The Dynamics of Urban Activity Distribution with Respect to the Advance of High-Speed Transit Systems

Yudai Honma[1*] and Osamu Kurita[2]

[1]*Tokyo Metropolitan University, Tokyo, Japan*
[2]*Keio University, Yokohama, Japan*
[*]*E-mail address: yudai@sd.tmu.ac.jp*

(Received May 31, 2008; Accepted October 27, 2008)

The dynamics of commercial activities in cities has been explored by the Harris-Wilson's balancing-mechanism model. As properties of balancing-mechanism, it is known that the derived distribution depends on the various elements such as the shape of region or transportation network. In this paper, we take the balancing-mechanism in the general urban activities, and analyze the dynamics of urban activity distribution with respect to the advance of high-speed transit system. In particular, focusing on the Japanese railway system, we examine how the construction of Shinkansen bullet train affects the developments of cities in Japan. As a result, we clarified that the opening of high-speed transit system promotes the further developments of large cities, and miserable declinations of small cities.
Key words: Balancing-Mechanism, Urban Activity, High-Speed Transit System, Japanese Railway Network, Magnetically Levitating Train

1. Introduction

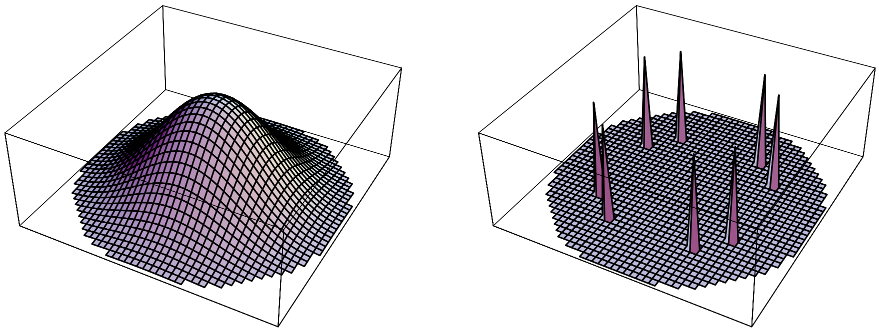
The purpose of this study is to analyze the dynamics of urban activity distribution with respect to the advance of high-speed transit system. In particular, focusing on the railway network system in Japan, we consider how the construction of high-speed transit systems such as *Shinkansen* bullet train affects the developments (or declinations) of cities in Japan. The method we adopt in the study is Harris-Wilson's **Balancing-Mechanism** (Harris and Wilson, 1978; Clarke and Wilson, 1983; Clarke, 1985), which incorporates the mutual interdependence between the attractiveness of zones and the number of visitors.

There are a plenty of urban activity distributions in the real world: distribution of population, business establishments, or industrial plants would be listed as examples. It is certain that these distributions about urban activities are important information in terms of understanding the social and economic structures of regions. In this point of view, a lot of researches have discussed principles of the formation of urban activity distributions.

Balancing-mechanism, which was proposed by Harris and Wilson (1978), is one of the researches to clarify the dynamics of urban activity distribution. Particularly, they focused on the retail shopping activity, and analyzed the "equilibrium" distribution that the attractiveness and the number of visitors are balanced. The basic idea of the model is as follows. First, the individual's movements of shopping behavior are formulated, and the number of visitors in each zone is derived. Now, it is natural that the zones which attracted lots of visitors become more developed and vice versa. To describe this property, the number of facilities in a zone, which is a measure of attractiveness, is renewed in proportion to the number of visitors. Consequently, these calculations are repeated until the distribution being stable.

The stability of balancing-mechanism is also discussed in the number of researches. As the features of the model, it is clarified that equilibrium distribution depends on parameters catastrophically, and that the distribution becomes either continuous or discrete. Especially, when the equilibrium distribution is discrete, highly accumulated zones are emerged (see Fig. 1). Then, what do the accumulated zones correspond to in the real world? It would say that it depends on the area of region we will analyze. For example, if we assume a city as a region, such area could be regarded as the (sub) centers of the city. On the other hand, if the model is applied to island scale, then each city is interpreted as such zone. It is well known that the location of such zones are affected to various elements such as the shape of region, transportation network, and so on. Therefore, the advance of transit system leads the change of the location of accumulated zones.

Shinkansen bullet train is one of the most typical high-speed transit systems in Japan. Since Tokaido Shinkansen started the services between Tokyo and Shin-Osaka in 1963, number of lines such as Sanyo, Tohoku, Joetsu, Nagano, and Kyushu Shinkansen was opened to traffic. Some of lines like Yamagata and Akita are existed as Mini-Shinkansen (Umehara, 2008). Furthermore, *JR-Central* recently get launched on a project of magnetically levitating train which connects Tokyo, Nagoya, and Shin-Osaka (Linear Chuo Express Kensetsu Suishin-Kisei Domei-kai, 2008). As imagined from the discussion about balancing-mechanism, these high-speed transit systems would activate the social interactions between multiple areas and affect the developments (or declinations) of each area. Therefore, in



(a) continuous distribution (b) discrete distribution

Fig. 1. Examples of the equilibrium distributions in balancing-mechanizm.

this paper, we focus on the advance of high-speed railway systems in Japan, and analyze how it has affected to the developments of cities based on balancing-mechanism.

There are only a few empirical researches based on balancing-mechanism. Besides our previous research (Honma and Kurita, 2005), Saito and Motomura's approach (Saito and Motomura, 1992) and Zhang's approach (Zhang, 1992) are only analyses which focus on cities in Japan. This study is interpreted as the generalization of our previous research in terms of the consideration of actual railway network.

This paper is organized as follows. In Sec. 2, we will discuss the formulation and the features of balancing-mechanism. Then, especially focusing on the construction of Shinkansen, we summarize the advance of Japanese railway network (Sec. 3). In Sec. 4, finally, the model is applied to Japan islands, and examined how the advance of high-speed transit systems affects the developments of cities.

2. Formulation

First, we formulate a model to describe the dynamics of distribution of facilities for urban activity. Basically, the model in present section follows arguments proposed by Harris and Wilson.

2.1 Model

Let us introduce a region which consists of K zones and also assume that there are residences and facilities for an urban activity in each zone. Furthermore, suppose that i indexes residence zone ($i = 1, 2, \cdots, K$), and O_i is the number of individuals in zone i. Similarly, let j index activity zone ($j = 1, 2, \cdots, K$), and S_j is the number of facilities in zone j.

Let us imagine a situation that individuals in the region visit a facility to carry out some kind of urban activity. There are a variety of activities and facilities, which could be intended in the model. For example, if we suppose "shopping" as the activity, then intended facilities would be "retail stores". Our first objective is to formulate the movements of individuals from their residences to the facilities using random utility theory.

For this purpose, let us assume that all individuals choose their visiting facilities to **maximize the utility**. In addition, we set the utility $U_{j|i}$ when an individual who lives in zone i visits the facility in zones j as follows:

$$U_{j|i} = V_{j|i} + \varepsilon_{ij}, \tag{1}$$

where $V_{j|i}$ is a function that depends on the observed characteristics of visiting from residence in zone i to the facility in zone j, and ε_{ij} is an independently identically distributed extreme value. We assume that $V_{j|i}$ is determined by the travel cost between zone i and j (c_{ij}), and the number of facilities in zone j (S_j) :

$$V_{j|i} = V_{j|i}\left(c_{ij}, S_j\right). \tag{2}$$

If c_{ij} becomes greater, individuals would hesitate to visit. Hence, $V_{j|i}$ should be a monotonically decreasing function of c_{ij}. On the other hand, the number of facilities S_j is taken as a measure of attractiveness in zone j, so it is natural that $V_{j|i}$ is a monotonically increasing function of S_j.

Since the preceding formulation is equivalent to multinomial logit model (Train, 2003), the modeled probability $P_{j|i}$, which the individual in zone i visits a facility in zone j, is given by

$$P_{j|i} = \frac{\exp\left[\lambda V_{j|i}\right]}{\sum_{j=1}^{K} \exp\left[\lambda V_{j|i}\right]}. \tag{3}$$

Then, under the assumption that all individuals curry out the activity once per unit term, we derive the number of individuals t_{ij} who lives in zone i visit a facility in zone j as

$$t_{ij} = O_i \times P_{j|i} = O_i \frac{\exp\left[\lambda V_{j|i}\right]}{\sum_{j=1}^{K} \exp\left[\lambda V_{j|i}\right]}. \tag{4}$$

Furthermore, the total number of individuals F_j^{c} who visit facilities in zone j is obtained as follows:

$$F_j^{\mathrm{c}} = \sum_{i=1}^{K} t_{ij} = \sum_{i=1}^{K} O_i \frac{\exp\left[\lambda V_{j|i}\right]}{\sum_{j=1}^{K} \exp\left[\lambda V_{j|i}\right]}. \tag{5}$$

Now, we would like to discuss the *equilibrium* values of $\left\{S_j\right\}$. If the standard capacity of one facility is θ, the total

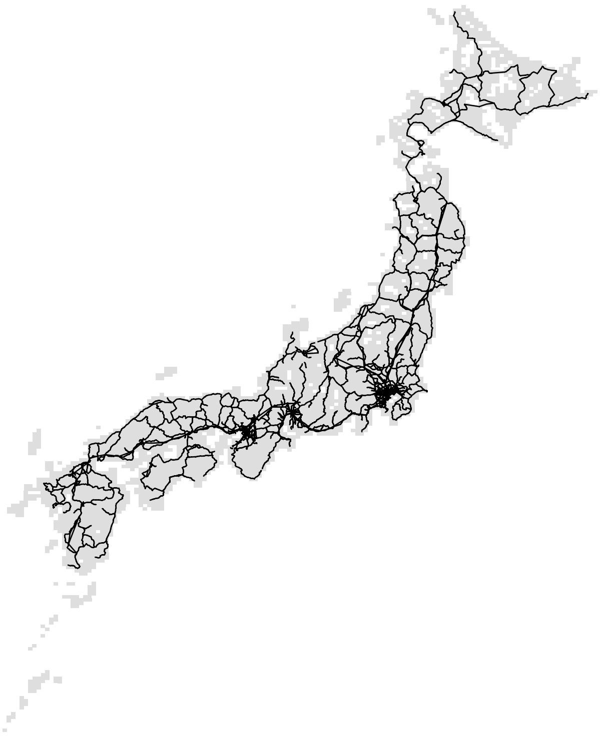


Fig. 2. Railway network in Japan.

capacity of facilities in zone j is given by θS_j. Hence, the most appropriate state is that the following equitation is satisfied in every zone:

$$F_j^c = \theta S_j. \tag{6}$$

Since F_j^c is a function of $\{S_j\}$, (6) constitutes K equations in the K-variables $\{S_j\}$. Therefore, the equilibrium distribution of $\{S_j\}$ is given as the solution of (6).

2.2 Assumptions

In this study, we assume that $V_{j|i}$ is defined as the summation of (i) c_{ij} :travel cost between residence zone i and activity zone j, and (ii) $\ln S_j$: the logarithm of the number of facilities in zone j:

$$V_{j|i}\{c_{ij}, S_j\} = -ac_{ij} + b \ln S_j, \tag{7}$$

where a and b are positive parameters. Generally, S_j is perceived sensuously, so we assume that $V_{j|i}$ is in proportion to the logarithm of S_j which implies the Fechner law (Goldstein, 1989). Meanwhile, c_{ij} can be perceived rather numerically, then we define that $V_{j|i}$ is a linear function of c_{ij}. The validity of preceding assumption have been discussed in detail (Kurita, 2002).

Now, substituting (5) and (7) for (6),

$$S_j = \frac{1}{\theta} F_j^c = \frac{1}{\theta} \sum_{i=1}^{K} O_i \frac{S_j{}^{\alpha} \exp[-\gamma c_{ij}]}{\sum_{j=1}^{K} S_j{}^{\alpha} \exp[-\gamma c_{ij}]} \tag{8}$$

is obtained where $\alpha = b\lambda$, $\gamma = a\lambda$. Unfortunately, it is quite tough to solve (8) analytically, so we regard (8) as iterative equations and calculate the equilibrium distribution numerically. The next step in the argument is to discuss the property of distribution.

2.3 Property of equilibrium distribution

The model stated above is basically equivalent to the formulation of **Balancing-Mechanism** proposed by Harris and Wilson (1978). Using catastrophe theory, Harris *et al.* analyzed the properties of equilibrium distribution, and clarified the following features:

[feature 1] equilibrium distribution $\{S_j\}$ is continuous when $\alpha \leq 1$, and discrete when $\alpha > 1$.

[feature 2] highly accumulated zones are emerged when the distribution becomes discrete, and the number of these zones decreases for higher α and lower γ.

In addition, Rijk and Vorst (1983) derived the following condition about equilibrium distribution:

[theorem 1] (8) has a unique positive solution $\{S_j\}$ when $0 < \alpha \leq 1$.

[theorem 2] (8) has at least one equilibrium solution $\{S_j\}$ when $\alpha > 1$.

From these theorems, the existence of equilibrium solution is assured. In this study, we assume uniform distribution as initial distribution, and calculate (8) numerically iteratively. The reason is to clarify the basic feature of model. Though, [theorem 2] pointed out the possibility of the existence of multiple equilibrium distribution, we consider that these analyses are essential.

3. Advances of Railway Network in Japan

In this section, we summarize the railway network system in Japan. Since we will apply the preceding model to Japan islands in next section, the discussion stated below is a preparation for analysis in Sec. 4.

3.1 Railway Network in Japan

As of January 2008, there are 9,277 stations and 516 lines in Japanese railway network. This railway network puts on all over the whole country, and it is indispensable for our daily life. In this study, we extracted the data of Japanese railway network from "*Ido-Keido tsuki Zenkoku-Ensen Eki Database*" edited by Japan Geographic Data Center (2008). This database summarized the latitude-longitude of all stations and line information such as network structure. Therefore, using the database, we are able to calculate the travel time between two arbitrarily chosen stations. The railway network adopted in the study is shown in Fig. 2.

3.2 Construction process and future plans of Shinkansen

Shinkansen bullet train is one of the noteworthy projects of Japanese railway network system. It is a representative high-speed transit system in Japan, and promotes mutual interactions in the islands. Total railway length of Shinkansen is over 2,000 km now, and it covers from Hachinohe to Kagoshima. *Mini-Shinkansen* is also a kind of bullet train which is operated on the conventional railway lines. Although, the highest speed of Mini-Shinkansen (130 km/h) is slower than that of Shinkansen (270 km/h), this system frees passenger from a transfer at the station because it directly connect to Shinkansen lines. Yamagata and Akita Shinkansens adopt a Mini-Shinkansen system. Construction process of Shinkansen is summarized in Table 1.

Even now, there are some of plans to construct new lines

Table 1. Construction process of Shinkansen.

Years	Constructed sector
October 1963	Tokyo–Shin-Osaka
March 1972	Shin-Osaka–Okayama
March 1975	Okayama–Hakata
June 1982	Omiya–Morioka
November 1982	Omiya–Nigata
March 1985	Ueno–Omiya
June 1991	Tokyo–Ueno
July 1992	Fukushima–Yamagata (※)
March 1997	Morioka–Akita (※)
October 1997	Takasaki–Nagano
December 1999	Yamagata–Shinjo (※)
December 2002	Morioka–Hachinohe
March 2004	Shin-Yachiyo–Kagoshima-Chuo

※Mini-Shinkansen.

Table 2. Future plans of Shinkansen.

Years	Planed sector
2011	Hachinohe–Shin-Aomori
2011	Hakata–Shin-Yachiyo
2014	Nagano–Kanazawa
2015	Shin-Aomori–Shin-Hakodate
2020	Shin-Hakodate–Sapporo

of Shinkansen. Table 2 indicates the list of projects which have been approved to construct as of January 2008, and some of them have already been constructed (Aomori Prefectural Government, 2008; Federation of Hokkaido Chamber of Commerce and Industry, 2008; Hokuriku Shinkansen Kensetsu Sokushin Domei-kai, 2008; Kumamoto Prefectural Government, 2008). In addition, several projects such as *Nagasaki Shinkansen* and *Hokuriku Shinkansen* are requiring to get approved (Nagasaki Prefectural Government, 2008).

3.3 Magnetic Levitation project

A *Maglev*, or magnetically levitating train is a railway system powered by superconducting electromagnet, and expected as a new high-speed transit system whose speed exceeds that of Shinkansen. Since this method allows trains to suspend, it has a potential to be faster and quieter than wheeled train systems. In fact, the highest recorded speed of a maglev train system is 581 km/h, which is achieved by JR-Central in 2003. This system have already been matured technologically, so construction cost is a next barrier for commercial run (JR-Central, 2008).

On December 2007, JR-Central announced to construct the Linear Shinkansen by totally their own budget. Their plan expresses to start the service between Tokyo–Nagoya by 2025, which result to connect both cities only in 40 minutes. In the future, they also plan to extend it to Osaka. More precise deliberation about financial condition and the determination of track route are future tasks.

4. Application to Japan Islands

In this section, we apply the model in Sec. 2 to Japan islands. In particular, we focus on the developments (or declinations) of cities with respect to the construction of high-speed transit system such as Shinkansen and Maglev.

Please note that it is inadequate to suppose purchasing behavior as urban activity in the model, because our objective region is whole of Japan. Hence, we should suppose larger scale activities such like wholesale, administration, or management. The aim of following discussion does not describe the urban activities precisely, but depicts the macroscopic dynamics.

4.1 Assumption

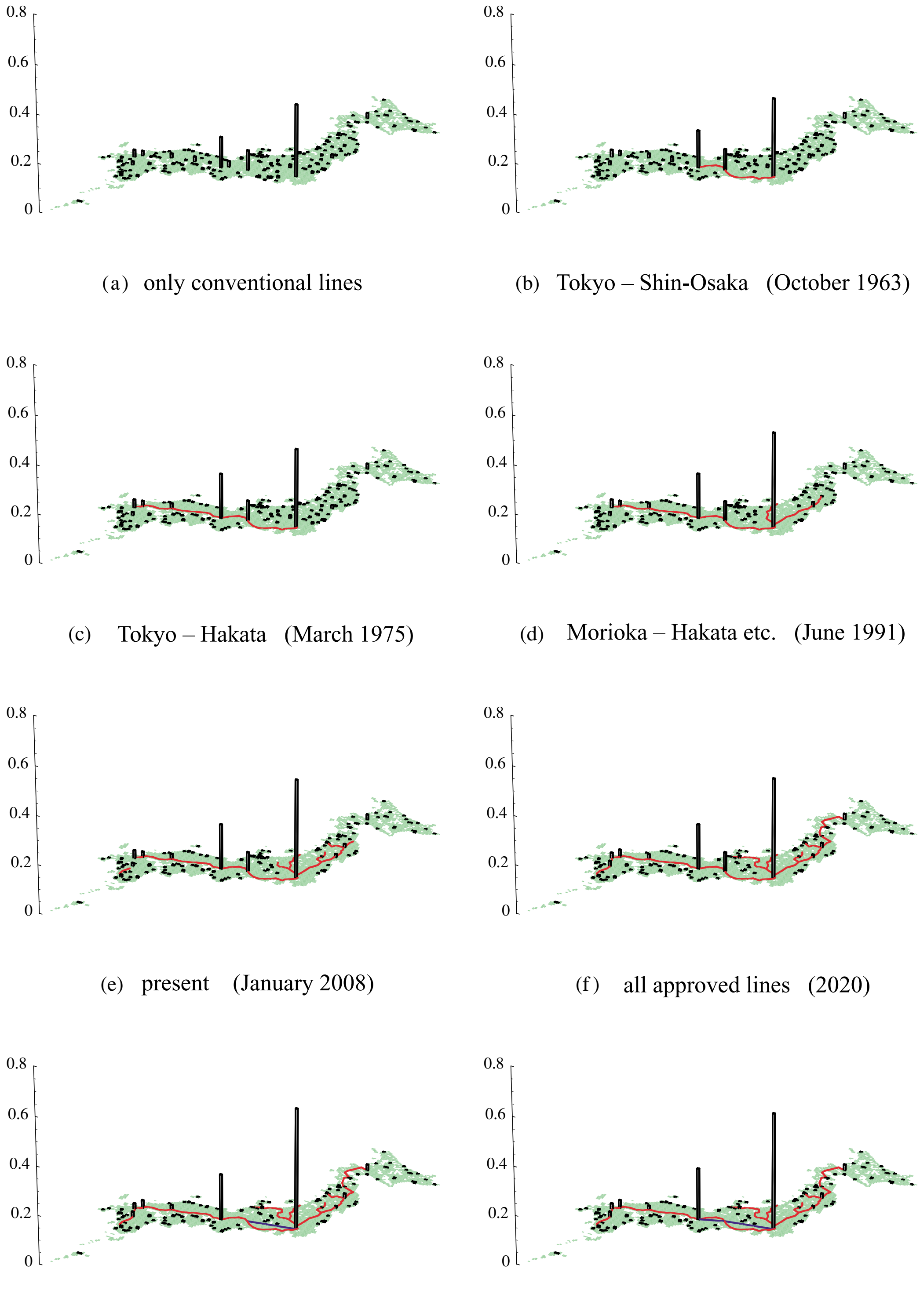
Let us explain the assumption to apply the model to Japan islands. First, we assume the region as the all of Japan without *Okinawa* prefecture (i.e. 46 prefecture), and prepare the 10km grid system data from the national population census held in 2000 (gray parts of Fig. 2). We regard each grid as a zone and use the real population as the number of individuals O_i.

While, the travel cost between two zones is given by minimum travel time when individuals are allowed to move straightly and to use railway network. To calculate the travel time, we prepared the unified network which connects the grids and the railway system. In particular, each grid are connected to any other grid and five nearest station (to describe access/egress). Hence, the size of unified network is 13,485 nodes (4,208 grids and 9,277 stations) and 8,885,014 edges (10,342 for between two stations, 4208×5 for between grid and station, and $4,208^2/2$ for between two grids). Furthermore, each speed is set as follows: straight movement 10 km/h, conventional lines 50 km/h, mini-Shinkansen 100 km/h, Shinkansen 200 km/h, and Maglev 400 km/h.

4.2 Change of Urban-activity distribution

As indicated in Tables 1 and 2, since Shinkansen network has been developed step-by-step, travel time between two zones also changes at each term. This fact means that the *modelled* equilibrium distribution also change at each term. In this point of view, we calculated the travel time at each term, and derived the equilibrium distribution respectively. The calculation results under several parameters are shown from Figs. 3 to 5.

Since the urban activities which is assumed in this section are social interactions generated over whole island level, it would be interpreted that S_j describe the number of nodal facilities. Therefore, Figs. 3 to 5 indicate how the locations of these facilities change as the advance of high-speed railway system. From the result, we can confirm that small-scale zones located on the newly opened line declined (or sometimes disappeared) because of being absorbed in other larger zones. On the other hand, metropolitan area such as *Tokyo*, *Nagoya*, and *Osaka* result to develop continuously as Shinkansen opened. That is to say, **the opening of high-speed transit system promotes the further developments of large cities, and miserable declinations of small cities**. This tendency is clearer in Figs. 3(g) and (h), which describe the situation after the opening of Maglev. In this case, even Nagoya area is disappeared, and highly concentration to Tokyo and Osaka areas is happened.



(a) only conventional lines

(b) Tokyo – Shin-Osaka (October 1963)

(c) Tokyo – Hakata (March 1975)

(d) Morioka – Hakata etc. (June 1991)

(e) present (January 2008)

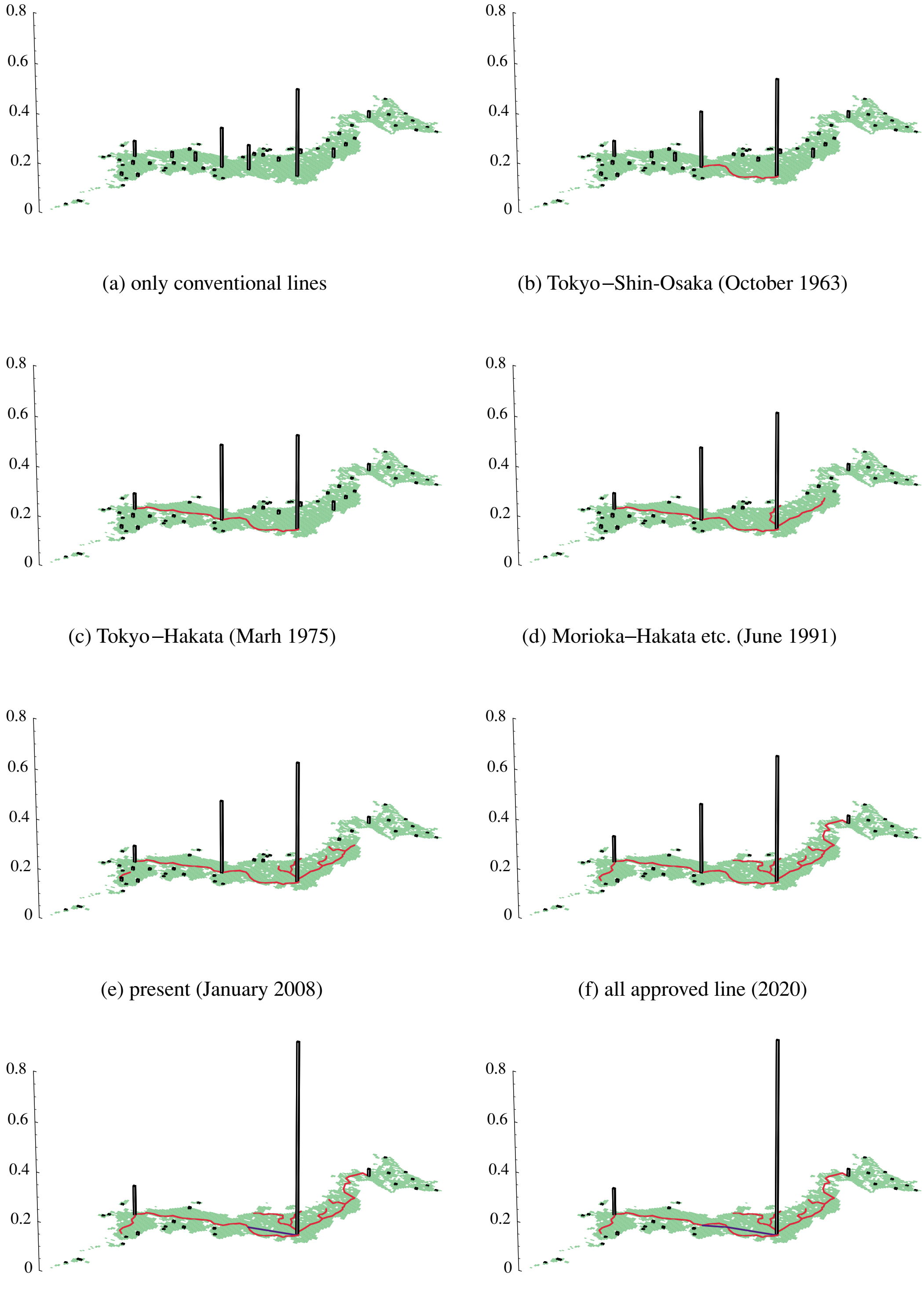
(f) all approved lines (2020)

(g) Magrev between Tokyo – Nagoya

(h) Magrev between Tokyo – Shin-Osaka

Fig. 3. Equilibrium distribution $\{S_j\}$, ($\alpha = 1.1, \gamma = 0.4$).

Whether cities develop or decline depends on not only the advance of railway network, but also the model parameters (i.e. criteria of individual's activity). Figure 4 is a result whose parameter is $\alpha = 2.0$, and even *Osaka* area disappeared unfortunately. Since α measures the importance of attractiveness of activity zone, **high α accelerates the severe concentration to large cities**. On the other hand, if we set $\gamma = 0.8$, we can describe a scenario that lots of cities coexists. γ measures the ease of long travel, and **high γ illustrates that individuals tend to visit nearby zones**. However, please note that it is only the result that **concentration to the metropolitan area is moderated**. If



(a) only conventional lines (b) Tokyo−Shin-Osaka (October 1963)

(c) Tokyo−Hakata (Marh 1975) (d) Morioka–Hakata etc. (June 1991)

(e) present (January 2008) (f) all approved line (2020)

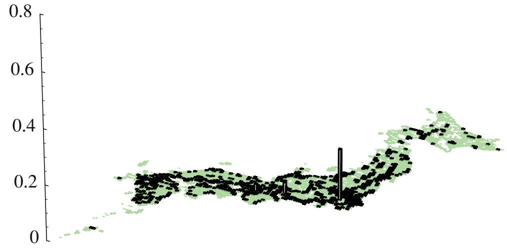
(g) Maglev between Tokyo−Nagoya (h) Maglev between Tokyo−Shin-Osaka

Fig. 4. Equilibrium distribution $\{S_j\}$, ($\alpha = 2.0$, $\gamma = 0.4$).

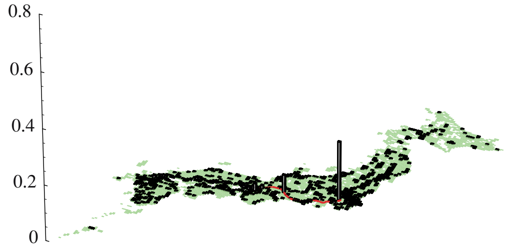
we would like to describe the developments of small cities by the advance of high-speed transit system, $\alpha < 1$ must be satisfied.

5. Conclusion

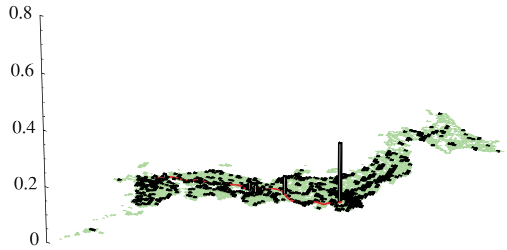
In this study, we applied the Harris–Wilson's balancing mechanism to Japan islands, and analyzed how the advance of railway network system affects the developments of cities. As a result, we clarified that the existence of high-speed transit system such as Shinkansen and Maglev accelerates the accumulation to large metropolitan cities. Though, our model does not several elements such as incorporate multiple activities or regulation of land-use, it obtains a clear explanation to the phenomenon of urban activity distributions.



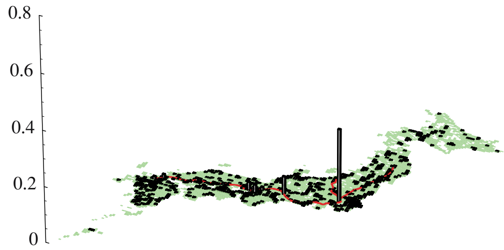
(a) only conventional lines



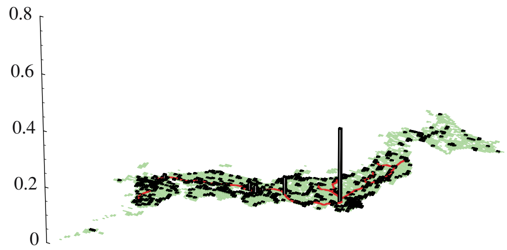
(b) Tokyo–Shin-Osaka (October 1963)



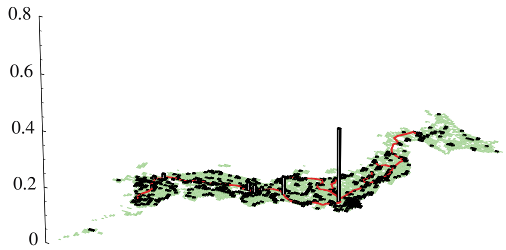
(c) Tokyo–Hakata (March 1975)



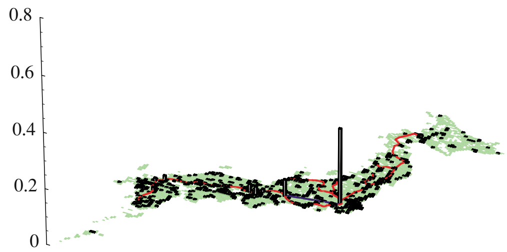
(d) Morioka–Hakata etc. (June 1991)



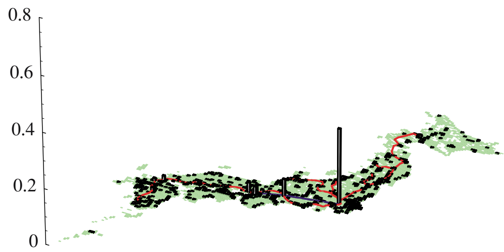
(e) present (January 2008)



(f) all approved line (2020)



(g) Maglev between Tokyo–Nagoya



(h) Maglev between Tokyo–Shin-Osaka

Fig. 5. Equilibrium distribution $\{S_j\}$, $(\alpha = 1.1, \gamma = 0.8)$.

In this paper, to clarify the effects of railway networks, we did not incorporate the road network and air network, but they also affects the developments of urban activities. Hence, it must be a future work to incorporate such other transportation system. In addition, we should expand the model to determine the population distribution simultaneously, which is given in this study.

References

Aomori Prefectural Government (2008): Aomori Shinkansen Group Web Page, http://www.pref.aomori.lg.jp/kokikaku/shinkansen/sinkansentop.html (could be accessed on February 2008).

Clarke, M. (1985) The role of attractiveness functions in the determination of equilibrium solutions to production-constrained spatial interaction models, *Environment and planning A*, **17**, 175–183.

Clarke, M. and Wilson, A. G. (1983) The dynamics of urban spatial structure: progress and problems, *Journal of Regional Science*, **23**, 1–18.

Goldstein, E. B. (1989) *Sensation and Perception*, Wadsworth Publishing Co.

Federation of Hokkaido Chamber of Commerce and Industry (2008): Hokkaido Shinkansen Web Page,
http://www.do-shinkansen.com/index2.html (could be accessed on February 2008).

Harris, B. and Wilson, A. G. (1978) Equilibrium values and dynamics of attractiveness terms in production-constrained spatial interaction models, *Environment and planning A*, **10**, 371–388.

Hokuriku Shinkansen Kensetsu Sokushin Domei-kai (2008): Hokuriku Shinkansen Official Home Page,
http://www.h-shinkansen.gr.jp/ (could be accessed on February 2008).

Honma, Y. and Kurita, O. (2005) The dynamics of urban commercial developments with respect to customer's spatial choice behavior—Effects of city shapes and road network patterns on the ballancing-mechanism—, *Journal of the City Planning Institute of Japan*, **40**, 97–102 (in Japanese).

Japan Geographic Data Center (2008) *Ido-Keio Tsuki Zenkoku-Ensen Eki Database*,
http://www.kokudo.or.jp/database/sub/sub08.html (could be accessed on February 2008).

JR-Central (2008) LINEAR EXPRESS Web Page,
http://linear.jr-central.co.jp/ (could be accessed on February 2008).

Kumamoto Prefectural Government (2008) Kyushu Shinkansen Home Page,
http://www.pref.kumamoto.jp/traffic/sinkansen/index.html (could be accessed on February 2008).

Kurita, O. (2002) Effects of the Advance of Regional Transportation Systems on the Sales of Stores in a Region —An Analytical Approach by Use of the Huff's Models—, *Journal of the City Planning Institute of Japan*, **37**, 55–60 (in Japanese).

Linear Chuo Express Kensetsu Suishin-Kisei Domei-kai (2008) Linear Chuo Express Home Page,
http://www.linear-chuo-exp-cpf.gr.jp/ (could be accessed on February 2008).

Nagasaki Prefectural Government (2008) Kyushu Shikansen Nagasaki Route Home Page,
http://www.pref.nagasaki.jp/shinkansen/ (could be accessed on February 2008).

Rijk, F. A. A. and Vorst, A. C. F. (1983) Equilibrium points in an urban retail model and their connection with dynamical systems, *Regional Science and Urban Economics*, **13**, 383–399.

Saito, S. and Motomura, H. (1992): Computing competitive equilibrium spatial distribution of retail shopfloor area of dynamical retail model using fixed point algorithm, *Journal of the City Planning Institute of Japan*, **27**, 451–456 (in Japanese).

Train, K. (2003) *Discrete Choice Methods with Simulation*, Cambridge University Press.

Umehara, J. (2008) *Shinkansen Tettei-Tsuikyu Nazo to Fushigi*, Tokyodo Publishing Co. Ltd. (in Japanese).

Zhang, C. (1992) An analysis of the equilibrium location pattern of retail and its dynamics in Tokyo, *Geographical Review of Japan*, **65A**, 395–418 (in Japanese).