} \tag{11}$$

Inter-city communications (business trips) are described by the following gravity-type model,

$$R_{ij} = \frac{\gamma \xi\, Y_i Z_j N_j d_{ij}^{-\frac{\xi}{1-\xi}}}{d_{ij} \sum_{k \neq i} Z_k N_k d_{ik}^{-\frac{\xi}{1-\xi}}} . \tag{12}$$

2.2 The general equilibrium model of city systems

Each individual in the economy owns an equal share of capital of the whole economy. We have assumed the public ownership of land by local residents, which means that the revenue from land is equally shared among the population within each city. The total land rent of a city is equally distributed to all households in the city. On the other hand, we assume that capital stocks are owned collectively by all individuals of the whole economy through shares in a national bank. Local capital markets are interconnected within the framework of the national capital market. Further, we assume mandatory saving. All individuals are obliged to hold the same amounts of capital stocks irrespective of locations within the economy. The revenue from capital rents is divided up equally among all individuals.

The net income per household consists of three parts: wage income, income from land ownership and interest payment for capital holding. When land rents are divided up equally among residents, then the per person land rent income in city i is given by

$$p_i = \frac{P_i}{N_i} \, . \tag{13}$$

The capital rent is given by

$$k = \frac{\sum_j r_j K_j}{N} \tag{14}$$

where N is population of the whole economy. Then, the net income per capita is defined by summing up wage rate, land rent, and capital rent while substituting savings. Thus,

$$y_i = \omega_i + k + \frac{P_i}{N_i} - s \, , \tag{15}$$

where s represents mandatory saving.

The capital can freely move among cities, and the total capital stocks of the whole economy is competitively allocated among local capital markets. Through arbitration, there holds the following equilibrium condition among local capital markets:

$$\begin{aligned} & r_1 = \ldots = r_M = r \, , \\ & \sum_i^M K_i = K(t) \, , \end{aligned} \tag{16}$$

where $K(t)$ is the total amount of capital stocks at time t; r is the equilibrium interest rate guaranteeing that capital stocks are cleared in the national-wide capital market. It has also been assumed that there is perfect employment of local labor force and no inter-city commuting. The wage rate of a particular city is determined to bring into equilibrium the supply and demand for local labor force. Eventually, the wage rates are regionally differentiated, reflecting the geographical conditions of local labor markets. The population can freely move among cities. The population distribution among cities can be brought into equilibrium when no households have incentive to move. Thus, the equilibrium of population distribution can be characterized by

$$\sum_i N_i = N(t) ,$$
$$V_i = \ldots = V_M = V , \tag{17}$$

where V is the equilibrium utility level and $N(t)$ is exogenously given total population of the system.

2.3 *The city-system growth model*

As in the neoclassical growth model, we assume that the industrial product can be either invested or consumed. The neoclassical growth model describes the accumulation to total capital stock $K(t)$ of the economy, which in turns is to be allocated to the cities according to (16). The capital accumulation process is described by

$$\frac{\mathrm{d}K}{\mathrm{d}t} = \iota \sum_i Y_i - \delta_K K , \tag{18}$$

where $\iota = sN(t)/\sum_i Y_i$ is saving propensity, and δ_K is the depreciation rate of capital stock. Research and development activities by industry and inter-urban knowledge exchange produce new knowledge and uplift productivity (Kobayashi, Batten, Andersson 1991). Such knowledge accumulation in each city is described as follows:

$$\frac{\mathrm{d}Z_i}{\mathrm{d}t} = \frac{f\,Y_i}{N_i\,(1 + h\,Z_i)} + g\left\{\sum_{j \neq i} Z_j\,N_j\left(\frac{R_{ij}}{Z_j\,N_j}\right)^{\xi}\right\}^{\gamma} - \delta_Z\,Z_i , \tag{19}$$

where f, h, g are parameters which describe learning by doing effect, its diminishing return to scale and knowledge exchange effect, respectively (Zhang 1992, 1996). δ_Z is the knowledge depreciation rate. The first term measures the effects of learning by doing by the industrial sector upon knowledge accumulation. It implies that the knowledge accumulation is positively related to the production scale. The second term implies that the creativity of the industry is positively related to the frequency of face-to-face contacts over city networks. (19) assumes that knowledge can be altered in three ways: learning by doing, inter-regional learning and deterioration. One important omission is the improvement of knowledge through migration. When highly qualified people move to a less highly qualified region, the productivity per capita might increase for the whole region, and vice versa. In this model, knowledge levels are regarded as an aggregated regional index (Zhang 1996) which is rarely affected by the personal knowledge of individuals in the region. As soon as people move elsewhere, they instantaneously obtain the full set of the new knowledge stored in the destination region, and abandon the old knowledge in the origin region. Thus, knowledge is assumed to be region-specific, not person-specific. The region- as well as person-specific knowledge are both extreme assumptions. If we adopt the assumption of fully person-specific knowledge, we must disaggregate population and migration with respect to human knowledge; this is obviously a more complicated task.

3. The structure of city system

The revenue of the business sector in each city is divided into three parts of factor payment, i.e., capital income of capital owner, wage income of employee, and transportation costs. When perfect competition dominates the factor markets and production technology of each city is identical and constant-returns-to-scale, we have

$$\frac{r K_i}{Y_i} = a$$
$$\frac{\omega_i N_i}{Y_i} = \beta ,$$
$$\frac{D_i}{Y_i} = 1 - a - \beta , \tag{20}$$

where $D_i = \sum_{j \neq i} d_{ij} R_{ij}$ is transportation cost for face-to-face communications. From Eq. (11) the fraction of transportation cost to a particular destination j to the total transportation cost paid by business sector in city i, $v_{ij} = D_{ij}/D_i$, is described by

$$v_{ij} = \frac{Z_j N_j d_{ij}^{-\frac{\xi}{1-\xi}}}{\sum_k Z_k N_k d_{ik}^{-\frac{\xi}{1-\xi}}} . \tag{21}$$

The demand for inter-city communications to city j per unit production in city i is:

$$\frac{R_{ij}}{Y_i} = \gamma \xi \frac{v_{ij}}{d_{ij}} . \tag{22}$$

From this equation and Eqs. (10), (11),

$$\omega_i = \Omega r^{-\frac{\alpha}{\beta}} ACC_i^{\frac{\alpha}{\beta}} Z_i ,$$
$$ACC_i = \left(\sum_{j \neq i} Z_j N_j d_{ij}^{-\frac{\xi}{1-\xi}}\right)^{1-\xi} , \tag{23}$$

where $\Omega = \alpha^{\frac{\alpha}{\beta}} \beta (\xi \gamma)^{\frac{\xi\gamma}{\beta}}$. The term ACC_i represents the accessibility to knowledge resources distributed in the city system. It is learned that the wage rate of city i is regulated by knowledge stocks Z_i and knowledge accessibility ACC_i. Thus, the arrangement of the high-speed railway systems changes the spatial profiles of knowledge accessibility, and then play a decisive role in controlling wage rate disparities within the city system.

Economic geography is controlled at each point in time by equilibrium conditions (17). From Eqs. (15), (23) and (9), it is seen that the indirect utility is given by

$$V_i = \Omega r^{-\frac{\alpha}{\beta}} \left(\sum_j Z_j N_j d_{ij}^{-\frac{\xi}{1-\xi}}\right) Z_i + e - \frac{2}{3} c_i \pi^{-\frac{1}{2}} N_i^{\frac{1}{2}} . \tag{24}$$

where $e=k–s$. Thus the indirect utility is also controlled by city size, knowledge stocks, and knowledge accessibility.

The impacts of high-speed railway systems are complex. The railway project changes inter-city cost parameters, d_{ij}, and then impacts the city system economy in various ways. For simplicity, two extreme cases are considered: 1) inter-city transportation cost being very high, $d_{ij}=\infty \, (i \neq j)$, in the extreme, and 2) inter-city transportation cost being sufficiently cheap, $d_{ij}=d$ for all city pairs (i, j), where d takes a small constant value.

First, consider the case where inter-city communications are forbidden, $d_{ij}=\infty$. The indirect utility is simplified to

$$V_i = \Omega r^{-\frac{\alpha}{\beta}} (Z_i N_i)^{\phi} d_{ii}^{\psi} Z_i + e - \frac{2}{3} c_i \pi^{-\frac{1}{2}} N_i^{\frac{1}{2}} , \tag{25}$$

where $\phi=(1-\xi)\gamma/\beta$, $\psi=-\gamma\xi/\beta$. ϕ plays a decisive role to control the multiplicity of spatial equilibria. If $0<\phi<1/2$, V_i becomes a single peaked function of N_i with the system may possessing two or more stable equilibria. If $1/2<\phi<1$, V_i is a monotonous decreasing function of N_i with the city system having a unique equilibrium. Lastly, if $1<\phi$, V_i becomes an U-shaped function of N_i. In this last case, the city system has the possibility of a large number of equilibria, and exhibits very complicated dynamics.

Next, let us consider the other extreme case, where inter-city transportation costs are negligible. Then, the indirect utility is given by

$$V_i = \Omega r^{-\frac{\alpha}{\beta}} \left(\sum_j Z_j N_j\right)^{\phi} d^{\psi} Z_i + e - \frac{2}{3} c_i \pi^{-\frac{1}{2}} N_i^{\frac{1}{2}} . \tag{26}$$

The indirect utility is monotonously decreasing with respect to city size. There is an unique stable equilibrium of the system at each point in time. Economic geography of the city system is conditional to the spatial profile of knowledge stocks in the short-run. If knowledge resources are equally distributed among cities, then economic activities and population are fully decentralized among cities. The real world may stand somewhere between two extreme cases. When three or more cities are considered, the problem goes far beyond the scope that analytical investigation can be made. At this point, computer simulation must be relied upon. In our modeling, knowledge accumulation processes are decisive for the spatial pattern of economic growth. The high-speed railway systems regulate the knowledge exchangeability among cities in the short-run and play crucial role in determining the economic geography of knowledge distribution in the long run.

4. Computer simulation

Exogenous variables of the model are total population $N(t)$ and transportation conditions c_i, d_{ij}, while K_i, Z_i, Y_i, ω_i, R_{ij}, D_i, y_i, V, N_i, F_i, P_i, T_i, s, r are endogenous variables. The computational procedures are summarized in Fig. 2. Into this, discrete time systems are to be introduced. In simulation, each iteration corresponds to a distinct point in time. At the beginning of each iteration, the values of $K(t)$ and $Z_i(t)$ are predetermined by the output of the urban growth model. Given the initial values of N_i, K_i, the urban economics model produces other endogenous variables in the follow-

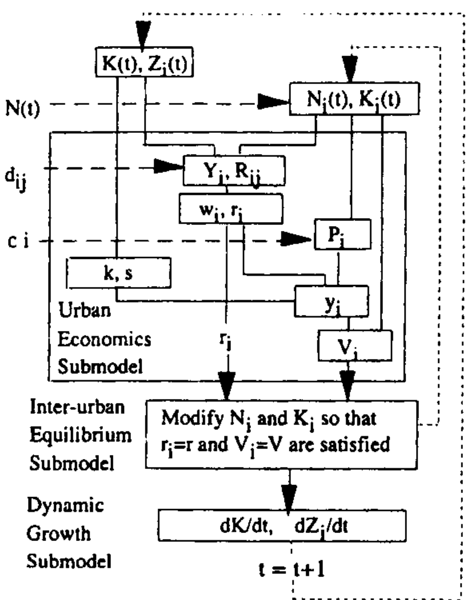

Fig. 2. Computational procedure

ing manner. First, from Eqs. (10)–(12), Y_i, r_i, ω_i, R_{ij} can be determined given N_i, K_i. Second, Eq. (7) gives P_i and Eq. (15) determines y_i. Then, the indirect utility V_i is calculated via Eq. (9). However, the calculated r_i, V_i need not bring the markets into equilibrium. If it does not, the general equilibrium model revises K_i, N_i given the calculated r_i, P_i, Y_i, ω_i, R_{ij}, P_i, y_i. These revisions are repeated until the city system is brought into equilibrium. If it is made, the urban growth model forecasts $K(t+1)$, $Z_i(t+1)$, and the same procedure described above is repeated.

The bench mark case (case a)

In the simulation, consider a city system comprising five cities connected by a straight high-speed transportation system (see Fig. 3). In the bench mark case (called case *a*), all cities are assumed to be identical, at the beginning of simulation, in terms of population, capital stocks and knowledge resources, $N_i=40$, $K_i=100$, $Z_i=0.7$. The unit commuting costs are fixed to $c_i=0.6$ in all cities. Under this setting, city 3, endowed with the prominent accessibility in the city system, can enjoy faster growth of production and population than other cities as shown in Fig. 4. In the model, population and capital stocks are assumed to be freely mobile. It means that the differences of the initial values of population and capital stocks are instantly accommodated and have no long-run influence upon economic development of the city system.

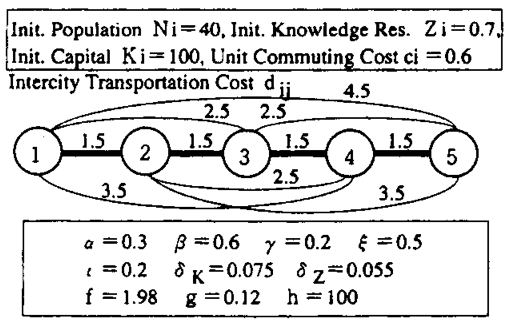

Fig. 3. A hypothetical city system

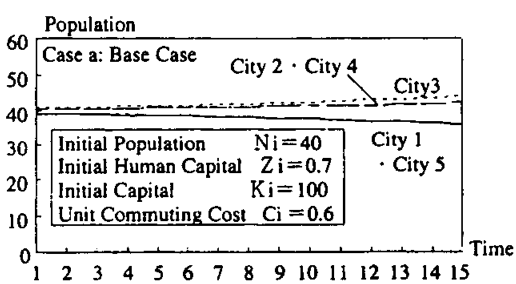

Fig. 4. Population growth of the base case

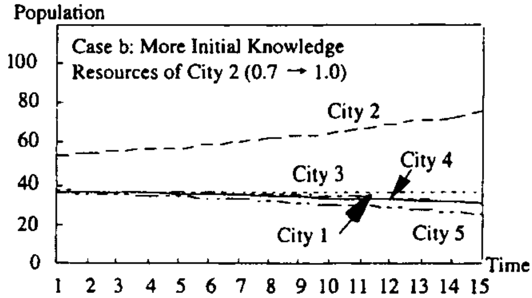

Fig. 5. Population growth and knowledge resources

The impacts of initial knowledge stocks (case b)

By the assumption of the free mobility of population and physical capital, their initial differences across cities have no memory in economic development. But, initial differences in knowledge resources are decisive for the growth of the city system. Assume that a university is provided in city 2 by policy. Figure 5 shows the population growth path when city 2 possess more initial knowledge resources ($Z_2(0)=1.0$) than other cities ($Z_i(0)=0.7$, $i \neq 2$). From Fig. 5, it can be seen that city 2 can gather more population than in case *a*.

The impacts of unit commuting cost (case c)

The reduction of commuting costs encourages the growth of city economy and has the long-run impacts upon the growth path of the city system in direct and indirect ways. Figure 6 shows the population growth path in the case when commuting cost is improved at the initial time in city 2; that is $c_2=0.45$ in city 2, while $c_i=0.6$, $i \neq 2$. The differences in city size between city 2 and other cities may expand as time goes. City 2 becomes a hub city gathering population, while other cities cannot grow as fast.

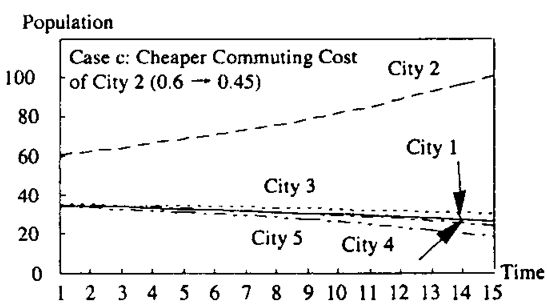

Fig. 6. Population growth and commuting costs

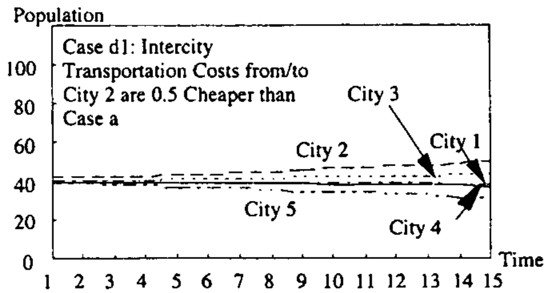

Fig. 7. Population growth and inter-city railway systems

The impacts of high-speed railway systems (case d)

First, the hub-type of railway network are considered, where inter-city high-speed railway systems only connect the hub city (city 2) with other cities (case d_1). Figure 7 shows the population growth patterns when transportation costs between city 2 and other cities are improved and reduced to the half level of that in case a, while the transportation costs of other city pairs remain at the same level of case a. Thanks to relative superiority in knowledge accessibility, city 2 gathers more population than in other cases and becomes the hub of the city system. The growth rates of other cities are regulated by the accessibility to city 2. For example, city 1 grows faster than city 4, though it is located at the edge of the system.

Next, consider another case where inter-city transportation costs are equally and remarkably decreased to a level which can almost cope with the average commuting costs (case d_2). Assume that $d_{ij}=d$ for every city pair (i, j). When simulation is started with an impartial initial state as depicted in case a, the system exhibits the fully decentralized balanced growth: all cities continue to grow with the same shares of population, capital stocks and knowledge resources.

These fully balanced growth patterns can be brought about in another geographical setting where inter-city communications are prohibited, while capital and population can freely move among cities (case d_3). In this case, the city size is unchanged over time. Any small disturbances in the initial profile of city size are instantly accommodated and cause no substantial impacts upon economic development of the city system. As discussed in 3, there may exist multiple equilibria dependent upon the value of ϕ. If $0<\phi<0.5$, we can see that cities with very small initial populations can be instantly eliminated. Such cities can not be sustained over long periods of time. This fact explains the multiplicity of spatial equilibria.

The welfare comparison

The welfare comparison of different economic development patterns can be made based upon the equilibrium indirect utility levels (9). Figure 8 compares the changing patterns of the equilibrium indirect utility for all cases mentioned above. The equilibrium utility increases for all cases as capital

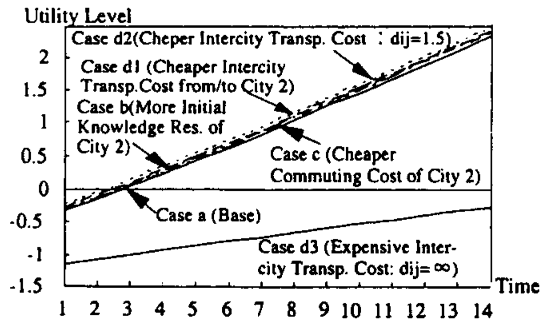

Fig. 8. Utility growth paths

stocks and knowledge resources are accumulated. Compared with case a, the case where the investment to the high-speed railway is made enjoy higher levels of the equilibrium utility.

It should be noted that, in the model, initial profiles of population and capital stocks show no substantial impacts upon the subsequent economic development of the city system. On the other hand, the spatial distribution of knowledge resources and intra/inter-city transportation technology are unquestionably crucial for the change of economic geography. The investment to the high-speed railway systems can guarantee the increase of utility levels of the households. When inter-city communications are forbidden, learning-by-doing is the only means for knowledge creation, and economic growth is largely discouraged when compared to the case where inter-city knowledge exchange are allowed. The spatial structure of the rapid railway network is very decisive in determining the economic structure of the city system. With the hub-type of railway network, the growth of the hub-city is encouraged, while the non-hub-oriented network structure may result in much more decentralization of population, knowledge, and capital. In the extreme case (case d_2), the city system exhibits ubiquitous growth patterns. This ideal case d_2 shows the fastest growth of the equilibrium utility levels thanks to the ideally organized high-speed railway networks. Needless to say, these findings are only valid for the hypothetical illustration taken up in this paper. The more realistic conclusions are reserved for future case studies.

5. Conclusion

This paper proposed a dynamic multi-regional growth model with free mobility of capital and population to investigate the short- and long-run impacts of the high-speed railway systems upon the economic geography of city systems. The model describes a dynamic interdependence between capital and knowledge accumulation, wage and land rent structures, urban patterns with endogenous city size and inter-city interactability. It is emphasized how differences in geographic and qualitative factors of high-speed railway systems may affect the evolving processes of economic geography. The model can simulate the dynamic processes of economic development of city systems.

It is important to note that only one sector economy without international trades has been analyzed. However, the models may be extended in different ways. It is important to examine the impacts of international trade upon economic geography. It is also possible to extend the model to a multiple sectors case, though analytical difficulties may be greatly increased. The models may also be simulated with various combinations of the policy parameters.

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