An Urban Transport and Activity Location Model for the Evaluation of Commuting Rail Improvement

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1. INTRODUCTION

For economic analysis or financial analysis in the feasibility study of urban railway projects, as well as other transport projects, it is necessary to forecast not only the traffic volume but also the effect such as the location change of urban activities. In urban railway projects, the latter is of high importance because a large share of demand for new railway service might be generated from new locations along the rail. Transport-location models which have been called "land-use-transport models" have been proposed and applied for such study.

In Japan, there also exist many types of transport-location models. For example, Hayashi et al. (1990) developed a model in order to measure the benefits of transport improvement including the external effects. Miyamoto (1992) also proposed a model which employ the concepts of random utility and random rent-bidding. However, most of the existing models deal with only land markets. This is partly because data of floor use have not been available, and partly because their prototype were developed in the US or Europe, where building and land are traded in one set. In Japan, as they are traded separately, the bias sprung from ignoring that floor use is not proportional to land use may influence the transport demand forecast, and therefore may do feasibility study. With these backgrounds, we are now developing a new type of transport-location model which can deal with land markets and building markets simultaneously. For this purpose, our model is based on the theoretical framework of Walrasian (general) multimarkets equilibrium.

On the other hand, since existing models require a huge volume of data in case we apply them to a whole metropolitan area, while in practical railway planning, most effects of a project are likely to appear in the jurisdictions along the rail (called "project area" in the rest of this paper), we should modify the models for the purpose of less data requirement. In our model, in order to measure the effects in project area effectively without treating the huge volume of data, many zones where impacts of a project are not significant are aggregated into a representative large zone, while project area is still segmented into many small zones.

In this paper, we will explain the characteristics of our model and report some results of application. The remainder of this paper consists of 5 sections. In section 2, we explain major assumptions and concepts. In section 3, we define variables and functions which play the most important role in our model. We state conditions for an equilibrium in the model in section 4. In section 5, we will report some results of application. Section 6 concludes the paper.

2. STRUCTURE OF THE MODEL

Major assumptions and concepts in the model are summarized as follows.

1) Spatial coverage of the model is, first, segmented into the project area and the non-project area. The former, then, consists of zones labeled by \( j = 1, \ldots, J \). Each zone has one land market and one building market.

2) Economic agents considered in the model are, several types of locator, developers, and landowners. Total number of each locator is given from the other models such as a multi-regional macro-econometric model. Hence, an urban system in the model is a closed as defined in urban economics. Locators are classified into two types as the residential and the retail and service. Residential locators are furthermore grouped according to their commuting areas. There is only one representative developer and one landowner in each zone. Each representative developer can supply floor service and demand for land service only within its own zone. Also, each landowner can supply land service in its own zone.

3) Each economic agent behaves so as to maximize his/her utility or profit.

4) To focus on the effects in project area, location choice behavior is modeled as bi-level nested-logit model.
5) Theoretical framework of the model to describe a market equilibrium is based not on the bid-rent theory but on the Walrasian (general) multimarkets equilibrium as well as in the line of thought shown by Anas (1982). Any markets in the model are to be cleared in each period in a calendar discretely denoted by \( t = 1, \ldots, T \).

The outline of the model structure is sketched in Figure 1.

3. BEHAVIOR OF THE ECONOMIC AGENTS

3.1 Locator

A locator chooses his/her location where he/she is likely to attain the highest level of attractiveness. The attractiveness for locators is called "location (or locator's) surplus" in this paper.

We define it as,

\[
v_i = f(R_i) + W_i \tag{1}
\]

- \( v_i \) : locator's surplus (location surplus)
- \( k \) : type of locators
- \( f(R_i) \) : the surplus of floor consumption
- \( R_i \) : floor rent
- \( W_i \) : utility term dependent on the attributes of zone

Nakamura, Hayashi, and Miyamoto (1981, 1983) first proposed the concept of "location surplus". However, Ueda (1992) redefined it to be consistent with optimization behavior in microeconomics, by using a quasi-linear utility function. "Location surplus" in this paper follows the definition by Ueda (1992).

We assume that an individual floor demand function \( q \) is a linear function of rent, \( R \) as,

\[
f(R_i) = \int_{0}^{\infty} \max\{0, q_d(R_i)\} dR \tag{2}
\]

\[
q(R_i) = c - d \cdot R \tag{3}
\]

- \( q_d(R) \) : individual floor demand

Finally, we specify \( W_i \) (for residential locators) as,

\[
W_i = \gamma_d \cdot \ln(D_i) + \gamma_o \cdot \ln(A_i) + \gamma_t \cdot Z_i + \gamma_r \cdot \ln(T_i) \tag{4}
\]

- \( A_i \) : accessibility from shopping area
- \( T_i \) : time required to get to the office
- \( Z_i \) : the level of infrastructure for utility service
- \( \gamma_d, \gamma_o, \gamma_t, \gamma_r \) : parameters

Location choice is modeled as a bi-level nested logit model. At the first stage the locators choose area \( A \) or \( B \). Area \( A \) is the one where the railway system is to be improved and area \( B \) is the rest. At the next stage the locator who has chosen area \( A \), again chooses one zone in area \( A \) (Fig. 2).
The locator's surplus that a representative locator attains in area $A$, defined consistently with multi-nominal logit model, is defined as a log-sum function.

$$S(V_A) = \frac{1}{\theta} \ln \left[ \sum_m \exp(\theta \cdot v_m) \right]$$  \hspace{1cm} (5)

The probability that $k$ type locator chooses area $A$ is given by

$$P_{A(k)} = \frac{\exp[\alpha \cdot S(V_A)]}{\exp[\alpha \cdot S(V_A)] + \exp[\alpha \cdot S(V_B) + \delta_k]}$$  \hspace{1cm} (6)

$P_{A(k)}$ : probability that a locator chooses area $A$

$\delta_k$ : threshold

$\alpha$ : parameter ($>0$)

We assume that $S(V_B)$ is constant. Thus,

$$P_{A(k)} = \frac{1}{1 + C_k \cdot \exp[-\alpha \cdot S(V_A)]}$$  \hspace{1cm} (7)

$C_k$ : parameter ($>0$)

Since $C_k$ is estimated as a parameter in the model, we have only to collect the data for the project area in order to calculate the locator's surplus $v_m$, and therefore $v_A$. This is a merit of bi-level nested logit model for a location choice behavior in avoiding the collection of a huge data set for the whole metropolitan area.

The probability that a locator chooses zone $m$, under the condition that area $A$ has been already chosen, is given by

$$P_{m|A} = \frac{\exp[\theta \cdot v_m]}{\sum_m \exp[\theta \cdot v_m]}$$  \hspace{1cm} (8)

$P_{m|A}$ : conditional probability of choosing zone $m$, given the area $A$

Number of $k$ type locators that choose area $A$ is

$$N_{A(k)} = N_{(k)} \cdot P_{A(k)}$$  \hspace{1cm} (9)

Thus, number of locators that choose zone $m$ is

$$N_{Am} = N_A \cdot P_{m|A}$$  \hspace{1cm} (10)

$$N_A = \sum_k N_{A(k)}$$  \hspace{1cm} (11)

$N_{A(k)}$ : the number of type $k$ locators in area $A$

$N_{(k)}$ : the total number of type $k$ locators

$N_A$ : the total number of locators in area $A$

### 3.2 Developer

In order to consider the floor markets and land markets simultaneously, we introduce "developer" as an agent who joins the floor market and land market in each zone. In each
period, developer borrows land from landowner and invests it in building construction to supply floor service for locators.

We suppose that developer maximizes the profit, as formulated,

\[ \pi_i = \max_{\xi_i} \left[ R_i \cdot Q_i - C(Q_i) \right] \]  
\[ C(Q_i) = \min_{L_i} (P_i \cdot L_i + I \cdot K_i) \]  
\[ s.t. \quad Q_i = A \cdot L_i^a \cdot K_i^b \]

- \( \pi_i \) : the profit of developer
- \( Q_i \) : floor area which developer supplies
- \( C(Q_i) \) : production cost for floor service
- \( L_i \) : land area supplied to developer
- \( I \) : the material price for construction
- \( K_i \) : the material inputted for production of floor service
- \( A, a, b \) : parameters (>0)

This problem gives its solution as,

\[ \pi_i = \phi_1 \cdot R_i^{\frac{1}{a+b}} \cdot P_i^{\frac{a}{1+b}} \]  

The F.O.C. yields floor supply function as,

\[ Q_{si} = \phi_2 \cdot R_i^{1+b} \cdot P_i^{\frac{a}{a+b}} \]  

From Hotelling's lemma, land demand function is given by

\[ L_{di} = \phi_3 \cdot R_i^{1+b} \cdot P_i^{\frac{a}{a+b}} \]  

- \( \phi_1, \phi_2, \phi_3 \) : parameters (>0)

3.3 Landowner

We express land supply at period \( t \) as:

\[ L_{si} = L_{si-1} + L_i^a \]  

- \( L_{si} \) : land area supplied at period \( t \) (endogenous at \( t \))
- \( L_{si-1} \) : land area supplied at period \( t-1 \) (given at \( t \))
- \( L_i^a \) : additional land area supplied at period \( t \) (endogenous at \( t \))

Landowner maximizes money metric utility per unit of land, or in terms of land rent, through the choice between supply or reservation. The money metric utility for supply is, needless to say, land rent in this period. For reservation, the utility is defined as the expected level of land rent in next period, which is extrapolated by the linear function of the land rent in the previous period.

Then, the landowner's choice can be specified as the following binary logit model.

\[ L_i^a = \frac{\exp[\eta \cdot (P_i - \tau \cdot L_i^a)]}{\exp[\eta \cdot (P_i - \tau \cdot L_i^a)] + \exp[\eta \cdot ((P_i - \tau \cdot L_i^a) + x_i)]} \]
\[ L_t^* = \frac{L_t}{1 + \exp\left(\eta \left(\frac{1 - \frac{r}{i + \tau}}{r + i + \tau} (P_t - P_{i}) + X_i \right)\right)} \quad (19) \]

- \( L_t^* \): farmland area available at period \( t \)
- \( P_t \): the extrapolated land rent
- \( LP_t \): the extrapolated land price
- \( P_i \): land rent at period \( i \)
- \( LP_i \): land price at period \( i \)
- \( X_i \): utility that doesn't concern land rent
- \( r \): the rate of land tax
- \( i \): the rate of interest
- \( \eta \): parameter (>0)

4. EQUILIBRIUM CONDITIONS

In the framework of Walrasian multimarkets equilibrium, all markets are cleared simultaneously at each period. Hence, market equilibrium is defined as:

**Building markets**

\[ N_i(R_i) \cdot q_d(R_i) - Q_s(R_i) = 0 \quad (\text{for all } i) \quad (20) \]

**Land markets**

\[ L_d(P_i) - L_s(P_i) = 0 \quad (\text{for all } i) \quad (21) \]

As for location equilibrium, we can define it as a state where the locators no longer has an incentive to relocate. In other words, no locator expect that he/she can enjoy the higher level of location surplus in the other zones than the present zone.

Since all endogenous variables \( N=\ldots,N_i,\ldots, \), \( R=\ldots,R_i,\ldots \) and \( P=\ldots,P_i,\ldots \) are mutually dependent, they should be determined simultaneously. In other words, we can get the solution of the simultaneous equilibrium by solving the system of equations (20), (21) and (9), (10) (Fig. 3) (See Ueda et al (1993)).

5. APPLICATION

5.1 Case Study Area

In order to verify the computability, and furthermore to show the applicability of the model in practical use, we have tried a case study where we assume that a new commuting rail will be opened in Tokyo Metropolitan Area (T.M.A.) in 2000 (Fig. 4).

This rail project would be accompanied with many urban development projects and would reduce the travel time from about 85 minutes by existing line to about 45 minutes in the zones locating at 20 km distant from CBD. The new locations in the project area might generate new demand for railway service, adding to the demand diverted from the existing rails. Again, that is why we have to focus on the location changes in the area.

For application we divide residential locators into groups labeled by 6 working places and 3 age classes of householders.

5.2 Calibration
We calibrate the parameter, supposing the simultaneous equilibrium of location and market (Table 1). As most of parameters show high t-value, we can say that specification of functions and estimation of parameters were almost sufficiently successful.

5.3 Simulation Result

We first simulated allocations of locators, landuse, and flooruse in 1990. Then, we compare the outputs with observed data to evaluate the performance of our model. Judging from correlation coefficient, we can conclude that our model has a good performance in simulating allocation of locators, landuse and flooruse.

We also forecast and compare them with and without project in 2020 (Fig. 5). In the area where the increasing rate of residential locators in the 30 years from 1990 to 2020 is the highest, the rate is 64% with project and 25% without project, while that of T.M.A. is 22%. In the same area, the increasing rate of floor area is 20% with project, while that of land area is only 3%. This shows the floor use is not proportional to land use and makes us confirm that the concept of general equilibrium of land and building market is of high use, or more strongly, inevitable for precise forecast of location changes.

Here, we should note that there might be an over-estimation. This might be because the value for the total number of locators, which was forecasted in the period of growing economy, might be higher than the real (in recent economic depression in Japan). Needless to say, when another and well-estimated data of locators are prepared, we can easily make a simulation again, replacing the over-estimated total with them.

6. CONCLUDING REMARKS

In this paper, we proposed a transport-location model based on general multimarkets equilibrium. Again, we should note that the concept of general equilibrium of land and building markets is remarkable, compared with existing models. With this concept, we have a way to forecast the location more precisely than ever before.

Then we also proposed a way to forecast the impacts of a project effectively by aggregating many zones into a representative large zone where the impacts are not significant. Through application we confirm that our model reduces routine works for collecting a huge volume of data, and that the model is applicable for practical use in spite of such reduction.

However, there still remain tasks that we should tackle with in the next stages.

For example, to check the sensitivity and stability of the model in the environmental change of macro-economy remains to be done (See Ueda et al (1993)).

As we calibrate the parameters with regression analysis etc. for each equation, we cannot consider the variance of forecasted outputs. In order to use the concept of general equilibrium strictly, we should develop a method for simultaneous estimation.

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REFERENCES


Figure 1. Outline of the model structure

Figure 2. Location choice model
to fix the external related terms
\( N_{kl} = N_{kl}^0 \quad N_{lA} = N_{lA}^0 \)

equilibrium condition
\[
K \sum_{t=1}^{N_{kl}} q(R_t) - Q_L^2(R, L, T) = 0 \quad L_F^2(R, L, T) - L_F^2(L, T) = 0
\]

\( N_{kl}^1(V_{kl}(R_0)) \quad R_i(N_i) \quad L_P(N_i) \)

\[
|N_{kl}^2 - N_{kl}^1| < \varepsilon
\]

YES \( S_A(V_{kl}) = \frac{1}{\theta} \ln \left( \sum_{i} \exp(\theta \cdot V_{kl(i)}) \right) \)

\( N_{kl}^3(S_A(V_{kl})) \)

NO

\[
|N_{kl}^2 - N_{kl}^3| < \varepsilon
\]

solution of the model

YES

\( N_{kl}[V_{kl}(R_t)] \quad R_i(N_i) \quad L_P(N_i) \quad N_{kl}[S_A(V_{kl})] \)

---

**Fig. 3 Searching algorithm for simultaneous equilibrium**

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**Fig. 4 Case study area**
a) Locator

<table>
<thead>
<tr>
<th>parameter</th>
<th>parameter value (value of t)</th>
<th>correlation coefficient</th>
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</thead>
<tbody>
<tr>
<td>$\theta$</td>
<td>0.925(25.8)</td>
<td></td>
</tr>
<tr>
<td>$\theta \cdot \gamma_d$</td>
<td>0.555(48.8)</td>
<td></td>
</tr>
<tr>
<td>$\theta \cdot \gamma_e$</td>
<td>$3.07 \times 10^{-2}(2.8)$</td>
<td></td>
</tr>
<tr>
<td>$\theta \cdot \gamma_t$</td>
<td>$1.70 \times 10^{-2}(18.3)$</td>
<td></td>
</tr>
<tr>
<td>$\theta \cdot \gamma_c$</td>
<td>-3.31(-33.3)</td>
<td></td>
</tr>
<tr>
<td>$\gamma_a$</td>
<td>$3.26 \times 10^{-2}(20.8)$</td>
<td>0.997</td>
</tr>
<tr>
<td>$\gamma_d$</td>
<td>$1.60 \times 10^{-4}(-4.9)$</td>
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</table>

b) Developer

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<th>correlation coefficient</th>
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<td>a</td>
<td>0.586(46.7)</td>
<td>0.749</td>
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<tr>
<td>b</td>
<td>0.317(9.0)</td>
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c) Landowner

<table>
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<th>correlation coefficient</th>
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</thead>
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<td>$\eta$</td>
<td>0.175(9.3)</td>
<td>0.724</td>
</tr>
<tr>
<td>$X_t$</td>
<td>21.1(53.7)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Specifications and estimation of the parameters

Fig. 5 The result of application