Modeling Urbanization by Population Potential Considering the Greenbelt Effect and Various Accessibility Measurement Methods

Dae-Sik Kim*, Kei Mizuno* and Shintaro Kobayashi*

1. Introduction

Population migration between urban and rural areas and the relationship between population migration and level of urbanization have been analyzed by several studies using spatial interaction models. After Stewart extended the physical analogy to include the concept of population potential in the gravity model, Anderson generalized the potential concept with a nonlinear distance exponent (Carrotherst, 1956). Hansen (1959) suggested a model introducing the gravity potential concept, which is known as the gravity-type model, in order to analyze development potential considering the holding capacity in each region. This gravity-type model represents the energy of a region created by one mass of other regions, not the force between regions (Rich, 1980). There are several studies on application of the gravity-type model for analysis of economic, market, public service, accessibility, and employment potentials (Williams and Senier, 1978; Linneker and Spence, 1992; Handy and Niemeier, 1997; Bruinsma and Rietveld, 1998; Talen and Anselin, 1998; Vickerman et al. 1999; Wu, 1998). For analysis of urbanization in periphery areas surrounding a central city, however, there are few empirical studies using the gravity-type model, but one such study was done by Hansen (1959). Rustiadi and Kitamura (1998) analyzed the ratio of urban land uses according to the distance from a central city considering an agglomerated index of a region. Kim et al. (2001) simulated the ratio of urban land uses in rapid growth areas using two types of multi-gravity centers in order to reflect a hierarchical settlement system with one big and several middle sized cities and rural areas. However, these models were simplified by introducing the concept that the urbanization of periphery areas is influenced by one or two gravity centers, unlike the principle of gravitational potential that represents the energy created at one mass of a region by another. To analyze urbanization in areas surrounding a central city, this study is more concerned with the total potential energy generated in a region by all the masses of regions in a system. Studies considering the effects of all regions have generally used a population potential model. Although relationships between population potential and activities in a region was not well defined, as an empirical study, Rich (1980) suggested a quadratic regression function showing good-fitness between net employment change as a dependent variable and population potential as an independent variable. As an application of such a model, Mfungahema and Kitamura (1998) showed that there was a high correlation between population potential and the ratio of urban land uses in areas surrounding a central city. In order to consider the influence of all regions for analysis of urbanization, this study is also intended as an investigation of relations between population potential and urbanization in areas surrounding a big city.

As accessibility is one of the most important factors that influence urbanization in urban fringe areas, the correlation between the development ratio of urban land and the measures of accessibility to employment and population is quite high (Hansen, 1959). Considering time variance of accessibility, the population potential calculated by distance between all regions is sensitive not only to accessibility changed over time by the development of transportation infrastructure, but also by the distance measurement methods used, such as Euclidean, road, and time dis-

* 京都大学農学研究科 Graduate School of Agriculture, Kyoto University
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stances. For the measurement of accessibility, several studies have adopted Euclidean distance, road distance (Al-Sahili and Aboul-Ella, 1992; Gong and Kitamura, 1994; Mfungahema and Kitamura, 1998; Rustiadi and Kitamura, 1998) or time distance (Linnkeker and Spence, 1992; Spiekermann and Wegener, 1994; Handy and Niemeier, 1997; Bruinsma and Rietveld, 1998; Talen and Anselin, 1998; Cervero and Appleyard, 1999; Vickerman, et al., 1999; Kim et al., 2001). Euclidean distance is a time invariant variable, while road and time distances are time variant variables. Although several studies of the spatial interaction model have used the reasonable distance concept, there is yet little agreement as to which kind of distance is well suited to their various research purposes. This study uses the three types of distance for calculation of the population potential, and analyzes response of a new model by the three types.

A greenbelt, where new development of urban land is generally forbidden, plays an influential role on the spatial distribution of urbanization in fringe areas of big cities. A greenbelt is usually established outside the urban fringe for conservation of public amenities such as clean water and air, scenery, and recreation away from congested urban areas. Through urban growth of a big city, possible residential areas within the greenbelt line are saturated by urbanized land until the urbanized area reaches that line (Lee and Fujita, 1997). The continuous urban expansion and a population dispersion policy promoted by governments of big cities accelerate the urbanization of rural areas and areas surrounding satellite cities. In this case, curves, such as population density (Wang and Zhou, 1999), bid-rent (Lee and Fujita, 1997), and urban land ratio according to distance from the center city, have discontinuous forms through the greenbelt area, because the values there do not increase over time, while the values in areas surrounding the greenbelt increase continuously. Thus, the distribution of urban land uses in areas surrounding a big city with a greenbelt cannot be analyzed by simple distance decay functions. Thus, the main purpose of this study is to develop a model considering the restriction effect on urbanization by the greenbelt in order to analyze the urbanization in periphery areas of a big city. For this purpose, this paper models urbanization by population potential introducing the greenbelt effect using several accessibility measurement methods.

II. Model formulation

Distribution of urbanization levels (hereafter ratio of urban land uses to possible residential area, $\tilde{U}_i(\%)$) in a region $i$ at time $t$ generally shows a form of distance decay function from a center city. This $\tilde{U}_i$ is assumed to have a close relationship with population potential, $\Phi_i$. Thus, the $\tilde{U}_i$ can be written as Eq. (1).

$$\tilde{U}_i = f(\Phi_i), \forall i$$

(1)

The population potential is generally expressed as Eq. (2) with a distance exponent, $\alpha$, after Anderson (Carrothers, 1956).

$$\Phi_i = k \sum_{j=1}^{m} \frac{P_j}{d_{ij}^\alpha}, \forall i$$

(2)

where $k$ denotes a constant, $m$ the number of regions, $P_j$ population of a region $j$, and $d_{ij}$ distance such as Euclidean, road, or time distance (hereafter ED, RD, and TD, respectively) between region $i$ and $j$. Here, considering Fig.1 for quantifying the urbanization restriction effect of a greenbelt area on new development, a $\tilde{U}$ curve at time $t$ when the greenbelt was established presents a continuous distance decay function, while $\tilde{U}_{t+1}$ shows the discontinuous forms in the case that the greenbelt area was absolutely restricted from urbanization pressure. Thus, the next Eq. (3) in the greenbelt area can be defined.

$$\tilde{U}_{t+1} = \tilde{U}_{t}, i \in G$$

(3)

where $G$ denotes a set of regions within the greenbelt area. Introducing the greenbelt effect, the curve of $\tilde{U}_{t+n}$ at time $t+n$ after $n$ years from establishment of the greenbelt becomes a discontinuous form in the greenbelt area as shown in Fig.1. This can be generally defined as Eq. (4).

$$\tilde{U}_{t+n} = f(\Phi_i) - \epsilon_{t+n} h, \forall i$$

(4)

where $\epsilon_{t+n} h$ denotes a term of restriction effect by the greenbelt area in region $i$ at time $t+n$. This study defined the $\epsilon_{t+n} h$ as Eqs. (5) for the total greenbelt area, considering Fig.1.

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where \( t+1A \) denotes the area conserved from urbanization pressure within the greenbelt between time \( t \) and \( t+1 \) as shown in Fig.1. Herein, in order to quantify the greenbelt effect, considering the unit area of the greenbelt \( (d_g) \) and the control effect \( (t+1C) \) in the above site of Fig.1, Eq.(6) can be expressed.

\[
(t+1A) = (t+1C)d_g = \sum_{i=1}^{m} (t+1C)d_{gi},
\]

where \( (t+1C) \) and \( d_g \) denote a coefficient of the greenbelt effect and length of the greenbelt in Fig.1, respectively. From the above Eqs. (5) and (6), this study defined the restrictive effect \( (t+nh_i) \) as Eq.(7), considering the width of greenbelt in region \( i \) \( (d_{gi}) \) as area ratio of the greenbelt in each region.

\[
(t+nh_i) = (t+nh_i)(O_{gi}/O_i), \quad i \in G
\]

where \( O_{gi} \) and \( O_i \) denote the area of greenbelt and the total area of region \( i \), respectively. Since the relationship between population potential and the ratio of urban land uses has never been defined theoretically, this study adopted an empirical quadratic equation that has been used in existing studies (Rich., 1980; Mungahema and Kitamura, 1998) as shown in Eq.(8).

\[
f_{(t+nh_i)} = (t+1a) + (t+1b)(t+nh_i) + (t+1c)(t+nh_i)^2, \quad \forall i
\]

According to Eq.(4) considering the restriction effect of the greenbelt in the quadratic equation, this study developed a general governing equation that is expressed as Eq.(9).

\[
(t+nh_i) = (t+nh_i)(P_i/\alpha_i) + \sum_{j=1}^{m} \frac{(t+nh_i)(P_j)}{(t+nh_j)} + (t+nh_i)^2 - (t+nh_i)(O_{gi}/O_i), \quad \forall i
\]

where \( t+1a, \ t+1b, \) and \( t+1c \) denote parameters (herein, \( t+1b = t+1bk \) and \( t+1c = t+1ck^2 \)).

III. Application of the model
1. Description of study area

For this research a case study area located in the south of Kyunggi Province, an area south of Seoul and the most rapidly growing area in the ROK was selected (Fig.2). This area spans 3,988km² and consists of 79 county subdivisions (Myun in Korean) and cities as shown in Fig. 2. Satellite cities and rural lands in this area have been rapidly urbanized by the outward-migration of population from Seoul since the 1960s. Seoul has especially strongly influenced the urbanization of this area, because the area east of Seoul is conserved due to water supply dam for the metropolitan area, the area north is
controlled for military facilities for the national defense, and the area west is restricted by geographical condition nearby the Yellow Sea, greatly limiting development in those directions. Several policies such as the National Land Use and Management Act, the Capital Regional Planning, and the Greenbelt System have influenced the land-use changes in this metropolitan area (Hang, 1999, Kim et al., 2002). Therefore, this study defined this study area as the system for analyzing urbanization level of each region within this area, considering population potential of all regions in this area including Seoul. Here, we assumed that the surrounding areas of Seoul except for the south have influence hardly on the each region in the study area, because population migration of this area has been focused on Seoul due to the land-use policies.

In order to control the urbanization of Seoul, a part of the area to the south was established as a greenbelt in the early 1970s (Fig. 2). Although the greenbelt established by the City Planning Act since the early 1970 has restricted new development for urban land within the area, the development and improvement such as buildings and public facilities have been partly permitted by revision of related laws (Lee et al., 1999). This greenbelt area, in which new development of urban land is forbidden, is distributed in 19 areas (Myuns) among 79 areas (Myuns) in the study area. However, the urbanization of the study area has continuously accelerated, jumping over the greenbelt. By statistical data, the population increase of this area was 212% over the 15 years from 1980 to 1995, and the area of urbanized land use increased by 208%, showing 1.7 and 1.4 times those of Seoul for the same period, 122% and 151%, respectively (Kim et al., 2002).

2. Statistics and GIS data

As basic data for analysis of urbanization in the study area, this study constructed data sets on land uses and population for subdivisions of counties and cities for the three years of 1985, 1990, and 1995 from "statistical yearbooks of cities and counties." We defined the urban land-uses as five types, residential, industrial, school, road, and railroad by summarizing uses defined in the yearbooks (Kim et al., 2002). For GIS data, this study constructed not only the greenbelt boundary for calculation of the greenbelt area in each area, but also the road network of 1985, 1990, and 1995, respectively, considering road construction information of the three years. The center of each area for ED was defined as the center of each polygon for area, and representative points of areas for RD and TD were established on the road networks of the three years (Fig. 3). These maps showed that highways were constructed rapidly in the study area. The possible residential area (PRA) was defined as areas with slopes less than 15 degrees by a slope map generated from DEM converted from a 1:50,000 contour digital map, excluding river and lake areas. The PRA of each area was extracted by overlaying an administration boundary map constructed from a 1:25,000 geographic map.

3. Distance measurement

In this study GIS functions for distance measurement of three types were used. A matrix of ED that has been conveniently used in several studies was calculated.
from UTM coordinates of the geometric centers of areas. In order to measure the RD and TD, a network analysis program was made for this study which can extract the matrices of RD and TD between all pairs of areas. The RD and TD between two areas should be measured on the shortest road path, though there are several paths between the areas. In order to compute TD (or weighted road distance), road impedance, $w_{ij}$, can be defined as Eq. (10), with relative speed of 60 km/h (Kim and Chung, 2001).

$$w_{ij} = \left( \frac{60}{v_{ij}} \right)$$  

where $v_{ij}$ denotes a design speed of the shortest path between areas $i$ and $j$. However, there are generally several road sections with different impedance in the shortest path between the two nodes. To consider all these different sections, assuming that the number of all sections on the shortest path, $SP_{ij}$, between areas $i$ and $j$ is $z_{ij}$, $SP_{ij}$ can be expressed as

$$SP_{ij} = 60 \sum_{k=1}^{z_{ij}} \frac{d_{ij}}{v_{ij}}$$  

where $k$ denotes a number of sections between nodes $i$ and $j$, and $SP_{ij}$ relative time distance at 60 km/h of the shortest path. Herein, in the case of $v_{ij}=60$ km/h for all sections, $SP_{ij}$ is road distance on the shortest path. For development of the program, Dijkstra’s shortest path algorithm was adopted for this study (Kim and Chung, 2001). In order to calculate the road impedance, 100 km/h, 60 km/h, and 40 km/h were adopted as the design speed for railroads and highways, national roads, and local roads, respectively (Kim et al., 2002).

4. Optimization of the model

The five coefficients of the new model should be optimized for the data set of the three years. Non-linear optimization techniques have been commonly used to optimize the spatial interaction models that could not be solved by a simple logarithmic transformation method (Rustiadi and Kitamura, 1998; Kalaba et al., 1999; Kim et al., 2002). However, the proposed model is not easily optimized by conventional non-linear optimization techniques either, due to matrix calculation for population potential considering all combinations between areas. If the distance exponent ($a$) is defined as a constant, the problem is simplified to optimization of a quadratic equation. Although the traditional potential concept used $a=1$ as a constant, this is being questioned in the socio-economic field, because there is no practical or theoretical definition for the exponent (Mfungahema and Kitamura, 1998). Considering the exponent as a calibration parameter, therefore, this study optimizes the new model from the objective function of RMSE minimization considering the weighted least square (WLS) using a trial and error method. The WLS estimation is probably the most commonly used technique, because ordinary least square techniques are based on the assumption that the residual variance around the regression line is the same across all values of the independent variable, which is not realistic. For accuracy and time-saving for the optimization, two steps for optimizing after a search of feasible ranges for all parameters were used in this study. At first, after calculation of population potential in the cases of $a=0.5$ and $a=1.0$, this study optimized the parameters, $a$, $b$, $e$, and $C$ of the new model (10) for the three periods using the Quasi-Newton method. Then, we optimized all parameters including the $a$ one more time by a trial and error method, after establishment of feasible ranges of all parameters as $a(0.0-20.0)$, $b(-5.0-5.0)$, $e(0.0-0.5)$, $C(0.0-20.0)$, and $a (0.1-$

<table>
<thead>
<tr>
<th>DV (%)</th>
<th>Distance</th>
<th>Year</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>$e$</th>
<th>$C$</th>
<th>RMSE</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>UL/PRA</td>
<td>ED</td>
<td>1985</td>
<td>-6.49</td>
<td>-0.809</td>
<td>0.177</td>
<td>7.020</td>
<td>0.941</td>
<td>4.155</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>1990</td>
<td>6.930</td>
<td>-0.502</td>
<td>0.154</td>
<td>7.922</td>
<td>0.916</td>
<td>5.334</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1995</td>
<td>9.999</td>
<td>-1.144</td>
<td>0.101</td>
<td>12.738</td>
<td>0.703</td>
<td>7.790</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RD</td>
<td>1985</td>
<td>15.502</td>
<td>-2.410</td>
<td>0.175</td>
<td>6.151</td>
<td>0.733</td>
<td>4.077</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>1990</td>
<td>9.746</td>
<td>-1.414</td>
<td>0.157</td>
<td>6.862</td>
<td>0.761</td>
<td>5.170</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1995</td>
<td>11.000</td>
<td>-1.395</td>
<td>0.090</td>
<td>9.380</td>
<td>0.600</td>
<td>7.886</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TD</td>
<td>1985</td>
<td>12.250</td>
<td>-1.942</td>
<td>0.200</td>
<td>3.153</td>
<td>0.881</td>
<td>3.381</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>1990</td>
<td>11.749</td>
<td>-1.590</td>
<td>0.141</td>
<td>4.309</td>
<td>0.761</td>
<td>4.327</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1995</td>
<td>7.750</td>
<td>-0.966</td>
<td>0.076</td>
<td>8.840</td>
<td>0.638</td>
<td>7.150</td>
<td>0.83</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 The optimization results of the model

DV: dependent variable, PRA: possible residential area, UL: urban land area, ED: Euclidean distance, RD: road distance, TD: time distance (weighted road distance)
2.0), respectively. The optimized results were summarized in Table 1 and Fig. 4, showing high R2s from 0.78 to 0.86 for all data sets and distance measurement methods.

5. Comparison of the new model with a simple quadratic equation and a distance decay function

A simple quadratic equation excluding the greenbelt effect in Eq. (10) was also optimized in order to evaluate the accuracy of the new model considering the greenbelt effect. Table 2 presents the optimization results for all data sets. Comparing the results with those of the new model, as shown in Fig. 5, R2s of the new model are higher than the simple quadratic model in all cases. The distance decay function (U_i = a_dj, where j is Seoul) was also regressed for all data sets for comparison with the new model as shown in Table 3. The result shows that the distance decay function is not well fitted with distribution of urban land uses in the study area, designating R2s are somewhat low ranging from 0.25 to 0.53. The coefficients and exponents are increased over time, and the corresponding R2s are also increased.

In three distance types, the case using TD has the highest R2 followed by those of RD and ED. This also means that the proposed model agrees well with the study area with the greenbelt, where analysis using the existing simple models is difficult. As shown in Table 4 showing the statistics for three types of distance from Seoul, it was demonstrated that the ED is a time invariant variable, while the

| Table 2 | The optimization results of the existing model without greenbelt effect |
|---------|--|---|---|---|---|---|
| DV (%) | Distance | Year | a | b | c | C | a | C | a | C | a | C |
| UL/PRA | ED | 1985 | 8.409 | -0.903 | 0.414 | — | 1.305 | 4.511 | 0.74 |
| | 1990 | 9.979 | -0.966 | 0.361 | — | 1.248 | 5.785 | 0.74 |
| | 1995 | 15.305 | -1.593 | 0.142 | — | 0.839 | 8.212 | 0.78 |
| | RD | 1985 | 8.956 | -1.361 | 0.432 | — | 1.057 | 4.389 | 0.77 |
| | 1990 | 10.614 | -1.483 | 0.286 | — | 0.994 | 5.606 | 0.77 |
| | 1995 | 11.362 | -1.188 | 0.113 | — | 0.724 | 8.195 | 0.79 |
| | TD | 1985 | 11.836 | -2.146 | 0.278 | — | 0.997 | 3.537 | 0.82 |
| | 1990 | 15.863 | -2.423 | 0.205 | — | 0.868 | 4.583 | 0.83 |
| | 1995 | 18.535 | -1.192 | 0.107 | — | 0.707 | 7.312 | 0.81 |

DV: dependent variable, PRA: possible residential area, UL: urban land area, ED: Euclidean distance, RD: road distance, TD: time distance (weighted road distance)

| Table 3 | Regression results of the distance decay function from Seoul (U_i = a_dj, where j is Seoul) |
|---------|--|---|---|---|---|---|
| Distance | Year | 1985 | 1990 | 1995 |
| | a | b | R2 | a | b | R2 | a | b | R2 |
| ED | 85.96 | -0.634 | 0.25 | 147.18 | -0.736 | 0.28 | 592.04 | -1.032 | 0.42 |
| RD | 159.74 | -0.758 | 0.31 | 289.02 | -0.870 | 0.34 | 1137.50 | -1.148 | 0.47 |
| TD | 267.36 | -0.928 | 0.44 | 555.57 | -1.088 | 0.49 | 1280.7 | -1.244 | 0.53 |

ED: Euclidean distance, RD: road distance, TD: time distance

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RD and TD are time variant variables decreasing by development of accessibility according to time, and the TD decreased more rapidly than the RD.

6. Analysis of the greenbelt effect

The coefficient of greenbelt effect, C, optimized in the new model, became larger by year in all distance measurement methods (Fig. 6). This result indicates agreement with the model assumption that the C value increased along with the _\text{t+nU}_ curve, which has high value according to time, because of urbanization by population increase. Analyzing C values of the three periods, that of 1995 increased more rapidly than those of the other two years. This designates that the corresponding _\text{t+nU}_ curve increased more than those of _\text{t+U}_ and _\text{n+U}_, namely, urbanization between 1990 and 1995 occurred more rapidly than between 1985 and 1990. This is demonstrated by the simple statistics of Table 4, indicating the average increase rate of the study area for 1985−1990 is 1.6%, while the increase rate for 1990−1995 is 3.5%.

7. Model response to accessibility measurement methods

The results of impact assessment for the model accuracy of the three distance measurement methods show that population potential using TD has the highest correlation followed by RD and ED (Fig. 7). This indicates that TD considering transportation among the three distance measurement methods is the most appropriate method for accessibility measurement, as a driving force of population movement. In addition, as shown in Fig. 5 and Table 2, despite the simple quadratic model without the term for greenbelt effect, their R^2's in the cases using TD were higher than those of ED and RD, and differences between those and the new model's results were smaller than those of ED and RD, relatively. These results indicate that the correlation between population potential and the ratio of urban land uses in areas excluding the greenbelt is higher in the case using TD than the other cases.

8. Change of population potential surface

Fig. 8 presents maps of contour lines generated using the function TINCONTOUR in ARC/INFO from population potential calculated by the optimized distance exponent. The distribution of population potential in the study area shows relative low values compared with Seoul, due to difference of population between Seoul and each area. The optimized model has various a values for the three data sets and three distance types, as relative values to 100 set for Seoul, population potential of each area was increased according to year. In addition, the population potential

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Statistics of urban land ratio and three distance measures from the center of Seoul</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>1985</td>
</tr>
<tr>
<td></td>
<td>Avg</td>
</tr>
<tr>
<td>UL/PRA (%)</td>
<td>8.5</td>
</tr>
<tr>
<td>ED (km)</td>
<td>49.3</td>
</tr>
<tr>
<td>RD (km)</td>
<td>59.3</td>
</tr>
<tr>
<td>TD (min)</td>
<td>49.2</td>
</tr>
</tbody>
</table>

PRA: possible residential area, UL: urban land area, ED: Euclidean distance, RD: road distance, TD: time distance, Avg: average, Min: minimum, Max: Maximum, Std: standard deviation

Fig. 6 Control effect coefficient (C).

Fig. 7 R^2 of the new model by different accessibility.
using TD shows the highest values spatially, while that using ED showed the lowest values in the same year. After Anderson generalized the population potential model with a distance exponent, the exponent has never been defined theoretically as a constant, so that several studies have empirically suggested the value of distance exponent for their research purposes. In this study, the new model has various distributions of $\alpha$ such as 0.703–0.941 for ED, 0.600–0.761 for RD, 0.638–0.851 for TD, which are lower values than those of the simple quadratic model. The $\alpha$ value is sensitive to not only model types, but also data sets for analysis over time.

9. Discussion

It is generally agreed that there is a close relationship between population potential and urbanization. However, although population potential in the greenbelt area surrounding Seoul is very high, the ratio of urban land uses, as level of urbanization, is relatively lower than that outside the greenbelt, due to restriction of new development within it. This reason is that if urbanization is restricted perfectly in the greenbelt, the level of urbanization in the greenbelt area is fixed at the initial value of the first year when it was established. Results of this study showed that the new model considering a term of the greenbelt effect had reasonable value for a coefficient of the greenbelt effect, C, that agreed well with the model assumption, in which the C value is increased, relatively, according to urbanization over time. Although the three types of distance measurement used in the calculation of population potential, up to now, have been adopted empirically for the research purposes of many studies, the relationship between population potential and $\rho, \lambda^*U$, the response of the model by accessibility measurement methods has never been analyzed. In the results of this study, the model using TD showed the highest $R^2$ followed by the RD and ED. This indicates that the most accurate accessibility measure that has influence on movement of population in a suburbanization process is TD, followed by RD. Up to now, although the distance exponent in the population potential model had been adopted as a constant, the value had not been defined as a constant theoretically in the field of regional science after Anderson generalized it. This study demonstrated that the distance exponent has various distributions by data sets and distance measurement methods. Spatial distributions of population potential by the optimized distance exponents present that the more urbanization proceeds, the higher population potential each area has, and the case using TD has higher values than those of RD and ED. The new model was optimized nearby $\alpha = 1.0$ in the case using ED, while the model was optimized close to $\alpha = 0.5$ in the case us-
ing TD. According to the increase of population in areas and urbanization, it shows that the value $a$ tends to be from 0.5 to 1.0. The distribution of urban land ratio by distance from Seoul showed low $R^2$, less than 0.53 in all cases. It indicates that the ratio of urban land uses in the study area is not well fitted to the general location theory, in which a curve of population density or a bid-rent curve is well fitted with a distance decay function. The reason is that the study area consists of not only a complex settlement system with several satellite cities and many rural areas, but also the greenbelt area near Seoul. In the rapid growth areas with a big city and middle sized cities, the proposed model was well applied to analysis of urbanization using population potential. Statistics for distance from Seoul designate that although the ED has static values for all years, the RD and TD have dynamic values decreasing toward Seoul according to time. Moreover, TD decreased toward the central city more rapidly than RD, because it reflects transportation methods including road development that RD also considers.

IV. Conclusion

This study modeled the relationship between population potential (PP) and level of urbanization (UL/PRA) indicated by the ratio of urban land uses (UL) to possible residential area (PRA) in each area, considering the restriction effect on urbanization by the greenbelt. The model was tested with a case study area located south of Seoul, the capital city of ROK. Three types of distance measurement methods (Euclidean, road, and time distance) for calculation of population potential were used and response of the new model to the three methods was analyzed.

The UL/PRA was well fitted with a quadratic function of PP, considering a term for the greenbelt effect, while the simple distance decay function by distance from Seoul and a simple quadratic function were not well fitted with the UL/PRA in all data sets. This paper showed that time distance is the most reasonable accessibility measurement method, rather than road or Euclidean distance. This study suggests that a more detailed term for the greenbelt effect should be considered for the urbanization analysis in further studies, though this study used a simple term that multiplies a coefficient by the ratio of greenbelt area to total area. Spatial distribution of PP by the optimized distance exponent showed high values in the greenbelt area nearby Seoul. The values of the distance exponent were distributed variously ranging from 0.600 to 0.941. This result demonstrated that the distance exponent of the general PP model could have various values empirically according to practical problems. It also designates that the exponent is sensitive to distance measurement methods. This paper also suggests that the exponent should be empirically used as a calibration parameter to be applied to practical problems because there is no constant value in socio-economic phenomena theoretically.

Although the greenbelt has been considered as a factor affecting the discontinuity phenomena theoretically on continuous curves of bid-rent and population density, it has never been empirically applied to practical problems for modeling spatial distribution of urbanization, using data sets of real areas. This study demonstrated the applicability of the new model, and it is expected that the approach of this study can be applied to simulation of urbanization in other areas surrounding big cities considering the effects of zoning systems including greenbelts.

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グリーンベルト効果と近接性の測定方法を考慮した都市化水準のモデリング

金 大 権, 水 野 啓, 小 林 懲太郎

I 結論
中心地周辺における都市化現象を重力モデルによって分析したこれまでの研究では、中心地の影響のみを考慮するポテンシャル概念が用いられてきた。本研究では、全ての地区からの影響を考慮した人口ポテンシャルを用いて、各地域の都市化水準との関係をモデルリングする。この人口ポテンシャルは、道路や公共交通の発達によって変化する地区間の近接性（アクセスビリティ）の影響を大きく受けるため、ここでは直線、道路、および時間の三種類の距離を用い、それぞれに対するモデルの構築を分析する。
一方、中心地からの距離と都市の土地利用比率の関係は、グリーンベルトなどのゾーニングが存在することで不連続となる。こうした現象は単純な立地モデルによって説明することができないため、本研究ではグリーンベルトによる都市化抑制効果を考慮した新たなモデルを開発し事例地域に適用する。

II モデルの構築
(i) 時期の区をもつ都市化水準（）を、可住地地盤に対する都市の土地利用面積の比率によって表す。はどの地区のもつ人口ポテンシャル（）と密接な関係があると考えられる。また人口ポテンシャルは、距離指数（）を伴う(1)式で表される。

\[
(U_i = f_i(\Phi_i), \forall i)
\]

(1)

\[
\Phi_i = \sum_{j=1}^{m} \frac{P_j}{d_{ij}}, \forall i
\]

(2)

ここで、は比例定数、は地区数、は地区の人口、は地区の間の距離、は時間距離である。統計的にグリーンベルトが影響すると、過去グリーンベルト内での都市化の抑制性の比較する（3）式で表される。

\[
(i = 1, U_i \in G)
\]

(3)

ここで、Gはグリーンベルトに含まれる地域の集合である。このグリーンベルト効果を考慮すると、(i)期からn年後のを時間はグリーンベルトで不連続となる（1）式から得られる、グリーンベルトを伴う地域での都市化水準は1式のように一般化される。

\[
(i = 1, j = 1, U_i = f_i(\Phi_i), -r_i U_i, \forall i)
\]

(4)

ここで、は(i + n)期におけるグリーンベルトによる都市化の抑制効果を示す項である。これ

\[
\sum_{j=1}^{m} \frac{P_j}{d_{ij}} \frac{C_d}{C_i}, \forall i
\]

(5)

ここで、は1から1+nの期間にグリーンベルト内で都市化の抑制を固定された面積である（図1）。この効果を定量化するためにグリーンベルトの単位面積を考慮すると(6)式が成立する。

\[
(i = 1, C_d = \sum_{j=1}^{m} \frac{C_d}{C_i}, \forall i)
\]

(6)

ここで、CとDはそれぞれグリーンベルト効果の係数とグリーンベルトの長さを示す。各地域におけるグリーンベルト面積を用いてグリーンベルト効果を一般化すると(7)式が導かれる。

\[
(i = 1, C = \sum_{j=1}^{m} \frac{C_d}{C_i}, \forall i)
\]

(7)

ここで、はDの面積とグリーンベルト面積である。人口ポテンシャルと都市の土地利用比との関係は、経験的な2次方程式を用いて(8)式のように表される。

\[
(f_i(\Phi_i) = a_i + b_i \int_0^\infty (s_i + \Phi_i)^2, \forall i)
\]

(8)

(4)式に基づきグリーンベルトの都市化抑制効果を考慮すると、(9)式に表される一般的な支配方程式が定義できる。

\[
(i = 1, j = 1, U_i = f_i(\Phi_i), -r_i U_i, \forall i)
\]

(9)

III モデルの適用
1 対象地域の概要
本研究では、韓国でも近年もっとも急速に開発が進行した地域であるソウル南部を対象に事例分析に取扱い、総面積は3,983㎢であり、その単位（面積の下部単位）および部で構成されている（図2）。ソウル周辺の都市化の進行を抑制するため、本地域の一部は1970年代初頭に新規の都市開発を規制したグリーンベルトに指定された。その範囲は対象地域79面積のうち19地区に及んでいる。

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2 統計及びGISデータ

韓国の市郡統計年報から1985、90、95の各年について面／市単位の土地利用および人口に関するデータベースを構築した。またGISデータとして、グリーンベートの境界ならびに三時期の道路および鉄道区間を作成した（図3）。また地区間の距離計測のため、各地区の幾何学重心を求めるため、最近の道路基を投射して各地の中心点とした。各地区的可住地面積は、地区総面積から河川・湖を除いた傾斜15度未満の面積とした。

3 距離測定の方法

地区間の直線距離は、各地区中心点のUTM座標より計算した。時間距離を求めめるための道路負荷（W0）は、60km/hを基準とする相対速度として00式で表される。

\[ W_0 = \left( \frac{60}{V_i} \right) \quad \text{(01)} \]

ここで、\( V_i \)は地区と地区間の最短経路における道路の計測速度である。最短経路（SP）に含まれる道路区間数を\( n \)とすると、\( SP_0 \)は00式で定義できる。

\[ SP_0 = 60 \sum_{k=1}^{n} \frac{d_k}{v_k} \quad \text{(11)} \]

ここで、\( k \)は1-2間の最短経路の1つを示す。\( d_k \)はkm/hでの距離とした。それぞれの間の距離を示す。全ての道路区間に関して\( V_i = 60 \)km/hである場合には、\( SP_0 \)が最短経路上の道路間距離と一致する。道路負荷として、高速道路と鉄道には100km/h、国道には60km/h、地方道路には40km/hの計測速度を用いた。

4 モデルの最適化

加重最小自乗法によってRMSEを最小化するよう試行錯誤法を用いてモデルを最適化した結果、\( R^2 \)が0.78から0.86となった（表1）。

5 既存モデルとの比較

本モデルを評価するためにグリーンベート効果を含む2次方程式を最適化した結果、本モデルの適合度が全ての場合において高いことが示された。また、人口ポテンシャルを考慮せず、単純な距離減衰関数を用いた場合の\( R^2 \)は最大で0.53であった。これらの結果から、既存の単純なモデルではグリーンベートを伴う地域の都市化現象を説明することが困難であり、本モデルの有効性が高いことが示された。

6 グリーンベート効果の分析

本モデルで適応されたグリーンベート効率係数Cは、図6のように全ての距離測定法において年次と年次とともに増加し、特に1995年に著しく高くなっている。これは1995年のU区間が1985年および1990年から大きく高に移動したことを意味し、1985-90年の都市の土地利用の平均増加率1.6%に比べて1990-95年は3.5%と急激に高くなっていること（表4）とも合致する。

7 近接性の測定法に対するモデルの反応

三種類の距離を用いて求めた人口ポテンシャルと都市の土地利用比率の相関は、時間距離を用いた場合に最も高くなった（図7）。

8 人口ポテンシャル分布の変化

人口ポテンシャルの空間分布を、ソウルを100とする相対値として図示すると、各地区的人口ポテンシャルは年とともに増加していることがわかる（図8）。同じ年度でも、時間距離を用いた場合に比べ直線距離による人口ポテンシャルは低い値を示している。距離指標（\( \alpha \)）は距離の種類や年度によってさまざまな値となる。

9 結果と考察

グリーンベート内の地区は極端に高い人口ポテンシャルをもつが、都市の土地利用比率は相対的に低く抑えられている。この現象を考慮することで、高い適応度をもつモデルは構築できたと考えられる。また、異なる距離測定法を用いた比較から、交通手段・経路選択の多様性を反映した時間距離が、直線および距離距離に比べて人口移動のドライビングフォースをより的確に反映することができる。

IV 結論

本研究では、グリーンベートの都市化抑制効果と近接性の測定方法を考慮して、人口ポテンシャルと都市化水準（可住地に対する都市の土地利用の比率）の関係を示すモデルを構築し、都市ソウルの南部地域に適用した。その結果、従来の単純モデルに比べて極めて高い精度で都市化現象を説明できることが示された。本研究で提案するモデルは、このようなゾーニングを含む都市周辺地域における都市化の進行を推定する上で有用である。

Key Words：1）都市化，2）グリーンベート，3）近接性，4）人口ポテンシャル，5）時間距離

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