Research on time-of-use pricing method of shared bicycles

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Abstract. Shared bicycles have become an important mode of urban slow traffic, and the operation and management of shared bicycles have attracted more and more attention. In order to alleviate the shortage of supply during peak period and accelerate the turnover rate during flat peak period, this paper proposes a differentiated pricing strategy of shared bicycles. By establishing a bilevel programming model of shared bicycles fare and using a particle swarm optimization-based global pricing model solution algorithm, the purpose of minimizing the generalized travel cost of travelers and maximizing the economic benefits of shared bicycles enterprises are achieved. Based on the actual traffic situation in Beijing, the model parameters are calibrated to verify the validity of the model and the algorithm. The proposed model can provide a reference for the pricing strategy of shared bicycles and provide a scientific basis for the operation and management of shared bicycles enterprises.

1. Introduction
Shared bicycles provide a convenient way for urban green travel, affecting the daily travel mode of urban residents. There are also a series of problems in the use of shared bicycles. The demand for bicycles in morning and evening peak is much higher than that in flat peak[1]. Such unbalanced demand for bicycles affects the travel quality and satisfaction. And rent, as the main source of revenue, is increasingly unable to meet the increasing input costs. Therefore, changing the traditional pricing method to increase revenue may be the top priority for the continuation and survival of shared bicycles.

At present, most of shared bicycles pricing strategies adopt the uniform charging method, but the demand for shared bicycles at different times is highly flexible. This paper will introduce differentiated pricing strategy and adopt time-of-use pricing method according to the periodic change of bicycles demand with time. It can control the supply of shared bicycles, alleviate the shortage of supply in peak period, and speed up the turnover rate in flat peak period. It can not only optimize the efficiency of the use of shared bicycles in flat peak period, but also maintain the normal operation of shared bicycles enterprises and realize the sustainable development of shared bicycles enterprises.

2. The Review of the Current Research
The basic principle of time-of-use pricing is the congestion pricing theory, which was first proposed in the 1920s by A.c.Pagou of the university of Cambridge and Knight, a famous American economist. It studied how to control and adjust the total road demand through economic means under the existing traffic supply scale, so that the traffic volume can be reallocated in time and space to alleviate the contradiction of imbalance between supply and demand. In the 1970s, Walters and Vickery further
developed this theory, which is mainly divided into the optimal congestion pricing theory of general roads and congestion pricing theory of bottleneck sections. Among them, Vickery proposed the bottleneck model of road toll system in 1969 and analyzed the choice of residents' travel time and travel cost by dynamic charging strategy[2].

Sergio R and Jara Diaz analyzed multiple pricing schemes in Santiago metro system by establishing non-aggregate demand model and using multi-output cost function, which showed the feasibility of time-of-use pricing in metro system abroad[3]. In China, Xiaoyi Zhan introduced how to improve the income level of rail transit enterprises through differential pricing[4]. Zhansheng Wang believed that the research idea of using economic leverage to regulate urban traffic was adopted in the traffic demand management. And he also put forward the idea of dynamic pricing of rail transit through sensitivity and game analysis[5].

3. Feasibility analysis

3.1. Analysis on the use of Shared bicycles at different periods

Taking Beijing as an example, this paper will study the usage rate of shared bicycles in peak periods and flat peak periods, evaluate the importance of factors affecting the pricing of shared bicycles and improve the irrationality of unified charging in peak and flat peak periods. The research data in this paper comes from the 2017 Mobike cup algorithm challenge. Among them, the full sample of usage data of users covers the usage of 485,500 Mobike users in Beijing, including user ID, bicycle ID, bicycle types, starting time of bicycle use, starting point and ending point of bicycle ride. These data are based on users' completely spontaneous behavior, which can reflect traveler's behavior characteristics and time requirements more objectively.

Figure 1. Distribution characteristics of cycling demand time in a day.

In order to reduce the influence of weather conditions on the research results, this paper selects May 10, a sunny working day, for the full time analysis. After data visualization, the morning peak period is set as 7:00 ~ 9:00, and the evening peak period is set as 17:00 ~ 19:30. The cycling amount in these two periods is much higher than the cycling demand in other periods. The amount of riding in the flat peak is far less than the peak. It is considered that the supply is greater than the demand during peak periods. Therefore, it is of realistic significance to implement pricing increase and discount at peak and flat peak.

3.2. Shared bicycles trip distance analysis

In order to study the pricing of shared bicycles riding, it is necessary to estimate the riding distance of each vehicle. In this paper, the distance between starting and ending points is estimated by starting point coordinate and ending point coordinate. Geographical coordinate system adopted in this paper is WGS 84[6]. Considering that most urban roads in Beijing are oriented to the south, north, or west, east, the distance between the starting and ending points is defined as Manhattan distance.

\[
d_i = |D_{x(i)} - O_{x(i)}| + |D_{y(i)} - O_{y(i)}|
\]

The data visualization analysis of the results show that the average cycling distance on that day was 1.8 km. Combining with the distribution map of cycling demand, the cycling distance of 2km is set as the competitive distance between shared bicycles and other modes of transportation to study the pricing problem of shared bicycles in this paper.
3.3. **Survey and analysis of time-of-use pricing intention**

The key to time-of-use pricing implementation is the acceptability of residents. Therefore, the study of time-of-use pricing strategy and model should be based on the full understanding of residents’ travel intention. The time-of-use pricing implementation scheme and change intention statistics of departure time for the bicycles users are presented in the following table.

| Project | Be willing to travel early or late | Accept differential pricing | Rising prices will reduce the use in peak | Reducing price will increase the use in flat peak |
|---------|----------------------------------|-----------------------------|----------------------------------------|--------------------------------------|
| Probability | 18.6% | 86.4% | 15.7% | 68.6% |

| Project | Price rises in peak | Price cuts in flat peak | Price rises and cuts in peak and flat peak |
|---------|---------------------|------------------------|-----------------------------------------|
| Probability | 8.2% | 60.4% | 31.4% |

Table 2. Time-of-use pricing implementation program intention.

The majority of travelers will not change their travel time because of the pricing change. Therefore, the effects of different time periods on the allocation of passenger flow are no longer considered in this paper. Most travelers are willing to accept differentiated pricing method, which contains price increases and discounts. The price increase in peak has little influence on the behavior of travelers, while the price reduction in flat peak will lead a large number of travelers to choose shared bicycles. For the implementation scheme of time-of-use pricing, travelers are most inclined to the time-of-use pricing strategy of flat peak price reduction, which shows that the time-of-use pricing method has certain implementation necessity and feasibility.

4. **Bilevel programming model and algorithm design**

4.1. **Introduction to the model**

In this paper, a bilevel programming model is proposed as the basic model for the time-of-use pricing. The upper decision-maker is the enterprise and the lower decision-maker is the travelers. The enterprises can change the generalized travelers cost through the changes of fare and service quality. It affects travelers’ choice of transportation mode, but cannot control their choice behavior. Travelers choose their own modes of transportation according to their own needs after comparing existing modes of transportation. This relationship can be described using a bilevel programming model.

\[
\begin{align*}
(U) \max & F(x, y(x)) \\
\text{st.}& \ G(x, y(x)) \leq 0
\end{align*}
\]  

Where, \(y(x)\) is obtained from the lower planning.

\[
\begin{align*}
(L) \min & f(x, y(x)) \\
\text{st.}& \ g(x, y(x)) \leq 0
\end{align*}
\]  

4.2. **Upper level programming model**

The objective is to maximize the profit of shared bicycles enterprises, mainly including the following parameters.

\[
\max R(P, Q) = \sum_m Q^m (\alpha Y + \delta^m P^m - a^m)
\]  

In the function, the time periods \(m\) include peak period \(m_1\) and flat peak period \(m_2\); \(R\) is the enterprises income at various time periods; \(P^m\) is the normal ticket price of shared bicycles in different time periods; \(Q^m\) is the passenger flow of shared bicycles at different time periods; \(\alpha\) is the benefit from a deposit for shared bicycles; \(Y\) is the deposit from users of shared bicycles; \(\delta^m\) is the discount rate or increase rate of shared bicycles in each time period, which is the decision variable of upper planning;
\( a_{kn} \) is the cost of each mode of transportation in each time period; \( \delta^\text{max} \) is the lowest price discount rate of travel mode; \( \delta^\text{max} \) is the highest price increase rate of travel mode.

### 4.3. Lower level programming model

The lower level planning is the traffic flow distribution model. Based on the Wardrop equilibrium distribution principle, the flow distribution among various traffic modes in each period can be equivalent to the flow distribution among various section.

\[
\begin{align*}
F_n^k(Q_n^k) &= f_n^k(Q_n^k) & Q_n^k > 0 \\
F_n^k(Q_n^k) &\geq f_n^k(Q_n^k) & Q_n^k = 0
\end{align*}
\]

\( F_n^k(Q_n^k) \) is the generalized cost in equilibrium state and \( f_n^k(Q_n^k) \) is the broad travel cost for travelers to choose different modes of transportation at the same time. Referring to the power function form adopted in literature [7], this paper will express the generalized cost of the Kth transportation mode in different time periods considering the service characteristics of different transportation modes.

\[
f(Q_n^k) = a(Q_n^k)^b - V_n^k
\]

In the function, \( a,b \) is the parameter to be determined, which can be obtained from traffic survey and statistical analysis; \( V_n^k \) is the utility value that can be observed by different traffic modes in different periods of OD pairs, which can be represented by the following formula.

\[
V_n^k = \frac{a_1P_n^k + a_2K_n^k + a_3B_n^k + a_4S_n^k}{A_n^k}
\]

\( P_n^k \) is the economy of the k mode of traffic; \( K_n^k \) is the rapidity of the k mode of traffic; \( B_n^k \) is the convenience of the k mode of traffic; \( S_n^k \) is the amenity of the k mode of traffic; \( A_n^k \) is the safety of the k mode of traffic in each period. \( a_1, a_2, a_3, a_4 \) represent the weight of economic, express, convenience and comfort cost of the selection of type k passenger transport. The objective function of the lower level planning model is the minimum travel cost of travelers in a generalized sense.

\[
\min U_m = \sum_{m} \sum_{k} \int_{0}^{Q_n^k} \{a(x)^b - V_m^k\} \, dx
\]

\[
\text{st.} \sum_{m} \sum_{k} Q_n^k = Q \\
0 < Q_n^k < K_n^k
\]

In the function, constraint condition 1 indicates that the total number of travelers remains unchanged before and after the implementation of time-of-use pricing method. \( K_n^k \) is the maximum capacity of the k mode of traffic. Constraint condition 2 indicates that the passenger flow of various modes of traffic should be controlled below transport capacity and not negative.

### 4.4. Model solving algorithm

In this paper, particle swarm optimization algorithm is used to solve the bilevel programming model of time-of-use pricing method. Firstly, PSO algorithm is applied to solve the upper level programming and feed back to the lower level. Then, the general optimization method is used to solve the lower level programming, which is fed back to the upper level. Iterate repeatedly between the upper and lower layers until the optimal solution of the bilevel programming is approached.

**Step1:** Initialize of PSO algorithm.

1. Initialize the parameters: \( \omega, c_1, c_2, r_1, r_2, t, T, v_{\text{max}}, x_{\text{max}}, \eta, \) etc.;
2. Randomly initialize the size of the population and the position \( X_i^0 = (x_{i1}^0, x_{i2}^0, x_{i3}^0, \ldots x_{ik}^0)^T \) and velocity \( V_i^0 = (v_{i1}^0, v_{i2}^0, v_{i3}^0, \ldots v_{ik}^0)^T \) of each particle in the population;
3. Set each particle current position to \( P_{\text{best}} \) and record optimal particle position as \( G_{\text{best}} \).

**Step2:** Solve the lower layer model.

Take the solution of the upper model \( X_i^t (i = 1,2,\ldots,n) \) into the lower model. The optimal solution of the lower layer model \( Y_i^t (i = 1,2,\ldots,n) \) is solved by the general optimization method.
Step 3: Calculate fitness function value.

Bring the $X^j_i$, $Y^j_i$ into the upper model and calculate the fitness function value $F = (X^j_i, Y^j_i)$, that is, the revenue of the shared bicycles enterprise $R(P, Q)$.

Step 4: Update individual extreme value and group extreme value.

If the fitness function value corresponding to $X^j_i$ is better than the fitness function value of the current optimal location $P_{best}$, then $P_{best}$ is updated to $X^j_i$, and the optimal solution of the corresponding lower layer is updated to $Y^j_i$.

If the fitness function value corresponding to $X^j_i$ is better than the fitness function value of the current global optimal location $G_{best}$, then $G_{best}$ is updated to $X^j_i$, and the optimal solution corresponding to the lower layer is updated to $Y^j_i$.

Step 5: Judge whether the convergence condition is satisfied. If so, turn to Step 8, or turn to Step 6.

Step 6: Carry out optimal solution interference.

Let $G^{j+1}_{best} = G_{best} \times (1 + \rho)$, the general optimization method is used to solve the corresponding optimal solution $Y^{j+1}_{best}$ of the lower layer model.

Step 7: Update the velocity and position of particle swarm according to formula $v^{j+1}_{ik} = \omega v^j_{ik} + c_1r_1(p^j_{ik} - x^j_{ik}) + c_2r_2(p^j_{pg} - x^j_{ik})$ and $x^{j+1}_{ik} = x^j_{ik} + v^{j+1}_{ik}$, then turn to Step 2.

Step 8: The optimal solution of the upper and lower level problem of the bilevel programming and the corresponding upper and lower level optimal function value are outputted to end the algorithm.

5. Analysis of the example

We take the morning peak as an example in this paper. According to the basic data of traffic economy in Beijing, we can get that the cost includes 0.410 yuan each time and 17% VAT on rental income. The labor cost is 0.040 yuan and the business cost is 0.100 yuan each time. The depreciation charge is 0.271 yuan each time. The income includes fare income and deposit income, in which the fare income is based on the actual situation and the deposit income is about 0.085 yuan each time.

A questionnaire survey on the travel characteristics of travelers at a distance of 2 km in Beijing got the weight of transportation supply factors during the peak period. The service factor value of each mode of transportation is analyzed and calculated according to the basic data of traffic economy in Beijing and the calculation formula of each index. The results of the importance of each transport service attribute and the value of the service attribute during the peak period are shown in Table 3.

Table 3. Observable travel costs.

| Transport mode | Economy | Rapidity | Convenience | Comfort | Safety | Observable cost |
|----------------|---------|----------|-------------|---------|--------|-----------------|
| Shared bicycles | $\delta$ | 4.70 | 3.13 | 3.76 | 0.95 | 3.09+1.058 |
| Public bicycles | 0.00 | 4.70 | 6.27 | 3.76 | 0.95 | 3.66 |
| Bus | 1.00 | 5.37 | 7.52 | 5.01 | 0.90 | 5.23 |
| Subway | 3.00 | 2.51 | 12.53 | 4.39 | 1.00 | 5.50 |
| Taxi | 14.00 | 5.01 | 5.64 | 3.13 | 0.85 | 7.70 |
| Car | 4.40 | 5.01 | 5.01 | 3.76 | 0.85 | 5.20 |
| Walk | 0.00 | 15.04 | 0.00 | 9.40 | 1.00 | 6.24 |

According to the survey of traveler’s pricing intention, the minimum discount rate and maximum price increase rate of shared bicycles are set as 0.5 and 3.0 respectively in this paper. In this example, let $a=1$ and $b=0.25$. The increase rate and the passenger flow of different transportation modes can be calculated by using the two-layer iterative particle swarm optimization algorithm. Assuming that the morning peak travel within 2 km of Beijing is 1 million people, the fare increase rate of shared bicycles is calculated to be 1.52, and the shared bicycles passenger volume is 122,400.
In the case of unified pricing (1 yuan /0.5 hours) for each time period of existing shared bicycles, combined with table 3, the observable travel costs of travelers choosing different modes of passenger transport can be calculated. This article assumes that $\mu$ is equal to 0.1, We can calculate the share rate of different passenger transport modes in the whole passenger transport market.

$$W_{ij} = \frac{\exp\left[-\mu v_{ij}\right]}{\sum_k \exp\left[-\mu v_{ik}\right]}$$

(9)

In the function, $v$ is observable travel costs. It is assume that the morning peak travel within 2 km of downtown Beijing is 1 million people. In the present pricing model and the passenger ticket pricing optimization model, we calculate the revenue of the shared bicycles enterprises as shown in table 4.

Table 4. Shared bicycle enterprises earnings in different pricing methods.

| Pricing method                      | Ticket price (yuan) | Passenger flow (Ten thousand people) | Shared bicycles enterprises Total income (Ten thousand dollars) |
|-------------------------------------|---------------------|--------------------------------------|---------------------------------------------------------------|
| Uniform pricing method              | 1                   | 16.10                                | 160                                                           |
| Time-of-use pricing method          | 1.52                | 12.24                                | 187                                                           |

It can be seen that the implementation of time-of-use pricing method reduces the passenger flow of shared bicycles by 23.98% during the early peak period and increases the income by 16.88%, which is beneficial to the sustainable operation of enterprises. It can be seen that the pricing model constructed in this paper is reasonable and feasible. It can guide the passenger flow distribution of travelers to a certain extent. Therefore, it is necessary for shared bicycle enterprises to change the current pricing system and adopt differential charging policy for travelers in different periods.

6. Conclusion

Reasonable fare level is helpful to balance the traffic and meet the needs of society. Taking the time-of-use pricing method can control shared bicycles supply, relieve peak supply, and speed up the flat peak turnover situation. It also can maintain the normal operation of enterprises and realize the sustainable development of enterprises.

This paper establishes a bilevel programming model of shared bicycles pricing and realizes the goals of minimizing the generalized travel cost of travelers and maximizing the economic benefits of shared bicycle enterprises. Then this paper presents an algorithm based on particle swarm search to solve the whole pricing model. With the actual traffic condition of Beijing as the background, the model parameters are calibrated to verify the validity of the model and the algorithm. The model can be used as a reference for the establishment of shared bicycles pricing and can provide a scientific basis for the establishment of shared bicycles pricing.

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