Inter-urban Transportation Network for System of Compact Cities [1]

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Abstract: In the age of globalization, optimal size of a city can never be determined by herself, rather is determined as an equilibrium point in the system of cities. In typical system of cities, there is a trade-off relationship between the required intra-urban traffics and the needs of inter-urban transportation to support production activity. Uni-central structure, which is economically efficient because of stronger agglomeration and accessibility effects, require larger intra-urban transportation needs and larger environmental impacts, while evenly distributed middle size cities require smaller intra-urban transportation needs, if we endure inefficiency in the economy.

Inter-urban transportation network configuration strongly affects on the geographic structure of system of cities. Once we choose a desirable geographical structure, we come to the question what configuration of inter-urban transportation network can realize that structure. Moreover, we should know whether such network improvement could be selected by stepwise selection under normal cost benefit criterion or not.

This paper suggests a framework to analyze the above trade-off structure between economic and environmental impacts via system of cities model. It also proposes a simulation method to check the feasibility of the desirable network structure supporting a desirable city system structure, via link improvement process of inter-urban network.

Key words: Compact cities, Network formation, System of cities, Simulation, CBA

1 Introduction

Compact city is a city of appropriate size and density enough to support public transportatio and other public service. Internal density structure of a compact city has been often discusse and studied, but optimal size of city has not [1,2]. In the age of globalization, most of urba economic activities do their business utilizing several type of inter-urban interactions. Scal

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economy of each city is, therefore, strongly affected by accessibility and other geographic cor ditions of the system of cities. Therefore, optimal size of a city can never be determined b herself, rather is determined as an equilibrium point in the system of cities.

In typical system of cities, there is a trade-off relationship between the required intra-urba commuting traffics and the needs of inter-urban transportation to support production activit Typically, the former is supported more by automobile, while the latter use railway or airway energy consumption per person is smaller than the former intra-urban traffics. Then considerin environmental impacts, we must focus much on intra-urban traffics.

Let us consider uni-central country structure, where there is one large capital city and man small local cities. In this case, inter-urban interaction needs are almost limited to the capita peripheral OD pairs, but all cities must communicate with the capital, then, the total inter-urba transportation volume would be large. Simultaneously, the system can enjoy stronger agglon eration and accessibility effects of the large capital city and perform economically efficient. O the other hand, total intra-urban commuting transportation is larger, because commuting neec for the capital city becomes very large. Then, stronger positive economic and stronger negativ environmental impacts are expected.

On the contrary, in case of system of middle size cities distributed evenly in country spac only small amount of mutual inter-urban interactions are expected, while no city require larg amount of commuting transportation needs; we expect less environment and less economi impacts.

Inter-urban transportation network configuration strongly affects on the geographic structu of system of cities. Once we choose a desirable geographical structure, we come to the questio what configuration of inter-urban transportation network can realize that structure. Moreove network improvement requires certain amount of money. When we sequentially use net benef criterion for whether each link should be improved or not, can that network pattern be selected

Net benefit criterion is based on the prospected transportation demand of each link. Onc geographical structure of the city system does change, inter-urban transportation demands b come different, due to the population distribution change. They affect the following calculatio of net benefit value and then, network improvement history. In that way, network structu and geography of city system are mutually corresponding in the evolution process[3]. We ca understand the process as a co-evolution process of these two systems. Hereafter, we focus o passenger transportation such as high speed railway system as inter-urban transportation.

This paper suggests a framework to analyze the above trade-off structure between economi and environmental impacts via system of cities model. It also proposes a simulation metho to check the feasibility of the desirable network structure, supporting a desirable city syste structure, via link improvement process of inter-urban network.

The reminder of the paper is structured as follows; section 2 describes the simulation model system of cities. In section 3, project selection process is described. Following two sections a devoted to report the result of numerical simulations; feasible network improvement patter are described in section 4 and the trade-off between economic and environmental impacts a discussed in section 5. The last section concludes this study and discuss the future study.

2 System of cities model

As a model of system of cities connected with passenger transportation system, we use a mod by Kobayashi and Okumura(1997)[4]. That model formulates the contribution of passeng transportation for inter-urban knowledge exchanges indispensable for knowledge productio activities. In order to make our analysis clearly focused on the co-evolution process of th network and the city system, we use a simpler version model from their model by omitting th knowledge accumulation and the capital accumulation.

Our model then takes the following suppositions;

- Each person lives in housing lot of constant area in one city($i(=1, \cdots n)$), and all perso (total population: N) can freely migrate between the cities.
- In each city, all jobs are located at CBD. All people commute to the CBD of the residin city, by a congestion-free intra-urban commuting means[5] (unit cost per unit distance given by c_i).
- Manpower and knowledge are thrown, and numeraire good (Y_i) is produced in each cit
- Knowledge is exchanged through the passenger traffic between the cities (R_{ij}).
- Full employment is attained in each city.

Utility level is measured by the disposable numeraire good. Due to the arbitration of lan rent and to area balance that total urban area is proportional to the urban population (N_i indirect utility of the residents of city i is given by the following function of income (y_i) an population (N_i).

$$V_i = y_i - c\pi^{-\frac{1}{2}} N_i^{\frac{1}{2}}. \quad (1$$

The collective production of the industrial sector in city i (Y_i) is given as the following functio of labor input (N_i) and inter-urban trips generated from that city (R_{ij});

$$Y_i = N_i^{\alpha} \left\{ \sum_j N_j \left(\frac{R_{ij}}{N_j} \right)^{\xi} \right\}^{\gamma}. \quad (2$$

First order conditions of profit maximization determine wage rate (w_i) and inter-urban tri (R_{ij});

$$w_i = \alpha \frac{Y_i}{N_i}, \; R_{ij} = \gamma \xi Y_i \frac{N_j d_{ij}^{-\frac{\xi}{1-\xi}}}{d_{ij} \sum_k N_k d_{ik}^{-\frac{\xi}{1-\xi}}}. \quad (3$$

When we assume local public ownership of land in each city, income of a representative perso
in city i is given by,

$$y_i = w_i + \frac{1}{3} c_i \pi^{-\frac{1}{2}} N_i^{\frac{1}{2}}. \quad (4$$

Equilibrium condition under f free migration assumption is given by

$$\sum_{i=1}^{n} N_i = N, \quad V_i = \bar{V}(if \quad N_i > 0), \quad V_i \leq \bar{V}(if \quad N_i = 0), \quad (5$$

where $\bar{V}$ is the equilibrium utility level, endogenously determined in the model.

In this system, total population N and intra-urban unit commuting cost c_i are exogenousl given. For each set of inter-urban transportation costs d_{ij}, endogenous variables, $Y_i, w_i, R_{ij}, y_i, \bar{V}$ are solved in the model.

As inter-urban transportation network, we assume railway network consists of several numbe of links. Each link can be utilized to pass several OD pair traffics. Once, OD traffics R_{ij} ar solved, they are attributed to the shortest path. If several paths give the same cost, OD traffic are evenly divided to those shortest paths. As a result of aggregation, we can get link traffi X_{kl}.

3 Improvement link selection in the inter-urban network

In order to select efficient projects, cost benefit analysis (CBA) recently becomes very popula Here, we consider link improvement project to decrease the link cost from d_{ij} to $d'_{ij}(= 0.8d_{ij}$ by a constant project cost: C.

As Kanemoto and Mera(1985) suggested, benefit of network improvement can be calculate by increase of consumer surplus based on the demand curve given by a general equilibriu model[6)]. More practically and simply, we can estimate it by Harberger(1971)'s Trapezoid For mula: $B_{trap} = \frac{1}{2}(X_{kl} + X'_{kl})(d_{kl} - d'_{kl})$, where, d'_{kl} and X'_{kl} are link cost and link traffic volum after improvement, respectively[7)]. Hicks also proposed a utility based criteria, EV and CV which are free from the non-uniqueness problem of line integral for consumer surplus. Thos criteria are iequivalent to the utility change: $B_{util} = \sum_i (\bar{V}' - \bar{V})N_i$, where $\bar{V}'$ is utility leve after the improvement.

These benefit calculations, however, require huge calculation of traffics of all links and resulte equilibrium utility level for each combination of link improvements. Those combination numbe can easily explode. If we can admit that induced traffic is expected to be proportional to th present traffic volume, the following very simple formula can be used to measure the benefit;

$$B_{rect} = X_{kl}(d_{kl} - d'_{kl}). \quad (6$$

This formula requires only the present traffic volume: X_{kl}.

As an efficiency based selection procedure, we consider a sequential application of net-benef criterion($B - C$). First, we begin the network in which no link has been improved. Calculat

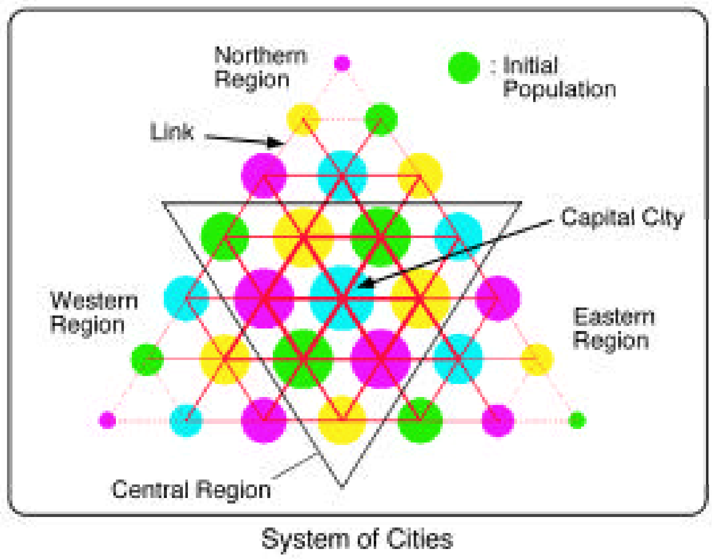

Fig-1 Example network and system of cities

the system of cities model and find the most heavily used link. According to the eq.(6), tha link is selected to be improved first. Next, we calculate again the system model with improve network, and find the heaviest used link out of the links not improved yet. If the estimate benefit does not exceed the improvement cost:C, net benefit becomes negative, then we sto the improvement process. Otherwise, we proceed the link improvement and calculation of th model again.

This stepwise selection procedure is too myopic to select the strategic links which becom focal links afterward in the evolution process. Then, we also simulate strategic selection proces where some number of links are selected strategically without considering myopic efficiency i early stage, and we take net-benefit criterion, afterward.

In the utility function (eq.(1)) of our model, we ignore non-economical aspects, such as env ronmental impacts. Because in many cities in the world, intra-urban commuting are done b automobiles, those are major non-point source of CO_2 emission. Then we consider total intra urban commuting distance as a environmental impact measure. Based on that environmenta aspect, net-benefit based selection process does not promise to be the most desirable evolutio process.

4 Network and city system evolution patterns

4.1 Settings

Let us consider a hypothetical country, where 28 cities are connected by railway network of 6 links, as shown by **Fig-1**. Each link can be improved once in the process. It requires cost ($C = 16$ regardless the location or present traffic volume of the link.

Parameters in the model are set as follows, $\alpha = 0.7, \gamma = 0.5, \xi = 0.6, c_i = 0.2, N = 280($

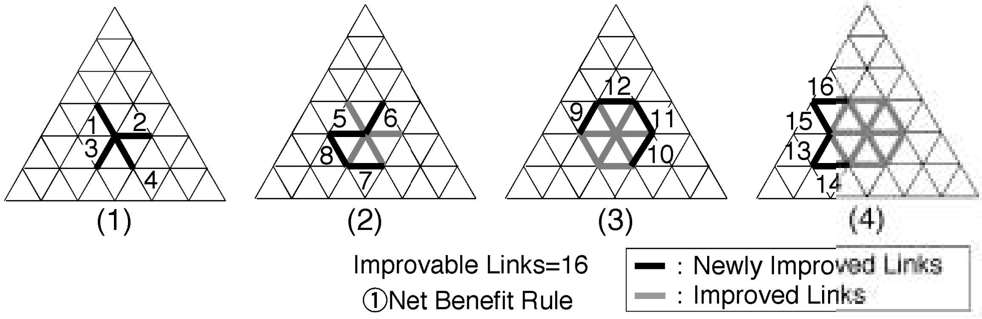

Fig-2 Link improvement history under (1) Net Benefit rule

By each link improvement, link transportation cost is reduced from $d_{kl} = 2.0$ to $d'_{kl} = 1.($ regardless the present traffic volume: X_{kl}.

As the initial condition, all link transportation cost are set to be $d_{kl} = 2.0$. In that situatioı cities located center in the country can enjoy a prominent accessibility to the other cities. Thε accessibility difference causes unequal productivity and income levels, and uneven populatio distribution. **Fig-1** also shows the initial equilibrium population distribution reflecting th accessibility difference, based on the equilibrium solution of the system model.

4.2 Network evolution by net-benefit criterion

Fig-2 shows the sequence of the link improvements under the net-benefit criterion. We ca this case as **(1) Net Benefit.** At initial geography, city population is negatively related to th distance from the capital city, and the traffic volume of links also decrease along the distanc from the center. Corresponding to the traffic volume, six links around the capital city (cente of gravity) are selected. After those 6 radiational links, small hexagonal loops is improve(Thirdly, four other links spanning out from the hexagon are improved. After the improvemer of those 16 links, further improvement cannot yield positive net benefit, anymore. As a resul 9 cities are served by the 16 improved links.

4.3 Strategic network evolution patterns

Now let us consider several strategic improvement cases, with referencing **Fig-3.**

(2) Large Loop: In order to expand growth to wider area, let us strategically improve larg hexagonal loop consist of 12 links. In the simulation, these improvements are proved to b inefficient and hard to be supported; 6 out of the 12 strategic links did not give positive ne benefit. But, once the outer loop is improved, the following improvements become more effectiv links in Eastern Region and those around the capital city are automatically selected by ne benefit rule. As a result, 28 links are improved and 18 cities are connected by the improve links.

(3) Medium Loop: First, a triangular loop of 9 links is strategically improved, and followe by net-benefit based selections. After the strategic triangle is completed, links inside the loo

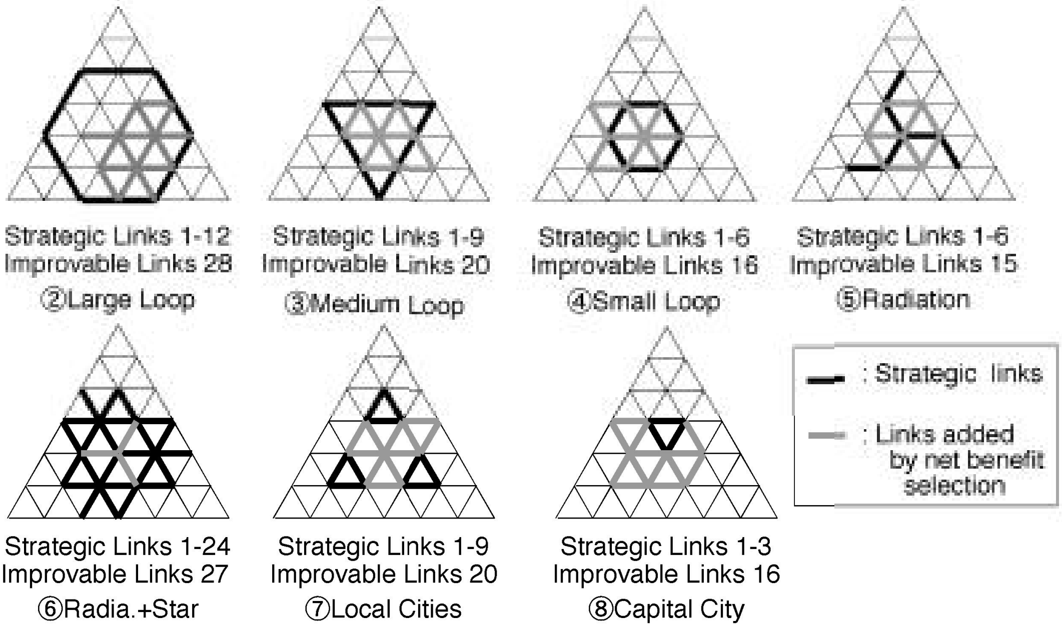

Fig-3 Link improvement history by other strategic rules

are selected by net benefit rule. Lastly, two other links improvements can give positive ne benefit. At last, 20 improved links connect 11 cities.

(4) Small Loop: This strategy builds improved links along the small hexagonal loop aroun the capital city first, and after then, net-benefit selection rule is applied. After the hexagona loop, 6 radiational links around the capital city are selected. It results to be the same geograph as **(1) Net Benefit.** At last, 9 cities are connected by 16 improved links.

(5) Radiational: In order to efficiently improve the accessibility of peripheral areas, radiationa network from the capital city seems promising. Here, 2 links are expanded along 3 directior strategically, and net benefit rule follows. Similar to **(1) Net Benefit**, the other 3 radiationa links are improved from the capital, followed by the small hexagonal loop. At last, 10 cities ar connected by 15 improved links.

(6) Radiational+Star: In order to stimulate peripheral area, star shaped ring consisted c 18 links is improved after 6 radiational links. Small hexagonal loop around the capital cit strategically follows to the star formation. Three radiative links from the capital are selecte by net benefit rule after the strategic improvements of 24 links. At last, 17 cities are combine by 28 improved links.

(7) Local Cities: This strategy improves 9 links connecting peripheral region centers with th central region. After taking net benefit rule, links connecting between two peripheral regior are selected, followed by the 6 radiational links from the capital city. At last, 20 links servin 11 cities are improved.

(8) Capital City: The last strategy is aiming to stimulate the centrality of the capital regior

Then a triangle in the central region is strategically improved first, followed by net benefit base selections. After 8 links are improved, we come to the same situation as **(1) Net Benefi** Therefore, the improvement process stops after 16 links improvements.

4.4 Efficiency comparison between the evolution patterns

Change of the total net benefit along the processes are shown in **Fig-4**. In each strategy, onc they begin to follow net benefit criterion, the selection process stops if the largest net benefit i the candidate links becomes negative. However, negative net benefit of a link does not mean tha following all improvements give negative net benefit. In **Fig-4**, gray lines show the net benef curves derived if net benefit based selections are continued even after when net benefit of lin improvement becomes negative. Thick black lines in the figure represent strategic improvemer history, some of them have negative slope. If positive benefit rule is strictly applied to each lin improvement, those projects were rejected.

Comparing to all other strategies, **(1) Net Benefit** rule gives the swiftest growth of ne benefit level, although it is myopic selection procedure. In the long run, however, other strategie can give more efficient situation; for example, the last network by **(3) Medium Loop**, an that by **(7) Local Cities** mark the higher total net benefit than **(1) Net Benefit** rule..

5 Trade-off between economic and environmental impacts

The simulation model can show the expected population of each cities along the network evolu tion process. Due to the limit of space in the paper, we do not show the population distributior calculated, but you can naturally expect that population growth is strongly connected with ac cessibility improvement caused by the link selection.

In the model, commuting length in city i can be calculated as $2(\pi^{-0.5}N_i^{1.5})/3$. Total intra urban commuting length in the city system is, then, proportional to $\sum_i N_i^{1.5}$, under the conditio that total population is constant ($\sum_i N_i = N$). This formula says that total commuting nee becomes the larger, as population distribution becomes uneven.

For example, in case of **(1) Net Benefit**, network improvement concentrated to the centra region, especially the cities inside the small hexagonal loop. As a result, those 7 cities gai population, and the other cities lost; population distribution becomes very strongly concentrate to the capital city and 6 cities surrounding it. This mono-centric population distribution make intra-urban commuting longer. In this case inter-urban trips are generated strongly inside th central region, and between periferal cities and the capital city, we expect large total inter-urba trip length. In our model, inter-urban trips are considered as one of indispensable input fc production. According to the Cobb-Douglas formulation of the production function (2), tota inter-urban trip cost is $\gamma\xi\sum_i Y_i$, roughly proportional to the utility level: $\bar{V}$.

Comparing to the mono-centric case yielded by **(1) Net Benefit**, strategic network evolutio process such as **(7) Local Cities** stimulates the growth of the peripheral cities and gives mor even population distribution; we can expect smaller needs of intra-urban commuting. Becaus

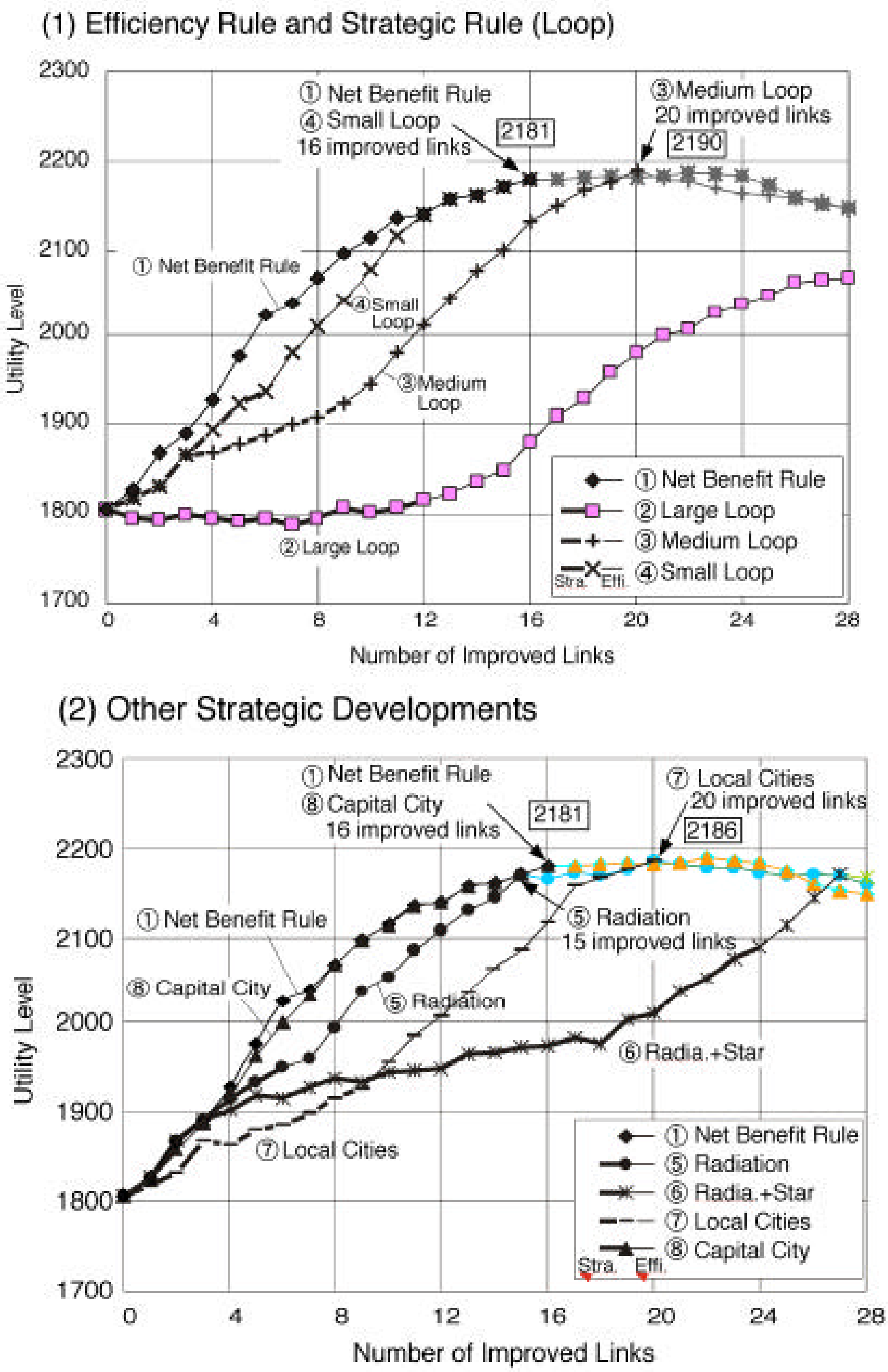

Fig-4 Net benefit growths by each strategy

that situation lacks a focal large city enjoyable strong agglomeration or accessibility, economi efficiency become smaller. But, if the reduction of the utility level is not so large, we can ge better trade-off between inter-urban needs/ economic utility and intra-urban commuting lengt reflecting environmental emission.

Fig-5 shows the net benefit and total intra-urban commuting length paths, according to th simulated network evolution processes. At a glance, we understand the positive slopes in th figure, which means the basic trade-off between economic and environmental criteria. In orde to get the larger economic satisfaction (described by utility level), the larger environment emission (represented by total intra-urban commuting length is required.

In these figures, lines locating upper left means superior trade-off; structure smaller enviro mental emission for same level of economic utility, or higher economic outputs with the sam level of environmental impacts. There are several strategies more efficient than **(1) Net Ben efit** rule. **(7) Local Cities** gives higher utility in early stages, while **(6) Radiational+Sta** economize the length of intra-urban commuting in late stages in the process. Both **(5) Radi ational** and **(4) Small Loop** give upper left orbits than the case (1). But **(8) Capital Cit** and **(2) Large Loop** strategies give undesirable results considering the trade-off.

The above results show that in order to realize environmentally desirable system of cities, w must consider the inter-city transportation network configuration, as well as internal structu of compact cities.

6 Conclusion

In the age of globalization, any city cannot determine her population size independently fro other cities. In this study, therefore, we have developed a system of cities model, connecte with the project selection process, and through the simulation, we got the expected co-evolutio processes of the network and system of the cities. Considering the economic criterion, stepwis application of net benefit rule got enough efficient result, while we found some strategic proje selection got more desirable result in long run.

Through the same simulations, trade-off structure between inter-urban transportation/econo impacts and intra-urban commuting/environmental aspect has been analyzed. As a result, ec nomic growth requires longer length of total commuting length, but the trade-off ratio is n always same. If we take some strategic improvement process, more efficient trade-off situatio is expected to be realized.

These results teach us that mechanical application of cost benefit analysis is not efficient t build a system of compact cities; we should learn more from further analysis of city system b further improved models and theories.

Here, we want to conclude our study by showing the future study issues.

First, we have neglected actual time scale of the evolution process or discounting facto When we discuss the trade-off between economic and environmental criteria, the former shoul be discounted while the latter should not.

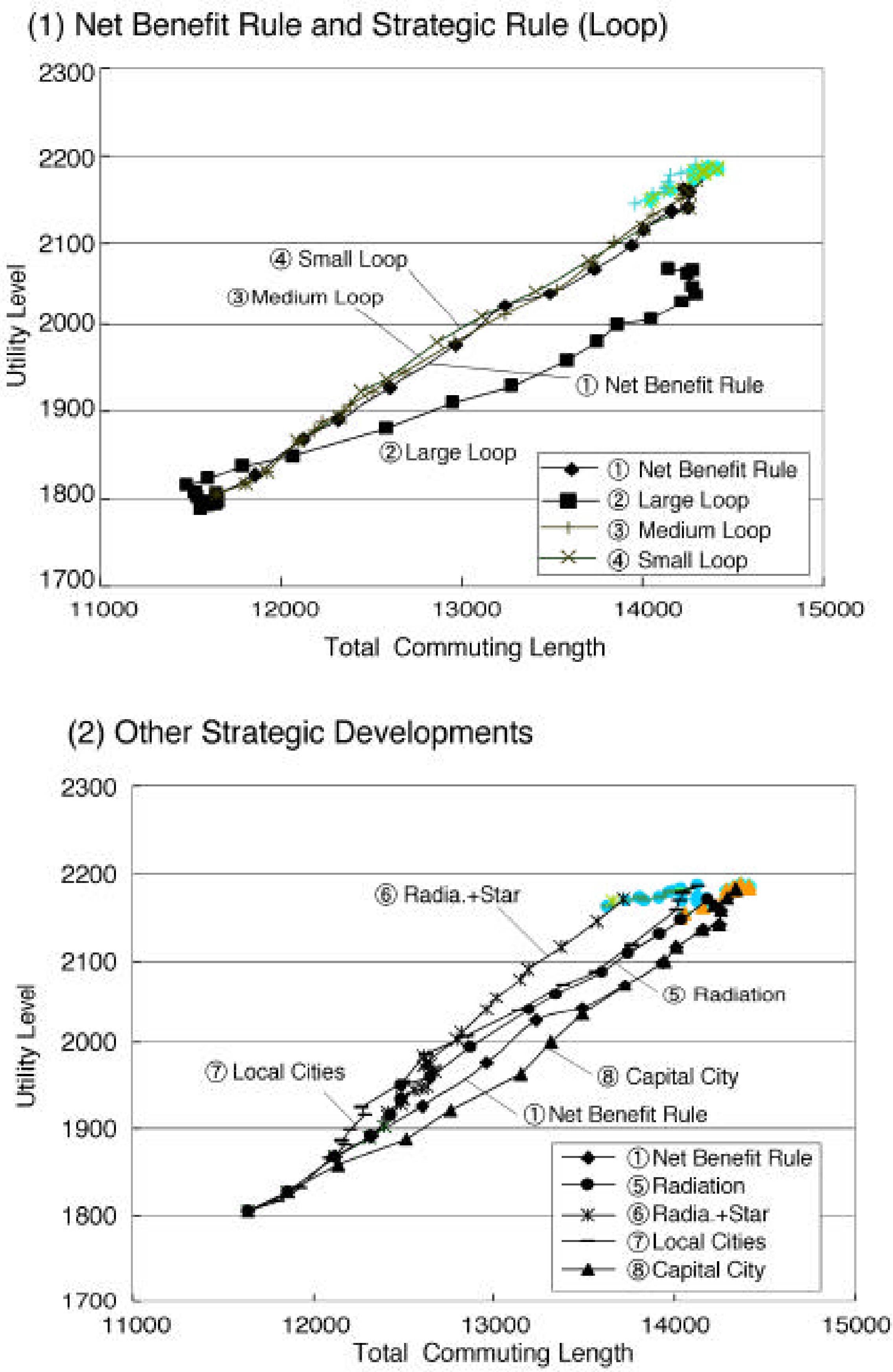

Fig-5 Net benefit growths and intra-urban commuting cost

Secondly, strategies were ad-hoc built in our simulations. We should introduce some opt mization method to build efficient strategy.

Thirdly, our calculation was only hypothetical, not based on the realistic setting or realisti parameter values. We must try to make the model more realistic and practical one.

Fourthly, recent development of Informational Technologies (IT) alter the communicatio and transportation. If telecommunication can substitute face-to-face transportation betwee cities, or if it make tele-commuting to significant extent, basic trade-off structure betwee transportation and environment becomes very different one. The impact of IT is a difficult be very important issue in the near future.

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