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# A WELFARE ANALYSIS OF A SYSTEM OF CITIES IN TRANSPORT NETWORK

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## Abstract

This paper shows first a general framework and some examples of analyzing a system of cities with interregional transport network. Second, the impact of interregional transport improvement on the structure of a system of cities, or population distribution in the system is examined to derive some political implications for nationwide spatial planning. Third, changes in population distribution in a system of cities caused by transport improvement are evaluated in terms of social welfare.

## Prize

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# INTRODUCTION

## Most serious issue in nationwide spatial planning

Intercity competition is now becoming a key in the context of the unification of European countries, globalization of economy. A city in a network should compete with each other to attract firms and population to sustain regional economy and society under more severe constraints than ever experienced before.

On the other hand, unbalanced distribution of population has been the most serious issue in nationwide spatial planning. Over-agglomeration in metropolitan area results in urban issues such as congestion, environmental pollution and so on, while poor agglomeration in the peripheral regions leads to underdevelopment in economy and to cheerless atmosphere in society.

Not only from such a viewpoint, also from that of environmental challenges against the greenhouse gas problem, we have to think of the spatial structure of a nationwide system of cities. In other words, we should seek for the structure of a system of cities that generate less environmental loading such as $CO_2$ emission.

The improvement of interregional transport system has been in the list of policy options to realize the well-balanced distribution of population among cities. However, we don't have any proof that the improvement of interregional transport system never fail to contribute to the favourable structure of a system of cities from the point of national welfare.

## Purpose and organization of this paper

Because of the above reasons, first, this paper aims at showing a general framework and some examples of analyzing a system of cities with interregional transport network. Second, the impact of interregional transport improvement on the structure of a system of cities, or population distribution in the system, is examined to derive some political implications for nationwide spatial planning. Third, changes in population distribution in a system of cities caused by transport improvement are evaluated in terms of social welfare.

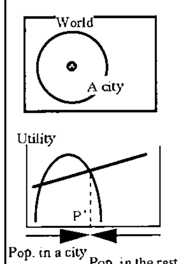
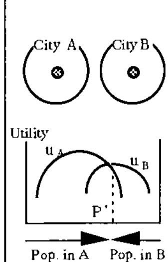
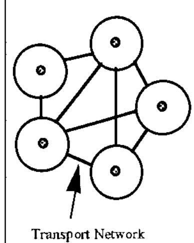
This paper is organized as follows. We briefly overview the state of the art and then we show a model which is developed for the above purpose. Next, we illustrate some interesting structures of a system of cities to make properties of the system more visible. In the following section, we attempt at the impact analysis of interregional transport improvement, then in the next section, the impacts on population distribution are evaluated from the point of social welfare. Finally, we summarize the paper.

## Overviewing the state of the art and research strategy in this paper

A lot of theories on a system of cities have been developed in recent decades. The streams of the studies can be summarized as follows. After the age of empirical analysis of city size distribution resulting in a finding like Rank Size Rule or Hierarchy of cities, the first stream was sprung from the development of the aggregate city model (say, Henderson (1974)). Starting from Alonso's monocentric city model or from many assumption simplifying spatial coverage of a city, the realized level of utility was derived as a function of the population size in a city (say, Abdel-Rahman (1991)). Along this line of thought, agglomeration economy such as increasing return to scale or Marshallian externality in basic industry has been introduced to explain the emergence of a metropolis in a system of cities (say, Kanemoto (1991), Kanemoto (1994)). However, the models in this stream have not considered interregional transport explicitly, although the c.i.f price of exported goods sometimes reflected interregional freight cost as an exogenous variable. In impact analysis of policy options, they have dealt only with a intra-city infrastructure or local public goods. Thus, the first stream of modeling has not been able to analyze the impact of interregional transport improvement.

The second stream of modeling, sprung in recent years, has been developed with a setting of spatial price equilibrium (SPE) and location equilibrium (say, Krugman (1991a), Ueda (1993), Fujita and Krugman (1993)). This deals with interregional transport cost explicitly in either demand or supply functions, and therefore, is available for the impact analysis of interregional transport. However, models in the stream are still too restrictive to generate a variety of structural patterns in a system of cities, because they have focused on each interesting channel through which agglomeration economy emerges in a city. These streams in spatial economics or in regional science can be summarized in Table 1.

**Table 1 Transition of modeling of a system of cities**

| | 60s | 70s | 80s | 90s |
|---|---|---|---|---|
| Outline of the models | A system of a city  | A system of a city and the rest  | A system of two cities  | A system of cities  |
| Papers | Alonso (1963) etc.. | Henderson (1974) etc. | Fujita (1989), Kanemoto (1988), Sakashita (1985), etc.. | Fuita & Krugman (1993) Fujita (1993), Ueda (1993), etc.. |
| Factors considered | · Intra-city Transport | · Agglomeration Economy | · Agglomeration Economy · Intra-city infra · Intercity income transfer | · Agglomeration Economy · Intra-city infra · Inter-city Transport |

Beside the above two streams, there are the other streams in regional science or in geography related to a system of cities, such as migration theory (say, Hagg and Weidrich (1990)). However, they seem to be interested in the process of forming the structure of a system of cities rather than in the structure itself.

Judging from the state of the art in related fields as mentioned above, we should first try to build a general framework of modeling a system of cities where a lot of patterns of the structure can be generated according to the interregional transport system. Then, we should examine typical impacts of transport improvement on a system of cities, in particular, the question whether or not it results in the dispersed structure.

# MODEL

## Types of behavior and equilibrium in a system of cities

It goes without saying that behavior and equilibrium are important keys in any modeling of spatial economic system. Economic agents in a spatial economy has three types of behavior: Location choice behavior, Consumption and production behavior, and Transport (Trip) behavior. These are formulated as mathematical programming representing utility (profit) maximization. We can define three types of equilibria in the system: Location equilibrium, Market equilibrium, and

Transport Equilibrium, according to types of behavior. They are the states where no economic agent has an incentive to change their choice because of no possibility for better-off. From the purely theoretical point of Game Theory, these equilibria are nothing but Nash equilibrium. The interdependency between three types of behavior and therefore between equilibria can be conceptually shown in the Figure 1.

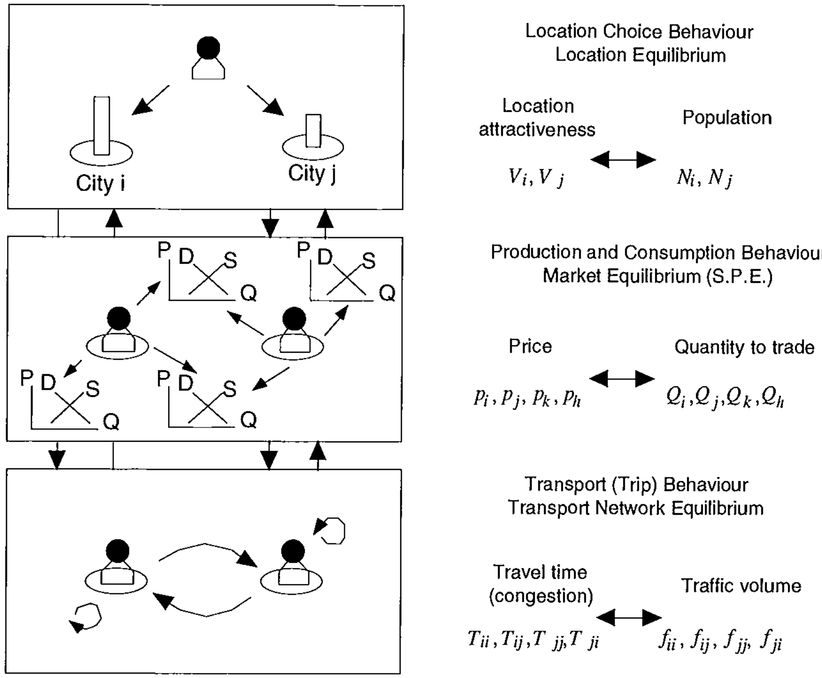



**Figure 1 Behaviour and equilibrium in a spatial economy**

For the purpose of this study, we need only the location attractiveness as a function of population distribution, interregional transport cost, and some other exogenous variables denoting locational attributes. If we have the function, then we only focus only on the location choice behavior and location equilibrium, without considering other behaviors and equilibria explicitly (see Ueda et al. (1992).) However, it is too difficult for us to solve conditions of market and transport equilibrium analytically in order to get the explicit function for the location attractiveness. Then, in this paper, we are going to specify the function without discussing the conditions for market and transport equilibrium explicitly, but with some empirical interpretations.

## Major assumptions

In this paper, we assume:

1. A system consists of $I$ cities labeled by $i = 1, \cdots, I$ and locating at nodes in an interregional network of a single transport mode. $i$th city has the population $N_i$ and total population $N_T$ in the system is exogenous.
2. Each individual chooses his/her city to locate, where he/she can enjoy the highest location attractiveness. However, since he/she faces uncertainty of location (city's) attractiveness, their choice is stochastic.
3. In equilibrium state in a system of cities, no individual has an incentive to relocate, because he/she has no hope to enjoy higher attractiveness in other locations (cities).

According to these assumptions, here we define the following notations.

$N=[N_1,\cdots,N_I]$: a vector associated with population in each city

$V=[V_1,\cdots,V_I]$: a vector associated with locational attractiveness

$\tau_i=[\tau_{i1},\cdots,\tau_{iI}]$: a vector associated with physical distances from city $i$ to others

## Locational attractiveness as a function of population distribution

Because of the reasons mentioned in the previous section, we assume that the function for the location attractiveness as, in the case of $i$ th city for example,

$$V_i=\left\{\sum_{j=1}^{I}N_j\exp(-\gamma\tau_{ij})\right\}^{\alpha_i}-\left(\frac{1}{L_i}\right)N_i^{\beta_i}+A_i \tag{1}$$

where

$A_i$: exogenous attribute of city $i$

$\gamma$: a generalized transport cost for an unit physical distance

$L_i$ : a capacity of space

$\alpha_i$: a parameter governing the dominance of accessibility and agglomeration economy in locational attractiveness

$\beta_i$: a parameter governing the dominance of agglomeration diseconomy

Inside of { } in the first term represents the utility dependent on the accessibility derived form a class of transport demand models like logit model or entropy model. Ueda and Morisugi (1994) derived the accessibility term from the transport of commodities, Ueda (1994), Ueda (1991a), Nakamura et al. (1993), also did from passenger trips for business, or behavior of face-to-face communication, and Ueda (1991b) did so from passenger trips for leisure or social activity. Anyhow, the accessibility term is derived with some generality from various types of transport behavior.

This term is furthermore important in the model because it can represent the agglomeration economy, that is, the more population a city has, the more attractive it becomes. Major concepts categorized into agglomeration economy, such as Marshallian externality, face to face merit in communication (Kanemoto 1989), love of variety (Fujita and Krugman 1993), polling effect, home market effect, hub effect (Krugman 1991a, Krugman 1991b), club merit (Kanemoto 1991) can be interpreted as specified cases of what this term represents.

The second term is the disutility of agglomeration, in contrast to the first term, the more population, the less attractive. It includes rising of land price, congestion in public service, degrading of environmental quality and so on. Since this type of disutility can be relaxed if a city has a large space capacity, the term is defined as a decreasing function of $L_i$.

The last term is the utility dependent on exogenous attributes of a city such as climate, richness in natural resource, and so on. It is needless to say that a city having mild climate is likely to be attractive.

## Location choice behavior and location equilibrium in the system

*Location choice behavior*

As mentioned in the major assumptions, the location choice behavior of any individual is stochastic. This is assumed to be formulated as the following mathematical programming giving the Logit Model.

$$S(V) = \max_{a_i} \sum_{i=1}^{I} \left\{ V_i a_i - \left(\tfrac{1}{\theta}\right) a_i (\ln a_i - 1) \right\} \qquad (2)$$
$$s.t. \quad \sum_{i=1}^{I} a_i = 1$$

where

$S(V)$; inclusive location attractiveness, or logsum function of Logit Model,

$a_i$ ; choice probability that an individual chooses city *i*,

$\theta$; logit parameter denoting the uncertainty in choice

The F.O.C. of the above programming gives,

$$N_i = N_T a_i = \frac{N_T \exp(\theta V_i)}{\sum_{j=1}^{I} \exp(\theta V_j)} \qquad (3)$$

*Location equilibrium*

In equilibrium, the model of location choice behavior gives the population distribution $N = [N_1, \cdots, N_I]$ by (3). On the other hand, the population distribution affects the location attractiveness $V = [V_1, \cdots, V_I]$ through the definition (1). From the assumption mentioned earlier, (1) and (3) must be consistent in equilibrium, in other words, they are regarded as a system of simultaneous equations giving population distribution in equilibrium as its solution.

*Some properties of equilibrium*

Existence of equilibrium can be proved by using the Brouwer's fixed point theorem. From the assumption that total population $N_T$ is exogenous, it is obvious that $N = [N_1, \cdots, N_I]$ is a point in a simplex in $\{N_i | \sum N_i = 1, N_i > 0\}$. Inserting (1) into (3), we have a mapping from the simplex to itself. So far as the function defined in (1) is continuous, the mapping is also continuous. Then, from Brouwer's theorem, the system of equation consisting of (1) and (3) has a solution.

Uniqueness is not always guaranteed. As shown later, we can easily illustrate the case of multiple equilibria.

Programmability of the equilibrium holds only in a very restrictive case. Analogy to the Beckmann's formulation ( no interaction between routes, or independent link cost function ) for transport network equilibrium makes it clear. The case where the equilibrium is programmable is that the function for location attractiveness $V_i(\cdot)$ includes only $N_i$ or the location attractiveness of a city depends on only its population size, not on population of other cities. This means that the equilibrium is programmable when there exist no cross-region (city) externalities.

The stability of equilibrium is also an important property to discuss. Although Tabuchi (1986) discussed the stability of equilibrium in a system of cities, the conditions shown in that work seem to be restrictive for the purpose of this study. We adopt Routh-Hurwitz's conditions for examining the stability in this paper (see Takayama 1985).

## SOME ILLUSTRATIONS OF A SYSTEM OF TWO CITIES

The system of cities formulated in the previous section can potentially show various patterns of population distribution. To make properties of the system more visible, let us examine cases of a system of two cities. Suppose that both cities have identical parameters and exogenous variables. This is a case of physically twin cities, or two identical cities in "First Nature" (Krugman 1991b).

What population distribution may emerge in this system? Intuitively, we can say that the population distribution would be " half and half". This is depicted in Panel (a), Figure 2. The locational attractiveness $V_i$ is specified as a decreasing function of population $N_i$ , which can be generated with the assumption of a great value of $\beta$ and with that of a small one of $\alpha$. The point in the center of horizontal axis representing an equilibrium state is unique and stable. However, we can depict another case which is really noteworthy.

$$V_i - V_j = V_i(N_i, N_j, \tau_i) - V_j(N_j, N_i, \tau_j)$$

$$N_i = \frac{N_T \exp(\theta V_i)}{\exp(\theta V_i) + \exp(\theta V_j)} = \frac{N_T}{1 + \exp(-\theta(V_i - V_j))}$$

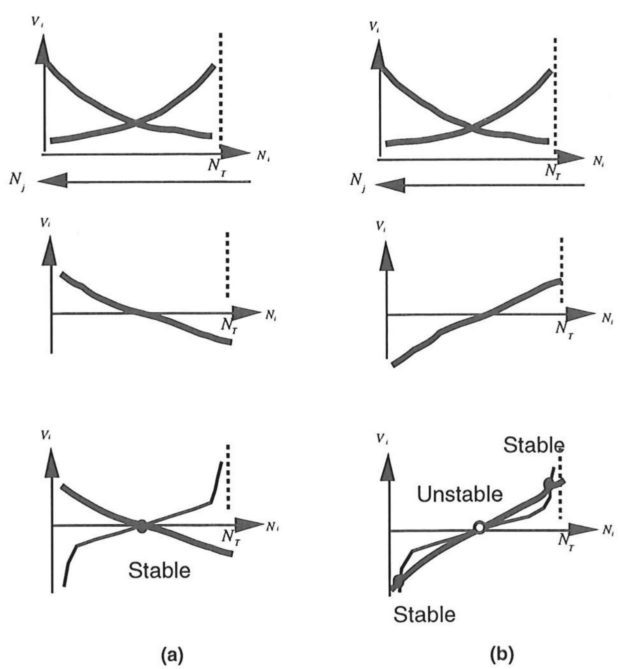



**Figure 2 Equilibria in a system of two cities**

Suppose that the attractiveness $V_i$ is specified as a increasing function of population $N_i$, which means the case where we have a great value of $\alpha$ and a small one of $\beta$. There potentially exist 3 states where the equilibrium conditions hold. However, the equilibrium in the center is unstable, not to be attained. Either of the remaining two states can be attained. Hence, one city becomes greater than the other. Notice that, even in the case where both cities have identical exogenous variables, uneven population distribution can emerge. This is a kind of "breaking of symmetry".

## IMPACTS OF TRANSPORT IMPROVEMENT ON POPULATION DISTRIBUTION

### Factors governing impacts

It is obvious that most of factors governing the impacts of interregional transport improvement are represented by exogenous variables in the model. These factors are categorized into two types. One is a region(city)-specific factors denoted by $\alpha_i, \beta_i, L_i$, *and* $A_i$. The other is, of course, interregional transport cost $\tau_i$ *and* $\gamma$.

Although it is of high interest to examine the roles of region-specific factors, we mainly focus on those of transport network. Therefore, we here assume that any kind of region-specific factors are at identical level for all cities.

### Impacts on a system of cities: numerical approach

A system of equations that states an equilibrium in (1) and (3) has a non-linear structure. It is hard for us to get a solution in an analytical way. Then, we examine the system by numerical experiments. To examine the impact of interregional transport improvement in numerical simulation, we assume the following set of values.

$$I = 9$$

$$N_T = 1.0 \times 10^7 \to 1.0 \times 10^8$$

$$\gamma_i = \gamma = 1.0 \times 10^{-4} \to 1.0$$

$$\alpha_i = \alpha = 0.1 \to 1.2$$

$$\beta_i = \beta = 0.1 \to 1.0$$

$$\tau_{ij} = \textit{number of links in shortest path} \times 10 + 10$$

$$L_i = L = 1.0$$

$$A_i = A = 0.0$$

$$\theta = 0.0001$$

Transport network is specified as 3 configurations as, a linear network, a triangle network, and a ring network as shown in Figure 3.

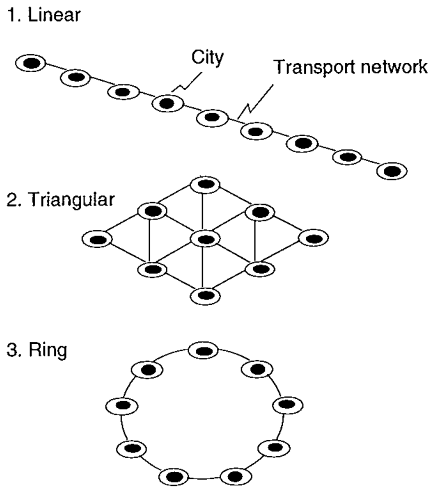
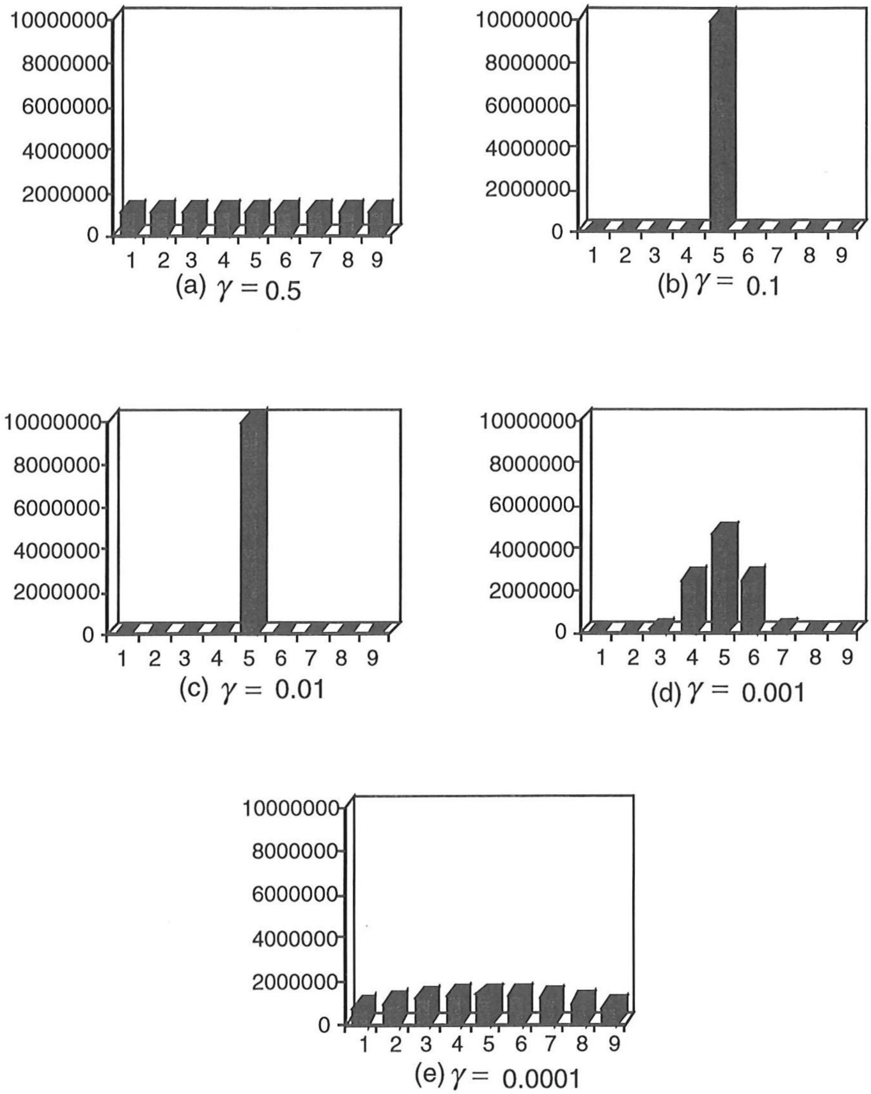



**Figure 3 Configurations of transport network**

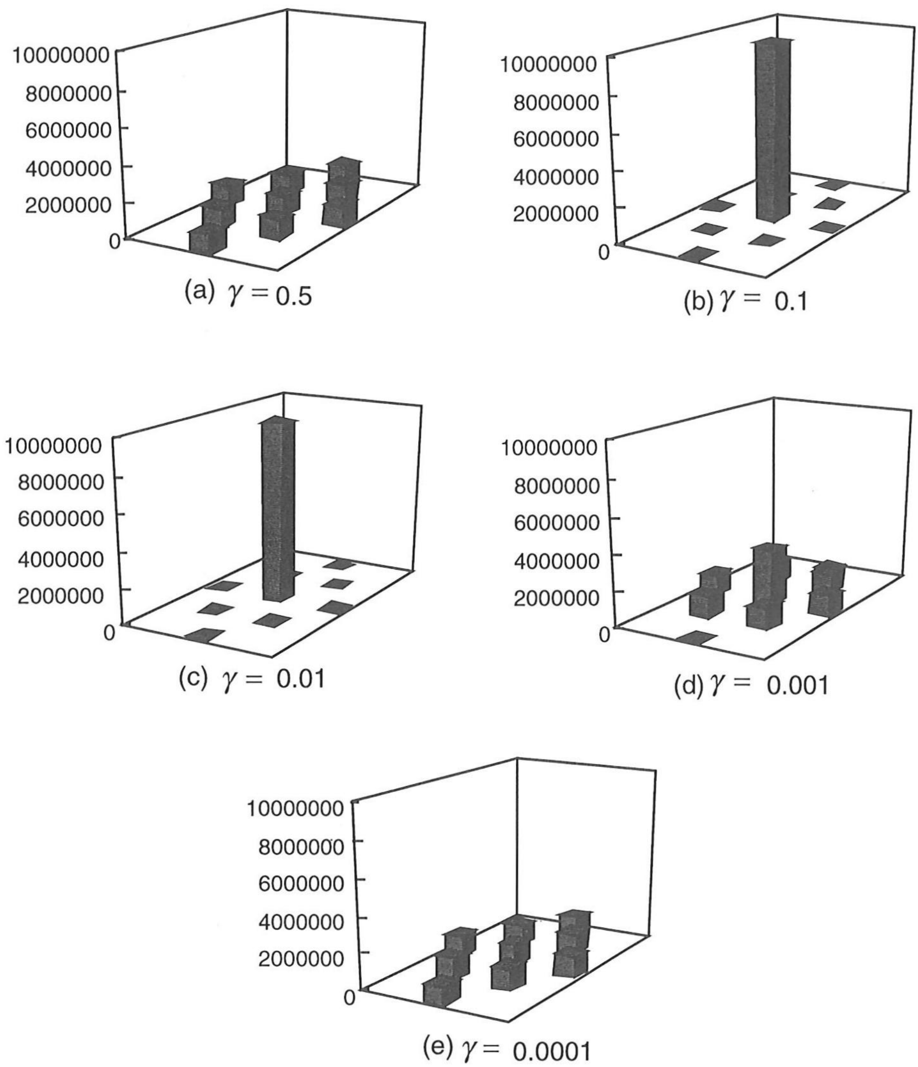
The interesting results are shown in Figures 4, 5, and 6. In any cases of 3 networks, the population distributes uniformly when the unit transport cost is very high. When transport cost is medium, there appears a pole, or a center of population. Setting the unit transport cost very low, then we have again the dispersed distribution. Although the implication from such results is very poor, we can say that if the realization of the dispersed structure in a system of cities would be major policy objective, then there might exist a minimum critical effort in reduction of transport cost. Why do they happen? In the case of high transport cost, the accessibility term is not determinant to the location attractiveness, in other words, everywhere is *inconvenient* in interregional communication or commodity trade. Then, to avoid the disutility of agglomeration, any cities have an almost equal size. In the case of medium transport cost, the central city in a system of cities is definitely advantageous. The accessibility term in the attractiveness might overcome the disutility of agglomeration, resulting in the mono-centric structure. In the case of low transport cost, everywhere is *convenient* in interregional transport, then peripheral cities are not disadvantageous. Therefore, the location attractiveness becomes much sensitive to disutility of agglomeration, resulting the dispersed structure as well as the case of high transport cost. Although this finding is highly dependent on specification of the functions and setting of parameter values, it suggests that when the central government intends to use the transport network improvement as a major strategy to realize the dispersion of population to peripheral cities, the transport cost must be reduced drastically. This is, in other words, there exists a minimum critical effort in reduction of transport cost to realize the dispersed structure as an object in nationwide spatial policy.

We have another finding to be remarked here. In the cases of linear and triangular networks, the city locating in the center is potentially advantageous in terms of transport cost. However, in the case of a ring network, any cities in the network have an equal level of advantage in terms of transport cost. As well as the case of physically twin cities, the uneven distribution can emerge in the system. This is due to "the Second Nature", again named by Krugman (1991b).



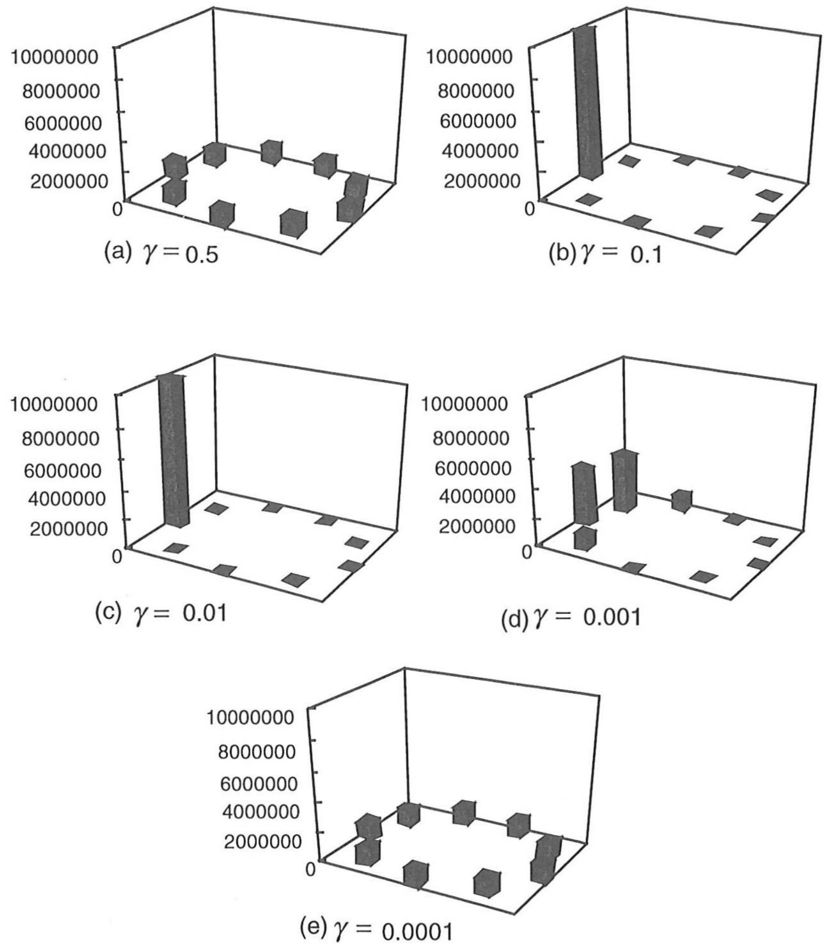

$(\alpha=1.1, \beta=0.85, N_T = 1\times10^7)$

**Figure 4 Population changes in a linear network**




$(\alpha=1.1, \beta=0.85, N_T = 1\times10^7)$

**Figure 5 Population changes in a triangular network**




$$(\alpha=1.1, \beta=0.85, N_T = 1\times10^7)$$

**Figure 6 Population changes in a ring network**

## WELFARE CHANGES IN THE SYSTEM

The previous section showed interesting changes in population distribution due to the reduction of transport cost. The question that we have to discuss is whether or not such changes are favourable from the point of social welfare. To evaluate them, we should prepare the following two welfare measures. The first one is the level of attractiveness that individuals in the system can enjoy in equilibrium. Since we have modeled the location choice behavior by the Logit Model, we have to define the attractiveness that a representative individual is enjoying in equilibrium as a logsun function or as an inclusive level of attractiveness in (2). The second is the amount of environmental loading due to interregional transport, which is not perceived by individuals.

Although we might have many kinds of proxy for environmental loading, we regard the total trip length as the proxy.

These measures are formulated as,

$$S(V) = \left(\tfrac{1}{\theta}\right)\ln\left\{\sum_{i=1}^{I}\exp(\theta V_i)\right\} \tag{4}$$

$$T = \sum_{i=1}^{I} N_i \tau_{ij}\left\{\frac{N_j \exp(-\gamma\tau_{ij})}{\sum_{j'=1}^{I} N_{j'}\exp(-\gamma\tau_{ij'})}\right\} \tag{5}$$

Here, the destination choice from the origin city $i$, denoted by the inside of { } in (5), is assume to be modeled as the Logit Model which is consistent with the definition of accessibility in (1). The values of these two welfare measures vary as shown in Figure 7, with changes in population distribution shown in Figure 4 (the case of liner network). Both of the attractiveness in (4) and the total trip length in (5) increase as the transport cost decreases. The reduction of transport cost that individuals in the system should pay potentially makes activities in any cities in the system more efficient, resulting in higher attractiveness. Since individuals in the system can choose more attractive city than that he/she has ever located, the attractiveness measure leads to be improved in new equilibrium after the transport improvement. One might think that the total trip length in the mono-polar structure would be much less than that in the dispersed structure. However, the result shown in the Figure is reasonable when we consider the following properties.

$$T \to N_T \tau_{ii} \quad \left[\frac{N_j \exp(-\gamma\tau_{ij})}{\sum_{j'=1}^{I} N_{j'}\exp(-\gamma\tau_{ij'})} \to \begin{bmatrix} =1 & for & j=i \\ =0 & for & j\neq i \end{bmatrix} \quad and \quad N_i \to \tfrac{N_T}{I}\right] \quad as \quad \gamma\to\infty \tag{6a}$$

$$T \cong N_T \tau_{ii} \quad \left[N_j \to 0 \quad for \quad j \neq center \quad and \quad \frac{N_j \exp(-\gamma\tau_{ij})}{\sum_{j'=1}^{I} N_{j'}\exp(-\gamma\tau_{ij'})} \to \begin{bmatrix} =1 & for & j=i \\ =0 & for & j\neq i \end{bmatrix}\right] \tag{6b}$$

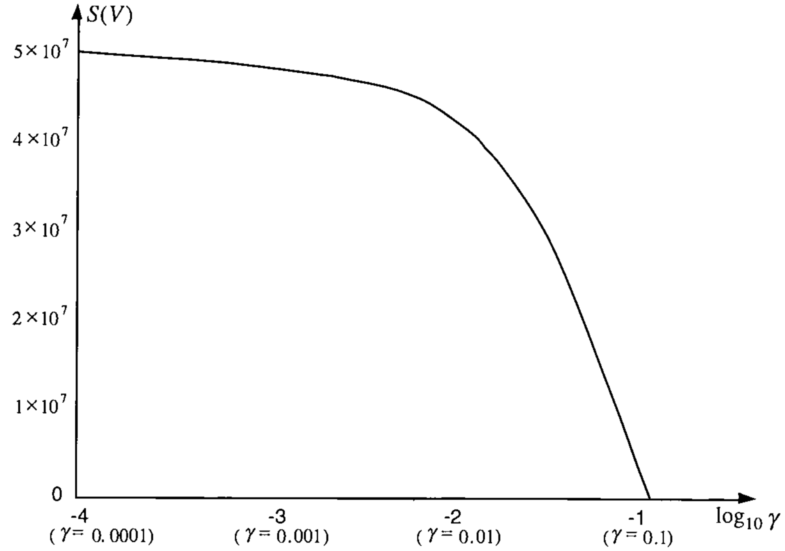
$$T \to N_T\left(\sum_{j=1}^{I}\tau_{ij}\right) \quad \left[\frac{N_j \exp(-\gamma\tau_{ij})}{\sum_{j'=1}^{I} N_{j'}\exp(-\gamma\tau_{ij'})} \to \frac{1}{I} \quad and \quad N_i \to \tfrac{N_T}{I}\right] \quad as \quad \gamma\to 0 \tag{6c}$$

Although indicators defined both in (4) and in (5) show a increasing tendency, they have quite a different implication. The reduction of transport cost can always improve the level of welfare perceived by individuals, but leads to *more environmental loading*. It goes without saying that the former is favourable and the latter is unfavourable. Although we know that a political implication derived from extremely simplified discussion is rather risky, we can say that the nationwide policy aiming the dispersed structure of a system of cities should not be always acceptable. We must keep it in mind that the dispersed structure might be accompanied with more environmental loading due to transport than before the transport improvement.

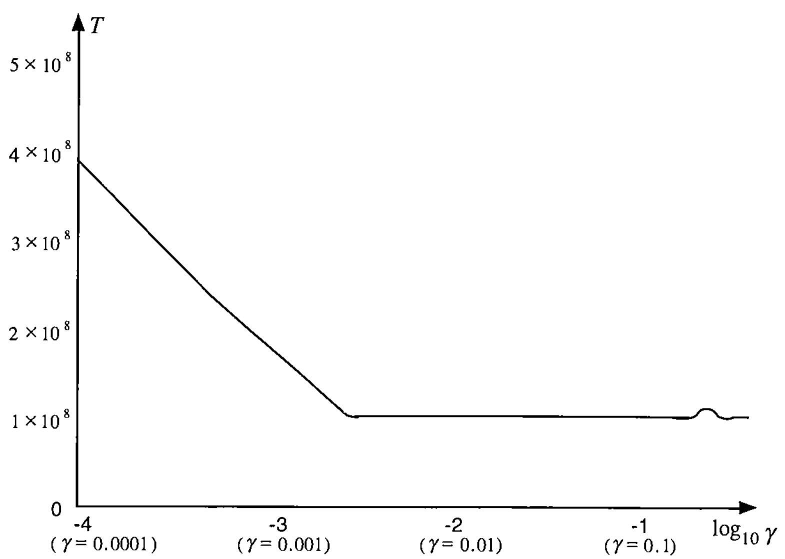
## CONCLUDING REMARKS

This paper has shown a framework for analyzing the impact of interregional transport improvement on a system of cities, and also some examples of impacts and their properties. The major political implications derived through the analysis are: i) there exists a minimum critical effort in the reduction of transport cost to realize the dispersed structure of a system of cities; and ii) such a policy might result in more environmental loading from transport. Although these are based on the simulation under extremely simplified specifications, we should keep them in mind.

It is needless to say that there still remain many tasks to be tried in steps next to this paper. One of tasks is mircoeconomic foundation for the derivation of the function for location attractiveness. The other is the extension of cases in numerical simulation, for example, asymmetric transport network and setting of cities, and, of course, modifications for approaching to a real system of cities.




**(a) The attractiveness that a representative individual is enjoying in equilibrium**




**(b) The total trip length as a proxy for environmental loading by transport**

**Figure 7 Changes of welfare of a system of cities by transport improvement (in a linear network )**

## ACKNOWLEDGMENT

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