Effect of Road Infrastructure on Urban System

Lee, Woohyung
Faculty of Economics, Kyushu University

Arakawa, Kiyoshi
Department of Civil Engineering, Kyushu University

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Woohyung Lee* and Kiyoshi Arakawa**

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1 . Introduction

Urban Economists have devoted to analyze the system of cities theoretically over the last two decades or so. Henderson (1974) argued that an equilibrium or optimal city size is reached when the marginal social benefits due to economies of scale equal the marginal social costs due to diseconomies of scale such as increased housing and commuting costs, and showed that the hierarchical urban system of cities are formed. Abdel-Rahman (1988) introduced the monopolistic competition model developed by Dixit and Stiglitz (1977), and applied increasing return to scale to urban system model. Tabuchi (1998) combined the monopolistic competition model with the location theory [Alonso (1964)], and showed the impacts of transportation cost decrease on urban concentration and dispersion in a two-city system framework. Because of ignoring a spatial distribution of cities, these types of models do not provide explanation for the spatial hierarchy of cities.

On the other hand, central place theory [e.g., Christaller (1966), Losch (1954)] explains the system of cities spatially. While this theory shows hierarchical distribution of cities, it lacks the economical foundations. More precisely, this type of model cannot show how the distribution of cities emerges from the economic interaction of families or firms. Whereas Wang (1999) improved the central place theory by introducing economic factors such as consumption and production, this research do not provide an urban growth such as emergence of new cities.

Fujita and Mori (1997) and Mori (1997) analyzed the spatial formation of urban system by using monopolistic competition theory. Their research had economic foundations and clarified the spatial urban growth with hierarchical distribution of cities such as central place theory.

* Faculty of Economics, Kyushu University
** Department of Civil Engineering, Kyushu University

However, their model explained how differentiated products affect urban growth, it lacks how a road infrastructure exerts agglomeration force for urban system. In this paper, we add a road infrastructure radiating from cities in all direction in Fujita-Mori model, and shows that the agglomeration force of cities increases with the number of roads.

This paper is organized as follows: next section discusses the model, and section 3 explains how the road infrastructure affects the urban growth, numerically. In Section 4, we discuss the social welfare of the urban systems. Section 5 offers concluding remarks.

2. The model

We suppose that the economy lies on a homogeneous land, and has a continuum of homogeneous workers of size N, each of which is endowed with a unit of labor. The workers can be either manufacturing workers (M-workers) or agricultural workers (A-workers). M-workers live in cities whose sizes are fixed, and A-workers live in agricultural hinterlands surrounding the cities. We also assume that the spaces for workers' living can be ignored. The consumers can also be workers or landlords, where the former can choose their locations freely and jobs while the latter are attached to their land. Each consumer has the same taste and consumes a homogeneous agricultural good (A-good) and a continuum of differentiated manufactured goods (M-goods) of variety size n. The utility function of a consumer is given by

$$U=z_A^{\alpha_A}\left(\int_0^n z_M(\omega)^\rho d\omega\right)^{\alpha_M/\rho}, \tag{1}$$

where z_A is the amount of the A-good consumed; $z_M(\omega)$ is the consumption density of the M-good indexed by $\omega\in[0,\ n]$; α_A and α_M are the expenditure shares of the A-good and the composite of M-goods satisfying $\alpha_A+\alpha_M=1$; and $\rho\in(0,\ 1)$ is a substitution parameter. Each consumer maximizes his utility subject to the budget constraint given as

$$p_A z_A+\int_0^n p_M(\omega)z_M(\omega)d\omega=Y, \tag{2}$$

where Y is nominal income and p_A and $p_M(\omega)$ are set of prices for $\omega\in[0,\ n]$. Maximizing the utility function under the budget constraint, we get demand functions of A-good and M-goods and indirect utility functionsas follows;

$$z_A=\alpha_A Y/p_A, \tag{3}$$

$$z_M(\omega)=\frac{\alpha_M Y}{p_M(\omega)}\frac{p_M(\omega)^{-\gamma}}{\int_0^n p_M(\omega)^{-\gamma}d\omega} \text{ for each } w\in[0,\ 1], \tag{4}$$

$$U=\alpha_A^{\alpha_A}\alpha_M^{\alpha_M}Y/\left\{p_A^{\alpha_A}\left[\int_0^n p_M(\omega)^{-\gamma}d\omega\right]^{-\alpha_M/\gamma}\right\}, \tag{5}$$

where $\gamma=\rho/(1-\rho)$;. Equation (4) implies that each M-good has the same price elasticity given by $1+\gamma$, and equation (5) means that the utility of consumers rises with the variety size, n, of

M-goods. The production of A-good is subject to the Leontief technology requiring a_A units of labor and one unit of land to produce one unit of output, and is taken place in the hinterland of the cities. The production of each variety of M-goods uses only labor as an input factorand exhibits increasing return to scale. Then, the total labor input, L, for producing Q units of any M-good is given by $L=f+a_M Q$, where f and a_M are the fixed and the marginal labor inputs, respectively. Because of scale economies in production, a single firm produces each M-good. The transport cost for each good is assumed to take Samuelson's iceberg form: if a unit of i-good ($i=$AorM) is shipped over the distance d, only a fraction, $e^{-\pi_i d}$ -units, actually arrives. It follows that if an M-firm locating at x chooses an f.o.b. price $p_M(x)$, the delivered price of this good at location y is given by

$$p_M(y/x)=p_M(x)e^{\tau_M|y-x|}. \tag{6}$$

The profit-maximization condition for each firm acting on its own is the familiar equality of marginal revenue and marginal cost. By using the price elasticity, $1+\gamma$, we have each active firm:

$$p_M\left(1-\frac{1}{1+\gamma}\right)=a_M W(x), \tag{7}$$

and we obtain the prices of M-goods as

$$p_M(x)=a_M W(x)/\rho, \tag{8}$$

where $W(x)$ is the wage rate at x. Let the demand of M-goods, Q, the profit of the M-firm locating at x can be written as

$$\pi(x)=p_M(x)Q-W(x)L=a_M\gamma^{-1}W(x)(Q-\gamma f/a_M). \tag{9}$$

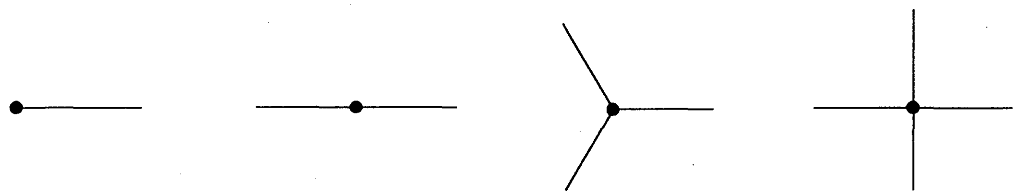
Since each firm earns zero profit in equilibrium, the output of each M-firm, Q^*, is a constant independent of location and is given by

$$Q^*=\gamma f/a_M. \tag{10}$$

The equilibrium labor input of each M-firm is then also a constant given by

$$L^*=f(1+\gamma). \tag{11}$$

Suppose that all the M-goods are produced in the single city at $x=0$ whose agricultural hinterland lies on the ν roads radiating form the city in all direction, and those lengths are l. Because directions are not concerned and roads have no hierarchy, we determine one road as a



(a) 1-road system (b) 2-road system (c) 3-road system (d) 4-road system

Figure 1 Urban road Systems

base-road and the others as sub-roads arbitrarily, and suppose that the base-road and the sub-roads are on the interval $[0, l]$ and $[-l, 0]$, respectively. Figure 1 explains the urban system. In the figure, dots mean the central cities, and the lines radiating from the dots, the central cities, are roads. By using the number of roads radiating from the central city, ν, we call the urban system as ν-road system as shown in figure 1.

Since all the excess A-good on the agricultural hinterland is shipped to the city, the price of A-good at each location is given by

$$p_A(y)=e^{-\tau_A|y|} \tag{12}$$

where $p_A(0)$ is normalized to be 1. The land rent at each location is then given by

$$R(y)=\max\{p_A(y)-\alpha_A W(y),\ 0\}, \tag{13}$$

which ensures zero profit of the A-good production. Since the land rent at the agricultural fringe (A-fringe), l, is 0, then $e^{-\tau_A l}=\alpha_A W(l)$ by (13), i.e., we have the A-fringe wage, $W(l)=\alpha_A^{-1}e^{-\tau_A l}$. Substituting the delivered price at location y of each M-good produced in the city, $p_M(y|0)=(\alpha_M W(0)/\rho)e^{\tau_M|y|}$ [by (8)] for $p_M(w)$, and (12) for p_A in (5), and using the A-fringe wage obtained above, the equilibrium wage rate at y, given the A-fringe distance l, can be obtained as

$$W(y)=\alpha_A^{-1}e^{-\alpha_M(\tau_A+\tau_M)l}e^{(\alpha_M\tau_M-\alpha_A\tau_A)|y|}\ \ for\quad y\in[0,\ l], \tag{14}$$

which ensures the equal utility level of workers at each location y $y\in[0, 1]$.

Next, since the number of A-workers, N_A, is given by $\nu\alpha_A l$, the number of M-workers in the city, N_M, can be obtained as $N_M=N-N_A=N-\nu\alpha_A l$. Agricultural fringe, l, can be obtained from the A-good market-clearing condition as follows. By (3), the excess supply of the A-good per unit distance at each y in the A-hinterland equals $1-[\alpha_A Y(y)/p_A(y)]=1-\alpha_A=\alpha_M$[where $Y(y)=\alpha_A W(y)+R(y)=p_A(y)$ by (13)]. Taking into account the fraction of the A-good consumed in transportation, the net supply of the A-good from the A-hinterland to the city is given by

$$\alpha_M\nu\int_0^l p_A(y)dy=\nu\alpha_M(1-e^{-\tau_A l})/\tau_A. \tag{15}$$

On the other hand, the demand for the A-good at the city equals $\alpha_A W(0)N_M$. Hence, using (14), the market-clearing condition for the A-good is given by

$$(\alpha_A/\alpha_A)e^{-\alpha_M(\tau_A+\tau_M)l}(N-\nu\alpha_A l)=\nu\alpha_M(1-e^{-\tau_A l})/\tau_A. \tag{16}$$

By (16), the equilibrium fringe distance, l^*, is determined uniquely, and it shows that l^* is depends on population N. If we define that $l^*=l^*(N)$, it is continuously function of N.

Finally, in order to derive the location equilibrium condition, suppose that an M-firm locates at x, and let $D(x)$ be the total potential demand for the product of this firm from the entire economy. Then, by substituting $D(x)$ for Q in (9), and using (10), the potential profit of this firm is given by

$$\pi(x)=\alpha_M\gamma^{-1}W(x)(D(x)-Q^*). \tag{17}$$

Above equation implies that $\pi(x)\geq 0$ as $D(x)\geq Q^*$ and $\pi(x)<0$ as $D(x)<Q^*$. If we define the market potential function of the M-industry by

$$\Omega(x)=D(x)/Q^{*}, \tag{18}$$

$\pi(x)\geq 0$ as $\Omega(x)\geq 1$ and $\pi(x)<0$ as $\Omega(x)<1$. Thus, the location equilibrium condition is satisfied if

$$\Omega(x)\leq 1 \quad \text{for all } x, \text{ and } \Omega(0)=1, \tag{19}$$

Using (2), (4), and (6), the potential value for an M-firm at each location x ca be calculated as

$$\Omega(x)=\frac{(1-\rho)/f}{W(x)^{\gamma+1}}\left\{\frac{a_M W(0)N_M}{nW(0)^{-\gamma}}e^{-\gamma\tau_M|x|}+\int_0^1\frac{a_M p_A(y)e^{-\gamma\tau_M|y-x|}}{nW(0)^{-\gamma}e^{-\gamma\tau_M|y|}}dy+(\nu-1)\int_{-l}^{0}\frac{a_M p_A(y)e^{-\gamma\tau_M|y-x|}}{nW(0)^{-\gamma}e^{-\gamma\tau_M|y|}}dy\right\}. \tag{20}$$

Each term in (20) can be interpreted as follows: $1/W(x)^{\gamma+1}$ represents the labor-cost advantage of the production of location x; $a_M W(0)N_M\equiv a_M Y(0)$ the market size for M-goods at the city; $e^{-\gamma\tau_M|x|}$ the accessibility of the production at location x to the market at the city; and $nW(0)^{-\gamma}$ the intensity of competition in the M-good market at the city. Thus, the profitability of an M-firm at each location depends on three elements: the labor-cost advantage (i.e., the wage pull), the market size and accessibility (i.e., the demand pull), and the intensity of competition at that location. It can be observed in the potential function (20) that by (14), the wage pull enhances the agglomeration force toward the city when the transportation cost of M-good is relatively high, i.e., $a_M\tau_M>a_A\tau_A$, otherwise it works as a dispersion force (except for a nongeneric case with $a_M\tau_M=a_A\tau_A$); there always exist the demand pull toward the city and that toward the A-hinterland; the intensity of competition becomes weaker as the M-firm moves toward the A-hinterland.

3. Impact of road infrastructure on urban growth

It can be inferred that there are close relationship between road infrastructure and urban growth. In generally, when an economy forms a monocentric urban system containing a small city and agricultural hinterland, i.e., the early stage of urban development, the patterns of road infrastructure are radial such as hub (city) and spoke (road). This is because that the most important factor for planning road construction in a monocentric urban system is connectivity between central city and small town in an agricultural hinterland. In the later stage, urban system has larger population as economy grows, and it needs a construction of belt highway. The reasons for this are population explosion, congestion of car traffic, and emergence of frontier new cities. For the formation of new cities, it is needed especially that not only road infrastructure between central city and frontier cities such as radial pattern, but also road networks among frontier cities such as beltway highway pattern. The ideal road infrastructure varies both qualitatively and quantitatively according to the developmental stages of urban growth. We explain, thus, how the constructions of radial road infrastructures affect urban growth in the early stage of urban development. The model is a nonlinear system of equations, and because of the complexity of the model it is impossible to obtain closed-form mathematical solutions.

Therefore, numerical methods are used to solve the model given set of exogenous parameters[1].

3.1. The monocentric urban system

There are many patterns of road infrastructure in a monocentric urban system as Figure 1. We show the agricultural fringe, l, and location of new frontier cities, e, at the time of Ω becomes one, i.e., just before the emergence of new cities. In other words, we consider the maximized population for each urban system. We also explain how the population of city residents (M-workers) and agricultural hinterland residents (A-workers) changes. For example, the potential curves for 3-road urban system are shown in Figure 2. As illustrated in the figure, if the population is small, i.e., $N=6$, the potential curve cannot be larger than one. That is, the population is small enough to emerge new cities. On the other hand, when the population reaches 8.8, the potential curve comes to one, and new cites emerge at $x=1.39$. Figure 3 shows the relations between l and e, and the number of roads radiating from the city, and it shows that both l and e increases as the number of roads logarithmically. The relations between N and L_m, and the number of roads are shown in Figure 4. It is quite different from Figure 3, and also represents both N and L_m increase exponentially as the number of roads. Therefore it can be said that, as the number of roads increases, total number of M-worker increases rapidly, i.e., urban concentration proceeds dramatically. Total population of city, N, is 0.95 when the number of roads is one, and N is 60.3 when the number of roads is 10, that is, the population gets 63.5 times larger. The increase of the number of roads brings the increase in the supply of lower priced

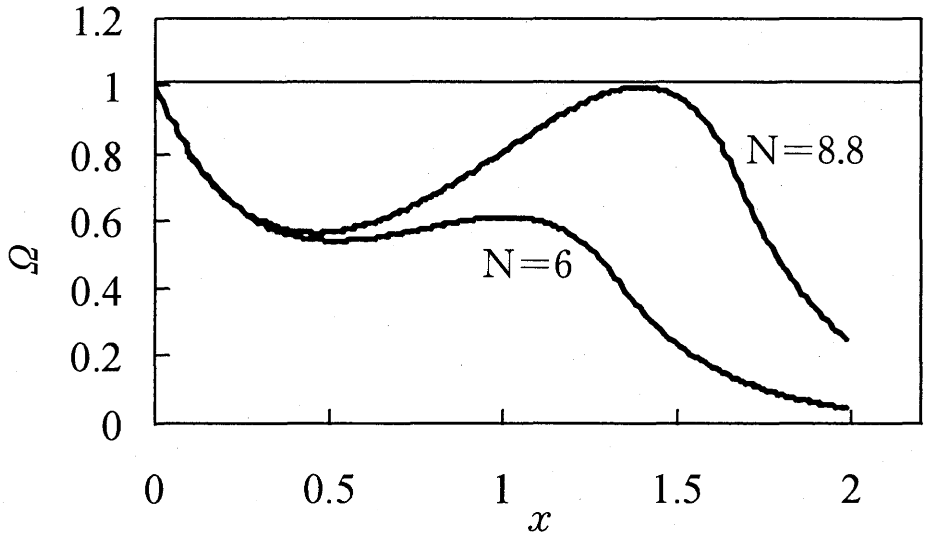


Figure 2　Potenitial curves of 3-road urban system

1) The set of parameters are $\alpha_A=\alpha_M=0.5$, $\tau_A=0.8$, $\tau_M=1$, $\rho=0.75$, (i.e., $\gamma=4$), and $\alpha_A=0.5$.

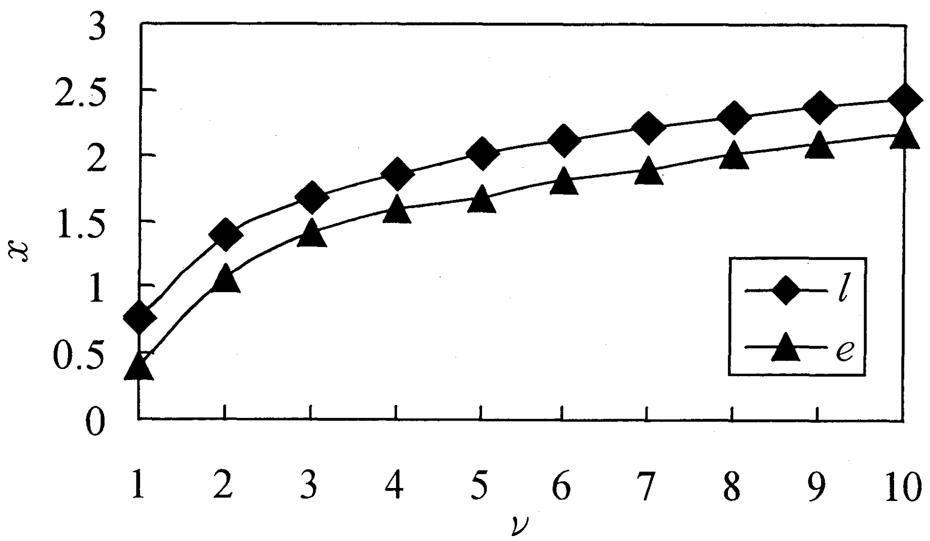


Figure 3 Agricultural fringe and location of new cities

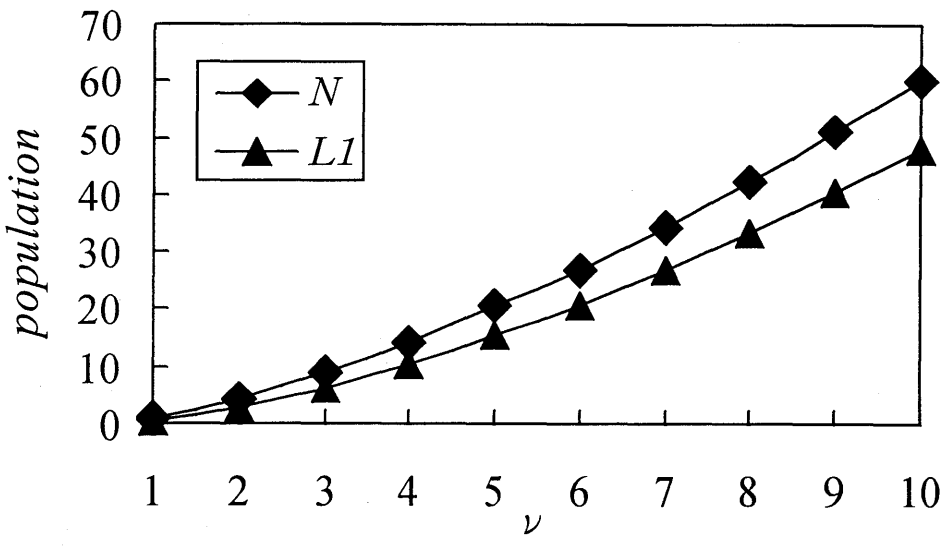


Figure 4 Total population and urban population

agricultural goods because of the accessibility to agricultural hinterland becomes better, and this causes the decrease in price index, and also improves the productivity of manufacture goods, and results in the population growth of M-workers. Figura 5 shows the relation between a ratio of the number of M-workers to that of A-workers and the number of roads. It represents the mechanism of urban growth. That is, the increases of M-worker, i.e., the increase of variety size of differentiated manufactured goods, decrease not only the price index of M-goods, but also

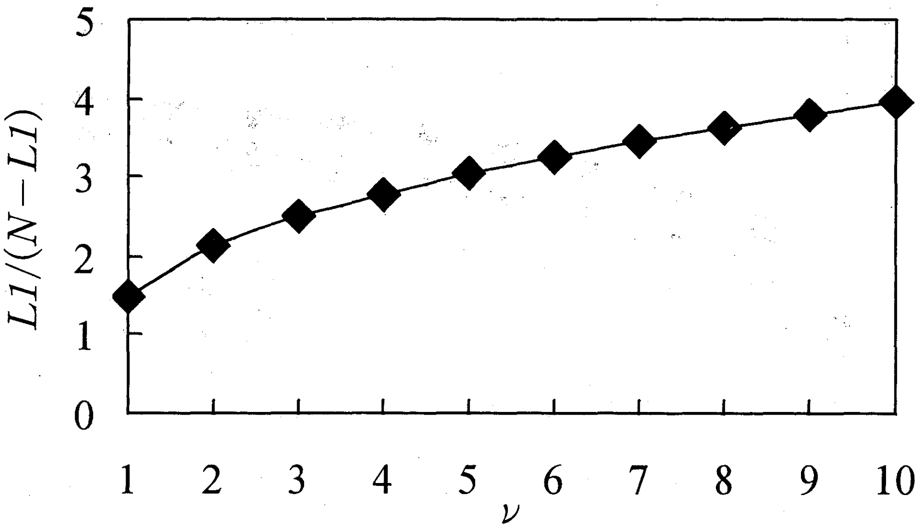


Figure 5　Ratio of population of city to rural area

relative price of M-goods to A-goods. This increases the demand for M-goods, and also increases the number of M-workers. Since the construction of road infrastructure increases close agricultural hinterlands, M-workers need not to buy A-good from distant agricultural hinterlands, that is, agricultural fringe, l, increase slightly. The location of the new frontier cities, e, increases with the number of roads, and with the growing urban population, new cities emerge at further location from the central city.

3.2. The emergence of new cities

In section 3.1., the monocentric urban system was just before the emergence of new frontier cities. Immediately after the transference of small M-workers to the location, e, new cities emerge and grow until the equilibrium of economy between the central city and the new cities becomes stable. Figure 6 describes the potential curves for 3-road urban system, and figure 7 describes the relations between each population and the number of roads. L_1 and L_2 are the population of central city and new cities, respectively. From the figure 7, it can be found that the exponential increase in N and L_1, and relatively low increase in L_2. Though L_2 is larger than L_1 when the number of roads is two, L_1 becomes larger than L_2 with increase in the number of roads, and the difference between L_1 and L_2 becomes larger rapidly. From the relation between the population of central city residents and the total of that of new cities as shown in Figure 8, urban concentration gets proceeded with the construction of the road infrastructure. The reason for this is that the improvement of connectivity between central city to new cities and agricultural hinterland makes productivity of central city increased.

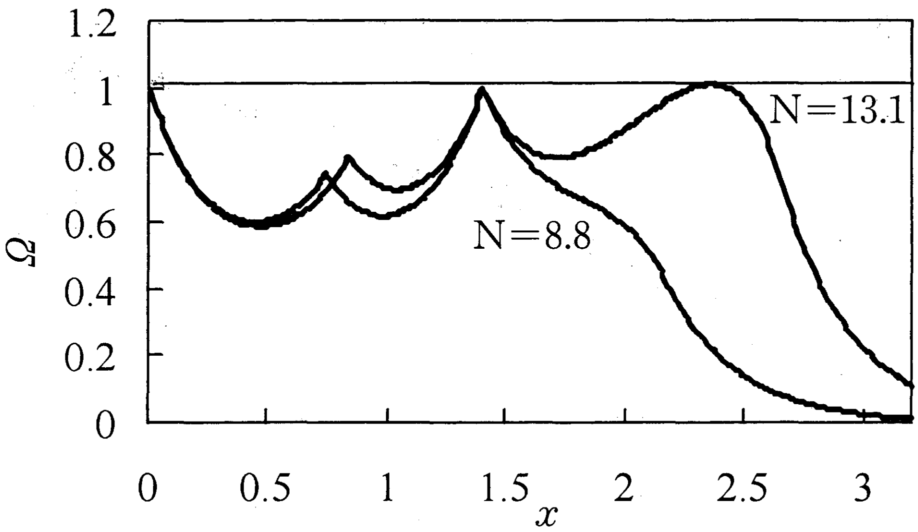


Figure 6 Potential curves of 3-road urban system

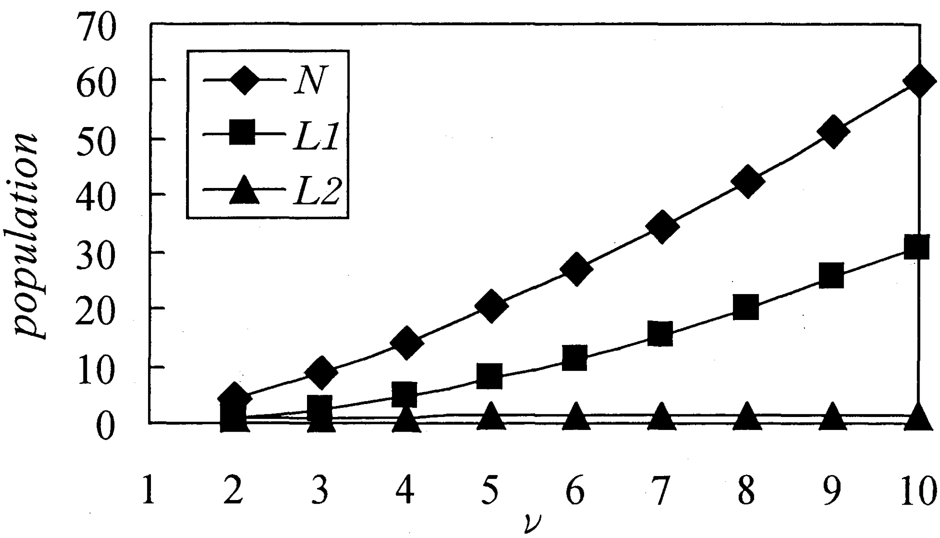


Figure 7 Population of just after the emergence of new cities

Next we consider the population growth. It is convenient to consider that the population just before the emergence of new frontier cities. For example, Figure 6 shows the potential curve of 3-road urban system, and when the population, N, is 13.1, the potential curve reaches one at $x=$ 2.4, that is just before the mergence of new cities. As population grows, the rate of population increase in the frontier cities gets smaller with the number of roads as shown in Figure 9. That is, the difference between population of the frontier cities just after the emergence, L_2min, and

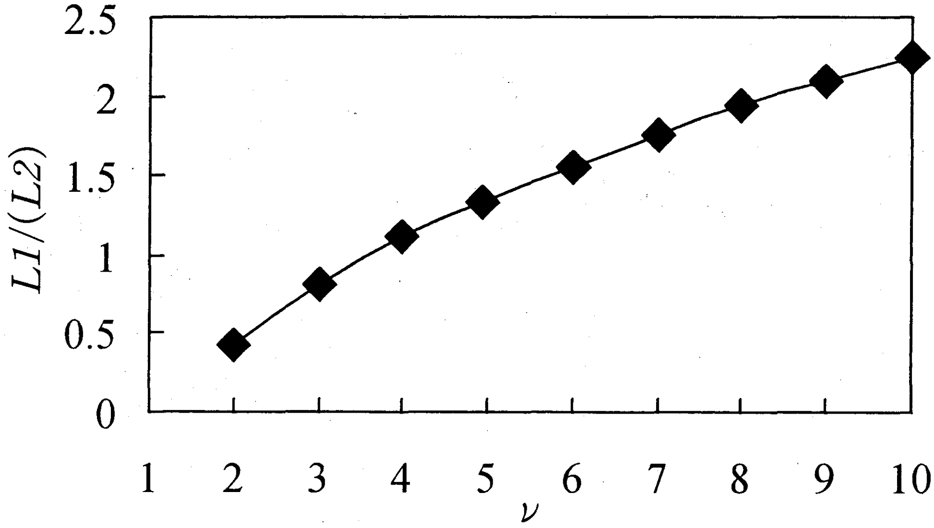


Figure 8　Ratio of population of central city to new cities

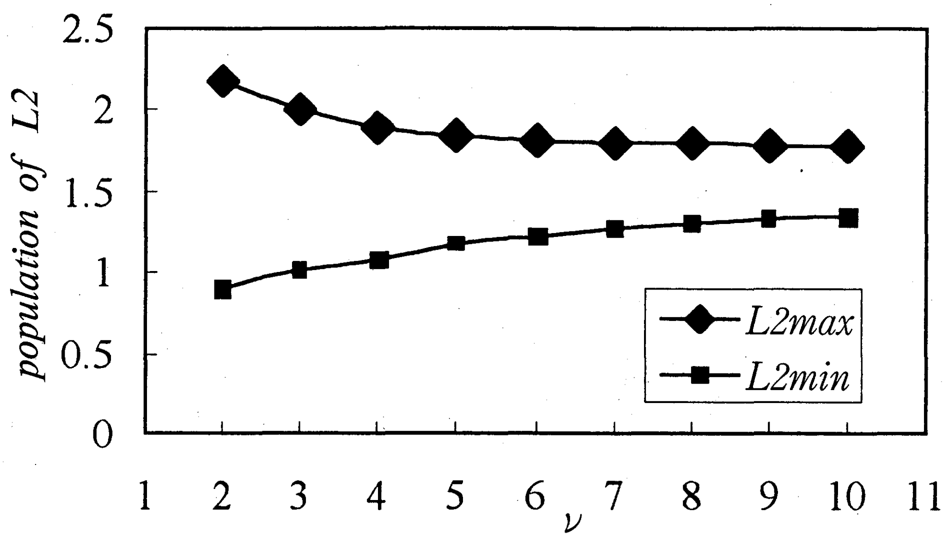


Figure 9　Population of new cities

just before the emergence of next frontier cities, L_2max, gets small as the number of roads get larger. Because the productivity of the central cities is large relative to the frontier cities as the construction of roads, growth of population of urban system contributes the growth of the central city rather than frontier cities. That is, if the number of roads radiating from central city is small (large), productivity of central city is also small (large), and the frontier cities get larger (smaller) relative to central city. As shown in Figure 9, the frontier cities become smaller, the numbers of roads radiating from the central cities become larger. This relation shows the recent trends of concentration of population and many activities in the central city, and also the depression of small cities or rural hinterlands.

4 . Road infrastructure on social welfare

We analyzed the urban growth brought by the construction of the road infrastructure from the view of the population and the productivity of city in the former chapter. In this chapter, we clarify the impact of road infrastructure on social welfare of residents.

Traffic congestion brought by the popularity of having own car decreases the welfare of people living in a city, and furthermore becomes to be a pollution especially near the arterial highway. Moreover, the problems of overpopulated in a central city or underpopulated in a local city are crucial in a study of urban growth. One of the reasons for these phenomenons is an existence of externality. Under the existence of externality, the market will not necessarily in a Pareto efficient provision of resources, and then social instruction such as government intervention is needed. Although regulations, especially city planning, are expected to play important parts in dealing with the urban externalities, city planning is practically decided with considering sorely on the smooth traffic flows not on the urban externalities that might have heavy influence on urban system. It is crucial to consider the welfare of residents through the urban externalities at the stage of planning a construction of road infrastructure.

In the next section, we define the overall social welfare of the economy, and analyze the effect of road infrastructure on the social welfare. We also propose a direction of optimal construction of road infrastructure.

4.1. Social welfare of monocentric urban system

In this section, we clarify the relation between road infrastructure and social welfare under the monocentric urban system. We define the total real land rent *(TRLR)* as follows;

$$TRLR=2\int_0^l R(y)/W(y)dy. \tag{21}$$

TRLR is the sum of land rents normalized by the equilibrium wage rate at each location. Since each income of $W(y)$ at location y yields an equilibrium utility of u^* for a worker there, $R(y)/W(y)$ represents the welfare measure of landlords at y in terms of u^*-units. Hence, *TRLR* represents the aggregate welfare measure of all landlords in terms of u^*-units. By using *TRLR,* the overall social welfare of the economy is defined by

$$SW=Nu^*+TRLRu^*. \tag{22}$$

To make the analysis simple, we use the social welfare per capita made of dividing the social

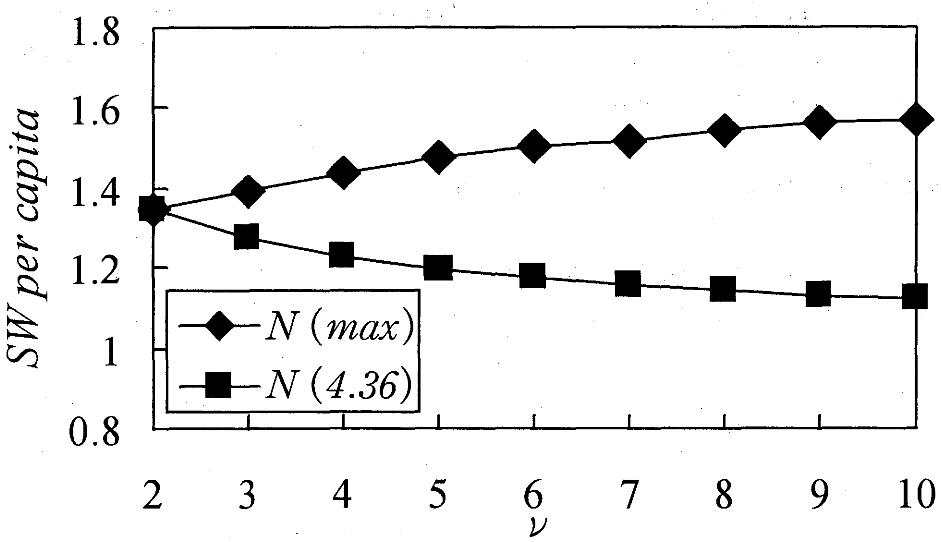


Figure 10　Social welfare under the monocentric urban systems

welfare by the overall population of urban system.

First, we analyze the social welfares per capita of the urban systems under the constant population, 4.36, the maximum population of 2-road system under the monocentric urban system. Figure 10 shows the relationship between the social welfare per capita and the number of road. Under the constant population, and it is clarified that the social welfare per capita increases with the number of road. The reasons for this relation are as follows. Because increase in the number of road enables the supplying lower priced A-goods for the hinterland, the price index of A-goods in city is decreased. In other words, the real wages of the city residents, M-worker, are increased. Hence, the increase in real wages of city residents or decreasing in price index of A-goods make the social welfare per capita increased under the constant population.

Next, we analyze the monocentric urban systems just before the emergence of new cities. The relation between number of road and the social welfare per capita is shown in Figure 10, and the figure shows that the increase in the number of road decreases the social welfare per capita. In other words, if the population of city becomes larger as a result of road construction, the social welfare of city residents decreased. The reason for this phenomenon is as follows. As shown in the former chapter, the productivity of city rises with the increase in the number of road, and as a result the population of city residents also increases. The increases in the population of city residents raise the demand of A-goods, and then the price index of A-goods is increased. This causes the real wages of city residents, M-worker, decreases, and the social welfare per capita is also decreased. Hence, is can be said that the productivity of city brought by the road construction and the social welfare is under the trade-off relationship.

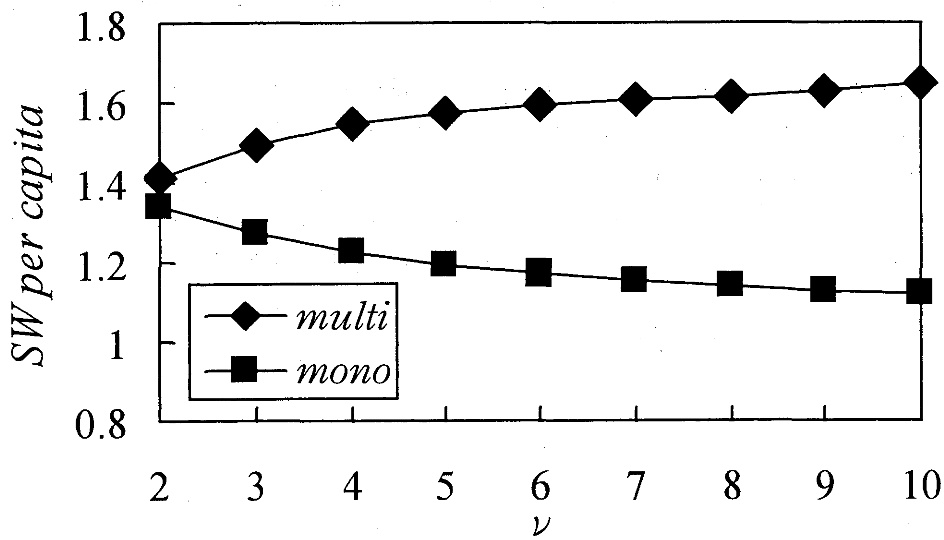


Figure 11 Social Welfare under the multiple urban systems

For the reasons mentioned above, it is clarified that the construction of road infrastructure decreased the price of A-goods, and the social welfare is increased. On the other hand, the increase in the population brought by the construction of road infrastructure also increases the demand for A-goods, and raises the price of A-goods. Consequently the real wage of city residents, M-worker, is decreased, and then the social welfare also decreased. Thus, to increase the social welfare, it is important to construct the road infrastructure, and to restraint the population by the government intervention such as the urban growth control.

4.2. Effect of emerging new cities on social welfare

As shown in the chapter 3, when the potential function, Ω, reaches one, the new cities emerge on the roads emanating form the central city. In this section, we analyze the impact of the emergence of the new cities on the social welfare.

Figure 11 shows the social welfare per capita just after the emerging of the new cities, and it is clarified that the emergence of new cities increases the social welfare. The reason for this phenomenon is as follows. There are moves of people from the central city to the new cities, when the new cities emerged. Hence, the residence of new cities can buy the lower priced A-goods because of the lager hinterland, and then the social welfare increases with the increase in their real wages. It is also clarified from the figure 11 that the ranges of increase in the social welfare are broadened with the number of road. This is because that the migration from the overpopulated central city brought by the road infrastructure to the emerging new cities raises the real wage of residents. It can be conclude that the large overpopulated cities such as Tokyo can be benefited from the policy dispersing the overpopulation of the central city to peripheral cities.

With considering the former section, we can conclude as follows. Construction of the road infrastructure decreases the price index of A-goods, and, as a result, the social welfare increases. Since the increased population brought by the road construction decreases the social welfare, it is necessary to restrain the population at the optimal level. In other word, the policy of urban growth control can play an important role in maintaining optimal social welfare. When the new cities emerge at the periphery, the overpopulation can be dispersed to the new cities, and then the social welfare increases. Then the policy stimulating the migration can maintain the social welfare.

5 . Conclusion

In this paper, we added the road infrastructure to the urban system model [Fujita and Mori (1997)], and analyzed how a number of roads radiating from central city affects the urban growth. As a result, we showed that at the early stage of urban formation, i.e., monocentric urban structure, construction of roads makes productivity of city increased, and it also increased the population of city rapidly. Because of increase in population of city, new frontier cities emerge, and the location of emergence of cities is farther from central city as the number of roads increased. Though increase in population of frontier cities was not so large, that of central city was quite large. This result represents the current serious problem of urban concentration and decrease in population of rural area. This is because that the construction of roads improves the connectivity between central cities and rural area, and, though it gives rural area some benefits, it increases productivity of central city, and it also stimulates the urban concentration. As population grows, population of the central city gets larger, and that of the frontier cities gets smaller with the number of roads. This model showed that the construction of road infrastructure is not always effective in measures of stimulating rural economy. In section 4, we showed by analyzing the social welfare that the benefit of road construction is larger, the number of roads increases. That is, the construction of road infrastructure is more effective in the large overpopulated cities, such as Tokyo, than in small cities.

Because of assuming that the city has no space, this model cannot consider the traffic congestion. Introducing traffic congestion into our model would explain the mechanism of dispersion force of urban formation, and it also gives us optimal construction of road network.

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