Eco Oriented and Multilevel Programming Problem Based Urban Multi-Mode Passenger Transportation System Pricing Policy Optimization

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1. Introduction

During the past decades, transport emission, energy consumption and traffic congestion, transportation facilities land use lack become the crucial problems of many cities, especially with the rapid development of urbanization in developing countries. To solve these problems, there has been an increased interested in research of eco-transportation planning method1), and to change the passenger transport mode share, develop the public transportation system, as well as to control the resorting to private cars has been considered one of the most effective methods2). On the other hand, mode split result of the urban passenger transportation system is directly conducted by user's travel mode choosing behavior, and their mode choosing was strongly influenced by the travel cost3).

Traditional pricing optimization studies are usually concentrated on road pricing on the networks. Furthermore, they only focus on the road tolling for automobile in order to alleviate traffic congestion, public transportation system usually can not be considered, the relationship between the eco-factors and the congestions can not be surveyed either. And on the implementation, not only skill difficulties, but also the uncertain of social acceptance un-acceptation are run across at the same time. Studies on energy and environmental reduction usually have focused only on the supplying side regardless the users, and they also did not consider changes in travel demand that could occur due to changes in transport service prices resulting from changes in costs of services. Furthermore, they usually do not consider the cost of travel time and congestion; in fact, there could be significant difference in travel time and congestion level between subway and traditional vehicle modes, and the flow variations on the network could also influence the emission factors. Eco city designing principles have been bought forward in the studies of Richard Register, Roseland M. etc. but they did not give the specific application methods in urban transportation system. This paper aims at determining an optimal mode share scheme for the urban passenger transportation system, which meets the eco-constrains in emission, energy consumption, land occupation limitation, and the government investment limitation at the lowest social cost. And at the next step, in order to change the user's mode choosing behavior, an optimal pricing policy for different traffic modes is achieved to meet the former mode split target, at the least general cost on the networks.

2. Methodology

Stackelberg game theory is used as the modeling approach because there are quantitative decision makers4) 5). Moreover, they are in different layers in the whole decision making system. The upper layer has guide rights just like the government or transportation system management agencies, who can make the decision of what kind of mode sharing result should be achieved under the eco-constrains, This mode sharing result is just the selection range for the under lower layer's. And the lower layer, the users of transportation system, can also implement his decision making right under its selection range to choose the travel mode they prefer to, according to the general travel cost. Obviously, they consider different things during their decision-making process. Furthermore, the belt of the two layers is pricing policy of different modes, because the pricing scheme is made by the upper layer, and accepted by the lower layer. As result, this transaction would be dealing with in different modeling sections as followings.

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2.1 Optimal eco-oriented passenger transportation mode share

Different mode has definitely different pollution contribution and energy consumption. Thus we can calculate the primal mode split under the consideration of environment disutility of different traffic mode. Meanwhile, different traffic mode has different land consumption demand, and costs different levels of construction fee. All these four aforementioned aspects should be the main factors considered by the government when they plan an optimal eco-oriented mode share in the planning year.

The objective of the model will work as decision making assistance for the government in determining an optimal mode share scheme of the urban passenger transportation system, which meets the eco-constrains in emission, energy consumption, land occupation and the government investment, at the lowest social cost. Total cost includes pollution treatment fee for different emission, e.g., CO_x , NO_x , SO_x and so on, energy price for different fuel mix consumption, e.g., gasoline, diesel, LPG, CNG, electricity and so on, the cost of land occupied by the facilities for different traffic mode, and construction fee for different traffic mode. And they all calculated by primary unite. The objective function can be expressed as:

$$Min\sum_i\sum_a\sum_k P^{G*}_{ki}\left(x^a_{ki}\frac{\alpha_i e^{\beta_i \overline{V^a_{ki}}}}{\gamma_i \overline{V^a_{ki}}}\right)+P^{E*}_{ki}\left(x^a_{ki}\frac{\lambda_i e^{\xi_i \overline{V^a_{ki}}}}{\psi_i \overline{V^a_{ki}}}\right)+P^{L*}_i(x_i c_i)+x_i d_i \tag{1}$$

Where $P^{G*}_{ki}\left(x^a_{ki}\frac{\alpha_i e^{\beta_i \overline{V^a_{ki}}}}{\gamma_i \overline{V^a_{ki}}}\right)$ is the costs of pollution treatment for different emission, P^G_{ki} is the cost of pollution treatment per capita kilometer for mode i emission type k , x^a_{ki} is capita kilometer of mode i emission type k on link a , $\frac{\alpha_i e^{\beta_i \overline{V^a_{ki}}}}{\gamma_i \overline{V^a_{ki}}}$ is emission factor for capita kilometer of mode i emission type k , it is related to the average speed $\overline{V^a_{ki}}$ on link a . α_i , β_i , γ_i are parameters for emission factor of mode i , and the emission factor for every mode is calculated under the consideration of average vehicle sharing coefficient of this mode.

Similarly, $P^{E*}_{ki}\left(x^a_{ki}\frac{\lambda_i e^{\xi_i \overline{V^a_{ki}}}}{\psi_i \overline{V^a_{ki}}}\right)$ is the costs of energy for different fuel mix consumption, λ_i , ψ_i , ξ_i are parameters for energy consumption factor of mode i . $P^{L*}_i\left(x_i c_i\right)$ is the cost of land occupied by the facilities for different traffic mode, x_i is capita kilometer of mode i , c_i is land use occupy rate for capita kilometer of mode i . $x_i d_i$ is construction fee for different traffic mode, x_i is also capita kilometer of mode i , d_i is construction fee rate for capita kilometer of mode i .

Emission constrains: Total passenger transport emission of type k in the planning year must be less than or equal to the emission at upper limit, G_k , which is decided by the environmental consideration or by national/local environmental regulations.

$$\sum_i\sum_a x^a_{ki}\frac{\alpha_i e^{\beta_i \overline{V^a_{ki}}}}{\gamma_i \overline{V^a_{ki}}}\le G_k,\overline{V^a_{ki}}=\frac{VMT^a_{ki}}{VHT^a_{ki}} \tag{2}$$

Where VMT^a_{ki} is vehicle miles traveled on link a of mode i , emission type k , VHT^a_{ki} is vehicle hours traveled on link a of mode i , emission type k . This can be received from the third level of modeling structure, which is introduced in section 2.3 of this paper.

Energy consumption constrains: Similarly, total passenger transport energy consumption of type k in the planning year must be less than or equal to the energy consumption at upper limit E_k, which is decided by the national/local energy consumption planning.

$$\sum_i \sum_a x_{ki}^a \frac{\lambda_i e^{\xi_i \overline{V_{ki}^a}}}{\psi_i \overline{V_{ki}^a}} \le E_k \tag{3}$$

Where $\frac{\lambda_i e^{\xi_i \overline{V_{ki}^a}}}{\psi_i \overline{V_{ki}^a}}$ is energy consumption factor of mode i fuel mix type k, it is also related to the average speed on link a. λ_i, ψ_i, ξ_i are parameters of mode i. Energy consumption factor for every mode is also calculated under the consideration of average vehicle sharing coefficient of this mode.

Land use constrain and investment constrain : Total passenger transport facilities land use and investment of different modes should be less or equal to the uper limit *L* and *I*, which is decided by a specific situation of a given city.

$$\sum_i x_i c_i \le L, \sum_i x_i d_i \le I \tag{4}$$

Other constrains : Total supply of all modes of urban passenger transportation should be equal to the demand forecasting for the planning year D; and supply of mode i should be greater than or equal to the lower limit (S_{iMin}) of passenger turnover quantity must be offered by mode i in the planning year, to avoid the waste of existing equipment and recourses, and be less than or equal to upper limit (S_{iMax}) of passenger turnover quantity can be offered by mode i in the planning year. All of them are with demission of person kilometer.

$$\sum_i x_i = D, S_{iMin} \le x_i \le S_{iMax} \tag{5}$$

2.2 Pricing scheme optimization designing of multi-mode passenger transportation system

Objective function of pricing scheme optimization model is an optimal pricing policy for different traffic mode, at the least general cost on the networks, meeting the mode split target that has been got in the model of optimal eco-oriented passenger transportation mode share. The decision variable is P^*, pricing level of chosen mode. The objective function can be expressed as:

$$Min \sum_n GC\left(P^*TT, P^*D, P^*P, P^*T, P^*R\right) \tag{6}$$

Seven main modes of an ordinary city can be considered in the model, they are: pedestrian (mode1), bicycle (mode2), private car (mode3) (automobile), taxi (mode4), bus (mode5), urban rail transit (mode6), motorcycle (mode7). Since pedestrian and bicycle are not motorization travel modes in the passenger transport system, they are definitely different in terms of travel cost, compared to other modes. Furthermore, it would not be realistic to have an extreme type of urban motorization vehicle mix that allows no pedestrian and bicycles. Therefore, certain minimum stocks could be set for pedestrian and bicycles. Consequently, constrain based on multinomial logit approach concludes only mode3 to mode7.

$$s.t. \begin{cases} P_{in} = \dfrac{x_i}{\sum x_i} = \dfrac{e^{W_{in}}}{\sum\limits_{j \in A_n} e^{W_{jn}}} \\ U_{in} = W_{in} + \varepsilon_{in} \\ \{i = 3,4,5,6,7\} \in A_n \end{cases}$$

(7)

In constrain formulation $P_{in} = \frac{x_i}{\sum x_i} = \frac{e^{W_{in}}}{\sum_{j \in A_n} e^{W_{jn}}}$, the demission of $\sum_i x_i$ is capita kilometer, which reflects the supply ability of transportation system. $\frac{x_i}{\sum x_i}$ means the contribution of every mode to the supply ability. The coefficient of x_i is 1, which means every mode has the same contribution to the supply ability of the passenger transportation system. Here we consider the passenger turnover quantity which is not sensitive to the change of mode split in a macroscopic modeling, regardless there are some actual effects from the mode choose result to the travel distance. That is to say by which mean to satisfy the demand is all the same to the degree of offering transportation supply. This can be better explained in the reality, because in one trip, when the motor mode (including the mode 3 to mode 7) transferred, there will be no change in the trip distance. So in a statistical sense, we can deem the choices of routes are almost the same for every mode. According to this, $\frac{x_i}{\sum x_i}$ should be equal to $P_{in} = \frac{e^{W_{in}}}{\sum_{j \in A_n} e^{W_{jn}}}$.

And where, multinomial logit approach is used to formulate utility functions, for example, for mode 3, utility function is as follows:

$$U_{n3} = W_{n3} + \varepsilon_3 = \theta_1 TT + \theta_2 \left(P^{G*} + P^{GT*} \right)_k D + \theta_3 P^* P + \theta_6 P^* I + \theta_7 P^* R + \varepsilon_3$$

(8)

TT is Travel Time, $\left(P^{G*} + P^{GT*} \right)_k D$ is price of distance, which equals to energy price, P^{G*} plus energy tax price, P^{GT*} by fuel mix type k, $P^* P$ is price of parking, $P^* I$ is price of income, $P^* R$ is price of road toll, $\theta_1 \sim \theta_7$ are parameters.

Ticket price is also constrained to be higher than or equal to the unit basic price for the network:

$$P^* T \geq B_{asic} P^* T$$

(9)

2.3 Joint traffic flow assignment on the network

Classic UE equilibrium based automobile traffic flow assignment model and Uon-UE transit flow assignment method, that means the flow assignment of transit line is according to the transit vehicle departure frequency, are jointly used to obtain traffic flow on every link. Objective function of UE equilibrium can be expressed as:

$$\min_y \sum_a \int_0^{y_a} t_a(y, RP) dy$$

$$s.t. \begin{cases} q_i^{rs} = P_{in} D_t \\ s.t. \ \sum_k f_{\mathrm{k}}^{\mathrm{rs}} = q_i^{rs}, \quad \forall r, s \\ f_{\mathrm{k}}^{\mathrm{rs}} \geq 0, \quad \forall k, r, s \\ \mathrm{y_a} = \sum_r \sum_s \sum_k f_k^{rs} \delta_{a,k}^{rs} \end{cases}$$

(10)

Where y_a is traffic flow on link a, f_k^{rs} is traffic flow on route k. Mean while, we can obtain the average speed $\overline{V_{ki}^a}$ on link a as an output by:

$$\overline{V_{ki}^a} = \frac{VMT_{ki}^a}{VHT_{ki}^a} \tag{11}$$

Where VMT_{ki}^a is vehicle miles traveled on link a of mode i, emission type k, VHT_{ki}^a is vehicle hours traveled on link a of mode i, emission type k.

3. Framework of Multi-Level modeling

Pricing scheme optimization designing of multi-mode passenger transportation system is the first level of the modeling structure, in this part, the government and public functions are combined with the belt of pricing policy because it is set out by managers, meanwhile, it directly influences the mode choice behavior of users.

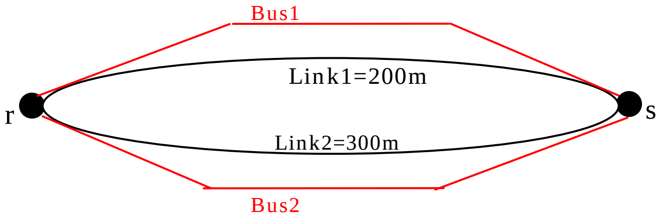
Optimal eco-oriented passenger transportation mode share is the second level, a modeling for government decision making on what kind of mode share scheme should be a target for the pricing policy, so this part is built under the benefit of government consideration. These two parts are main body of multi-level modeling.

Joint traffic flow assignment on the network is a supplemental part for the second level, and it is called as the third level, it is built on behalf of users' consideration. Furthermore, the calculation should begin with this part with the actual data for the actual situation of a city, and there is a loop between the second and third levels. The change of mode share would influence the traffic flow assignment and the flow assignment result would produce new speed on every link, consequently produce new emission factors, and then cause a new optimal mode share scheme. The difference between sequential iterations should gradually decrease before a convergence criterion is satisfied. Algorithm for multi-level modeling is as follows:

Step 1. According to the assignment results of the super net which is based on OD data and existing mode split of present situation of certain city, calculate the initial values for emission factor and energy consumption factor.
Step 2. With emission factor and energy consumption factor, solve the second lever model and receive the initial primal mode split as the new input to the third lever model.
Step 3. With the mode split results of step 2, compute the UE assignment again on the super net and compute new emission factor and energy consumption factor for next loop.
Step 4. Go to step 5 if objective function of the second level is not improved; otherwise repeat from step 2.
Step 5. With the mode split results of step 2 and the assignment results of step 3, solve disaggregate choice mode of lower lever model and get the primal pricing plan.

4. A numerical example

An artificial simple network is used to test the workability of the proposed modeling approach. To simplify, there are only two modes (mode 3 of automobile and mode 5 of bus) and two links in this network as figure 1. And the energy consumption constrains of the second level is omitted, as well as the item of costs of pollution treatment fee in the objective function.



4.1 Calculation Input

In this network, the flowing data is known as input of calculation, and assumption that the flow assignment of bus line is according to the bus departure frequency. Assumption first OD flow between r and s is Q_{rs}^1 equal to 100, and existing mode split is $(Auto:Bus)^1$ equal to 3:2, link performance function is $t=10+0.2y_a^2$, bus lines departure frequency ratio is $f_{bus1}:f_{bus2}=1:3$, emission factor of mode3 and mode5 in CO_2 emission(k=1) is $a_{1,3}=8a_{1,5}=3.3963\frac{e^{0.01456\bar{V}_3}}{10000\bar{V}_3}$, and $G_1, L, I, c_3, c_5, d_3, d_5, P_L, P_E, \theta_i, IP$ came from past actual projects, and OD flow between r and s, $Q_{rs}=120$,and capita kilometer of passenger overturn $D=30$, they are forecast demand of the planning year and the threshold for the ending of the recycle are also been set.

4.2 Calculation Result

The decision variable of first level is pricing scheme for bus ticket and energy tax of gasoline.

- The recycling between the second level and third level got convergence after three times recycle, and the optimization mode split meeting with the eco-constrains of the planning year is $(Auto:Bus)^4=3:3.77.$
- To meet this mode share target, the optimization price policy is got as following:
  - the bus ticket TP =1 unit of money per kilometer,
  - the energy tax DP = 1.3481 unit of money per kilometer,
  - and MIN of GC = 49599

5. Conclusion and future research

Stackelberg game theory based Multi-level modeling has following advantages:

- Different objectives can be analyzed simultaneously during the decision-making process
- Multi-value criteria for transport management and planning section, usually the government, and the users, are more similar to the reality, and the correction between them can be described.
- Modular structure of the modeling achieves a good flexibility for every modular, and makes the whole structure have a nice portability in different specific given city.

More complicated and realistic example would be done in the future research, and the sensitive analysis would be surveyed. And the study has considered only the passenger transport modes and has not included freight transportation options yet.

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