Impacts of Transportation External Cost Pricing and Transit Fare Reductions on Household Mode/Route Choices and Environmental Improvements

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

Abstract: This study explores how transportation external cost pricing and transit fare reductions impact household mode/route choices and environmental improvements in a metropolitan area. A household mode/route choice model and a bilevel model for transportation external cost pricing and transit fare reductions are sequentially constructed. In the first level of bilevel model, the pricing of transportation external costs, including congestion, air pollution, and noise, is measured applying the theory of marginal-cost pricing. The effects of transportation external cost pricing are analyzed in terms of variations in household mode/route choices, increased patronage of rail transit lines and reduced congestion, air pollution, and noise. In the second level of bilevel model, this study explores how to reduce rail transit fares to achieve equivalent benefits of environmental improvement as for the strategy of transportation external cost pricing. The analytical results reveal that, after the implementation of transportation external cost pricing and taxation, the number of commuting households attracted to rail transit lines will increase, and some commuting households may detour to more distant transit stations to avoid high congestion links on surface streets.

DOI: 10.1061/(ASCE)UP.1943-5444.0000036

CE Database subject headings: Rail transportation; Costs; Pricing; Fare; Commute.

Author keywords: Rail transit system; External cost pricing; Transit fare; Mode choice.

Introduction

Transportation externalities such as congestion, air pollution, and noise, which result from the increasing use of automobiles, are unsettled and result in social costs and impaired public health in metropolitan areas. Previous studies have explored transportation externality pricing and incorporated it into the total travel costs of travelers. Some studies applied the fundamental economic principle of marginal-cost pricing to analyze the relationship between congestion toll and traffic flow, and traveler route choice behavior (e.g., Yang and Bell 1997; Yang and Huang 1998). Meanwhile, dynamic models explore the influence of time-varying flows on congestion pricing and design discriminating and time-varying congestion pricing schemes during peak and off-peak periods (e.g., Yang and Huang 1997; Daganzo and Garcia 2000).

Moreover, some studies adopted the economic cost perspective and applied quantitative economic approaches to construct a road pricing model that incorporates congestion, air pollution, and noise based on the marginal-cost pricing or second-best pricing methods (e.g., Mayeres et al. 1996; Johansson 1997). Different transportation supply policies also influence transportation externality pricing. Therefore, some studies further analyzed transportation externality pricing under different transportation supply policies (e.g., De Borger and Wouters 1998; Romilly 1999; Verhoef 2000; Mayeres 2000). Furthermore, interactions exist between transportation and environment systems. Some studies devised an integrated evaluation framework for comprehensively investigating the environmental impacts of transportation projects by applying system analysis or multicriteria analysis (e.g., Lo and Hickman 1997; Tsamboulas and Mikroudis 2000).

Traffic congestion is prevalent in major metropolitan areas. Rail transit and private car induce different externalities, owing to their different service attributes. The rail transit system fits environmental protection goals because it is electricity operated in three construction forms; that is, surface, at grade, and underground, and thus results in less pollution. Some previous studies investigated the influences of new or improved public transport systems on traveler mode and route choices, and then estimated the patronage of public transport systems (e.g., Koppelman et al. 1993; Hsu and Guo 1999). Previous studies have also constructed multimodal transportation networks' models to explore passengers' shifting behavior and transit fare structure (e.g., Lozano and Storchi 2001; Lo et al. 2003; Lam et al. 1999). This study considers the pricing of three transportation externalities, namely, congestion, air pollution, and noise, and incorporates them into the total travel cost function of individual travelers by applying marginal-cost pricing theory. This study constructs models to (1) analyze variations in household mode and route choices due to extra cost burdens from transportation externalities such as congestion, air pollution, and noise and (2) estimate changes in the patronage of rail transit lines.

Authorities levying transportation externality taxes (e.g., congestion tax, air pollution tax, and noise tax) on surface road users

[1]Associate Professor, Dept. of Logistics and Marketing Management, Leader Univ., Tainan 709, Taiwan, Republic of China (corresponding author). E-mail: spguo@mail.leader.edu.tw

[2]Professor, Dept. of Transportation Technology and Management, National Chiao Tung Univ., Hsinchu 30050, Taiwan, Republic of China. E-mail: cihsu@mail.nctu.edu.tw

Note. This manuscript was submitted on October 28, 2008; approved on April 14, 2010; published online on November 15, 2010. Discussion period open until May 1, 2011; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Urban Planning and Development***, Vol. 136, No. 4, December 1, 2010. ©ASCE, ISSN 0733-9488/2010/4-339–348/$25.00.

can be considered a strategy for encouraging public transit. Increased total travel costs of private car users may result in private car users shifting to rail transit and consequent environmental improvements. Meanwhile, subsidies for transit operators can be transferred to passengers, thereby reducing rail transit fares and increasing the attractiveness of rail transit. Some studies analyzed the influences of bus or transit fare changes on traveler mode choice behavior, ridership, and operator revenues (e.g., Benjamin et al. 1998; Taylor and Carter 1998; Ling 1998). Reducing public transportation fares is a transparent strategy for travelers since it allows travelers to know their total travel costs before making their trips. This strategy is also easy to implement, particularly if it can achieve equivalent environmental improvements to the strategy of transportation external cost pricing. Consequently, this study further explores how to decrease rail transit fares at each transit line section used by commuters to travel from their homes to work to achieve equivalent environmental improvements compared to the strategy of transportation external cost pricing.

Household Mode and Route Choices without Considering External Cost Pricing

This study applied the continuum approximation method to assume the study area to be a dense network represented by a two-dimensional coordinate system D. Surface streets were assumed to be continuous and homogeneous networks, and thus the actual surface networks were not captured. The rail transit networks were represented in the form of actual networks. Let graph $G(N,A)$ represent the actual rail transit network, where N denotes the set of nodes and A represents the set of links in the graph. Moreover, residential sites and rail transit stations are indicated by a two-dimensional coordinate. The main reason for applying the continuum approximation method in this study is to estimate car flows from all residential sites to each transit station using a simplified data collection process and without collecting detailed road network information. Commuting car flows generated from each residential site can be estimated based on the trip generation rate for work trip purposes at each residential site. For long-term planning purposes, this study applies a continuum approximation method to estimate commuting car flows transferring at each rail transit station.

In relation to generalized travel cost function on surface streets, this study refers to and revises the link travel time function in conventional traffic assignment models (e.g., Sheffi 1985) to formulate the generalized travel cost function $c_{ij}(v_{ij})$ of individual commuting households from residential site $i=(i_1,i_2)$ to residential site $j=(j_1,j_2)$ via an artificial link on the surface streets, as in Eq. (1). Because commuting households pass through residential sites between their residences and workplaces, the artificial link in this study is defined as the artificial commuting link which connects two adjacent residential sites. To simplify the model formulation, this study assumed that each household uses a single car to commute and that workplaces of household members are highly concentrated in the central business district (CBD). That is, this study explores travel patterns from numerous origins to a single destination (CBD). Car pooling is commonly adopted by household members when driving to workplaces, especially in a city with a large CBD

$$c_{ij}(v_{ij}) = c_{ij}^0[1+\tau(1+v_{ij}/C_{ij})^{\varpi}] \quad \forall\ (i,j) \in F \tag{1}$$

In Eq. (1), F denotes the set of all artificial links on surface streets between residential site pairs in the study area. Moreover, c_{ij}^0 represents the generalized travel cost which is independent of the car flows of commuting households on the artificial link from site $i=(i_1,i_2)$ to site $j=(j_1,j_2)$. Moreover, v_{ij} denotes the car flows of commuting households on artificial link from site $i=(i_1,i_2)$ to site $j=(j_1,j_2)$. Furthermore, C_{ij} denotes the capacity of the artificial link from site $i=(i_1,i_2)$ to site $j=(j_1,j_2)$, and τ and ϖ are parameters. Eq. (1) formulates the generalized travel cost of individual households on the artificial link via surface streets. When v_{ij} is zero, i.e., free flow state, $c_{ij}(0)$ not only includes the generalized travel cost of flow-independent travel time on the artificial link via surface streets, i.e., c_{ij}^0, but also the out-of-packet cost, which is estimated and denoted by parameter τ.

Regarding the representation of rail transit networks, a transit line section is defined as a part of a rail transit route, which includes the set of all rail transit links that must be passed from a boarding station to the CBD station or a transfer station. Each rail transit line section corresponds to a rail transit station, i.e., the boarding station. Furthermore, the study of Hsu and Guo (2001) defines parameters of rail transit networks as follows. Let K denote the set of rail transit routes directly connected to the CBD without transshipment of passengers between rail transit lines. Moreover, let K^t represent the set of rail transit routes that are indirectly connected to the CBD with transshipment of passengers between rail transit lines. Passengers using rail transit routes in K^t must transship to rail transit routes in K to reach CBD. Furthermore, let S denote the set of nontransferring stations while S^t represents the set of transfer stations. Additionally, A^s is the set of rail transit line sections that directly connect to workplaces in CBD and whose initial stations are not transfer stations. Furthermore, A^t represents the set of rail transit line sections that directly connect to workplaces in CBD and whose initial stations are transfer stations. Moreover, T^s is the set of rail transit line sections that do not connect to workplaces in CBD and whose initial stations are not transfer stations. Meanwhile, $T_r(r \in S^t)$ denotes the set of rail transit line sections whose initial station is transfer station r. Additionally, W^s represents the set of initial stations that correspond to rail transit line sections in A^s and A^t. Finally, W^t is the set of initial stations that correspond to rail transit line sections in T^s.

The generalized travel cost t_a^s on rail transit line section a corresponding to initial station s for an individual commuting household includes onboard time, waiting time, parking time, and fares. Owing to constant running speed, fixed frequency, and given fares of rail transit systems, the weighted sum of the onboard time and fare for rail transit line section a is assumed to be constant and is denoted by $t0_a^s$. Since this study assumes workplaces to be highly concentrated on the CBD, the waiting time at each rail transit station is a function of the number of boarding passengers during the peak period. Let h_a^s denote the park-and-ride car flows at rail transit station s, i.e., the initial station of rail transit line section a. Surface street flows comprise vehicles, while rail transit network flows comprise passengers. Since this study assumes all commuting members of each household to simultaneously use the same car to travel to the CBD, the average number of commuting members per household, β, also represents the average vehicle occupancy factor. Passengers at transfer stations not only comprise park-and-ride travelers but also transfer from other rail transit routes that do not directly connect to the CBD. Therefore, generalized travel cost functions on rail transit line sections are constructed separately for both nontransferring stations and transferring stations and are formulated as Eqs. (2) and (3), respectively, where α and ρ are parameters

J. Urban Plann. Dev. 2010.136:339-348.

$$t_a^s(h_a^s) = t0_a^s + \alpha(\beta \cdot h_a^s/H_a^s)^\rho \quad \forall\, a \in (A^s \cup T^s), \quad s \in S \tag{2}$$

$$t_b^r(h_a^s, h_b^r) = t0_b^r + \alpha\left[\beta\left(h_b^r + \sum_{a \in T_r, s \in W^t} h_a^s\right)/H_b^r\right]^\rho$$
$$\forall\, b \in A^t, \quad r \in S^t \tag{3}$$

This study considers traveler waiting time and parking time as delay time at their park-and-ride stations on rail transit networks. Besides passenger flows, the main determinant of traveler waiting time is available capacity of rail transit trains, while the major influence on traveler parking time is parking availability at stations. H_a^s is defined as a synthetic parameter representing the above two supply capacities at boarding station of rail transit line section a. Correspondingly, this study constructs a household mode/route choice model using Eqs. (4)–(10) including decision variables of car flows of commuting households v_{ij} on artificial link on surface streets and transferring car flows, h_a^s and h_b^r, to transit stations based on the principle of user equilibrium. According to Eq. (9), the transferring car flows, h_a^s and h_b^r, can be substituted by the car flows of commuting households on artificial links connected to transit stations

$$\min TC_1 = \sum_{(i,j) \in F} \int_0^{v_{ij}} c_{ij}(v_{ij}) dv_{ij} + \sum_{s \in S} \int_0^{h_a^s} t_a^s(h_a^s) dh_a^s$$
$$+ \sum_{r \in S^t} \int_0^{h_b^r} t_b^r(h_a^s, h_b^r) dh_b^r \tag{4}$$

$$\text{subject to} \sum_{j \in D_i'} v_{ij} = g_i \quad \forall\, i \in B^F \tag{5}$$

$$\sum_{i \in D_j} v_{ij} = \sum_{k \in D_j'} v_{jk} \quad \forall\, j \in B^s \quad \forall\, i \neq j \neq k \tag{6}$$

$$\sum_{i \in D_j} v_{ij} + g_j = \sum_{k \in D_j'} v_{jk} \quad \forall\, j \in (B - B^F - B^S) \quad \forall\, i \neq j \neq k \tag{7}$$

$$\sum_{i \in D_o} v_{io} + \sum_{s \in (S \cup S^t)} h_a^s = \sum_{j \in B} g_j \tag{8}$$

$$h_a^s = \sum_{i \in D_s} v_{is} \quad \forall\, s \in (S \cup S^t) \tag{9}$$

$$v_{ij} \geq 0 \quad \forall\, (i,j) \in F \tag{10}$$

where g_j denotes the number of households at residential site $j = (j_1, j_2)$; D_j represents the set of upstream residential sites adjacent to residential site $j = (j_1, j_2)$; and D_j' = set of downstream residential sites adjacent to residential site $j = (j_1, j_2)$. Additionally, B denotes the set of all residential sites in the study area and B^F represents the subset of residential sites located within the boundaries of the study area; that is, $B^F \subset B$. Outflows of commuting households will only occur at residential sites of B^F. B^S denotes the subset of residential sites adjacent to rail transit stations, namely, $B^S \subset B$. Eq. (4) is the objective function minimizing the total generalized travel costs of commuting households on both surface streets and rail transit networks under the principle of user equilibrium. Moreover, Eqs. (5)–(9) are flow conservation constraints at each residential site and each rail transit station in the study area. Eq. (5) demonstrates that the outflows of commuting households at each residential site within the boundaries of the study area are equal to the number of households living at that residential site.

To implicitly indicate these commuting methods, the outflow of commuting households at each residential site adjacent to rail transit stations is formulated in Eq. (6) as equal to the inflow of commuting households at that residential site. Commuting households living at residential sites adjacent to each rail transit station generate passenger flows on the transit line section corresponding to that transit station and should be included in the generalized travel cost function on that transit line section. Restated, these passenger flows should be added to the variable h_a^s in Eq. (2) or Eq. (3), depending on whether the transit station is a nontransferring or a transferring station. Eq. (7) represents that the outflow of commuting households at each residential site, which is neither located within the boundaries of the study area nor adjacent to transit stations, should equal the inflow of commuting households at that residential site plus the number of households there. Eq. (8) reveals that the total number of households living at all residential sites equals the inflow of commuting households to the CBD from upstream residential sites plus the total number of transferring car flows to all of stations in the study area. Eq. (9) represents that car flow transferring to each transit station equals the inflow of commuting households to that station from upstream residential sites. Eq. (10) is the nonnegative constraint of each decision variable.

Transportation External Cost Pricing, Transit Fare Reduction, and Household Mode/Route Choices

Household Mode/Route Choice Model Considering Transportation External Cost Pricing

This study refers to Yang and Bell (1997), Yang and Huang (1998), and Verhoef (2000) and, besides congestion, further incorporates transportation externalities such as air pollution and noise in formulating transportation external cost pricing and household mode/route choice model. Car flow induced congestion results in online effects on transportation networks, while the air pollution and noise induced by car flows have both online and offline effects due to the dispersion and propagation attributes of air pollution and noise, respectively. Moreover, this study assumes that the cost burdens of transportation externalities resulting from rail transit systems are exempted with a lump-sum subsidy to encourage rail transit patronage. Therefore, this study neglects the pricing of transportation externalities caused by the rail transit system.

Transportation externalities such as pollution and noise are continuously dispersed and propagated over the study area. The spatial effects of pollution and noise are originally formulated using continuous functions. However, continuous spatial functions have difficulty calculating integrals and obtaining the optimal solution. Transportation studies mostly adopt a zoning method to divide the study area and then explore transportation planning issues. However, aggregation bias exists among these traffic zones. Therefore, this study applies a continuum approximation method to divide the study area into discrete residential sites and formulate the external cost functions of air pollution and noise at each residential site. This study also considers the dispersion and propagation of air pollution and noise since the offline effects of these externalities should be considered. This study refers to Hsu and Guo (2005) to derive the external cost function of air pollution $ae_x(v_{ij})$ at residential site $x=(x_1,x_2)$, which is induced by the car flows of commuting households v_{ij} on the artificial link from site $i=(i_1,i_2)$ to site $j=(j_1,j_2)$, as expressed in Eq. (11)

$$ae_x(v_{ij}) = \theta_1 \cdot \frac{v_{ij} \cdot Q}{2\pi \cdot}\left\{ \sum_{b_3 \in [R1,R2]} \frac{1}{\sigma_h \cdot \sigma_z \cdot |\bar{w}|} \times \exp\left(-\frac{1}{2}\left\{ \frac{|\bar{w}|^2 \cdot |i-x|^2 - [(i-x)\cdot \bar{w}]^2}{|\bar{w}|^2 \cdot \sigma_h^2} \right\}\right) \cdot \times \exp\left[-\frac{1}{2}\left(\frac{h_e - b_3}{\sigma_z} \right)^2 \right] \right\} \tag{11}$$

where Q denotes the emission rate per automobile and σ_h and σ_z represent the standard horizontal and vertical deviations of the concentration distribution, respectively. Additionally, $\bar{w}$ denotes the average wind velocity vector $(\bar{w}_1, \bar{w}_2, \bar{w}_3)$. h_e represents the effective emission height of air pollution. $[R1, R2]$ is the vertical range within which pollutants become detrimental to human health. Finally, θ_1 denotes the social cost per unit of air pollution.

Moreover, the external cost function of noise $ne_x^a(v_{ij})$ at residential site $x=(x_1,x_2)$, which is induced by the car flows of commuting households v_{ij} on the artificial link from site $i=(i_1,i_2)$ to site $j=(j_1,j_2)$, is derived as Eq. (12). In Eq. (12), L_W^a represents the average sound power level (dB *re* 10^{-12} W) caused by one car. Moreover, $\mathrm{DI}_\theta^a(i,x)$ denotes the directivity index of car flow noise traveling from residential site $i=(i_1,i_2)$ to residential site $x=(x_1,x_2)$. $\Omega^a(i)$ is the solid angle of car flow noise radiating from residential site $i=(i_1,i_2)$ and is assumed to be 2π. Furthermore, $A_{\mathrm{com}}^a(i,x)$ is the combined attenuation index of car flow noise from site $i=(i_1,i_2)$ to site $x=(x_1,x_2)$. Finally, θ_2 represents the social cost per unit noise

$$ne_x^a(v_{ij}) = \theta_2 \cdot \left[L_W^a \cdot v_{ij} - 20 \log \frac{\sqrt{(i_1-x_1)^2 + (i_2-x_2)^2}}{1m} + \mathrm{DI}_\theta^a(i,x) - 10 \log \frac{\Omega^a(i)}{4\pi} - 11 - A_{\mathrm{com}}^a(i,x) \right] \tag{12}$$

This study integrates the pricing of air pollution, noise, as well as congestion on surface streets into the total generalized travel cost function of an individual commuting household on an artificial link from site $i=(i_1,i_2)$ to site $j=(j_1,j_2)$, which is formulated as Eq. (13). This study assumes that the affected areas of air pollutants and noise generated from a residential site extend 3 km downwind and cover an approximately round area with a radius of 3 km. Therefore, in Eq. (13), B_{ij}^{ae} and B_{ij}^{ne}, respectively, denote the sets of residential sites affected by air pollutants and noise induced by the car flows of commuting households on the artificial link from site $i=(i_1,i_2)$ to site $j=(j_1,j_2)$. The third and fourth components of the right-hand side of Eq. (13), respectively, represent the marginal-cost burdens of air pollution and noise created in additional households

$$tc_{ij}^{sur}(v_{ij}) = c_{ij}(v_{ij}) + v_{ij} \cdot \frac{dc_{ij}(v_{ij})}{dv_{ij}} + v_{ij} \cdot \frac{d\left[\sum_{x \in B_{ij}^{ae}} ae_x(v_{ij})\right]}{dv_{ij}} + v_{ij} \cdot \frac{d\left[\sum_{x \in B_{ij}^{ne}} ne_x^a(v_{ij})\right]}{dv_{ij}} \quad \forall (i,j) \in F \tag{13}$$

This study constructs a transportation external cost pricing and household mode/route choice model, shown as Eqs. (14) and (15). Eq. (14) is the objective function for minimizing the total generalized travel costs of commuting households. Set SS^v in Eq. (15) represents the solution set of decision variables and comprises Eqs. (5)–(10)

$$\min TC_2 = \sum_{(i,j)\in F} \int_0^{v_{ij}} tc_{ij}^{sur}(v_{ij}) dv_{ij} + \sum_{s \in S} \int_0^{h_a^s} t_a^s(h_a^s) dh_a^s + \sum_{r \in S^t} \int_0^{h_b^r} t_b^r(h_a^s, h_b^r) dh_b^r \tag{14}$$

$$\text{subject to } v_{ij} \in \mathrm{SS}^v \quad \forall (i,j) \in F \tag{15}$$

This study further compares the results of the two models constructed here for estimating the benefits due to transportation external cost pricing in terms of the generalized travel cost saving and external cost reductions of air pollution and noise. The aggregated benefit after the implementation of transportation external cost pricing and taxation is derived as Eq. (16)

$$BF(v_{ij}^1, v_{ij}^2) = \sum_{(i,j)\in F} [v_{ij}^1 \cdot c_{ij}(v_{ij}^1) - v_{ij}^2 \cdot c_{ij}(v_{ij}^2)] + \sum_{s \in S \cup S^t} [h1_a^s \cdot t_a^s(h1_a^s) - h2_a^s \cdot t_a^s(h2_a^s)] + \sum_{(i,j)\in F} \sum_{x \in B} [ae_x(v_{ij}^1) - ae_x(v_{ij}^2)] + \sum_{(i,j)\in F} \sum_{x \in B} [ne_x(v_{ij}^1) - ne_x(v_{ij}^2)] \tag{16}$$

where v_{ij}^1 and v_{ij}^2 denote the car flows of commuting households on an artificial link on surface streets from site $i=(i_1,i_2)$ to site $j=(j_1,j_2)$, respectively, in the household mode/route choice model both with and without considering the transportation external cost pricing, while $h1_a^s$ and $h2_a^s$ represent the car flows of commuting households transferring at rail transit station s, respectively, in the above two models.

Household Mode/Route Choice Model Considering Transit Fare Reductions

In the second-level programming model, this study establishes a household mode/route choice model that considers transit fare reductions, with the aim of minimizing the generalized travel costs of individual households and with the constraint of achieving environmental improvements equivalent to those achieved by the strategy of transportation external cost pricing and taxation. The proposed idea is based on the following reasons. First, the pricing of transportation external costs is both difficult to determine and hard for citizens to realize. Additionally, the strategy of transportation external cost pricing is treated as punishment for ill behavior and is not welcomed by citizens. This study thus proposes a method of reducing transit fares to achieve equivalent environmental improvement benefits to the strategy of transportation external cost pricing. Transit fares are more transparent to citizens. However, the question of who will pay for fare reductions is also significant. To be fair, fair reductions might be implemented by the government levying a fuel tax on car users and then subsidizing transit operators. Levying a fuel tax offers a practical way to internalize some transportation externalities based on the principle of user charge. Furthermore, if citizens know that some fuel tax revenues are used to reduce transit fares,

J. Urban Plann. Dev. 2010.136:339-348.

their complaints will be reduced. The idea and results proposed in this study can also provide a reference to authorities for designing environmental improvement strategies.

The decision variables used in the second-level model include car flow of commuting households v_{ij} on each artificial link on surface streets and the transit fare p_a^s on rail transit line section a corresponding to initial station s. Herein, the transit fare p_a^s is extracted from the constant parameter $t0_a^s$, which was defined as the weighted sum of onboard time and fare in Eqs. (2) and (3), for rail transit line section a. The generalized travel cost functions on rail transit line sections for nontransferring stations and transferring stations, respectively, are reformulated as Eqs. (17) and (18). Meanwhile, $t0_a'^s$ and $t0_b'^r$ denote the generalized travel costs of onboard time on rail transit line sections for nontransferring stations and transferring stations, respectively.

$$t_a'^s(h_a^s,p_a^s) = t0_a'^s + p_a^s + \alpha(\beta \cdot h_a^s/H_a^s)^\rho \quad \forall\, a \in (A^s \cup T^s), \quad s \in S \tag{17}$$

$$t_b'^r(h_a^s,h_b^r,p_a^s) = t0_b'^r + p_a^s + \alpha\left[\beta\left(h_b^r + \sum_{a\in T_r, s\in W^t} h_a^s\right)/H_b^r\right]^\rho \quad \forall\, b \in A^t, \quad r \in S^t \tag{18}$$

Furthermore, this study compares the results of the household mode/route choice model with and without considering transit fare reductions. The aggregated benefit after the implementation of transit fare reductions is then formulated as Eq. (19) in terms of the generalized travel cost saving and external cost reductions associated with air pollution and noise

$$\begin{aligned} BF(v_{ij}^1,v_{ij}^3) = &\sum_{(i,j)\in F}[v_{ij}^1 \cdot c_{ij}(v_{ij}^1) - v_{ij}^3 \cdot c_{ij}(v_{ij}^3)] \\ &+ \sum_{s\in S\cup S^t}[h1_a^s \cdot t_a^s(h1_a^s) - h3_a^s \cdot t_a'^s(h3_a^s,p_a^s)] \\ &+ \sum_{(i,j)\in F}\sum_{x\in B}[ae_x(v_{ij}^1) - ae_x(v_{ij}^3)] \\ &+ \sum_{(i,j)\in F}\sum_{x\in B}[ne_x(v_{ij}^1) - ne_x(v_{ij}^3)] \end{aligned} \tag{19}$$

where v_{ij}^3 denotes the car flow of commuting households on an artificial link on surface streets from site $i=(i_1,i_2)$ to site $j=(j_1,j_2)$ in the household mode and route choice model considering transit fare reductions and $h3_a^s$ represents the park-and-ride car flow at rail transit station s, which is the initial station of rail transit line section a, in the household mode/route choice model considering transit fare reductions.

According to the above derivations, this study constructs a household mode/route choice model that considers transit fare reductions as Eqs. (20)–(22). Eq. (20) is the objective function which minimizes the generalized travel cost of individual commuting household. Eq. (21) is the same as Eq. (15). Meanwhile, Eq. (22) demonstrates that the aggregated benefit due to the implementation of transportation external cost pricing and taxation equals that of transit fare reductions

$$\begin{aligned} \min_{v_{ij},h_a^s,h_b^r,p_a^s} TC_3 = &\sum_{(i,j)\in F}\int_0^{v_{ij}} c_{ij}(v_{ij})dv_{ij} + \sum_{s\in S}\int_0^{h_a^s} t_a'^s(h_a^s,p_a^s)dh_a^s \\ &+ \sum_{r\in S^t}\int_0^{h_b^r} t_b'^r(h_a^s,h_b^r,p_a^s)dh_b^r \end{aligned} \tag{20}$$

$$\text{subject to} \quad v_{ij} \in \mathrm{SS}^v \quad \forall\,(i,j) \in F \tag{21}$$

$$BF(v_{ij}^1,v_{ij}^2) = BF(v_{ij}^1,v_{ij}^3) \tag{22}$$

Problem-Solving Procedure

To facilitate problem solving, this study applies the Lagrangian multiplier to relax the constraints of the three models and rewrites them as three Lagrangian functions, L_1, L_2, and L_3, and their corresponding Lagrangian multipliers, μ_m^r, μ_O^r, and μ_f^r. The Karush-Kuhn-Tucker optimality conditions are then derived for each Lagrangian function to determine the solutions of the decision variables. The solution steps involved in applying the Newton-Raphson's method for the models constructed here are clarified as follows.

Step 1. Set $k=0$. Determine initial values for the decision variables and Lagrangian multipliers. Set the maximal number of iterations $K=120$.

Step 2. Generate Jacobian matrices associated with the three sets of nonlinear simultaneous equations in the kth iteration.

Step 3. The increased (or decreased) values for the decision variables and Lagrangian multipliers of the three minimization problems are calculated during the kth iteration.

Step 4. Design a safeguard process to prevent divergent solutions. The variations between iterations may occasionally cause divergent solutions in cases where current approximate solutions are overshot. The safeguard process attempts to smoothly adjust variations eventuating from Step 3 and to induce search directions toward an equilibrium. This step restricts the percentage of variations in the kth iteration values of all decision variables and Lagrangian multipliers from exceeding 20% of the $k-1$th iteration values.

Step 5. Approximate numerical solutions for the $(k+1)$th iteration. Set $k=k+1$.

Step 6. If current solutions for the three minimization problems satisfy convergent conditions, stop the problem solving procedure and output the results. Otherwise, go to Step 7. The convergent conditions are satisfied and equilibrium solutions are obtained when the percentage variation in the value of each iteration for each decision variable is below 10%.

Step 7. If the number of iterations reaches maximum, go to Step 8. Otherwise, go to Step 2.

Step 8. Design a flow conservation inspection process to ensure that the constraints are satisfied. If not all constraints are satisfied, this study sequentially adjusts the corresponding car flows of commuting households for each unsatisfied constraint. Finally, the results are outputted.

Example

This study adopts the Taipei metropolitan area covered by the Taipei Mass Transit System, which is shown as Fig. 1, to demon-

J. Urban Plann. Dev. 2010.136:339-348.

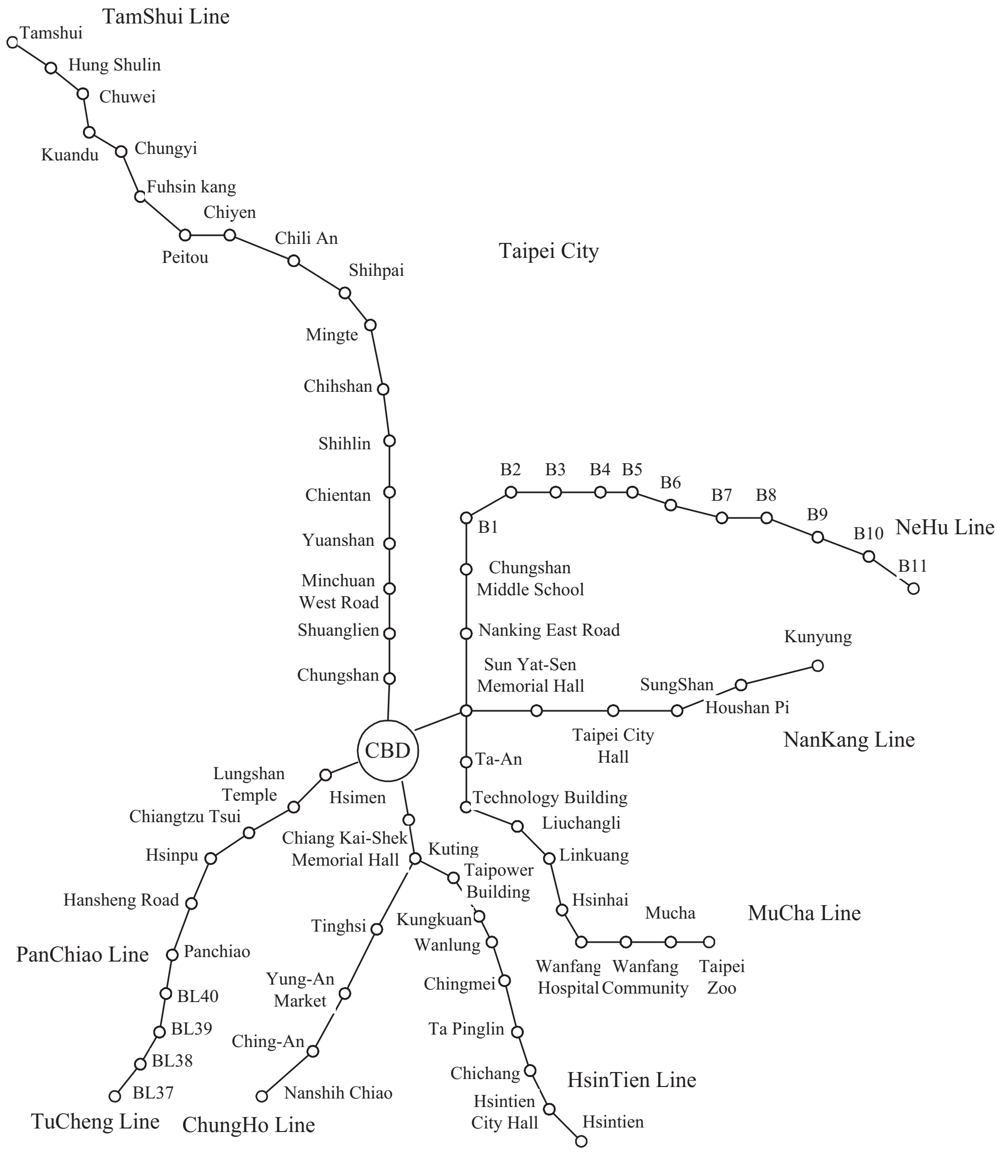

Fig. 1. Diagram of study area

strate the feasibility of applying the proposed models. To reduce the problem scale and facilitate problem solving procedures, transit stations with spacings of less than 1 km are consolidated and the rail transit networks are simplified. The study area is represented by a graph with 214 nodes (residential sites) and 340 artificial links, which connect two adjacent residential sites. In terms of generalized travel cost function on an artificial link, the range of C_{ij}, i.e., the capacity of artificial link from site $i=(i_1,i_2)$ to site $j=(j_1,j_2)$, is assumed to be [25, 120] (unit: thousands). The heterogeneity of artificial link capacity is simulated by generating random variables with respect to locations of residential sites. The generalized travel cost, c_{ij}^0, which is independent of the car flows of commuting households on the artificial link from site $i=(i_1,i_2)$ to site $j=(j_1,j_2)$ is converted from the travel time using the value of time. The value of c_{ij}^0 is estimated based on the length of the artificial link and the assumed parameters, such as the value of time of NT$7.0/min and the average speed of 35 km/h. Moreover, to facilitate problem solving and convergence, the values of parameters τ and ϖ are assumed to be 0.18 and 4.0, respectively. Regarding generalized travel cost on a transit line section and the external cost functions of air pollution and noise, this study refers to the parameter values in Hsu and Guo (2001, 2005).

Household Mode/Route Choices before and after Transportation External Cost Pricing

This study explored the influences of transportation external cost pricing and taxation on the mode/route choices of commuting households without considering the offline effects of these externalities. These results are shown in Table 1 and reveal that more commuting households are willing to shift to rail transit lines when offline effects of transportation external costs are incorporated. A possible reason for this situation is that external costs of air pollution and noise, induced by car flows passing through each residential site, cumulatively influence other residential sites in the study area. Therefore, the pricing of transportation external costs considering offline effects is higher than that without considering offline effects. More car flows of commuting households travel to transit stations.

Variations in the car flows of commuting households transferring at transit stations before and after transportation external cost pricing are summarized in Table 2. These results indicate that

J. Urban Plann. Dev. 2010.136:339-348.

Table 1. Car Flows Transferring at Transit Stations before and after Transportation External Cost Pricing without Considering Offline Effects (Unit: 1,000 Households)

Line	Station	Before pricing	After pricing	Variation
	Shuanglien	20.90	82.07	61.17
T	Yuanshan	28.96	43.28	14.32
A	Chientan	6.81	103.56	96.75
M	Shihlin	115.65	145.56	29.91
S	Mingte	55.57	85.78	30.21
H	Peitou	59.91	73.80	13.89
U	Fuhsin Kang	62.70	50.92	−11.78
I	Kuandu	37.20	41.16	3.96
	Chuwei	26.49	34.90	8.41
	Hung Shulin	9.73	17.93	8.20
	Tamshui	19.76	19.76	0.00
M	Technology	16.05	16.05	0.00
U	Building			
C	Linkuang	57.63	52.86	−4.77
H	Wanfang Hospital	73.22	60.95	−12.27
A	Taipei Zoo	95.16	70.14	−25.02
N	Chunghsiao Fuhsing	34.49	65.31	30.82
A	Sun Yat-Sen	16.42	53.42	37.00
N	Memorial Hall			
K	Taipei City Hall	88.46	60.26	−28.20
A	SungShan	57.08	43.68	−13.40
N	Kunyung	62.29	53.62	−8.67
G				
C	Tinghsi	37.04	44.46	7.42
H	Yung-An Market	54.77	52.52	−2.25
U	Nanshih Chiao	125.26	86.59	−38.67
N	G H O			
P	Hsimen	20.14	35.86	15.72
A	Lungshan Temple	22.90	23.20	0.30
N	Chiangtzu Tsui	45.11	24.35	−20.76
C	Hansheng Road	20.33	22.36	2.03
H	Panchiao	18.62	19.41	0.79
I	BL40	16.12	22.30	6.18
A	BL38	8.66	13.92	5.26
O	BL37	31.75	30.66	−1.09
H	Chiang Kai-Shek	0.00	22.75	22.75
S	Memorial Hall			
I	Kuting	7.94	26.35	18.41
N	Kungkuan	14.32	32.31	17.99
T	Wanlung	6.35	12.96	6.61
I	Chingmei	23.64	22.98	−0.66
E	Chichang	41.90	45.69	3.79
N	Hsintien	48.48	36.35	−12.13
N	Chungshan Middle	8.95	10.85	1.90
E	School			
H	B2	205.72	76.83	−128.89
U	B3	126.58	106.17	−20.41
	B5	50.20	52.86	2.66
	B7	53.72	52.59	−1.13
	B9	58.59	61.50	2.91
	B11	47.39	47.49	0.10

Table 2. Car Flows Transferring at Transit Stations before and after Transportation External Cost Pricing with Considering Offline Effects (Unit: 1,000 Households)

Line	Station	Before pricing	After pricing	Variation
	Shuanglien	20.90	35.97	15.07
T	Yuanshan	28.96	47.88	18.92
A	Chientan	6.81	58.17	51.36
M	Shihlin	115.65	96.15	−19.50
S	Mingte	55.57	92.51	36.94
H	Peitou	59.91	80.89	20.98
U	Fuhsin Kang	62.70	54.67	−8.03
I	Kuandu	37.20	40.75	3.55
	Chuwei	26.49	35.21	8.72
	Hung Shulin	9.73	18.55	8.82
	Tamshui	19.76	19.76	0.00
M	Technology	16.05	16.05	0.00
U	Building			
C	Linkuang	57.63	51.64	−5.99
H	Wanfang Hospital	73.22	49.72	−23.50
A	Taipei Zoo	95.16	97.07	1.91
N	Chunghsiao Fuhsing	34.49	34.82	0.33
A	Sun Yat-Sen	16.42	23.46	7.04
N	Memorial Hall			
K	Taipei City Hall	88.46	68.46	−20.00
A	SungShan	57.08	59.19	2.11
N	Kunyung	62.29	58.66	−3.63
G				
C	Tinghsi	37.04	29.45	−7.58
H	Yung-An Market	54.77	53.10	−1.67
U	Nanshih Chiao	125.26	106.17	−19.09
N	G H O			
P	Hsimen	20.14	27.82	7.68
A	Lungshan Temple	22.90	27.29	4.39
N	Chiangtzu Tsui	45.11	45.97	0.86
C	Hansheng Road	20.33	20.33	0.00
H	Panchiao	18.62	24.74	6.12
I	BL40	16.12	19.94	3.82
A	BL38	8.66	12.27	3.61
O	BL37	31.75	42.05	10.3
H	Chiang Kai-Shek	0.00	16.43	16.43
S	Memorial Hall			
I	Kuting	7.94	21.72	13.78
N	Kungkuan	14.32	21.18	6.86
T	Wanlung	6.35	7.54	1.19
I	Chingmei	23.64	18.57	−5.07
E	Chichang	41.90	58.31	16.41
N	Hsintien	48.48	49.46	0.98
N	Chungshan Middle	8.95	9.14	0.19
E	School			
H	B2	205.72	193.21	−12.51
U	B3	126.58	125.19	−1.39
	B5	50.20	60.26	10.06
	B7	53.72	50.05	−3.67
	B9	58.59	52.68	−5.91
	B11	47.39	69.14	21.75

J. Urban Plann. Dev. 2010.136:339-348.

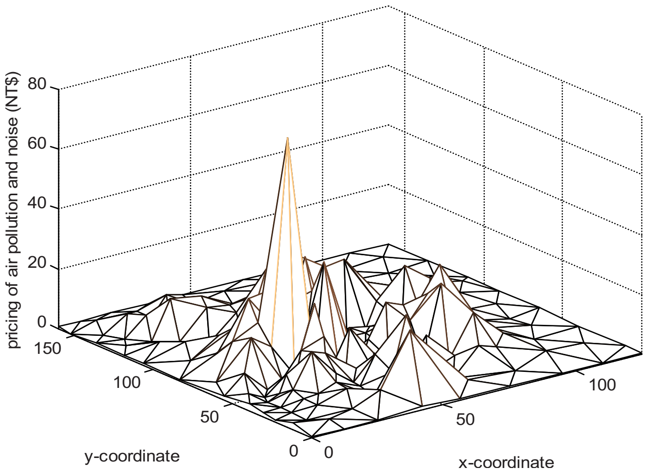

Fig. 2. Pricing of air pollution and noise—results of households' mode/route choice model with considering transportation external cost pricing (unit: NT$)

commuting households attracted to the Tamshui, Panchiao, and Hsintien Lines will increase after the implementation of transportation external cost pricing and taxation. Regarding the competition among rail transit lines, some commuting households originally transferring to the Chungho Line will shift to stations along the Hsintien and Panchiao Lines. Comparing Tables 1 and 2 reveals that due to offline effects of transportation external costs, car flows of commuting households transferring to transit stations increase with total generalized travel costs on artificial links via surface streets. However, the increases are not significant.

Distributions of Transportation External Cost Pricing

Fig. 2 illustrates the distribution of air pollution and noise pricing in the study area after the implementation of transportation external cost pricing and taxation. The results indicate that situations involving high air pollution and noise pricing mainly occur in areas near the CBD and around the transit stations along the Chungho, Hsintien, and Mucha Lines. Finally, the results shown in Fig. 2 also provide a reference for future studies in designing the pricing system of transportation external costs.

For estimating the benefits of environmental improvement, this study assumes the benefits per household per day, θ_1 and θ_2, which resulted from 1,000-g reductions of cumulative air pollution and 1,000-dB(A) reductions of cumulative noise, respectively, to be US$$1.834\times10^{-5}$ and US$$0.912\times10^{-5}$ by referring to Aunan et al. (1998) and Otterstrom (1995). Furthermore, according to Eq. (16), the total environmental improvements due to transportation external cost pricing and taxation in the study area are estimated to be NT$1,574,472/day. Therein, the total generalized travel cost saving is NT$301,867/day, and the savings from reductions in air and noise pollution are NT$1,135,646/day and NT$136,959/day, respectively.

Result Analysis after Considering Transit Fare Reductions

Table 3 summarizes variations in both car flows of commuting households transferring at transit stations and fares on transit line sections before and after transit fare reductions. Initially, transit fares are expected to display an overall reduction to achieve the benefits of environmental improvement compared with the strat-

Table 3. Car Flows and Fares at Transit Stations before and after Transit Fare Reductions (Unit: 1,000 Households; NT$)

Line	Station	Before	After	Variation
	Shuanglien	(20.90/20)	(77.26/28.3)	(56.36/8.3)
T	Yuanshan	(28.96/20)	(67.03/20.4)	(38.07/0.4)
A	Chientan	(6.81/20)	(188.26/18.9)	(181.45/−1.1)
M	Shihlin	(115.65/25)	(131.24/23.5)	(15.59/−1.5)
S	Mingte	(55.57/25)	(88.36/21.8)	(32.79/−3.2)
H	Peitou	(59.91/30)	(57.87/23.4)	(−2.04/−6.6)
U	Fuhsin Kang	(62.70/35)	(42.06/31.12)	(−20.64/−3.88)
I	Kuandu	(37.20/40)	(31.20/36.58)	(−6.00/−3.42)
	Chuwei	(26.49/40)	(19.85/36.47)	(−6.64/−3.53)
	Hung Shulin	(9.73/45)	(7.77/41.87)	(−1.96/−3.13)
	Tamshui	(19.76/50)	(17.64/46.57)	(−2.12/−3.43)
M	Technology Building	(16.05/20)	(8.61/31.23)	(−7.44/11.23)
U				
C	Linkuang	(57.63/20)	(57.55/4.18)	(−0.08/−15.82)
H	Wanfang Hospital	(73.22/25)	(57.36/0.00)	(−15.86/−25.0)
A	Taipei Zoo	(95.16/30)	(79.63/7.76)	(−15.53/−22.24)
N	Chunghsiao Fuhsing	(34.49/20)	(99.61/0.00)	(65.12/−20.0)
A	Sun Yat-Sen			
N	Memorial Hall	(16.42/25)	(66.37/0.00)	(49.95/−25.0)
K	Taipei City Hall	(88.46/25)	(65.00/0.00)	(−23.46/−25.0)
A	SungShan	(57.08/30)	(44.68/5.76)	(−12.4/−24.24)
N	Kunyung	(62.29/30)	(33.86/5.88)	(−28.43/−24.12)
G				
C	Tinghsi	(37.04/20)	(61.12/25.03)	(24.08/5.03)
H	Yung-An Market	(54.77/25)	(54.79/28.80)	(0.02/3.80)
U	Nanshih Chiao	(125.26/25)	(89.38/15.10)	(−35.88/−9.9)
N	G H O			
P	Hsimen	(20.14/20)	(86.46/13.32)	(66.32/-6.68)
A	Lungshan Temple	(22.90/20)	(48.99/12.12)	(26.09/-7.88)
N	Chiangtzu Tsui	(45.11/25)	(35.26/29.70)	(−9.85/4.7)
C	Hansheng Road	(20.33/25)	(32.64/37.22)	(12.31/12.22)
H	Panchiao	(18.62/30)	(11.33/45.28)	(−7.29/15.28)
I	BL40	(16.12/30)	(15.05/44.26)	(−1.07/14.26)
A	BL38	(8.66/35)	(7.01/24.25)	(−1.65/−10.75)
O	BL37	(31.75/35)	(22.01/22.63)	(−9.74/−12.37)
H	Chiang Kai-Shek	(0.00/20)	(30.93/37.59)	(30.93/17.59)
S	Memorial Hall			
I	Kuting	(7.94/20)	(15.93/26.10)	(7.99/6.1)
N	Kungkuan	(14.32/20)	(13.89/10.73)	(−0.43/−9.27)
T	Wanlung	(6.35/25)	(7.50/4.69)	(1.15/−20.31)
I	Chingmei	(23.64/25)	(35.79/0.00)	(12.15/−25.0)
E	Chichang	(41.90/30)	(54.76/24.33)	(12.86/−5.67)
N	Hsintien	(48.48/30)	(33.24/6.93)	(−15.24/−23.07)
N	Chungshan Middle	(8.95/20)	(3.68/3.70)	(−5.27/−16.3)
E	School			
H	B2	(205.72/20)	(228.03/18.11)	(22.31/−1.89)
U	B3	(126.58/25)	(21.04/22.43)	(−105.54/−2.57)
	B5	(50.20/25)	(3.40/15.11)	(−46.80/−9.89)
	B7	(53.72/30)	(18.26/26.76)	(−35.46/−3.24)
	B9	(58.59/30)	(15.12/26.72)	(−43.47/−3.28)
	B11	(47.39/35)	(30.86/30.50)	(−16.53/−4.5)

J. Urban Plann. Dev. 2010.136:339-348.

egy of transportation external cost pricing. However, the results in Table 3 illustrate increased transit fares from some stations near the CBD, such as Shuanglien and Yuanshan on the Tamshui Line, Technology Building on the Mucha Line, Chiang Kai-Shek Memorial Hall, and Kuting on the Hsintien Line. This situation may occur because congestion on artificial links via surface streets intensifies with closeness to the CBD; therefore, fares from transit stations near the CBD rise sufficiently to restrain overflow of transferring commuting households. Namely, the degree of transit fare reduction increases with increasing distance from the boarding station to the CBD, thus attracting commuting households to transfer at transit stations near their residential sites. These situations occur at transit stations such as Wanfang Hospital and Taipei Zoo on the Mucha Line, and B38 and B37 on the Panchiao Line. Regarding car flow variations, commuting households transferring at some transit stations increase after transit fare reductions; however, numbers of transferring commuting households decrease at certain transit stations. This situation may occur due to the waiting time at transit stations; thus some commuting households prefer to drive by car via surface streets to the CBD for minimizing their generalized travel costs.

Conclusions and Suggestions

This study from the long-term planning perspective applies a continuum approximation method to develop static and deterministic models for exploring commuter mode/route choice behavior. Two policies for encouraging rail transit system; i.e., internalized transportation external costs and transit fare reductions, are proposed to analyze the influences on commuter mode/route choice behavior. Two major assumptions are assumed in this study. First, this study applies the continuum approximation method to assume the study area to be a dense network represented by a two-dimensional coordinate system. Second, this study assumes that each household uses a single car to commute and that the workplaces of household members are highly concentrated in the CBD. That is, this study explores patterns of travel from many origins to a single destination (CBD). The main results of the models are (1) the variation in the patronage of each transit station before and after transportation external cost pricing and transit fare reductions and (2) fare reductions at each transit station. The results related to fare reductions at each station can provide a guide for implementing a fare reduction scheme and thus can not only efficiently attract more passengers but can also effectively reduce externalities. Furthermore, results related to the variation in patronage can reveal which transit stations attract more patronage after transportation external cost pricing or transit fare reductions. The analytical results can also assist transit operators in planning facility capacity, adjusting schedules, and determining transit fares.

However, the proposed models have some limitations in potential applications for analyzing real-world issues. In respect to the applications of case studies, future studies should explore the influences of different temporal patterns of trip generation on the pricing of transportation externalities. Furthermore, this study adopts a metropolitan example and assumes that workplaces are highly concentrated in the CBD to simplify the model formulation. Future studies should extend to a multicentric urban configuration involving multiple mode/route alternatives to investigate the modal split for all available modes and optimize public transportation network fare structure. Since real-world situations are too complicated for model construction, future studies exploring real-world issues can select several major work centers to analyze commuter mode/route choice behavior and the influences of transit fare reductions by applying the model proposed here. The results of multiple travel patterns involving many origins to a single destination can then be combined. Third, to implement practical studies for operating purposes, future studies should apply actual road networks to indicate link flows. To explore the spatial effects of air pollution and noise, future studies could also apply geographic information system technology to obtain precise data from various locations. Fourth, since traffic congestion and the resultant noise and air pollution are correlated, adding them together as independent terms for the total generalized travel cost function might overestimate the total external costs. Future studies can further consider the correlated effects among external costs. Finally, commuting households may change their residence after the implementation of transportation external cost pricing. Future studies can construct an interaction model with mode/route choices and residence choices to explore household migration behavior before and after transportation external cost pricing.

Acknowledgments

The writers would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No. NSC91-2415-H-009-004.

References

Benjamin, J., Kurauchi, S., Morikawa, T., Polydoropoulou, A., Sasaki, K., and Ben-Akiva, M. (1998). "Forecasting paratransit ridership using discrete choice models with explicit consideration of availability." *Transp. Res. Rec.*, 1618, 60–65.

Daganzo, C. F., and Garcia, R. C. (2000). "A Pareto improving strategy for the time-dependent morning commute problem." *Transp. Sci.*, 34(3), 303–311.

De Borger, B., and Wouters, S. (1998). "Transport externalities and optimal pricing and supply decisions in urban transportation: A simulation analysis for Belgium." *Reg. Sci. Urban Econ.*, 28, 163–197.

Hsu, C. I., and Guo, S. P. (1999). "Access mode combinations for intercity transportation terminals in a metropolitan area." *Journal of the Eastern Asia Society for Transportation Studies*, 3(2), 333–348.

Hsu, C. I., and Guo, S. P. (2001). "Household-mode choice and residential-rent distribution in a metropolitan area with surface road and rail transit networks." *Envir. Plan. A*, 33(9), 1547–1575.

Hsu, C. I., and Guo, S. P. (2005). "Externality reductions in residential areas due to rail transit networks." *Ann. Reg. Sci.*, 38, 1–12.

Johansson, O. (1997). "Optimal road-pricing: Simultaneous treatment of time losses, increased fuel consumption and emissions." *Transp. Res. D*, 2(2), 77–87.

Koppelman, F. S., Bhat, C. R., and Schofer, J. L. (1993). "Market-research evaluation of actions to reduce suburban traffic congestion—Commuter travel behavior and response to demand reduction actions." *Transp. Res., Part A: Policy Pract.*, 27(5), 383–393.

Lam, W. H. K., et al. (1999). "A stochastic user equilibrium assignment model for congested transit networks." *Transp. Res., Part B: Methodol.*, 33, 351–368.

Ling, J. H. (1998). "Transit fare differentials: A theoretical analysis." *J. Adv. Transp.*, 32(3), 297–314.

Lo, H. K., and Hickman, M. D. (1997). "Toward an evaluation framework for road pricing." *J. Transp. Eng.*, 123(4), 316–324.

Lo, H. K., Yip, C. W., and Wan, K. H. (2003). "Modeling transfer and non-linear fare structure in multi-modal network." *Transp. Res., Part B: Methodol.*, 37, 149–170.

Lozano, A., and Storchi, G. (2001). "Shortest viable path algorithm in

J. Urban Plann. Dev. 2010.136:339-348.

multimodal networks." *Transp. Res., Part A: Policy Pract.*, 35, 225–241.

Mayeres, I. (2000). "The efficiency effects of transport policies in the presence of externalities and distortionary taxes." *J. Transp. Econ. Policy*, 34(2), 233–260.

Mayeres, I., Ochelen, S., and Proost, S. (1996). "The marginal external costs of urban transport." *Transp. Res. D*, 1(2), 111–130.

Romilly, P. (1999). "Substitution of bus for car travel in urban Britain: An economic evaluation of bus and car exhaust emission and other costs." *Transp. Res. D*, 4, 109–125.

Sheffi, Y. (1985). *Urban transportation networks: Equilibrium analysis with mathematical programming methods*, Prentice-Hall, Englewood Cliffs, N.J.

Taylor, S. R. W., and Carter, D. W. (1998). "Maryland mass transit administration fare simplification-effects on ridership and revenue." *Transp. Res. Rec.*, 1618, 125–130.

Tsamboulas, D., and Mikroudis, G. (2000). "EFECT—Evaluation framework of environmental impacts and costs of transport initiatives." *Transp. Res. D*, 5, 283–303.

Verhoef, E. T. (2000). "The implementation of marginal external cost pricing in road transport." *Papers in Regional Science*, 79, 307–332.

Yang, H., and Bell, M. G. H. (1997). "Traffic restraint, road pricing and network equilibrium." *Transp. Res., Part B: Methodol.*, 31(4), 303–314.

Yang, H., and Huang, H. J. (1997). "Analysis of the time-varying pricing of a bottleneck with elastic demand using optimal control theory." *Transp. Res., Part B: Methodol.*, 31(6), 425–440.

Yang, H., and Huang, H. J. (1998). "Principle of marginal-cost pricing: How does it work in a general road network." *Transp. Res., Part A: Policy Pract.*, 32(1), 45–54.

J. Urban Plann. Dev. 2010.136:339-348.