THE COMBINED TRIP DISTRIBUTION, MODAL SPLIT AND TRAFFIC ASSIGNMENT EQUILIBRIUM MODEL TO EVALUATE THE TRANSIT ORIENTED DEVELOPMENT POLICY

Yuichiro Kaneko[a] and Atsushi Fukuda[b]
[a]Department of Research and Consulting, Institution for Transport Policy Studies, 3-18-19, Tranomon, Minato, Tokyo, 105-0001, Japan, Tel.: +81-3-5470-8405, Fax: +81-3-5470-8401
[b]Dep. of Transportation Engg. and Socio-Technology, College of Science and Technology, Nihon University, 7-24-1, Narashinodai, Funabashi, Chiba, 274-8501, Japan,
Tel:+81-47-469-5355, Fax.: +81-47-469-5355
kaneko@jterc.or.jp, fukuda@trpt.cst.nihon-u.ac.jp

Abstract

This study aims to develop a quantitative method to evaluate the integrated land-use and transportation policies and apply this method to the developing city. Since the disordered expansion of urban area has made traffic and urban problems in developing cities serious, the strategic urban development together with mass transit development are compulsory for these cities. The Transit Oriented Development (TOD) which is the concept to develop the main transportation corridors priorly and then start the development of urban area along those corridors, has been applied and seems to be success. However, the numerical or quantitative model to evaluate an impact of the TOD on both land use and traffic is limited. Therefore, authors have developed the equilibrium model combining trip distribution model, modal choice model and trip assignment model on the 4th step estimation process as a tool to evaluate this TOD policy. In this model, land use plan under the TOD policy can be represented as the constraint of allocated population and employment in each zone.

In this study, we applied this model in Bangkok, Thailand and analyze the TOD policies. As a result, the guidelines for implementing effective land-use plan that constraints the rapid urbanization and motorization can be obtained.

Keywords: Equilibrium model; TOD; Developing city
Topic area: G1 Transport and Urban Development Issues

1. Introduction

Since in the most of developing cities it is hardly to improve an entire transportation network without insufficient budget, the traffic and urban problems caused by disordered expansion of urban area has never been solved. The Transit Oriented Development (TOD), which is the strategic development concept that several transportation corridor developments are prior and along these corridors, urban area is developed later, seems to be one of potential policies to solve this problem. And, it has been applied in several cities and seems to be success. So far, the most existing researches on the TOD are the review of successful cities, for example Cuririba in Brazil, Portland, Seattle in U.S.A. and so on (cf. Khasnabis, 1999; Shelton and Lo, 2003). However, the researches that evaluate the traffic and environment impact for whole city through the TOD policy using quantitative model are limited.

We have developed the equilibrium model combining trip distribution model, modal choice model and trip assignment model on the 4th step estimation process as a tool to evaluate TOD policy, and applied this model to the Bangkok Metropolitan Region (BMR), Thailand and analyzed the TOD policy. In BMR, bus transit system keeps playing a key role in the urban transportation systems, the Bangkok Mass Transit Authority (BMTA) operates about 10,000 buses and its modal share exceeds 40% (Japan International Cooperation Agency, 1997). Additionally, Skytrain which is the first urban mass transit system has been operated since December 1999 and the subway system going to be runned by the Metropolitan Rapid Transit Authority (MRTA). These public transit systems are expected to reduce the traffic congestion and the air pollution of automobile fumes.

As the results of rapid suburbanization in BMR, it is still difficult to control the increase of car usages, although the mass transit systems can be completed. Therefore the transportation planning is integrated with the land-use planning by setting up the dense use for the areas along transit routes, and controlling location to that end is very important policy.

First, the existing quantitative studies analyzing the effects of TOD are reviewed. Second, it focuses on developing the combined trip distribution, modal split and traffic assignment model with the users' attributes taken into consideration. Base on the developed model, the impact of the TOD targeted on BMR is estimated in the next section.

2. Existing quantitative studies

The exiting quantitative studies on TOD can be classified into two categories. The first is the comparative surveys to determine travel behavior differences, including trip generation and mode choice, the other is to explore the correlation of travel behavior and urban structure by using national and regional survey data (Dock and Swenson, 2002). For example , Cervero (1995) analyzed the relationship between car ownership in household and public transport utilization rate, distance from house to office and mode of transportation. Hess and Ong (2001) tested a model that explains auto ownership based on household, neighborhood, urban design characteristics in Portland, Oregon where TOD policy is investigated.

However the researches that evaluate the traffic and environment impacts in whole city by introducing the TOD policy in developing city are few. Furutani et al.(1999) evaluated several land-use patterns together with transport infrastructure construction in BMR. However user behavior on the transportation network was not considered in their study. Waddell et al.(2002) presented the results of a design process for new integrated land use and transportation models that recently completed for the Puget Sound Regional Council. In their study, the survey for public agencies around Puget Sound Region was conducted in order to obtain systematic inputs of the draft requirement for the development effort. It was shown that, the multimodal assignment is very important.

So in this study, the equilibrium model combining trip distribution model, modal choice model and trip assignment model on the 4th step estimation process which represent the equilibrium condition on route choice behavior of a private car users and public transport users have developed.

3. The combined distribution, modal split and traffic assignment user equilibrium model for transit oriented development

3.1. Formulation

To effectively evaluate TOD policy, the equilibrium model was developed by combining trip distribution model, modal choice model and trip assignment model on the 4th step estimation process. In this model, it was assumed that trip generation is exogenously given and related to the land-use pattern and the remaining three steps combined. The main components of this combined model consist of the constrained gravity type model for trip distribution, the logit type model for modal choice and the user optimal model for trip assignment (cf. Florian and Nguyen,1978; Abrahamson and Lundqvist, 1999).

$$x_a^1 = \sum_{r\in R}\sum_{s\in S}\sum_{k\in K_{rs}^1} f_{k,j}^{rs,1}\delta_{a,k}^{rs,1} \qquad \forall a \in A \tag{1}$$

$$\sum_{k\in K_{rs}^m} f_k^{rs,m} = q_{rs}^m \qquad \forall r \in R, s \in S, m \in M_{rs} \tag{2}$$

where x_a^1 : the flow of passenger car on link . a

$f_k^{rs,1}$: the flow of passenger car on path *k* from origin *r* to destination . *s*

$\delta_{a,k}^{rs,c1}$: the indicator variable (if link *a* is on the path *k* between *rs*:1, otherwise :0).

q_{rs}^m : the trip volume from origin *r* to destination *s* by mode.

M_{rs} : the set of mode *m* between *rs* (*m*=1: passenger car; *m*=2: bus).

Equilibrium conditions can be also expressed as follows;

$$f_k^{rs,m}(u_k^{rs,m} - u_{rs}^m) = 0 \qquad \forall r \in R, s \in S, m \in M_{rs}, k \in K_{rs}^m \tag{3a}$$

$$u_k^{rs,m} - u_{rs}^m > 0 \qquad \forall r \in R, s \in S, m \in M_{rs}, k \in K_{rs}^m \tag{3b}$$

$$f_k^{rs,m} > 0 \qquad \forall r \in R, s \in S, m \in M_{rs}, k \in K_{rs}^m \tag{3c}$$

where $u_k^{rs,m}$: the generalized cost from origin *r* to destination *s* by mode *m*.

u_{rs}^m : the minimum generalized cost from origin *r* to destination *s* by mode *m*.

Since the routes of public transport are fixed, we assume that user of public transport always choose some of them. Here, the generalized costs by passenger car and public transport are given by following equations;

$$u_k^{rs,1} = \sum_{a\in A} u_a^1 \delta_{a,k}^{rs,c} \qquad \forall r \in R, s \in S, k \in K_{rs}^m \tag{4a}$$

$$u_a^1 = p_a^1 + Vt_a^1 \qquad \forall a \in A \tag{4b}$$

$$u_{rs}^2 = p_{rs}^2 + Vc_{rs}^2 \qquad \forall r \in R, s \in S \tag{4c}$$

where :

u_a^1 : the generalized cost by passenger car users on link a .
p_a^1 : cost by passenger car users on link a .
V : the value of time.
t_a^1 : travel time by passenger car users on link a .
u_{rs}^2 : the generalized cost from origin r to destination s by bus users.
p_{rs}^2 : the cost from origin r to destination s by bus users.
c_{rs}^2 : the travel time from origin r to destination s by bus users.

Next, we express the number of trips between zones using the Wilson's entropy model with doubly constraints so as to evaluate the impact of the urban land development policy on trip distribution, as shown in eq.(5).

$$q_{rs}^{total} = A_r O_r B_S D_S \exp(-\theta_1 \tilde{u}_{rs}) \qquad \forall r \in R, s \in S \qquad (5a)$$

$$\tilde{u}_{rs} = -\frac{1}{\theta_2} \ln\left[\sum_{m \in M_{rs}} \exp(-\theta_2 u_{rs}^m)\right] \qquad \forall r \in R, s \in S \qquad (5b)$$

$$A_r = \frac{1}{\sum_{r \in R} A_r O_r \exp(-\theta_1 \tilde{u}_{rs})} \qquad (5c)$$

$$B_s = \frac{1}{\sum_{s \in S} B_s D_s \exp(-\theta_1 \tilde{u}_{rs})} \qquad (5d)$$

where q_{rs}^{total} : the total trip volume from origin r to destination s .
O_r : the number of trip originated from zone r .
D_S : the number of trip attracted to zone s .
θ_1, θ_2 : parameters.

The probability to choose a passenger car and public transport $p_{m|rs}$ can be given by using the logit model as follows;

$$P_{m|rs} = \frac{\exp(-\theta_2 u_{rs}^m)}{\sum_{m \in M_{rs}} \exp(-\theta_2 u_{rs}^m)} \qquad \forall r \in R, s \in S \qquad (6a)$$

$$q_{rs}^m = q_{rs}^{total} \cdot p_{m|rs} \qquad \forall r \in R, s \in S, m \in M_{rs} \qquad (6b)$$

The relationship between traffic volume and travel time by passenger car is given by BPR function.

$$t_a^1 = t_{a0}\left\{1 + \alpha\left(x_a^1 / c_a\right)^\beta\right\} \qquad \forall a \in A \qquad (7)$$

where t_{a0} : the free flow travel time on link a.

c_a : capacity of link a.

α, β : parameters.

The formulation derived from equation (1) to (7) can be formulated as Beckmann's mathematical optimization problem as follows;

$$\min \sum_{a \in A} \int_0^{x_a^1} u_a^1(x_a^1) d\omega + \sum_{r \in R} \sum_{s \in S} \left(q_{rs}^{total} P_{m|rs} \cdot u_{rs}^{mt} \right) + \frac{1}{\theta_1} \sum_{r \in R} \sum_{s \in S} \left(q_{rs}^{total} \ln q_{rs}^{total} \right) + \frac{1}{\theta_2} \sum_{r \in R} \sum_{s \in S} \left\{ q_{rs}^{total} \cdot \sum_{m \in M_{rs}} P_{m|rs} \ln P_{m|rs} \right\} \quad (8a)$$

subject to

$$\sum_{s \in S} q_{rs}^{total} = O_r \qquad \forall r \in R \quad (8b)$$

$$\sum_{r \in R} q_{rs}^{total} = D_s \qquad \forall s \in S \quad (8c)$$

$$\sum_{m \in M_{rs}} P_{m|rs} = 1, \quad q_{rs}^{total} > 0, \quad f_k^{rs,1} > 0, \quad P_{m|rs} > 0 \quad (8d)$$

The OD flow, link flow and travel time can be estimated by using the solution algorithm.

3.2. Algorithm

Large number of studies made on solution algorithm for the combined equilibrium model. Without considering the interaction between car and bus, the approaches have been proposed in two main approaches, consisting of the Frank-Wolfe algorithm and the partial linear approximation algorithm (Evans, 1976).

LeBlanc and Farhangian (1981) compared both mentioned methods by applying the algorithms for the combined distribution/assignment model. They concluded that the latter method is more stable than the former. Eventually, the partial linear approximation algorithm was selected to solve the combined model in this study.

4. Application to Bangkok metropolitan region network

4.1. Assumption for calculation

To test the reproducibility, this section focuses on the application of the developed model in the case study of BMR. Before doing so, some background of the study area should be described.

(1) Road Network

The network in BMR is shown in Figure 1. It consists of 2,122 links and 1,583 nodes as shown in Figure 1. This study area covers for 57 traffic zones.

(2) Generated and Attracted Traffic Volume

For the generated and attracted traffic volume during the period of commuter time, the trips departing between 6:00 a.m. and 9:00 a.m. were selected from among the commuter trips by passenger car or bus users derived from the person trip survey conducted by the Office of the Commission for the Management of Land Transport (OCMLT, 1997).

(3) Levels of Service

As to travel time on link, the BPR link cost function was utilized for passenger car, so that the effect of travel time increase due to congestion can be taken into account. For bus, as they run on ordinary roads and are significantly influenced by road traffic, so its travel time was fixed at twice of passenger car's, including time for passengers to get on and off.

(4) Travel Cost

For the travel cost of passenger cars, the values by travel speed are applied on the basis of existing reports (Japan International Cooperation Agency (JICA), 1990). For the travel cost of buses, since the person trip survey has revealed that many users use the Red Bus or the Blue Bus, the cost is fixed across the board at 3.5 Baht, the equivalent to their fare.

(5) Value of Time

As studied by JICA in 1990, the time value for Bangkokians was estimated at 40 Baht/h (JICA, 1990).

(6) Parameters

In the BPR link cost function shown in eq.(7), the travel speed derived from the road network data was used for the free flow speed. Parameter α and β in the study were 0.96 and 1.2, respectively (Mizokami et al., 1989). For the parameter of logit function in eq.(5b), θ_2, it was estimated for 0.02.

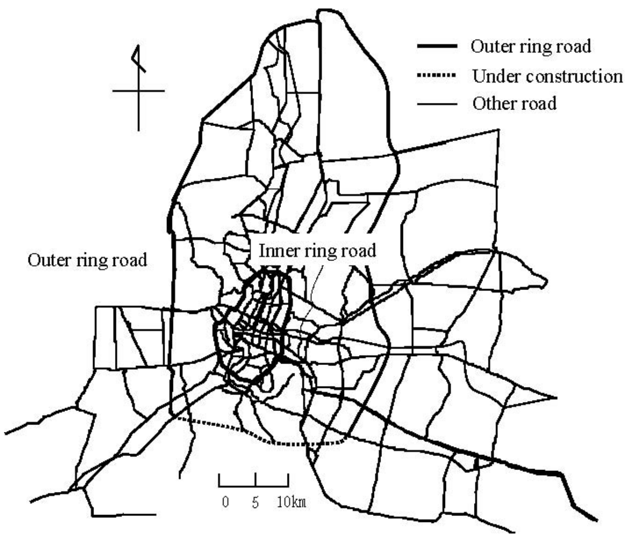

Figure 1. BMR network

4.2. Verification of the estimates

Our proposed model was tested by considering whether it can reproduce the OD traffic volume in BMR or not. The data for verification were derived from the person trip survey data (OCMLT, 1997). As the indicators to evaluate goodness of fit, the partial regression coefficient of regression function $y=ax$ and %RMSE were used. In Table 1, it was shown that the values of a and %RMSE were 0.69 and 84%, respectively. These indicators indicated that the predicted results of our model are sufficiently accurate and reliable for the whole city as illustrated in Figure 2.

Table 1. Verification of the Estimated OD Traffic Volume

Coefficient *a*	0.69
%RMSE	84%

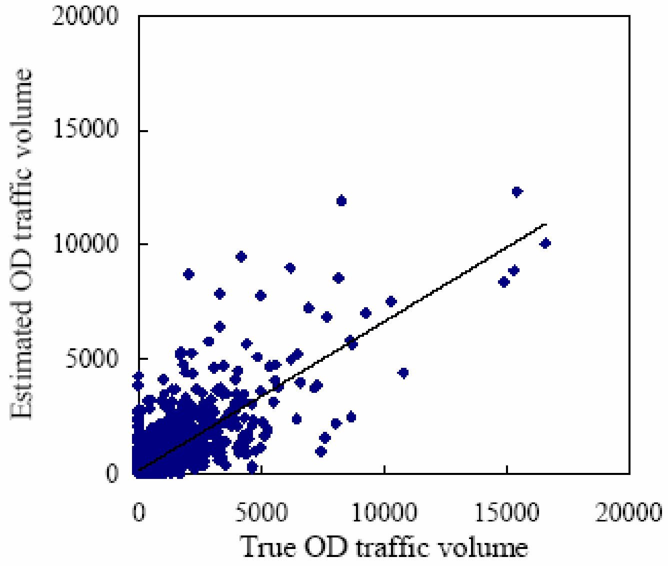

Figure 2. Verification of the Estimated OD Traffic Volume

5. Environmental effects of transit oriented development policy

5.1. Assumption for calculations

(1) Outline of TOD

As explained in the introduction, the integration of transportation and land-use planning through setting up the dense uses for the areas along transit routes, and controlling activity allocation to that end is very necessary for BMR, especially when it can be rapidly suburbanized. This TOD policy was also recognized by MIT, U.S.A., and they proposed it in “The Bangkok Plan” since 1995 as shown in Figure 3. To demonstrate the advantages of this proposed TOD policy, this study employed the combined network equilibrium model formulation in the previous sections to evaluate the traffic condition and the environmental effects caused by implementing the TOD policy.

(2) Assumption for Evaluations

1) Generated and Attracted Traffic Volume

The analysis of with and without the TOD policy was introduced for the evaluation. Without the policy, generated and attracted traffic volumes in 2011 were estimated by using the regression model concerning variables of daytime and night populations. In the opposite, if the TOD policy is implemented, some assumptions have to be established to estimate the traffic volumes. They include the following assumptions.

- 20% of resident in suburb relocate to area on the subway
- 20% of employee in inner-city district relocate to area on the subway

2) Level of Service

The fare of subway was fixed at 20 Baht/h and its travel speed was 45km/h based on the average values of the subway system.

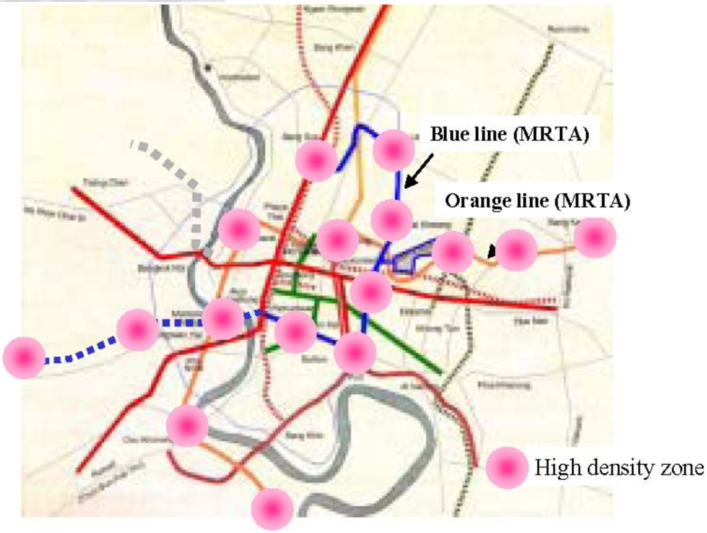

Figure 3. Railway Network and High Density Zone in BMR

5.2. Estimation of traffic volume and condition

In order to analyze how the passenger car traffic volumes and traffic conditions on the road networks would be changed after implementing TOD, the OD traffic volume of each transportation mode and the average travel speed on the networks with and without the project were estimated. Eventually, the proportion of change was examined.

Figure 4 show the changes in the OD traffic volume of each mode of transportation. Table 2 and 3 present the changes in the average travel speed and average travel distance, respectively. Because of the TOD implementation, the OD traffic volume of passenger car was declined from 898,010 trip/day to 780,104 trips/day, while for public transport it was increased from 1,026,790 trips/day to 1,144,696 trips/day (see Figure 4). In addition, the average travel speed in the network could be improved by 1.3 km/h or 6.7 %, and the average travel distance for private car in BMR would be reduced by 1.2Km or 8.7 %. These results indicate the significant benefits, so the planners in BMR are really recommended to seriously implement the TOD policy for integrating transportation improvement and land developments.

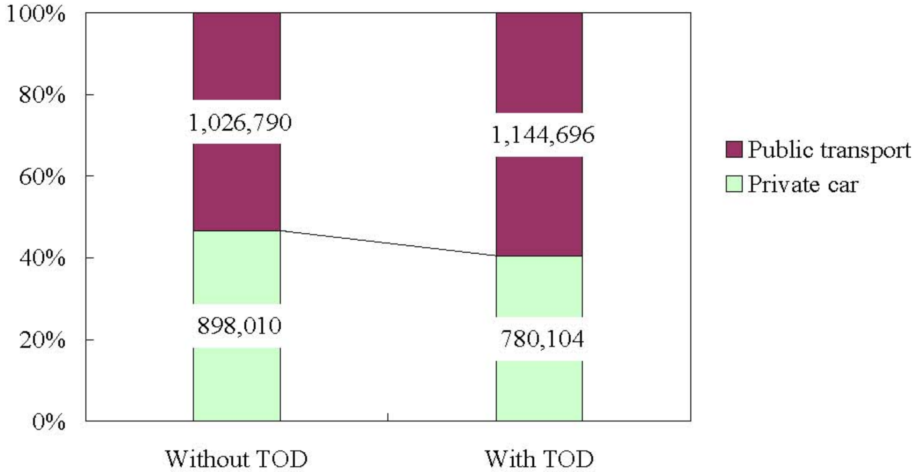

Figure 4. Total OD Trip Volume

Table 2. The Travel Speed

Average speed (km/h)	Private car
Without TOD	19.4
With TOD	20.7

Table 3. The Travel Distance

Average travel distance (km)	Private car
Without TOD	13.8
With TOD	12.6

5.3. Estimation of emission volume of air pollutant

In this section, with the estimated traffic volume on links and the estimated travel speed, the improvement in the air pollution by implementing the TOD policy is assessed. The NOx and CO emission factors at various speeds of small vehicle for BMR were utilized, as shown in Table 4 (JICA, 1997). The intermediate value was estimated by using the complementary method.

Figure 5 shows the changes of air pollution emission volumes. It can be seen that the TOD policy significantly decreased the NOx and CO emissions. This was because of the decreases of the OD traffic volume of passenger car and the improvement of travel speed.

Table 4. Emissions Factors

Pollutants	Vehicle Type	Average Speed (km/h)				
		0-1	8	16	24	32
NOx (g/km)	Small	5.23	2.06	1.87	1.85	1.93
CO (g/km)	Small	491.43	156.74	75.92	50.66	40.80

Note :
Small ; Passenger Car, Samlor, Taxi, Station Wagon
Source : Air Emission Database of Vehicles and Industry in Bangkok Metropolitan Region 1992 : PCD MOSTE

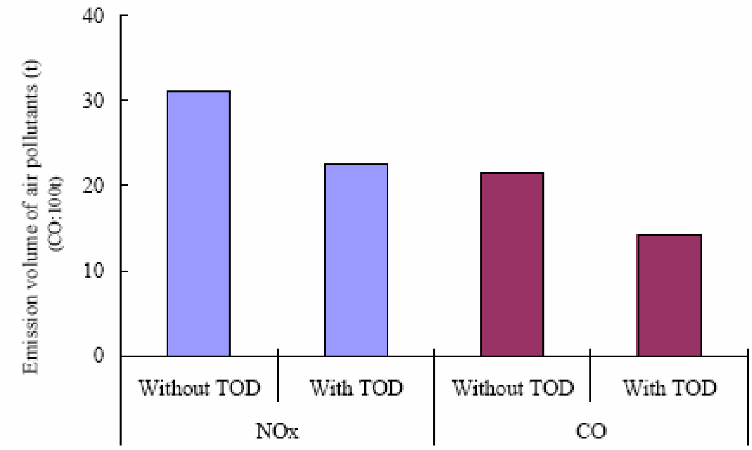

Figure 5. Emission Volume of Air Pollutants

6. Conclusions

In this study, a quantitative method to evaluate the integrated land-use and transportation policy such as TOD has been developed. In our proposed model, trip distribution model, modal choice model and trip assignment model were combined using the user equilibrium concept. The results of the simulation for BMR using the proposed model presented that the TOD policy is the effective land use development plan in decrease of traffic. Moreover, it can significantly improve the traffic conditions on the road networks, and also mitigates the traffic air pollution problem.

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