# Multi-modal Optimization of Pricing Policy for Sustainable Urban Passenger Transportation System: A Case Study of Shanghai City

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An optimization problem is developed in this paper to realize the concept of sustainable city, where an optimal mode share scheme for the urban passenger transportation system is determined, which meets the limitations of emission, land use consumption and the constraint of government investment at the lowest SC (social cost) and lowest EC (environmental cost), respectively, for comparison. At the next step, in order to change the user's mode choice behaviour, an optimal pricing policy for both road and transit modes is achieved to meet the optimal mode share scheme given at the former step, at the least GC (generalized cost) on the networks from the passengers' point of view in order to make sure the optimal pricing policy could be accepted as easy as possible. Multilevel programming problem of multi-modal system is used as the modelling approach because there are multiple decision makers. The data of Shanghai city was then used to apply this multi-modal system, where GA (genetic algorithm) was applied for the optimization. Several scenarios for pricing policy of the urban passenger transportation system were designed, and the performances of these pricing schemes are investigated. The results indicate that the mode share is optimized with higher transit share than the current situation, where the emission and congestion on the network are relieved with less government investment, and the EC, GC and SC on the network of most scenarios can be reduced compared to the current situation.

***Key Words:*** *sustainable city, low carbon, pricing policy optimization, multi-modal passenger transportation, modal share*

## 1. BACKGUOUND

Massive urbanization programmes are under way in many parts of the world, often in regions where the available land and resources are limited relative to the size of the population (e.g. the megacities on Chinese mainland). While urbanization is a natural consequence of economic development and industrialization, it does lead to many challenges. Particularly in urban transport system, the transport pollution, traffic congestion, energy consumption and lack of land for traffic infrastructure have become the crucial problems of many cities. These challenges are amplified by the severe problems already faced by the world, including climate changes, limited energy and lack of space of urban development. Since transport is one of most important community support systems, it is importation to develop transportation planning method for sustainable city, to find effective solutions to ensure a sustainable process of urban passenger transport systems, and to carry it out in a sustainable manner.

Eco-city design principles have been highlighted in studies by many researchers, but they do not propose specific methods for applying these principles to urban transportation system. Traditional pricing optimization studies usually concentrate on the effect of road pricing on the road networks. Furthermore, they focus only on the road tolls for automobiles as a means of alleviating traffic congestion. The public transportation system usually is not considered, and neither is the relationship between the eco-factors and congestion. In addition, implementation is affected by the skill of the implementers and the uncertainty of social acceptance.

## 2. METHOD OF SOLUTION

A sustainable city integrates environmental dimensions into the social and economic sectors in order to meet the needs of current generations without compromising those of the future. The most important advantage of a sustainable city is that it follows such a development path that allows for an integral and long-term development without compromising future generations. So the provision of effective urban transport systems as well as adequate financing, sufficient energy and a clean environment for a sustainable city should plan the passenger transport mode share, in some degree develop public transportation systems, and control the desire to use private cars by integrated transport pricing strategies, including the adjustment of public transport fares, charges for car use, and congestion toll (May et al. 2000). The pricing strategic options and the sustainable constrains could vary from study to study although the most common ones are efficiency in the use of resources; environmental protection; improved accessibility; sustainability; with an underlying requirement for financial feasibility (May and Roberts, 1995). This paper aims to find an optimal mode share scheme for urban passenger transportation system that meets the limitations of carbon emission, land consumption, and government investment at the lowest social cost (SC) or environmental cost (EC). This optimal mode share scheme could be used as a suggested mode-split target for an eco-oriented sustainable city. And then, proposes a method for changing the user's mode-choice behaviour by applying an optimal pricing policy to each traffic mode. This method meets the former mode-split target at the lowest general cost on the networks from the passengers' point of view to make them accept new pricing policy easier.

### (1) Modeling structure

Modeling structure could be shown as **Fig.1**.

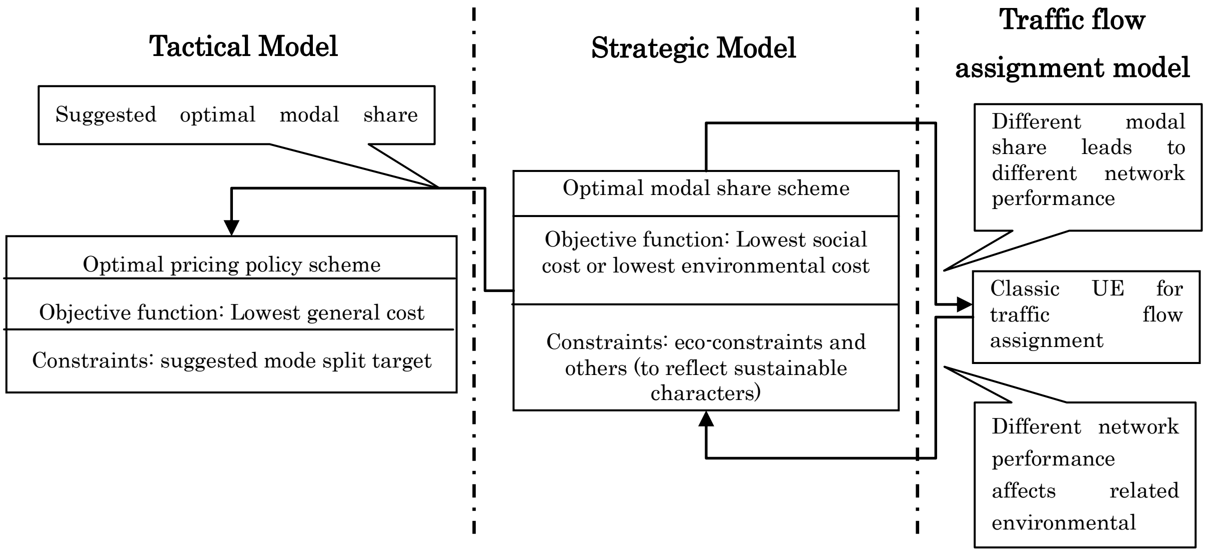


**Fig.1** Modeling structure

### (2) Optimization process

The resulting optimisation procedure is shown in **Fig.2**. It starts with the inputting of the OD data, the current mode-sharing and the basic network data for the city (Step 1). It then calculate the initial values for the carbon emissions factors and energy-consumption factors using the assignment results of the super net, which is based on the auxiliary part of strategic model (Step 2). Apply the carbon emissions factors to the strategic model and obtain the resulting initial primal-mode split and the initial SC value (Step 3). Use the mode-split results from step 3 to again compute the UE assignment on the super net and compute new emissions factors, and SC value (Step 2 and 3). Compare the new SC with the old one (Step 4), if it was improved, repeat from step 2, Otherwise, go to step 5. Use the last mode split results and the assignment results to solve the tactical mode and obtain the primal pricing plan of different scenarios.

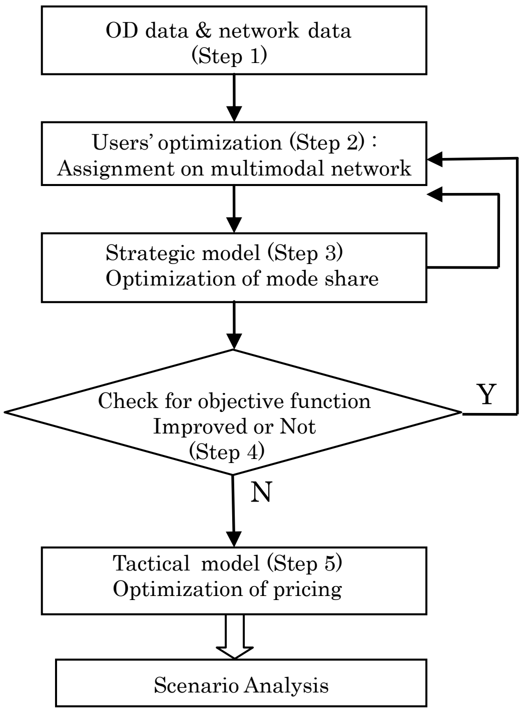


**Fig.2** Optimization process

### (3) Strategic model

#### a) EC objective function

$$\min \sum_i \sum_b \sum_k P^G x_{ik}^b F_k^G(v_i^b) + P_b^L(x_i^b c_i^b) + P_{ik}^{Invest,b} x_{ik}^b \tag{1}$$

$$F_k^G(v_i^b) = \frac{\alpha_i^k \exp(\beta_i^k v_i^b)}{\gamma_i^k v_i^b}$$

Where $P^G x_{ik}^b F_k^G(v_i^b)$ is the costs of carbon emission price according to emission market, $P^G$ is the cost of carbon emission price per passenger kilometre, $x_{ik}^b$ is passenger kilometre of mode $i$ energy mixed type $k$ in zone $b$, $F_k^G(v_i^b)$ is carbon emission factor for passenger kilometre of mode $i$ energy mixed type $k$ in zone $b$, it is a function of the average speed $v_i^b$ in zone $b$ The function of carbon emission factor is given as

$$F_k^G(v_i^b) = \frac{\alpha_i^k \exp(\beta_i^k v_i^b)}{\gamma_i^k v_i^b} \tag{2}$$

Where $\alpha_i^k$ , $\beta_i^k$ , $\gamma_i^k$ are parameters for carbon emission factor of mode $i$ energy mixed type $k$ from regression method, and the emission factor for every mode is calculated under the consideration of average vehicle sharing coefficient of this mode.

Similarly, $P_b^L(x_i^b c_i^b)$ is the shadow price of the land occupied by urban transportation system of mode i in zone b. $P_b^L$ is shadow price of land (per square meter) in zone b, $x_i^b$ is passenger kilometre of mode $i$ in zone $b$, $c_i^b$ is land occupy factor of mode i in zone b for per passenger kilometre. $P_{ik}^{Invest,b} x_{ik}^b$ is the shadow price for the construction of mode i in zone b, $P_{ik}^{Invest,b}$ is the shadow price for the construction of per passenger kilometre for mode $i$ energy mixed type $k$ in zone $b$, $x_{ik}^b$ is passenger kilometre of mode i energy mixed type k in zone b.

#### b) SC objective function

$$\min \sum_i \sum_b \sum_k P^G x_{ik}^b F_k^G(v_i^b) + P_b^L(x_i^b c_i^b) + P_{ik}^{Invest,b} x_{ik}^b + P^{Time} x_i^b e_i^b$$

$$F_k^G(v_i^b) = \frac{\alpha_i^k \exp(\beta_i^k v_i^b)}{\gamma_i^k v_i^b} \tag{3}$$

Compare with EC objective function, the item of $P^{Time} x_i^b e_i^b$ is added. This item means the the total value of time spent by the users in urban passenger transportation system. $P^{Time}$ is value of time, $x_i^b$ is passenger kilometre of mode $i$ in zone $b$. $e_i^b$ is average travel time for per kilometre of mode i in zone b.

#### c) Constraints

The first three constrains are $CO_2$ emission limit, invest budget and land consumption limit, respectively. The last two constrains are travel demand and supply limit, respectively.

$$s.t.\begin{cases}\sum_i\sum_b\sum_k x_{ik}^b F_k^G\left(v_i^b\right)\le Gas\\ \sum_i\sum_b\sum_k P_{ik}^{Invest,b}x_{ik}^b\le Invest\\ \sum_i\sum_b P_b^L(x_i^b c_i^b)\le Land\\ \sum_i\sum_k x_{ik}^b = Demand^b,\ \forall b\\ S_{iMin}^b\le x_i^b\le S_{iMax}^b,\ \forall i,b\end{cases}\qquad(4)$$

### (4) Tactical model

Optimization model of pricing policy is tactical model in the multi-modal system. The objective function of the pricing scheme optimization model is to achieve an optimal pricing policy for different traffic modes, at least general cost (GC) of the network from the passengers' point of view in order to make sure the suggested pricing policy could be accepted as easy as possible, that meets the mode split target obtained from the model of the optimal eco-oriented passenger transportation mode share.

$$\min\sum_n GC\left(TTV, P^*Dis, P^*Tic, P^*Park, P^*RP\right)\qquad(5)$$

The decision variable is $P*$, the pricing level of the selected mode, they could be the ticket level of bus system, ticket level of subway system, the pricing level of fuel tax, the pricing level of Road Pricing, or the level of parking.

Constrains for GC objective function and GC objective function are same, they can be expressed as follows:

$$s.t.\begin{cases}P_{in}=\dfrac{x_i}{\sum x_i}\Phi_i=\dfrac{e^{W_{in}}}{\sum_{j\in J_n}e^{W_{jn}}}\\ U_{in}=W_{in}+\varepsilon_{in}\\ P^{subtic}\ge B_{asic}P^{subtic}\\ P^{bustic}\ge B_{asic}P^{bustic}\end{cases}\qquad(6)$$

### (5) Traffic flow assignment

We use UE equilibrium method as the approach of traffic flow assignment, and software TransCAD is used to do it.

## 3. DATA AND POLICY DESIGN

The data used in this chapter is from Shanghai city, network data and OD data were collected in the Shanghai government transportation survey of 2004. We use the central urban area of Shanghai City as our research area, because 57% population and 73% trips is in this area. According to the traffic demand distribution, we divided it into 3 big zones: downtown area, central area and outside area. **Fig.3** shows the research area in Shanghai city.

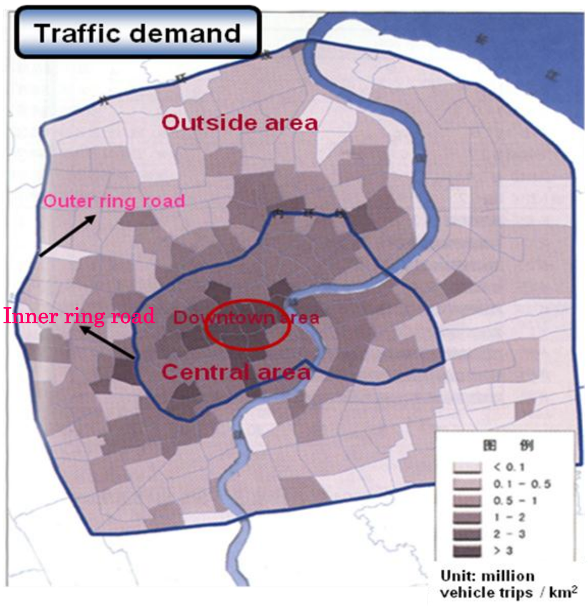


**Fig.3** Research area

We designed two cases, one case use EC objective function for the strategic model, the other one use SC objective function for the strategic model. And in every case, there are three scenarios: low road pricing, middle road pricing and high road pricing.

## 4. RESULTS AND DISCUESSIONS

**Table 3** shows the optimal modal share of six scenarios, as well as the modal share of three big zones in every scenario.The whole procession of the optimization indicates that the change of modal share between current situation and loop1 is biggest, and it got smaller and smaller, when the change is less than the ending threshold, the optimization stopped. We also noticed that the current modal shares in three big zones are almost the same, but after the optimization of strategic model, they became very different. This indicates in downtown area, more people are using the public transportation system because the congestion and heavy emission in this area; in outside area, more people are choosing private car for their travel.

We could observe obvious modal share shift from automobile to the public transportation system in all scenarios. This indicates that these optimal modal share schemes could achieve less EC or SC on network. Compare CASE EC and CASE SC we found in CASE EC the modal share shift from automobile to the public transportation system is bigger. Sharper reduction of the car using could be seen in CASE EC, because when we just minimize EC on the network, the modes of bus and subway receive more prioritise since they bring less negative environmental impact. When we use SC as our objective function, travel time is also considered; the mode of private car is obvious faster than bus, and faster than subway in most cases, so the mode split shit to more using of cars. We could draw a conclusion that the value of travel time on the network has big effect on our optimization, since this value is huge, when we consider the SC on the network, more people would choose pirate car for their travel. In reality, the same situation happens.

**Table 3** Optimal modal share of six scenarios

| Modal share *(Auto:Bus:Sub)* | Current | EC | | | SC | | |
|---|---|---|---|---|---|---|---|
| | | Low RP | Middle RP | High RP | Low RP | Middle RP | High RP |
| Average | 48: 41:11 | 35:49:16 | 36:48:16 | 36:48:16 | 45:40:15 | 45:40:15 | 46:39:15 |
| Downtown | 48:40:12 | 30:49:21 | 32:48:20 | 33:47:20 | 41:39:20 | 41:39:20 | 42:38:20 |
| Central | 47:42:11 | 34:48:18 | 34:47:19 | 34:48:18 | 51:38:11 | 51:38:11 | 50:38:12 |
| Outside | 49:47:4 | 38:53:9 | 39:53:8 | 38:53:9 | 52:42:6 | 52:42:6 | 52:42:6 |

**Table 4** Suggested pricing scheme (Unit: RMB)

| Pricing | Current | | EC | | | SC | | |
|---|---|---|---|---|---|---|---|---|
| | Zone | Aver. | LRP | MRP | HRP | LRP | MRP | HRP |
| Bus ticket | Downtown | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | Central | 2.2 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Outside | 3.4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Subway ticket | Downtown | 3.1 | 2.5 | 3.1 | 3 | 2.5 | 3 | 3 |
| | Central | 3.5 | 3.0 | 3.3 | 3.5 | 3.4 | 3.3 | 3.4 |
| | Outside | 3.9 | 3.1 | 3.6 | 4.0 | 3.5 | 3.8 | 4.1 |
| Parking pricing | Downtown | 10.8 | 7.3 | 6.3 | 2.8 | 6.5 | 5.9 | 2.4 |
| | Central | 7.4 | 7.7 | 7.0 | 6.7 | 7.1 | 6.6 | 6.3 |
| | Outside | 6.3 | 6.5 | 5.4 | 4.1 | 6.1 | 5.0 | 3.8 |

Road pricing are levelled in our scenarios, but the differences of optimal modal share in three scenarios of CASE EC are small, the same situation could be seen in the scenarios of CASE SC, this indicates that the variation of road pricing have small effect on the total modal share. But we noticed that the optimal modal shares in downtown of every scenario are very different, especially the modal share of automobile change greatly, this phenomenon could not be seen in Central and Outside area. This indicates the congestion pricing in downtown do affect the modal choose, some people shift to the public transportation system as well as the crossing of this area is decreased. So we could draw a conclusion that the variations of road pricing have bigger effect on the route choice for the drivers.

**Table 4** shows the suggested pricing scheme to realize the optimal modal share received in 6 scenarios. Blue figure is fixed price in this scenario, yellow figure is leveled price. Red figure means the pricing rise compare to the current level, green figure means the pricing descend compare to the current level, and black figure means the pricing equal to the current level. After the optimization, most pricing policy decrease compare to current pricing level, this means the suggested pricing scheme could be accepted by citizens.

We could observe the change of $CO_2$ emission on some classic links in **Table 5**. $CO_2$ emission decrease on most links, this indicates that with the modal share shift to public transportation system, the gas pollution get relieved, especially in CASE EC, all scenarios receive $CO_2$ mitigation on links. Situation in CASE GC is complicated, in downtown area, the $CO_2$ emission on links also dropped, but in Central and Outside area, most $CO_2$ emission increase, this is because after the optimization, the modal share of car decrease in downtown, however, it increase in the other two zones. At the same time, we could found that $CO_2$ mitigation on links is big, and the rising of $CO_2$ emission on links are small. As a result, the total emission decreases in all scenarios.

**Table 5** $CO_2$ emission on some classic links (Unit: kg/12h 8:00~20:00)

| Big zone | Link | Current | EC objective function | | | SC objective function | | |
|---|---|---|---|---|---|---|---|---|
| | | | LRP | MRP | HRP | LRP | MRP | HRP |
| Downtown | Expressway | 435 | 358 | 339 | 327 | 416 | 393 | 375 |
| | Secondary main | 649 | 542 | 530 | 523 | 625 | 596 | 589 |
| | Feeder road | 410 | 327 | 304 | 300 | 401 | 385 | 360 |
| Central | Expressway | 413 | 364 | 360 | 361 | 419 | 417 | 418 |
| | Secondary main | 382 | 342 | 343 | 346 | 388 | 389 | 390 |
| | Feeder road | 561 | 503 | 505 | 505 | 569 | 570 | 571 |
| Outside | Expressway | 789 | 715 | 720 | 724 | 794 | 795 | 790 |
| | Secondary main | 420 | 381 | 383 | 389 | 423 | 420 | 421 |
| | Feeder road | 371 | 334 | 336 | 336 | 373 | 372 | 371 |

## 5. Conclusions

Form the implement of multi-modal system, we find the following advantages in the application to optimize the mode share and price policy for sustainable urban passenger transportation system:

(1)Different objectives can be analyzed simultaneously during the decision-making process.

(2)Multi-value criteria for transport management and planning, usually by the government and users, could be treated as more realistic, and the interaction between them can be described properly.

(3)Modular structure of the modelling provides a good flexibility for every module and allows the entire structure to be applied in different cities with varying contexts.

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