A LOCATION CONTROL MODEL FOR TRANSIT ORIENTED DEVELOPMENT

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Abstract: The purpose of this study is to propose a location control model for determining a proper land-use pattern, which is required in carrying out Transit Oriented Development (TOD), such that road network capacity and population density will be in proportion.
The location control model is formulated as bilevel programming models by assuming that a land-use pattern for TOD is determined based on the behavior of the planner, who predicts user's behavior and implements land-use planning, and of the user, who decides behavior to maximize his utility according to this planning and drives on a road network.
In this study we estimate the location volume and link flow by using the proposed model. As a result, the guidelines for implementing effective land-use planning can be obtained.

1. INTRODUCTION

In recent years, many cities in Southeast Asia have been faced with serious traffic congestion due to rapid motorization. Although the most desirable way to solve the problem in these cities is to introduce rail transit such as a subway, it is so difficult to raise an enormous sum of funds for their construction that little progress has been made in such efforts (e.g., Bangkok MRTA project; Jakarta subway project). Accordingly it is expected that the bus transit system will keep playing a key role in the urban transportation system in most of those cities. At present, bus transit bears a large portion of transportation in Southeast Asian cities. For example, the Bangkok Mass Transit Authority operates about 10,000 buses and its modal share exceeds 40% (JICA, 1997).

Therefore, based on the view that improvement of bus service will help to solve the traffic problems, measures have been taken for expanding the capacity of bus transportation including application of bus exclusive lanes, but increasing car traffic has not been coped with.

In order to carry out the sustainable urban development that can control the use of cars and prevent urban sprawl in those cities, it is effective to coordinate bus transportation planning and land-use planning. Such a way of urban development centering on public transport, especially buses, has been already tried out in North and South America and Europe. The typical example is the Transit Oriented Development (TOD) under way in the city of Curitiba in Brazil. Curitiba drew up a comprehensive master plan for sustainable development in the 1960s when the city was growing. The backbone of the plan is TOD, in which bus transportation planning is integrated with land-use planning by setting up the dense use for the areas along bus routes, and controlling location to that end. This TOD project has been a great success so far (Nakamura, 1995). However, few numerical studies have been conducted about it.

In addition, because such intensive location with high density generates a new demand for cars, it is likely that road capacity will decline, causing more traffic congestion. Therefore, it is necessary to give careful consideration in advance to the influence of an increase in trip generation due to a change in location volume upon the road network.

This study quantitatively examines how much volume of location will be possible when TOD is put into practice in a real city. It pursues the reasonable location volume for the capacity of traffic facilities, which is expected to provide a guideline for the planner to regulate the land-use in TOD. In order to do this analysis, the present study builds up the location control model for calculating the maximum location volume in which the road network capacity taking into account the use of buses is in proportion to the area's population density. Using this model, the quantitative analysis of TOD becomes possible.

The composition of this study is as follows. Section 2, we formulate the location control model for TOD as bilevel programming models. Section 3, the solution algorithm for this model is investigated. Section 4, we apply the proposed model to the actual city. As a result, we can obtain the guidelines for implementing effective land-use planning.

2. FORMULATION

2.1 Location control model

Several number of studies have been made on the location control model for determining a proper land-use pattern, such that road network capacity and population density will be in proportion (Kiyota *et al.*,1985; Masuya *et al.*,1987; Iida *et al.*,1995). The purpose of these studies is to estimate the reasonable location volume for urban development in terms of network capacity. The main concern of these studies was to maximize population density under the given road network capacity which was indicated by the maximum OD trip volume (or trip generation).

Generally it is natural to assume that the land user chooses the best behavior for himself/herself regardless of the intention of the policy, while the planner enforces location control and restriction according to his policy. On the other hand, the planner is supposed to estimate the user's behavior and control location volume so that the road network will be efficiently used.

Based on these assumptions, Iida *et al.*(1995) formulated the location control model as the bilevel programming models that maximized the OD trip volume (trip generation) with the user's behavior as the constraint condition. Their study made it possible to explicitly treat the user's behavior by formulating location control as the bilevel programming models, and that is useful in examining comprehensive location problems.

2.2 Location control model for TOD

Assuming that a location for TOD is determined based on the behavior of the planner, who predicts user's behavior and implements land-use planning, and of the user, who decides distribution, mode, and route so as to maximize his utility under the condition of this land-use plan and a road network, the location control model can be formulated with the following bilevel programming models.

The upper-level problem is explained with the model to maximize OD trip volume on a network within the limits of road network capacity and of location capacity, and it clarifies the planner's behavior of controlling and regulating location and determining a land-use pattern in order to promote the use of buses and simultaneously make the road network used effectively.

Above assumption is consistent with reality. So TOD problem can be formulated as the bilevel programming models by modifying Iida *et al.*(1995).

Concretely, the lower-level problem of user's model should be rewritten using the combined equilibrium model to include public transport (buses in this study) as one of transportation mode. Also, the maximum location volume (represented as the number of person trips) should be the determinant variable and it must be maximized within the limits of location capacity and of road network capacity.

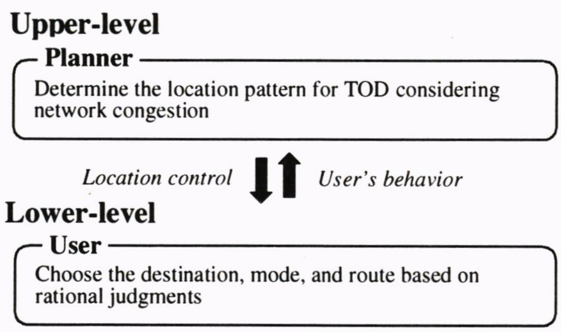

Figure 1. Bilevel programming framework for TOD

A large number of studies have been made on the network equilibrium analysis with a mathematical programming methods including public transport. In this study, user's behavior is described by using the combined distribution/modal split/assignment model proposed by Florian *et al.*(1978). The reason to use the combined equilibrium model is as follows.

1) Description of user's behavior is described theoretically. Especially, by using this model, the OD trip volume, the link flow and the equilibrium travel time can be determined endogenously.
2) Formulation as a single mathematical problem has made possible use the existing solution algorithm

Network conditions and user's behavior are described as follows.

(1) Network condition

Network consists of a set of links and nodes. Car and bus move on same link. The link flow and the travel time can be represented as follows.

$$x_a = \sum_{rs}\sum_{k} f_k^{rs}\delta_{a,k}^{rs} + x_a^{bus} \qquad \forall a \tag{1}$$

$$c_k^{rs} = \sum_{a} \delta_{a,k}^{rs} t_a(x_a) \qquad \forall k, r, s \tag{2}$$

$$c_k^{rs,bus} = \sum_{b} \delta_{b,k}^{rs,bus} c_b \qquad \forall k, r, s \tag{3}$$

where
x_a : flow on link a
f_k^{rs} : flow on path k connecting OD pair rs by car
$\delta_{a,k}^{rs}$: indicator variable (if link a is on path k between OD pair rs : 1, otherwise: 0)
x_a^{bus} : bus flow on link a (convert in PCU)
c_k^{rs} : travel time on path k connecting OD pair rs by car
$t_a(\cdot)$: travel time for link a
$c_k^{rs,bus}$: travel time on path k connecting OD pair rs by bus
c_b : travel time on bus link (fixed)

(2) User's behavior

It is assumed that the user simultaneously chooses his/her destination, mode of transportation and path so that utility will be maximized for him/her. In this model, utility is examined solely in terms of travel time. First, the OD trip volume in the case where the trip generation is given is offered by Logit function as shown in eq.(4).

$$q_{rs} + q_{rs}^{bus} = O_r \frac{\exp(-\theta c^{rs}) + \exp(-\theta c^{rs,bus})}{\sum_s \{\exp(-\theta c^{rs}) + \exp(-\theta c^{rs,bus})\}} \tag{4}$$

where
q_{rs} : trip volume between origin r and destination s by car
q_{rs}^{bus} : trip volume between origin r and destination s by bus
O_r : the total number of trips generating at node r
θ : parameter

The probability of cars or buses being chosen is also offered by Logit function as shown in eq.(5).

$$P_r = \frac{1}{1 + \exp[-\theta(c^{rs,bus} - c^{rs})]} \tag{5}$$

where
c^{rs} : minimum travel time between origin r and destination s by car
$c^{rs,bus}$: minimum travel time between origin r and destination s by bus

Assuming that car user chooses the minimum travel time route, following equilibrium conditions are formulated.

$$f_k^{rs}\left(c_k^{rs} - c^{rs}\right) = 0 \quad \forall k, r, s \tag{6a}$$

$$c_k^{rs} - c^{rs} \geq 0 \quad \forall k, r, s \tag{6b}$$

Similarly, assuming that bus user chooses the minimum travel time route, following conditions are formulated. Where, $c^{rs,bus}$ is the minimum travel time between origin r and destination s by bus since $c_k^{rs,bus}$ is fixed (see eq.(3)).

$$f_k^{rs,bus}\left(c_k^{rs,bus} - c^{rs,bus}\right) = 0 \quad \forall k, r, s \tag{7a}$$

$$c_k^{rs,bus} - c^{rs,bus} \geq 0 \quad \forall k, r, s \tag{7b}$$

where
$f_k^{rs,bus}$ passenger flow on path k connecting OD pair rs by bus (person trip).

The link flow and the OD trip volume satisfy the above-mentioned equilibrium conditions are obtained by solving a mathematical optimal problem.

[Optimal problem]

$$\min.\ \frac{1}{\theta}\sum_{rs} q_{rs} \ln q_{rs} + \sum_a \int_0^{x_a} t_a(\omega)d\omega + \sum_{rs} q_{rs}^{bus}\left(\frac{1}{\theta}\ln q_{rs}^{bus} + c^{rs,bus}\right) \tag{8a}$$

subject to

$$\sum_k f_k^{rs} = q_{rs} \quad \forall r,s \tag{8b}$$

$$\sum_k f_k^{rs,bus} = q_{rs}^{bus} \quad \forall r,s \tag{8c}$$

$$\sum_s (q_{rs} + q_{rs}^{bus}) = O_r \quad \forall r \tag{8d}$$

$$x_a = \sum_{rs}\sum_k f_k^{rs}\delta_{a,k}^{rs} + x_a^{bus} \quad \forall a \tag{8e}$$

$$f_k^{rs} \geq 0,\ f_k^{rs,bus} \geq 0 \quad \forall k,r,s \tag{8f}$$

$$q_{rs} \geq 0,\ q_{rs}^{bus} \geq 0 \quad \forall r,s \tag{8g}$$

2.3 Formulation as bilevel programming models

The location control model for TOD is formulated as the bilevel programming models based on above mentioned assumption about the behavior of the planner and user.

[Upper-level]

$$\max.\ \sum_r O_r \tag{9a}$$

subject to

$$x_a \leq \mu_a C_a \quad \forall a \tag{9b}$$

$$O_r^l \leq O_r \leq O_r^u \quad \forall r \tag{9c}$$

$$D_s^l \leq D_s \leq D_s^u \quad \forall s \tag{9d}$$

[Lower-level]

$$\min.\ \frac{1}{\theta}\sum_{rs} q_{rs} \ln q_{rs} + \sum_a \int_0^{x_a} t_a(\omega)d\omega + \sum_{rs} q_{rs}^{bus}\left(\frac{1}{\theta}\ln q_{rs}^{bus} + c^{rs,bus}\right) \tag{10}$$

subject to

(8b)-(8g)

where
C_a : capacity of link a
μ_a : tolerance congestion rate of link a
O_r : trip generation at node r
O_r^u : trip generation at node r (the upper limit)
O_r^l : trip generation at node r (the lower limit)
D_s : trip attraction for node s
D_s^u : trip attraction for node s (the upper limit)
D_s^l : trip attraction for node s (the lower limit)

The upper-level problem is formulated as the model to maximize OD trip volume on a network within the limits of the road network capacity and of the location capacity. The object function (eq.(9a)) maximizing the total number of trip generation O_r . O_r is a determination valuable in the bilevel programming models. Eq.(9b),(9c),(9d) are the constraint conditions. One of them, eq.(9b) is conditions on the link capacity. The link flow is estimated by the lower-level problem. Eq.(9c),(9d) are determined by the planner.

On the other hand, the lower-level problem is formulated as the equilibrium model that combines trip distribution, modal split and trip assignment, and it clarifies the user's behavior of choosing destinations, modes of transportation and paths based on reasonable judgments on the given network. The link flow and the OD trip volume are obtained by solving that combined model.

2.4 Existence of solution

The existence of solution for the proposed bilevel programming models is investigated. Generally, the condition for existing solution is as follows (Iida *et al.*,1992).

1) The object function of the upper and lower level problems and constraint conditions are continuous to the determination valuable.
2) Constraint condition of lower-level is convex and lower-level is feasible.
3) The constraint area of the upper-level problem is not void set.

The proposed model evidently satisfies the conditions 1) and 3). About 2), the constraint conditions of the lower-level problem is linear to route flow. Therefor the valuable set of this problem is the convex set, the solution existence is guaranteed.

3. SOLUTION ALGORITHM

3.1 Bilevel programming models

We employed the weighting average method for a solution algorithm for the bilevel programming models formulated in Section 2. Several strict solution methods for bilevel programming models have been developed. However, it is difficult to seek the optimal solution by using these methods because of the constraint condition of our model is non-linear and implicitly. Iida *et al.* (1992) proposed the constrained simplex method not using the direction. However in this method, the convergence of the solution can not be guaranteed when a network is large. For the reasons mentioned above, it is difficult to apply this strict method to our problem also.

We employed the weighting average method which is try and error approach for large network problem (Iida *et al.*, 1998). Since the first purpose of this study is to apply TOD to actual city and estimate the location pattern, this method is applicable. Using this method, the uniqueness of estimating location pattern is not guaranteed. However we will be able to obtain one of the location pattern for TOD. The solution algorithm of this method is as follows (Figure 2).

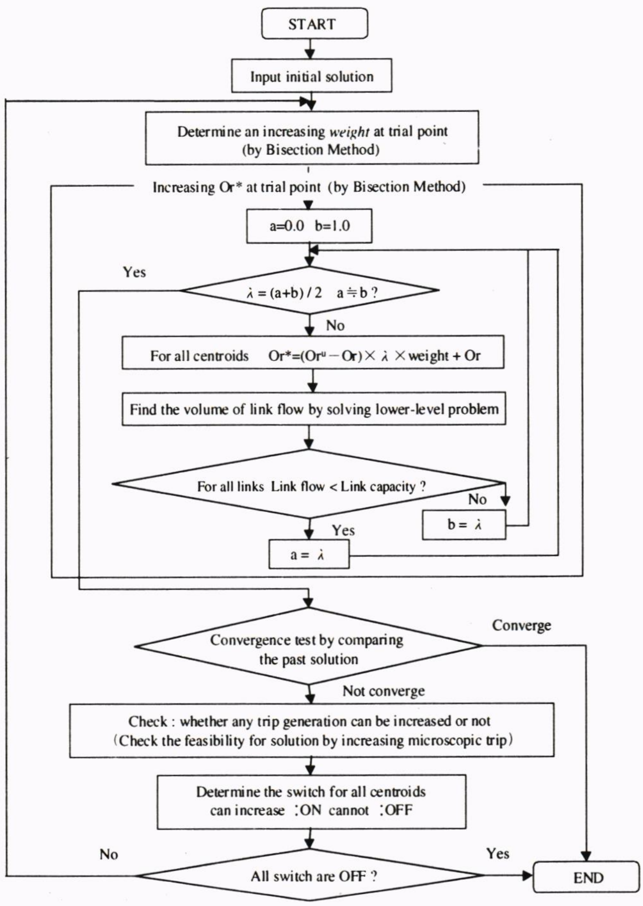

Figure 2. The weighting average method

3.2 Combined distribution /modal split /assignment model

Large number of studies made on solution algorithm for the combined equilibrium model. Two main approaches for that model not considering the interaction between car and bus are proposed (Matsui, 1998).

1) Frank-Wolfe algorithm
2) Partial linear approximation algorithm

LeBlanc *et al.*(1981) compared above two methods by applying the solution algorithm for the combined distribution/assignment model. He concluded the latter method is more stable than the former. Frank-Wolfe algorithm proposed by Florian *et al.*(1978) has been only known for solution algorithm for the combined distribution/modal split/assignment model. Therefore, we solve that model by using the partial linear approximation algorithm.

Here, the linear approximation of the first term of object function (eq.(8a)) is shown by (11a). The auxiliary program (linearized program) by decomposing each generation node for the direction finding is as follows.

[Auxiliary program]

$$\min.\ \hat{Z}^n(\mathbf{g},\mathbf{v})=\sum_s\left\{\sum_k c_k^{rs}(\mathbf{f}^n)g_k^{rs}+\frac{1}{\theta}v_{rs}\ln v_{rs}+\frac{1}{\theta}v_{rs}^{bus}\ln v_{rs}^{bus}+c^{rs,bus}v_{rs}^{bus}\right\} \tag{11a}$$

subject to

$$\sum_k g_k^{rs}=v_{rs}\quad \forall r,s \tag{11b}$$

$$\sum_k g_k^{rs,bus}=v_{rs}^{bus}\quad \forall r,s \tag{11c}$$

$$\sum_s (v_{rs}+v_{rs}^{bus})=O_r\quad \forall r \tag{11d}$$

$$g_k^{rs}\ge 0,\ \ g_k^{rs,bus}\ge 0\quad \forall k,r,s \tag{11e}$$

$$v_{rs}\ge 0\ \ v_{rs}^{bus}\ge 0\quad \forall r,s \tag{11f}$$

Where, g_k^{rs} denotes the auxiliary path flow corresponding to f_k^{rs}, v_{rs} and v_{rs}^{bus} denote the auxiliary OD trip volume corresponding to q_{rs} and q_{rs}^{bus}. By summarizing the first-order conditions for the auxiliary program, auxiliary OD trip volume by car can be represented as

$$v_{rs}=O_r\frac{\exp(-\theta u_{rs})}{\sum_s\{\exp(-\theta u_{rs})+\exp(-\theta u_{rs}^{bus})\}} \tag{12}$$

where u_{rs} and u_{rs}^{bus} is the minimum travel time between origin r and destination s by car and bus. Therefore the solution of auxiliary program is obtained by assigning above OD trip volume v_{rs} to minimum route. The algorithm can then be summarized as follows;

[Partial linear approximation algorithm]

Step 0: Initialization

Find an initial feasible solution $\{\mathbf{x}^1,\mathbf{q}^1,\mathbf{q}^{\mathbf{bus},1}\}$. Set $n=1$;

Step 1: Update of travel time

Set $t_a^n=t_a(x_a^n)$;

Step 2: Direction finding

(a) Compute $\{\mathbf{u}^n\}$ by searching the minimum route based on $\{\mathbf{t}^n\}$.

(b) Compute auxiliary OD $\{\mathbf{v}\}$, $\{\mathbf{v}^{bus}\}$ by Logit function (eq.(12)).

(c) Assign $\{\mathbf{v}\}$ to the minimum paths identified (a). This yields auxiliary link flow $\{\mathbf{y}\}$.

Step 3: Line search

Find α that solves the following problem.

$$\min.\ Z\left(\mathbf{x}^n + \alpha(\mathbf{y} - \mathbf{x}^n),\ \mathbf{q}^n + \alpha(\mathbf{v} - \mathbf{q}^n),\ \mathbf{q}^{\mathbf{bus}\,n} + \alpha\left(\mathbf{v}^{\mathbf{bus}} - \mathbf{q}^{\mathbf{bus}\,n}\right)\right)$$

$$\textit{subject to} \quad 0 \le \alpha \le 1$$

Step 4: Revise

Revise the flow and OD demand as following.

$$\mathbf{x}^{n+1} = \mathbf{x}^n + \alpha(\mathbf{y} - \mathbf{x}^n) \quad \mathbf{q}^{n+1} = \mathbf{q}^n + \alpha(\mathbf{v} - \mathbf{q}^n) \quad \mathbf{q}^{\mathbf{bus}\,n+1} = \mathbf{q}^{\mathbf{bus}\,n} + \alpha\left(\mathbf{v}^{\mathbf{bus}} - \mathbf{q}^{\mathbf{bus}\,n}\right)$$

Step 5: Convergence test

If $\max \left\{ \left|x_a^n - x_a^{n-1}\right| / x_a^n \right\} \le \varepsilon$, stop; otherwise, set n=n+1 and go to Step 1.

4. APPLICATION OF THE METHOD TO THE MODEL CITY

4.1 Conditions

This study computes the location pattern in the case where TOD is introduced in a model city based on a real city (hereinafter called model city). The available modes of transportation in model city are buses and cars, of which the transportation systems in most Southeast Asian cities consist. The network in model city is shown in Figure 3. It consists of 110 links, 81 nodes and 24 centroids. The conditions for calculation are detailed below.

(1) Bus routes

There are four bus routes, A, B, C and D (see Figure 3). All the routes run along the roadway sections where the use of public transport is promoted in the actual future development plan, and expansion of road capacity including application of bus exclusive or priority lanes is scheduled. In order to carry out TOD, it is important to take measures to promote the use of buses together with location policies.

(2) Level of bus service

The frequency of bus service is 300 round trips per day on route A, 100 round trips per day on route B, 200 round trips per day on route C and 300 round trips per day on route D. Travel speed is 20km/h on each route on the assumption that it may have a bus priority lane.

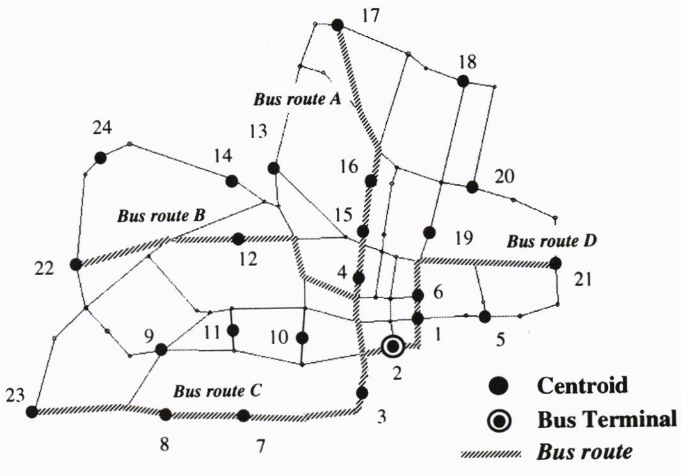

Figure 3. Model city's network

(3) Travel time on links

The relationship between traffic on a link and travel time is represented by BPR function (as shown eq.(13)).

$$t_a(x_a) = t_{ao}\left(1+\alpha(x_a/C_a)^{\beta}\right) \tag{13}$$

Where, t_{ao} is the free flow travel time on link a. Parameter α is 0.96 and β is 1.2 (by Mizokami *et al.*, 1989). PCU for the bus link flow is 3.(cf. eq.(1))

(4) Trip generation

The data obtained through the recent person trip survey is used as the present value.

(5) Parameter

Parameter of Logit function (eq.(4),(5)) is 0.1 in this study.

The upper limit of trip generation in each zone in eq.(9c) is defined so as to the use of buses will be promoted as follows;

1) The zones where bus routes are running (hereinafter called Bus Zones)
   Twice the present value.
2) Other zones
   The present value.

4.2 Result of Calculation

Under the foregoing conditions, calculation was made for the model city. The algorithm employed in this study is efficient because the CPU time for this calculation needs about 6 minutes (Pentium 266MHz), that is mostly spent by solving the lower-level problem.

The results of calculation are shown in Figure 4. As comparison between with case and without case, total trip generation increased by about 23%, from the current 162,886 trips to 200,244 trips, the trip generation with TOD increased exceeding the without case in all Bus Zones (No.1, 2, 3, 4, 6, 7, 8, 12, 15, 16, 17, 21, 22, 23), while it decreased in other zones. This result shows that the road network came to be used more efficiently because of TOD.

Improving of bus travel speed, from 20km/h to 25 km/h, 10,956 trips was increased. Thus it is clear that improvement of bus operation is effective for increasing of possible location volume.

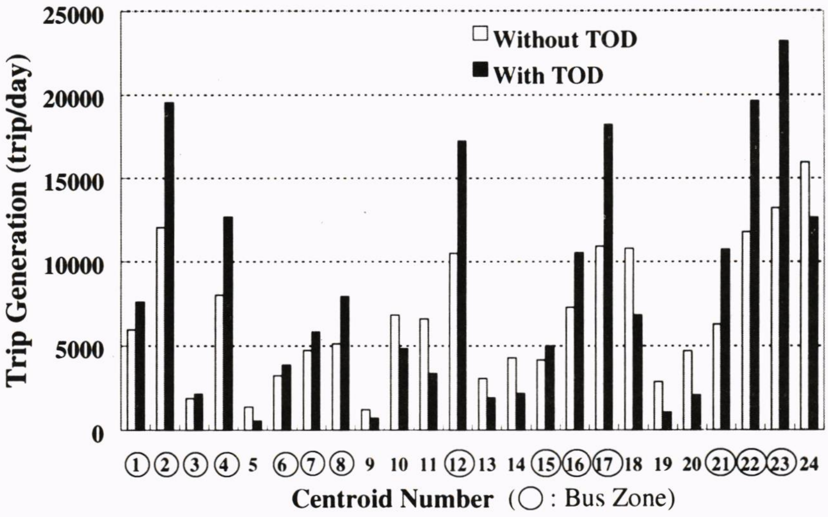

Figure 4. The location pattern for TOD

5. Conclusion

In conclusion, the findings of this study are as follows;

1) The location control model for TOD was formulated as the bilevel programming models.
2) As a result of application to the model city, the trip generation with TOD increased exceeding the without case in all Bus Zones. This result shows that the road network came to be used more efficiently because of TOD.
3) Improving bus travel speed, total trip generation was increased. Thus it is clear that improvement of bus operation is effective for increasing of possible location volume.

There are two subjects for the future study.

1) To incorporate land-use model in proposed model for calculating population density in each zones.
2) To develop the strict solution algorithm that can be used for calculation about large networks.

REFERENCES

Florian, M. and Nguyen, S.(1978), A Combined Distribution Modal Split and Trip Assignment Model, **Transportation Research, Vol.12**, pp.241-246.

Iida, Y., Asakura, Y. and Tanaka, H.(1992), Formulation and Solution Algorithm of Optimal On-ramp Traffic Control Model for Urban Expressway Network with Multiple Routes, **Journal of Infrastructure Planning and Management, No.449**, pp.135-144.

Iida, Y., Yan, L.(1995), A Study on Integration of Traffic Demand and Road Network, **Journal of Infrastructure Planning and Management, No.506**, pp.109-118.

Iida, Y. and Kurauchi, F.(1998), A study on Rode Traffic Management in an Earthquake Disaster based on the Actual Situation of Hanshin-Awagi Great Earthquake (4.6 Road traffic management system), **IATSS**, pp.229-241.

JICA(1997), The Study on Urban Environmental Improvement Program in Bangkok Metropolitan Area, Final report, Vol. 1,2,3.

Kiyota, M., Takada, H. and ,Chisyaki, T.(1985), A study on the Land-Use Pattern Considering the Capacity of Road Network in Urban Area, **Proceedings of infrastructure Planning, No.7**, pp.375-380.

Masuya, Y. and Saito, K.(1987), Allocation of Landuse Activities Considering the Road Network Capacity, **Traffic Engineering, Vol.22 No.4**, pp.9-22.

LeBlanc, L.J. and Farhangian, K.(1981), Efficient Algorithms for Solving Elastic Demand Traffic Assignment Problems and Mode Split Assignment Problems, **Transportation Science, 15(4)**, pp.306-317.

Matsui, H.(éds.)(1998), Equilibrium Analysis on Transportation Network, **JSCE**, Tokyo.

Mizokami, S., Matsui, H. and Kathi, T.(1989), Link Performance Function for Use in Traffic Assignment for Entire Day, **Proceeding of JSCE , No.401**, pp.99-108.

Nakamura, F.(1995), Trend of Bus-based Transit Oriented Development and its Applicability, **City Planning Review, 30**, pp.607-612.