CBD Oriented Commuters' Mode and Residential Location Choices in an Urban Area with Surface Streets and Rail Transit Lines

Chaug-Ing Hsu[1] and Shwu-Ping Guo[2]

Abstract: This study formulates a commuters' mode and route choice model as well as a households' residential choice model on a two-dimensional space. The commuters' mode and route choice model assumes that commuters select the mode and route alternative based on the least generalized travel cost. The households' residential choice model is formulated to maximize households' residential utilities subject to time and budget constraints. A simulation method is adopted to simulate household choice behavior and solve the households' residential location choice model with two-dimensional decision variables to prevent aggregation bias. A case study for Taipei metropolitan area is illustrated to analyze the variations of residential location choices for households working in the central business district (CBD) after different lines of Taipei Rapid Transit System are completed at various stages. Results indicate that (1) there is increased attraction of households in cities of Taipei County such as Pan-Chiao, Chung-Ho, Yong-Her, and Hsin-Tien due to the completion of rail transit networks and (2) residential locations better served by rail transit lines attract more households; thereby, resulting in higher residential densities.

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Introduction

Most residential location models in urban economic-related studies are originated from Alonso's location model (Alonso 1964). That model assumes that all workplaces are concentrated in a highly compact central business district (CBD) on the side of city configurations. Commuters' homes are continuously dispersed over the residential area surrounding the CBD. All commuters are employed at the CBD. Only homogeneous surface streets are assumed to be available on the side of transportation systems. Thus, the complicated two-dimensional city configuration can be simplified to a one-dimensional round city. Relevant studies include Higano and Orishimo (1990), Lund and Mokhtarian (1993), Higano (1991), Shibusawa and Higano (1995), and Shibusawa (1997). The previous literature was based on the assumption of the round city configuration and approximated traffic networks by continuous surface streets. Therefore, these studies usually neglected the effects of rail transit networks on commuters' residential location choices. Traffic congestion is attributed mainly to the temporal concentration of trips in the city with concentrated workplaces. Yang et al. (1994) assumed that two kinds of transportation systems, dense surface streets, and a discrete rail transit network are concurrently applied to alleviate traffic congestion in urban areas. On rail transit networks, the schedule and the speed of trains are controlled and monitored by a central control center; thus, passengers can predict their on-board time and rail transit company can also maintain schedule adherence. On the contrary, driving automobiles on surface streets can take the advantage of accessibility door-to-door services.

Residential location choice models on conventional transportation planning are based on traffic zones. Waddell (1993) developed a nested logit model of workers' choices of workplace, residence, and housing tenure under the assumption that choice of workplace was exogenously determined. Moreover, Eliasson and Mattsson (2000) designed a model for integrated analysis of household location and travel choices by applying a nested logit model. Each household made a joint choice of location (zone and house type) and travel pattern (trip frequencies, destination choices, and mode choices) so as to maximize utility subject to budget and time constraints. Martinez (1992) made a theoretical comparison of the bid-rent theory and the discrete-choice random-utility theory used in modeling urban land use. Watterson (1993) recognized the relationship between urban spatial form and urban transportation system by analyzing several variables such as transportation facility investments, demand management measures, and land-use controls. Hunt and Simmonds (1993) constructed an integrated land-use and transport framework with the concept of market and supply-demand analysis. Hunt et al. (2004) introduced the household allocation module of OREGON2 model with selection probabilities determined using logit models and sampling distributions. Wong et al. (2004) formulated a combined

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distribution and assignment model for travelers' choices for regional activity centers using a flow- and location-dependent transportation cost function. Hsu and Guo (2001) formulated a model integrating households' residential-mode choice and residential distribution in a metropolitan area with surface streets and rail transit networks using continuous analytical approaches and mathematical programming methods. The previous studies must collect extensive data about households, houses, land rents and transportation networks. Comprehensive and time-consuming programs are also required to obtain the equilibrium solution. The extension of those models to long-term time dependent analyses becomes a very complicated problem.

In practice, a household's residential location is determined by the residential utility of each location rather than traffic zones confined by administrative districts or census tracts. Thus, this study divides the study area into numerous equal-sized grids and allocates each household to a specific coordinate to scan the distribution of households in the study area. In addition, most studies involving the choices of households' residential locations in the metropolitan area of Taiwan constructed an allocation model which grouped the households into several groups according to factors such as income, automobile ownership, and the number of household members, such as in Feng and Yang (1989). Those studies also assigned each group of households to a traffic zone by using conventional land use models. In this manner, these models neglected the heterogeneity among individual households of the same group and, therefore, aggregation bias could not be prevented. For these reasons, this study applies a sampling method to collect data of households' attributes such as working hours, hourly salary, and living area so as to estimate the distribution of households' attributes. Accordingly, a simulation method is adopted to generate individual households with different attributes so as to describe an individual household's behavior more accurately.

Owing to heavy traffic at peak periods, rail transit with high capacities is normally implemented to streamline the transport of commuters from homes to their workplaces in the metropolitan area. In this study, two sequential models are constructed on a two-dimensional space to analyze the household distribution in a monocentric city with surface streets and rail transit lines. Surface streets are assumed herein to be dense networks and rail transit lines are assumed to be discrete networks. A mathematical programming model for individual household's optimal residential locations is formulated by maximizing residential utility subject to the household's budget and time constraints. Factors determining household's residential utilities are work time, leisure time, commuting time and cost, and the residual of disposable income deducted by the rent of floor areas and the commuting cost. In addition, the commuters' route and mode choice model is used to determine the commuting times from each of all residential locations to the CBD. Commuters in this route and mode choice model are assumed to either travel straight along dense surface streets to CBD or travel along dense surface streets to a rail transit station and, then, ride to the CBD by rail transit depending on which one has the least generalized travel cost. The interaction between the commuters' mode and route choice and household's residential location choice is established by solving two models iteratively in each time interval. The time intervals here are time spans between different rail transit lines are completed. In the meantime, the total number of immigrating households in each time interval is assumed to be exogenous.

Commuters' Mode and Route Choices

This study applies analytical methods to construct a static commuters' mode and route choice model. Commuters are assumed to have two mode and route alternatives. That is, a commuter can either travel straight along dense surface streets to CBD or travel along dense surface streets to a rail transit station and, then, ride a train to the CBD. The proposed model not only defines the generalized travel cost as the weighted sum of travel time and travel cost, but also derives the travel time and travel cost of each alternative from residential locations to the CBD under flow-independent assumption of travel costs and travel times. Commuters are assumed to maximize their utilities and to choose the alternative with the least generalized travel cost. On the side of surface streets, let B' represent the two-dimensional study area, as well as X and O denote the coordinate (x_1,x_2) of a residential location and the coordinate (o_1,o_2) of the CBD, respectively. Then, the travel distance on surface streets, $D(X,O)$, from residential location X to the CBD O is expressed as the sum of the horizontal and vertical distances between the two coordinates as

$$D(X,O) = |x_1 - o_1| + |x_2 - o_2| \quad (x_1,x_2) \in B' \tag{1}$$

The distance defined by Eq. (1) is usually called Manhattan distance. In addition, let v_L and f_L represent the average travel speed and the fuel cost per kilometer on surface streets, respectively. Let c_O denote the parking cost at CBD per work trip. Parameter ss is a constant over B' and stands for the scale which transforms the grid distance into the actual distance on surface streets for the study area. The round-trip travel time, $T_L(X)$, and the round-trip travel cost, $C_L(X)$, from residential location X to the CBD O via surface streets can then be expressed as the following equations, respectively,

$$T_L(X) = 2D(X,O)ss/v_L \quad \forall\ (x_1,x_2) \in B' \tag{2}$$

$$C_L(X) = 2D(X,O)ssf_L + c_O \quad \forall\ (x_1,x_2) \in B' \tag{3}$$

Eqs. (2) and (3) assume that route and mode choices to and from the CBD are completely symmetric. Namely, there is no round traveling from office for shop and then return for home. This study assumed surface streets to be dense networks and rail transit lines to be discrete networks. The major advantage of assuming surface streets to be dense networks is to avoid time-consuming data collection for surface streets. Based on a long-term planning perspective, this study adopts the average values to represent travel speed and fuel cost per kilometer on surface streets. Meanwhile, rail transit networks are constructed in different phases. This approach enables the relative advantage on mobility of rail transit over time to be captured and a reasonable result to be obtained though the assumption about surface streets is unrealistic from the perspective of the real world. On the side of rail transit lines, let M denote the number of rail transit lines and J_i represent the number of stations on the ith rail transit line where $i=1,2,\ldots,M$. The coordinate (y_1,y_2) of the jth station on the ith rail transit line is represented by S_{ij} where $j=1,2,\ldots,J_i$. Then, the travel distance on surface streets, $D(X,S_{ij})$, from each residential location X to station S_{ij} can be formulated by

$$D(X,S_{ij}) = |x_1 - y_1| + |x_2 - y_2| \quad \text{for } i=1,2,\ldots,M; \quad j=1,2,\ldots,J_i; \quad (x_1,x_2) \in B' \tag{4}$$

Let $L(S_{ij},O)$ represent the distance from the rail transit station S_{ij} to the CBD, v_{Ti} stand for the average running speed of trains on the ith rail transit line, $w_{S_{ij}}$ denote the total stop delay from station

S_{ij} to the CBD, h_i represent the average headway of the ith rail transit line, $f_{S_{ij}}$ stand for the fare from station S_{ij} to the CBD, and $c_{S_{ij}}$ denote the average parking cost at station S_{ij}. Then, the roundtrip travel time and the roundtrip travel cost from residential location X to CBD O by traveling along surface streets and then transferring to rail transit line i at station S_{ij} can be formulated by the following equations, respectively,

$$T_T(X,S_{ij}) = 2D(X,S_{ij})ss/v_L + 2w_{S_{ij}} + h_i + 2L(S_{ij},O)/v_{Ti}$$
$$\text{for } i = 1,2,\ldots,M \quad \text{and} \quad j = 1,2,\ldots,J_i;$$
$$\forall\,(x_1,x_2) \in B' \qquad (5)$$

$$C_T(X,S_{ij}) = 2D(X,S_{ij})ss \cdot f_L + c_{S_{ij}} + 2f_{S_{ij}}$$
$$\text{for } i = 1,2,\ldots,M \quad \text{and} \quad j = 1,2,\ldots,J_i;$$
$$\forall\,(x_1,x_2) \in B' \qquad (6)$$

Let θ denote the value of time and g_O denote the average generalized travel cost from stations at CBD to the workplace. Then, the generalized travel cost from residential location X to the CBD by traveling on surface streets, $Z_L(X)$, can be expressed as

$$Z_L(X) = \theta \cdot T_L(X) + C_L(X)\ \forall\,(x_1,x_2) \in B' \qquad (7)$$

For the generalized travel cost from residential location X to the CBD by traveling along surface streets and then transferring to rail transit at station S_{ij}, $Z_T(X,S_{ij})$, can be formulated by

$$Z_T(X,S_{ij}) = \theta \cdot T_T(X,S_{ij}) + C_T(X,S_{ij}) + g_O$$
$$\text{for } i = 1,2,\ldots,M; \quad j = 1,2,\ldots,J_i; \quad (x_1,x_2) \in B' \qquad (8)$$

Because rail transit lines cannot provide door-to-door transport service, commuters traveling along surface streets and then transferring to rail transit must spend more time and cost on walking or shuttle between the station in the CBD and workplaces. This situation is implied in this model with the parameter g_O.

Let $G^* = \min\{Z_L, Z_T\}$ denote the least generalized travel cost. Restated, the least travel time T^*, the least travel cost C^* and the optimal route and mode choice, which are decision variables in the model, can be determined by comparing the values of Z_L and Z_T in Eqs. (7) and (8) and then choosing the one with the least value.

Household's Residential Location Choice

Residential Location Choice Model

All commuters in a household are assumed to work at workplaces within the CBD in this study. Herein, a household's residential location choice model is constructed to maximize the household's residential utility. Factors influencing the ith household's utility at residential location X include the household's total work time t_{Wi}, the household's total leisure time t_{Li}, round-trip commuting cost $C^*(X)$ and roundtrip commuting time $T^*(X)$ from residential location X to the CBD, the residual of disposable income deducted the rent of floor areas and the commuting cost, I_i, and the existing number of households at residential location X after i-1 households are allocated to the study area $HH_{i-1}(X)$. This study defines $\bar{T}$ as the total time constraint for one person and supposes that the study period is one month measured by hours; that is, 720 h. Let w_i be the ith household's average hourly salary, $R_H(X)$ represent the rent per area unit (e.g., per pyng, which is a measurement unit of area in Taiwan and is equal to an area of $0.3025\ \mathrm{m}^2$) at residential location X, l_{Hi} represent the ith household's residential floor area, $\bar{t}$ denote the commuter's average monthly commuting frequency, and $\bar{n}$ denote the average number of commuters in a household. Then, the model for the ith household's residential location choice under time constraint and income budget can be formulated by

$$\max U_i = U(t_{Li}, C^*, T^*, I_i, HH_{i-1}X) \qquad (9)$$

$$\text{s.t} \quad \bar{n} \cdot \bar{T} - t_{Wi} - t_{Li} - \bar{n} \cdot T^*(X) \cdot \bar{t} = 0 \qquad (10)$$

$$w_i \cdot t_{Wi} - I_i - R_H(X) \cdot l_{Hi} - C^*(X) \cdot \bar{t} \cdot \bar{n} = 0 \qquad (11)$$

$$(x_1,x_2) \in B' \qquad (12)$$

Eq. (9) is the ith household's residential utility function. Eqs. (10) and (11) are the total time constraint and the budget constraint for a household, respectively. The chosen residential location confined to the study area B' is specified by Eq. (12). Similar to investigations such as Lund and Mokhtarian (1993), Shibusawa and Higano (1995), and Eliasson and Mattsson (2000), this study analyzes how the household's leisure time, commuting cost, and commuting time influence the residential utility. Moreover, the residual of disposable income deducted the rent of floor areas and the commuting cost markedly influences the household's consumption power. The number of households at each residential location determines the intensity of traffic congestion. Owing to the assumption of monocentric urban configuration, commuting households, who depart their homes to workplaces, cause congestion on the routes between their residences and workplaces. This study explores commuters' mode and residential location choice from the perspective of long term planning. To simplify network representation problem, this study represents surface streets as a dense grid network using continuous network approach by Newell (1980) and Vaughan (1987). This study uses the number of household at each residential location to approximately explain the effect of surface street congestion at the location while not dealing with detailed traffic assignment problem for surface street, which is usually regarded as short term operational problem. Additionally, the degree of air pollution and noise is closely related to the intensity of traffic congestion. Notably, the living quality of a residential location decreases with an increase of the number of households when the area at each residential location cannot be further expanded. That is, open spaces for parks, educational facilities, and other resorts become relatively insufficient, thereby degrading quality of life. In response to these factors, household's disposable income and the number of households at each residential location are considered in the residential utility function in this model. This study assumes factors such as commuting time, commuting costs, and leisure time may incur interactive and nonlinear effects on the commuters' residential utility, and formulates the residential utility function by applying a multiplicative functional form as

$$U_i = t_{Li}^{\alpha_1} C^*(X)^{\alpha_2} T^*(X)^{\alpha_3} I_i^{\alpha_4} HH_{i-1}(X)^{\alpha_5} \qquad (13)$$

where α_1, α_2, α_3, α_4, and α_5=parameters.

The main focus of this study is on exploring mode/route and residential location choices of commuting households, due to the completion of rail transit lines. To focus on the key issues, variables such as work hour, wage, and lot size are assumed to be exogenous and thus are assigned randomly. When rail transit lines operate sequentially, commuting time and cost from each residential location to the workplace gradually change. The optimal residential location of individual households thus might vary accordingly. Further, when households choose residential locations with different rents, their choices depend on their biding capability in terms of disposal incomes. Based on these considerations, this study adopts commuting time, commuting cost, leisure time, rent and residual of disposable income after deducting rent and commuting costs in the residential utility function.

Simulation Method

Decision variables of the household's residential location choice model, as formulated by Eqs. (9)–(12), are coordinates of two-dimensional residential locations for households. The commuting cost and the commuting time of each commuter in the residential location choice model are varied as the chosen residential location and the optimal mode choice change. Generally, conventional methods for solving mathematical programming model are inappropriate for solving problems such as the one with the above-mentioned two-dimensional decision variables. Therefore, the Monte Carlo simulation method is proposed herein to construct a stochastic simulation model for determining the optimal residential location of each household. Households with different attributes are generated sequentially by the next event incrementing method and, then, allocated to the optimal residential location. Further, the construction of rail transit networks is very time consuming and is usually implemented at several construction stages. Effects of rail transit networks on commuters' mode and route choices and household's residential location choice are also progressive. To differentiate the various lag effects of incremental rail transit lines completed at various stages, this study divides the study period into several time intervals. In each time interval, there are different numbers of rail transit lines completed. The commuter's mode and route choices model and household's residential choice model are then solved, respectively, for time intervals with the increasing numbers of completed rail transit lines.

Household's Attribute Generator

The household's attributes in this model include the monthly working hours, average hourly salary, and required residential floor area. This study postulates that these three types of attributes follow the triangular distribution. Reasons for selecting triangular distribution functions herein to simulate individual household's attributes are as follows. First, the function form of triangular distribution is bounded, meaning that extreme values are avoided and attribute values are confined to a reasonable range. Second, compared to a truncated normal distribution, the function form of the triangular distribution is linear and thus the inverse of its cumulative distribution is easily derived. The inverse is significant in simulation models, because a random number generator generally is designed to obtain a positive real number rather than a statistic representing household's attributes. The inverse function is crucial to converting the random number into an appropriate statistic. However, the normal distribution contains an integral term, making its cumulative distribution and inverse complicated to compute. To simplify the problem solving procedure, this study adopts the triangular distribution to explain households' attributes. Moreover, the generalized exponential family of distributions may be used to describe income distribution and generalized exponential family distributions include such useful distributions as normal, beta, generalized normal, generalized beta, etc. (Bakker and Creedy 2000). The triangular distribution formulated below is the special case of Beta distribution for $a=0$ and $b=1$ (Law and Kelton 1982).

The triangular distribution is formulated by $Y \sim \mathrm{triang}(a,b,c)$, where $a<c<b$ and c is the mode of the sample. In addition, $Y' \sim \mathrm{triang}[0,1,(c-a)/(b-a)]$ can be obtained by letting $Y'=(Y-a)/(b-a)$. Let $c'=(c-a)/(b-a)$, then, by referring to Law and Kelton (1982), the distribution function is easily inverted to obtain as shown for $0 \le u \le 1$, by

$$Y' = F^{-1}(u) = \begin{cases} (c'u)^{1/2} & \text{if } 0 \le u \le c' \\ 1-[(1-c')(1-u)]^{1/2} & \text{if } c' \le u \le 1 \end{cases} \tag{14}$$

Correspondingly, according to Law and Kelton (1982), the following inverse-transform algorithm can be stated for generating a household's attributes:

1. Generate a random variable $U \sim U(0,1)$ by applying linear congruential generators.
2. If $U \le c'$, set $Y'=(c'U)^{1/2}$; otherwise, set $Y'=1-[(1-c')(1-U)]^{1/2}$.
3. Set the household's attribute as $Y=a+(b-a)Y'$ and return.

This study adopts the linear congruential generators to generate a random variable following the uniform distribution, i.e., $U \sim U(0,1)$. This method recursively generates an integer sequence, $Z_1, Z_2, \ldots, Z_{i-1}, Z_i, \ldots$ in

$$Z_i = (aZ_{i-1} + c) \bmod m \tag{15}$$

where the modulus m, multiplier a, increment c, and seed Z_0 are nonnegative.

The triangular distribution is similar to the uniform distribution except there is an interception, the mode of sample, in the triangular distribution function. The modes of triangular distributions are estimated, respectively, by using the average values of working hours, hourly salary, and required residential floor area of the representative households; whereas the upper bounds and lower bounds of triangular distributions are estimated, respectively, by employing the maximal and minimal values of those of the households.

Processes of the Simulation Program

The simulation program in this study is written by C language. The basic concepts, assumptions and considerations of each phase in the program are explained as follows.

Phase 1: Set initial values of parameters a, c, m, and Z_0 for the random number generator. Initialize the parameters of the household's attribute generator. These include three classes of parameters. Parameters Ta, Tb, and Tc represent, respectively, the minimal value, the mode, and the maximal value for the triangular distribution of monthly working hours. Parameters Wa, Wb, and Wc signify the minimal value, the mode, and the maximal value for the triangular distribution of the average hourly salary, respectively. Parameters La, Lb, and Lc denote the minimal value, the mode and the maximal value for the triangular distribution of the required residential area, respectively. The basic requirement of disposable income deducted the rent of floor areas and commuting cost is assigned to maintain the living standard. The basic requirement of the leisure time defined as the time excluding the working time and commuting time is assigned in this program as well. Set initial time interval $k=1$.

Phase 2: Read data related to parameters of the commuters' mode and route choice model such as average travel speed and fuel cost per kilometer on surface streets, average parking cost per work trip at CBD, average running speed and fare on rail transit networks, etc. Solve the commuters' mode and route choice model in Sec. 2 to obtain the commuting cost and commuting time from each residential location to the CBD in time interval k and read the obtained data. Read data about monthly rent per pyng at each residential location. The monthly rent at each residential location is measured by the monthly monetary cost required to recover the real estate price per pyng. The interest rate and the recovery period are assumed to be 6% and 35 years, respectively.

Phase 3: Generate, randomly, three attributes, i.e., the monthly working time, the average hourly salary and the residential area according to the processes in Sec. 3.2.1 for each household in time interval k. The total number of households in the time interval k equals the total number of households in the previous time interval plus the net number of immigrating households in the time interval k.

Phase 4: Calibrate the values of parameters in the residential utility function by using simulated methods for time interval $k=1$. Collect data about the number of households at the beginning and the end of time interval $k=1$ at each residential location in the study area. Steps in the calibration process include:

- Initialize several alternative sets of values for parameters α_1, α_2, α_3, α_4, and α_5.
- Input simulated household attributes obtained in Phase 3. Solve, iteratively, individual household's residential location choice model as many times as the total number of households according to the principles described in Phase 5.
- Compare the model number of households with the actual number of households at each residential location by defining the deviation as |model number−actual number|/actual number. Choose the maximal deviation among those of all residential locations to represent the performance of model calibrated results.
- Apply the minimal of maximal principle for the deviations of models using alternative parameter value sets to determine an appropriate set of values for parameters α_1, α_2, α_3, α_4, and α_5.

Phase 5: Use parameters calibrated in Phase 4 and solve the household's residential location model of Eqs. (9)–(12) to identify the residential location with the maximal residential utility for a household. If the optimal residential location for a household is not unique, then an arbitrary decision is assumed for the household. Then, the number of households at each residential location is updated. On the other hand, if the residual of disposable income deducted the rent and commuting cost for the household allocated to the optimal location is less than the basic requirement, then the allocation of this household is negated. Similarly, if household's leisure time does not exceed the basic requirement, the allocation of this household is negated as well. Compare the updated demand and supply of residential areas at each residential site. If the capacity of individual residential site is saturated, then the residential site is unavailable for allocating households any more.

Phase 6: If the next time interval does not exceed the study period, update data about rail transit networks and households and solve the models by setting time interval to the next time interval, that is, $k=k+1$ and repeating Phases 2, 3, and 5. Otherwise, if the next time interval exceeds the study period, output the household density, average income, and average leisure time at each residential location for all time intervals in the study area.

This study defines time intervals as time spans between the completions of different rail transit lines. A completed transit line increases the accessibility of the area serviced, thus influencing rent of floor areas. Rent of floor areas at each residential location is also a critical influence on individual household's residential choice. In this study, rent per pyng, $R_H(X)$, at residential location X which appears in individual household's budget constraint, namely, Eq. (11), is further assumed to be a linear function of the number of household's in the previous time interval. That is, due to the households' bid-rent effect, rent per pyng at each residential location rises with increased number of households choosing to reside at that location. To elucidate the interaction between rent of floor areas and number of biding households, this study assumes the linear equation of rent per pyng $R_H^t(X)$ in time interval t to be the following equation and adjusts its value according to the number of households $HH_{i-1}(X)$ at residential location X at the end of time interval t-1:

$$R_H^t(X) = R_H^{t-1}(X)(1+\gamma) \tag{16}$$

Symbols t and $t-1$, respectively, represent time intervals t and $t-1$. Moreover, parameter γ=an adjustment factor of rent of floor areas. According to the study of Yuan (2003), the determination of land value variation in Taiwan involves substantial efforts in field survey and land policy from a time-consuming political process. The bidding effect of households on land rent exists and is demonstrated by many studies such as Alonso (1972) and Ching and Fu (2003). This study focuses on the relationship between land price and the number of bidding households using simplified equations as Eq. (16) and the following equation, where β_1, β_2, β_3, and β_4 are assumed to be 0.015, 0.030, 0.045, and 0.060, respectively, in the case study to show the increasing bidding effects of household numbers on land rent:

$$\gamma = \begin{cases} \beta_1 & \text{if } 0 < [HH^t(X) - HH^{t-1}(X)] \le 20 \\ \beta_2 & \text{if } 20 < [HH^t(X) - HH^{t-1}(X)] \le 40 \\ \beta_3 & \text{if } 40 < [HH^t(X) - HH^{t-1}(X)] \le 60 \\ \beta_4 & \text{if } 61 < [HH^t(X) - HH^{t-1}(X)] \end{cases} \tag{17}$$

Illustrative Example

Data for Commuters' Mode and Route Choices

This study demonstrates the application of the proposed model by presenting a case study with a metropolitan area covered by the Taipei Rapid Transit System, as illustrated in Fig. 1. The study area, which is represented by a two-dimensional coordinate system, is divided into $120 \times 150 = 18{,}000$ equal-sized grids. Surface streets are approximated by dense networks and assumed to be homogeneous in the study area. The completion dates of other rail transit lines are: (1) Nankang Line in 2001; (2) Panchiao Line in 2005; and (3) Nehu Line in 2009. The period from 1997 to 1999 is treated as time interval one. The period from 1999 to the completion date of Nankang Line is treated as time interval two. The period between the completion date of Nankang Line and that of Panchiao Line is treated as time interval three. Finally, the period between the completion date of Panchiao Line and that of Nehu Line is treated as time interval four. The numbers of immigrating households during four time intervals are estimated as 495,342, 208,566, 347,608, and 391,059, respectively. The illustrated example is used to analyze the residential location choices of households working in the region of the Taipei Central Rail Station (the center of CBD) after different lines of the Taipei Rapid Transit System are completed at various stages in the future. Interactions between transportation systems and land use

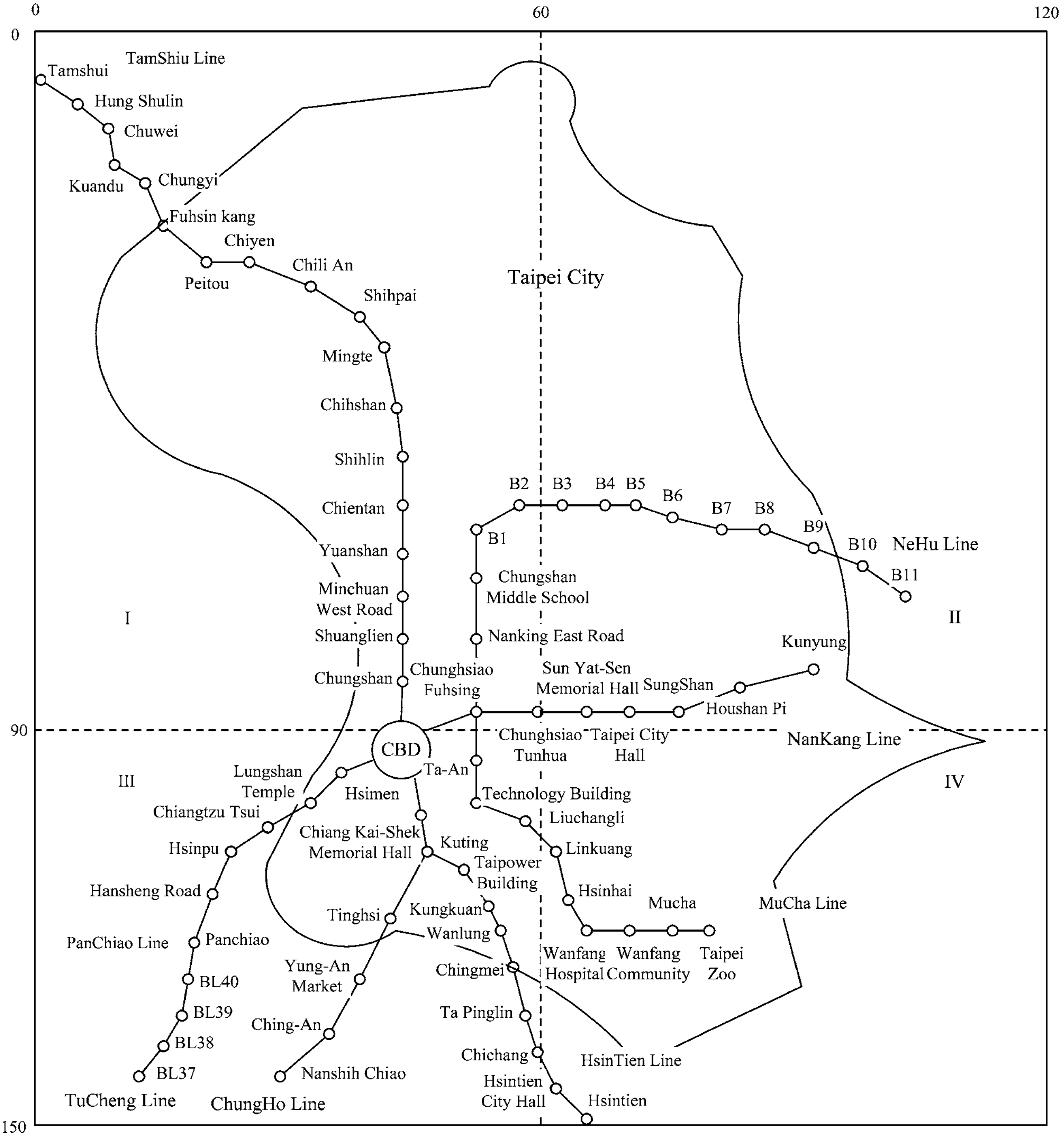

Fig. 1. Diagram of the study area

systems are established by iteratively solving the commuters' mode and route choice model and the households' residential location choice model. Although this study is assumed to be a monocentric city configuration, subsequent studies can extend it to multicentric city configuration by similar methods. In the commuters' route and mode choices model, data about surface streets include the average travel speed on surface streets, the fuel cost per kilometer on surface streets and the expected parking cost per work trip on the CBD. These data are estimated from relevant studies to be 32.5 km/h, NT\$3.8/km and NT\$240 (one U.S. dollar is equal to approximately NT\$33), respectively.

Data about the Taipei Rapid Transit System such as the network configuration, headway and average running speed of each line, fare and distance from each station to the CBD, expected parking cost per trip and average stop delay at each station are accumulated from the official reports of the Department of Rapid Transit Systems of Taipei City Government and other investigations and are summarized in Table 1. Other data such as the expected generalized travel cost from stations in the CBD to workplaces, the value of time and the scale of the grid are assumed to be NT\$60, NT\$4/min, and 0.2 km, respectively. Moreover, this study assumes that each station has enough parking facilities.

Data for Household's Residential Location Choice

The household's total working time, average salary and average residential area shown in Table 2 come primarily from *The Sta-*

Table 1. Mileage, Fare, and Parking Cost on Taipei Rapid Transit System

Line	Line section/ (parking cost: NT$)	Mileage[a] (km)	Fare[b] (NT$)	Line	Line section/ (parking cost: NT$)	Mileage[a] (km)	Fare[b] (NT$)
T[c]	CBD-Chungshan/(100)	0.6	20	P[c]	CBD-Hsimen(150)	1.4	20
A	CBD-Shuanglien/(100)	1.2	20	A	CBD-Lungshan Temple(150)	2.8	20
M	CBD-Minchuan West Road/(100)	1.7	20	N	CBD-Chiangtzu Tsui(150)	5.9	25
|	CBD-Yuanshan/(100)	2.7	20	|	CBD-Hsinpu(150)	6.7	25
S	CBD-Chientan/(100)	4.3	20	C	CBD-Hansheng Road(120)	7.7	25
H	CBD-Shihlin/(150)	5.4	25	H	CBD-Panchiao(120)	8.8	30
U	CBD-Chihshan/(150)	6.4	25	I	CBD-BL40(120)	10.4	30
I	CBD-Mingte/(100)	7.3	25	A	CBD-BL39(120)	11.8	35
	CBD-Shihpai/(100)	7.9	25	O	CBD-BL38(120)	12.4	35
	CBD-Chili An/(100)	9.2	30		CBD-BL37(120)	13.8	35
	CBD-Chiyen/(100)	10.0	30				
	CBD-Peitou/(100)	10.8	30	H[2]	CBD-Kuting(100)	2.5	20
	CBD-Hsin Peitou/(100)	11.8	35	S	CBD-Taipower Building(100)	3.4	20
	CBD-Fuhsin Kang/(100)	12.4	35	I	CBD-Kungkuan(100)	4.3	20
	CBD-Chungyi/(100)	13.9	35	N	CBD-Wanlung(100)	5.9	25
	CBD-Kuandu/(50)	14.7	40	|	CBD-Chingmei(100)	6.9	25
	CBD-Chuwei/(100)	16.8	40	T	CBD-Ta Pinglin(100)	8.1	30
	CBD-Hung Shulin/(50)	18.7	45	I	CBD-Chichang(100)	8.9	30
	CBD-Tamshui/(100)	20.8	50	E	CBD-Hsintien City Hall(100)	9.8	30
				N	CBD-Hsintien(100)	10.9	30
M[d]	Chunghsiao Fuhsing-Ta-An(100)	0.9	20				
U	Chunghsiao Fuhsing-Technology	1.6	20	C[d]	CBD-Kuting(120)	2.5	20
|	Building(100)			H	CBD-Tinghsi(120)	4.7	20
C	Chunghsiao Fuhsing-	2.8	20	U	CBD-Yung-An Market(120)	5.9	25
H	LiuchangLi(100)			N	CBD-Ching-An(120)	7.2	25
A	Chunghsiao Fuhsing-	3.6	20	G	CBD-Nanshih Chiao(120)	7.8	25
	Linkuang(100)			H			
	Chunghsiao Fuhsing-Hsinhai(100)	5.2	25	O			
	Chunghsiao Fuhsing-Wanfang	5.9	25				
	Hospital(100)			N[1]	Chunghsiao Fuhsing-Nanking	1.3	20
	Chunghsiao Fuhsing-Wanfang	7.1	25	E	East Road(100)		
	Community(100)			|	Chunghsiao Fuhsing-	2.2	20
	Chunghsiao Fuhsing-Mucha(100)	7.6	25	H	Chungshan Middle School(100)		
	Chunghsiao Fuhsing-Taipei zoo(100)	8.6	25	U	Chunghsiao Fuhsing-B1(100)	2.9	20
					Chunghsiao Fuhsing-B2(100)	4.3	20
N[1]	CBD-Chunghsiao Fuhsing(120)	2.7	20		Chunghsiao Fuhsing-B3(100)	5.9	25
A	CBD-Chunghsiao Tunhua(120)	3.4	20		Chunghsiao Fuhsing-B4(100)	6.7	25
N	CBD-S.Y.S. memorial Hall(120)	4.1	20		Chunghsiao Fuhsing-B5(100)	7.3	25
|	CBD-Taipei City Hall(120)	5.0	25		Chunghsiao Fuhsing-B6(100)	7.9	25
K	CBD-SungShan(120)	6.0	25		Chunghsiao Fuhsing-B7(100)	9.8	30
A	CBD-Houshan Pi(120)	6.8	25		Chunghsiao Fuhsing-B8(100)	10.6	30
N	CBD-Kunyung(120)	8.1	30		Chunghsiao Fuhsing-B9(100)	11.2	35
G					Chunghsiao Fuhsing-B10(100)	12.4	35
					Chunghsiao Fuhsing-B11(100)	13.0	35

[a] Mileage data came from Lan (1980).

[b] Fares are realistic data from official web site ⟨http://www.trtc.com.tw⟩, and fares about uncompleted rail transit lines are estimated according to standard pricing rules adopted by the Taipei Rapid Transit Corporation.

[c] Uncompleted rail transit line. Average operating speed, average headway, and average stop delay are assumed to be 33 km/h, 5 min, and 30 s, respectively.

[d] Average operating speeds, average headway, and average stop delays for Tamshui, Chungho, Hsintien, and Mucha Lines are 35 km/h, 10 mins, 30 s, 33 km/h, 5 min, 30 s, 33 km/h, 5 min, 24 s, and 33 km/h, 5 min, 30 s, respectively.

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Table 2. Estimate of Household Input Data

Item	Meaning	Value	Unit
(1)	Number of households in Taipei city	707,998	—
(2)	Number of employees per household	1.6	—
(3)	Average monthly working hour per employee	192[a]	—
(4)	Average monthly working hour per household	307.2[b]	—
(5)	Average monthly salary per household	74,168	NT$
(6)	Average hourly salary per household	220.3[c]	NT$
(7)	Total residential areas in Taipei city	22,109,000	pyng
(8)	Average residential areas per household	31.2[d]	pyng

[a] Original data of average daily working time per employee is 8 h and 4 min. This study assumes that on average each employee works 24 days per month.

[b] Estimated by (2) × (3).

[c] Estimated by (5) ÷ (4).

[d] Estimated by (7) ÷ (1).

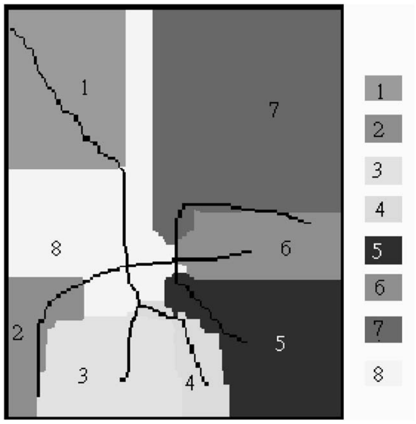


Fig. 2. Service areas of rail transit lines in the study area

tistical Abstract of Taipei City (Department of Budget, Accounting and Statistics 1997) and *The Report on the Time Utilization Survey* (DGBAS 1995) in Taiwan. The average monthly working hour, the average hourly salary and the average residential area in Table 2 are treated as sample modes of the three triangular distributions in Section 3.2.2. That is, they represent values for parameters *Tb*, *Wb*, and *Lb*, respectively. The remaining six parameters *Ta*, *Tc*, *Wa*, *Wc*, *La*, and *Lc* are estimated to be 225 h, 345 h, NT$180, NT$325, 26 pyng, and 50 pyng, respectively. Data regarding the real estate prices are accumulated from the *House and Life* magazine in Taiwan. Table 3 summarizes the data.

Result Analysis

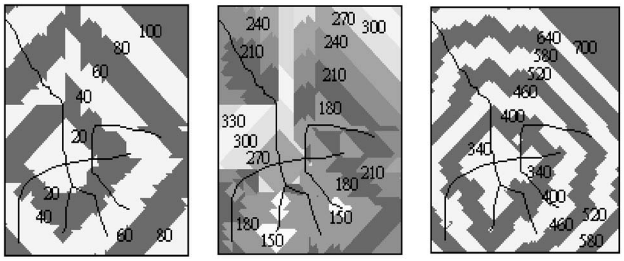
Mode and Route Choices

The commuter's mode and route choice model applied in the example not only estimates the least travel cost and travel time from each residential location to the CBD, but also determines the optimal mode choice for households who are living at each location of the study area and working in the CBD. Fig. 2 illustrates the optimal mode and route choice from each residential location to the CBD and the service area of each rail transit line after rail transit lines are totally completed; that is, in time interval four. Commuters living in Area 1 and traveling to the CBD should drive a car via surface streets and then transfer to the Tamshui Line so as to minimize their generalized travel costs. Optimal transferring rail transit lines for commuters living in Areas 2, 3, 4, 5, 6, and 7 and traveling to the CBD are the Panchiao Line, Chungho Line, Hsintien Line, Mucha Line, Nankang Line, and Nehu Line, respectively. The optimal mode choice for commuters living in Area 8 is driving a car directly via surface streets to the CBD. The previous results indicate that commuters with longer travel distances between homes and CBD tend to use rail transit lines as their main commuting modes, whereas commuters with shorter travel distances tend to use car directly to the CBD via surface streets. Besides, the service areas of rail transit lines are not only resulted from the competition between rail transit networks and surface streets but also from the competition between adjacent rail transit lines. For example, no rail transit line exists in the remote area between the east of the Tamshiu Line and the north of the Nehu Line; therefore, the service areas of these two lines are markedly large.

Table 3. Average Real Estate Prices per pyng (Unit: NT$ 10,000)

Taipei City		Taipei County	
District	Average price	Town	Average price
Chung-Jeng	27.9	Pan-Chiao	18.26
Ta-Tung	17.37	Shih-Jy	15.16
Chung-Shan	25.79	Yong-Her	20.56
Sung-Shan	30.05	Chung-Ho	17.87
Ta-An	32.51	Tu-Cheng	13.03
Wan-Hwa	18.40	San-Chong	15.73
Shin-Yi	28.19	Shin-Jung	15.09
Shih-Lin	27.99	Hsin-Tien	17.68
Pei-Tou	25.22	Lu-Jou	15.04
Nei-Hu	23.36	Tam-Shui	17.81
Nan-Kang	20.06	Kee-Long	11.92
Mu-Cha	20.89		

Figs. 3(a–c) illustrate, respectively, the equicommuting time (unit: minute), equicommuting cost (unit: NT$) and equigeneralized commuting cost (unit: NT$) contours from the CBD after rail transit lines are totally completed. Results of Fig. 3(a) reveal that equicommuting time contours are shaped into lozenge and increased outward from CBD. Results of Fig. 3(b) reveal that equicommuting cost contours are increased outward from the CBD along the configuration of rail transit networks. Commuting costs from residential locations near transit stations are lower than those from other residential locations with similar commuting dis-



Commuting time
Commuting costs
Generalized commuting costs

Fig. 3. Distribution of equitime contours and equicost contours

Table 4. Maximal Deviation of Parameter Alternatives for α_1, α_2, α_3, α_4, and α_5

Set	Parameter sets $(\alpha_1,\alpha_2,\alpha_3,\alpha_4,\alpha_5)$	Maximal deviation
1	(0.8, −0.65, −0.65, 0.7, −0.45)	30.000
2	(0.75, −0.65, −0.65, 0.7, −0.45)	30.000
3	(0.8, −0.65, −0.65, 0.65, −0.45)	29.500
4	(0.8, −0.65, −0.7, 0.7, −0.45)	33.875
5	(0.8, −0.65, −0.6, 0.7, −0.45)	26.500
6	(0.8, −0.6, −0.65, 0.7, −0.45)	27.750
7	(0.8, −0.65, −0.65, 0.7, −0.5)	22.375
8	(0.8, −0.65, −0.5, 0.5, −0.5)	14.625
9	(0.8, −0.6, −0.6, 0.5, −0.6)	11.250
10	(0.75, −0.5, −0.6, 0.5, −0.7)	7.000
11	(0.75, −0.45, −0.5, 0.45, −0.75)	4.625
12	(0.7, −0.6, −0.6, 0.45, −0.75)	6.875
13	(0.75, −0.35, −0.5, 0.45, −0.8)	3.625
14	(0.75, −0.35, −0.45, 0.45, −0.8)	3.250
15	(0.7, −0.35, −0.4, 0.45, −0.8)	2.875

tance but far away from stations. Equigeneralized commuting cost contours are also consistent with the service areas of transit lines and surface streets as shown by Fig. 3(c).

Calibrating Parameters

To calibrate the parameters of Eq. (13), some pretests are initially made to determine the possible value ranges for parameters α_1, α_2, α_3, α_4, and α_5 are assumed to be +0.5 or −0.5, depending on whether the influences of increasing t_{L_i}, $TC^*(X)$, $TT^*(X)$, I_i, and $HH_{i-1}(X)$ on residential utility are positive or negative. Therefore, the initial value set of $(\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5)$ is $(0.5, -0.5, -0.5, 0.5, -0.5)$.

This study applied an enumeration method by sequentially adjusting the five parameter values to pretest the fitness of the spatial distribution of households' residential location choices between the model results and collected data. The modulation of each parameter value is assumed to be either +0.05 or −0.05. Following these pretests, 15 sets of values are selected for parameters α_1, α_2, α_3, α_4, and α_5 to show fitness consequences. According to the parameter calibration procedures in Phase 4 of the simulation program, the fitness is represented by the residential location with the maximal calibration deviation among all residential locations in the study area. Lower maximal calibration deviation indicates better fitness consequences. The right column of Table 4 summarizes 15 sets of parameter values. The minimal deviation among all 15 sets is 2.875, and occurs in the 15th set, as shown in Table 4. The study area is represented by a two-dimensional coordinate system, and residential locations are composed of $120 \times 150 = 18{,}000$ equal-sized grids. However, average real estate prices per pyng, listed in Table 3, are categorized based on administrative districts. This study establishes a mapping layer between administrative districts and grids to convert collected data from the administrative district base into the grid base. The results of calibrated values for parameters α_1, α_2, α_3, α_4, and α_5 are 0.7, −0.35, −0.4, 0.45, and −0.8 as described previously. The calibrated parameters in Eq. (13) represent the interactive and nonlinear effects of decision variables on the commuters' residential utility. The calibrated results show that commuter's residential utility increases as total leisure time and the residual of disposal income deducted the rent and the commuting cost increase, while it decreases as round-trip commuting time, round-trip commuting cost and the number of households at the residential location increase.

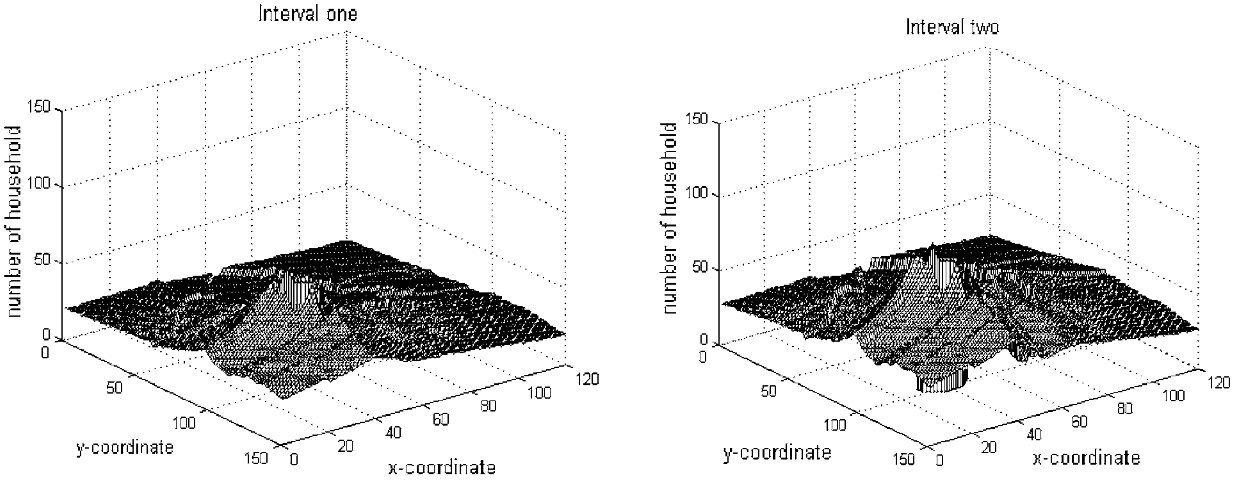
Residential Location Choices

Figs. 4(a–d) illustrate the surfaces of simulated numbers of household at all residential locations in four time intervals, respectively. The center of CBD in this study is located at coordinate (40, 95). Figs. 4(a–d) reveal that household densities increase with decreasing distance from the residential locations to the CBD, resulting in several peaks around the CBD. When the rail transit system is fully completed in time interval four, another peak emerges at the intersection of the Nehu, Nankang, and Mucha Lines. According to Figs. 4(a–d), the variation of residential densities is highly sensitive to the configuration of transit networks and the location of each station. As for individual transit lines, locations with significantly higher residential densities can be found to include locations at the south of both the Mingte Station (Tamshui Line) and the B1 Station (Nehu Line), locations at the north of the Panchiao Station (Panchiao Line), locations between the Chungho Line and the Mucha Line, and locations around the intersection of the Nehu, Nankang, and Mucha Lines. Comparing Figs. 4(a–d) with Figs. 3(a and b) reveals that residential densities become higher at residential sites with less commuting times and commuting costs. This comparison also indicates that the pattern of residential density coincides with the pattern of equitravel cost contours and equitravel time contours. This phenomenon reflects that the commuting time and the commuting cost are two of the key factors when households choose their residential locations. Consequently, this study can infer the following. The closer to the CBD implies a higher household density. In addition, the higher the rent implies less commuting time and lower cost. These inferences correspond to the conventional location theory.

Fig. 5 illustrates average household income at each residential location in four time intervals. Fig. 5 shows that households with higher income levels prefer to reside in districts of Taipei City such as Shih-Lin, Ta-Tung, Chung-Shan, Sung-Shan, Chung-Jeng, Ta-An, Shin-Yi, and Mu-Cha in time interval one. However, there is an increased attraction of households in cities of Taipei County such as Pan-Chiao, Chung-Ho, Yong-Her, and Hsin-Tien in the succeeding time intervals due to the completion of rail transit networks in these cities. Spatial distributions of average household incomes in four time intervals are not significantly different from each other. This phenomenon implies that different income level households reveal steady preferences for their favorite residential locations. However, spatial variations of average household income over the study area are slightly moderated when rail transit networks are totally completed.

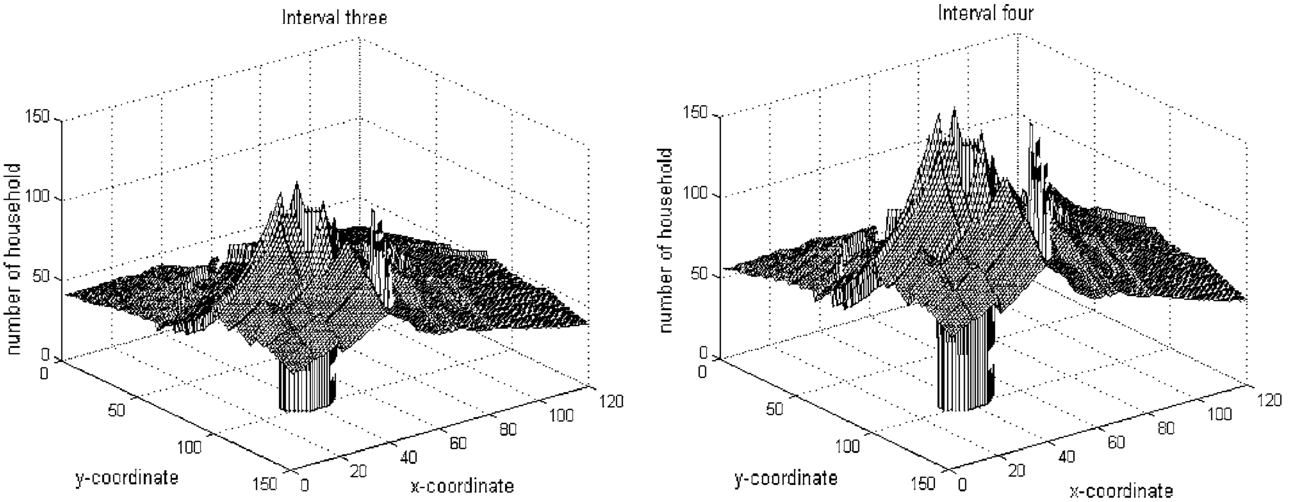
Conclusions and Suggestions

According to study results, impacts of rail transit networks on households' mode choices and residential location choices are summarized as follows. First, commuters with longer travel distances between homes and CBD tend to use rail transit lines as their main commuting modes, while commuters with shorter travel distances tend to use car directly to the CBD via surface streets. Second, variations in the residential densities are highly related to the configuration of transit networks and the location of each station. Finally, there are increased attractions of households in cities of Taipei County such as Pan-Chiao, Chung-Ho, Yong-



Time interval one

Time interval two



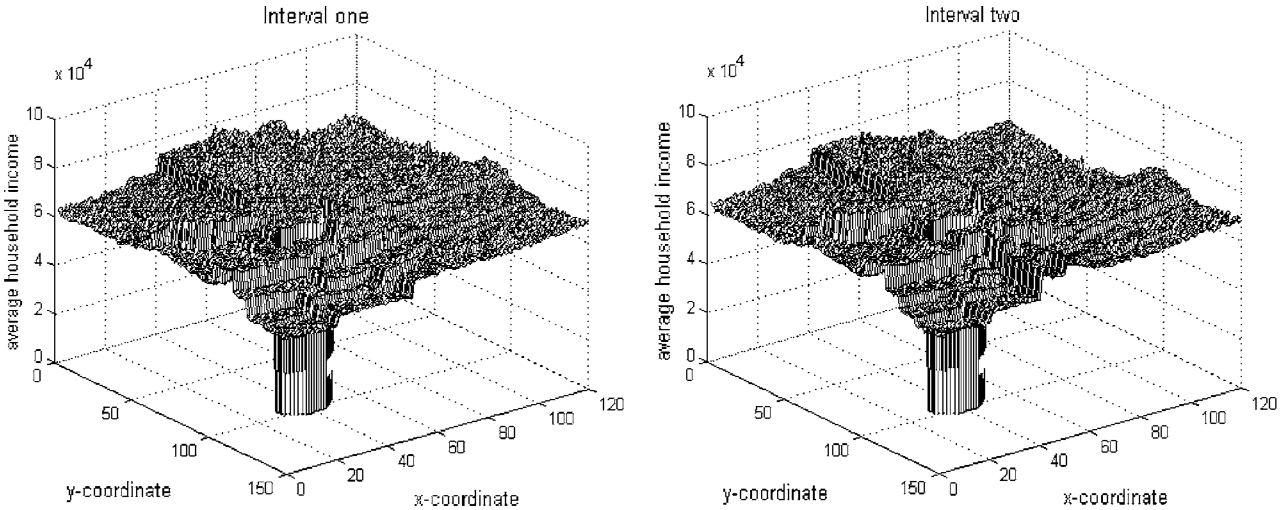
Time interval three

Time interval four

Fig. 4. Households' residential distribution

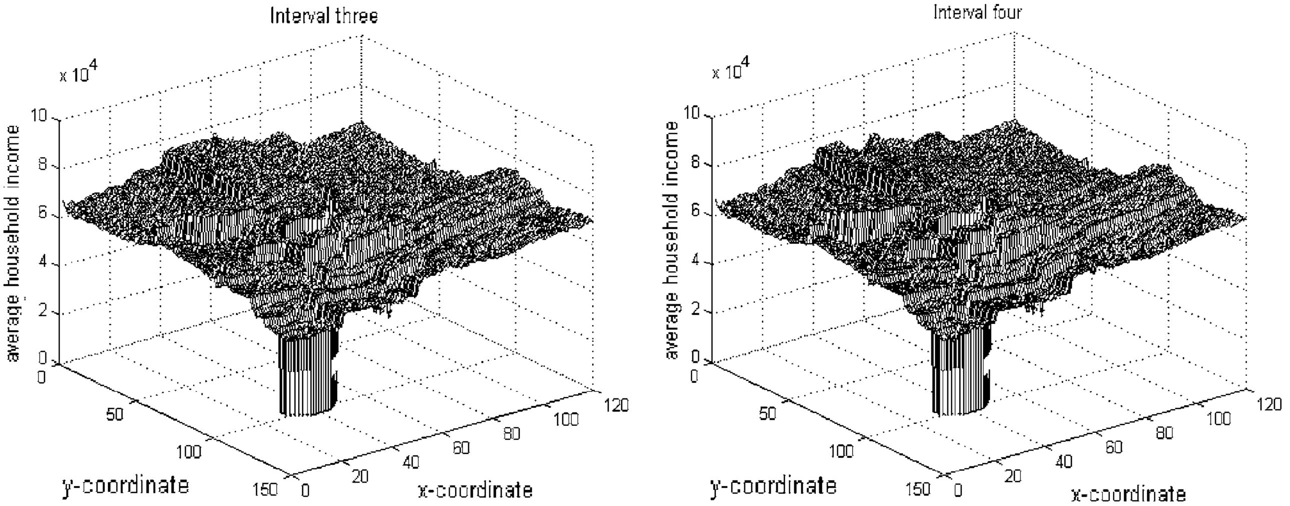
Her, and Hsin-Tien in the succeeding time intervals for the sake of increased mobility due to the completion of rail transit networks. Regarding the application, the models herein can be applied to highly concentrated urban areas with rail transit system that are in the planning stage or under construction. The formulation procedures in the commuters' modes and route choice models as well as the households' residential choice model, demonstrate the synthesis of two models in a sequential fashion. The developed models are useful for estimating travel demand for each rail transit line from a long-term planning perspective, and also for analyzing households' spatial distribution based on several major factors. However, as data for future periods are unavailable, the effectiveness of the model of commuters' modes and route choices models and household's residential location choice model is unclear. Future studies may justify the effectiveness of the results when further data become available in the future.

The models proposed herein have some limitations. First, the supply of land is assumed to be given and is not related to rent. Second, this study did not explicitly consider the situation of diagonal roads in specific areas that greatly reduce travel time, since the study area is represented as a grid network and the Manhattan distance is applied to simplify the complexity of problem. Future studies should consider diagonal roads and evaluate the benefits of diagonal roads. Third, this study is restricted to the monocentric city configuration and two kinds of transportation system. Results in this study can only describe the residential distribution for commuters working in the CBD of the Taipei metropolitan area and traveling by car and rail transit. To apply this model for more practical purposes, future studies with similar methods should be extended to the multicentric city configuration with all feasible transportation systems. Fourth, households' attributes, such as working hours, hourly salary, and required residential area, are almost certainly not independent but rather are significantly and positively correlated. However, these attributes are primarily quantitative factors for representing individual household's characteristics. Future studies should incorporate such correlations and consider qualitative factors such as individual preference and location amenity to estimate households' residential location choices. This study formulated an optimization model rather than a choice model; therefore, the model implies that it has accounted for all factors in the residential choice of individual household. In reality, households' residential choices might be better described as an individual probabilistic model. Fifth, the assumption of constant travel speed and fuel costs over time is unrealistic as fuel costs are dependent on travel speed, which in



Time interval one

Time interval two



Time interval three

Time interval four

Fig. 5. Average household income distribution

turn is affected by traffic flows in the real world. To establish a direct connection between travel time/travel cost and link flows, future studies should apply actual networks and incorporate the flow-dependent travel time function on surface streets to explore households' mode, route, and residential location choices. Sixth, the set of explanatory variables for residential location is certainly limited, and the alphas in the residential utility function may change over time. Future studies could further consider constraints such as two-career households, and factors such as school systems, and crime and aesthetic amenities and clustering of affinity groups. Further, future studies could contribute by calibrating the alphas for multiple years for which data are available, and could analyze any changes in weights given the various factors in the utility function.

Acknowledgments

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