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RESEARCH PAPER

Optimization Study on Road Pricing with Variable Bus Frequency

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Abstract: The paper proposes the optimization problem of road pricing with variable bus frequency on the basis of the relations analysis of mutual constraints between road pricing and increasing bus frequency considering the interaction of different travel modes. A bi-level programming model is developed by estimating the generalized travel cost of bus and private car traveling. The upper objective of the model maximizes total consuming surplus of network, while the lower is the user equilibrium model with elastic demand of combined mode. The optimal algorithm is also designed based on the simulated annealing algorithm. A numerical example illustrates that the model and algorithm can effectively solve the problem of road congestion.

Key Words: urban traffic; variable bus frequency; road pricing; bi-level programming; simulated annealing algorithm

1 Introduction

Road pricing aims to reduce traffic load on busy time and busy roads; and to attain the aim of easing traffic jam by charging part vehicles in certain time and road[1−6]. Ref. [1] using marginal cost pricing principle, charges on busy roads to increase the costs for using the roads, changes the distribution of traffic flow, and then relieves the traffic pressure. Ref. [2] supposed that park and ride does not influence the driving convenience and improve the bus using passion. Ref. [3] combines road capacity expansion with traffic congestion pricing to solve traffic jam from two aspects of road supply and traffic demand, using bi-level programming. Ref. [4], through the analysis of travel cost under the two strategies of road pricing and parking facility fee, builds a bi-level programming, maximizing the total consumer surplus as the upper optimization target and user balancing combined travel network under elastic demand as the lower optimization target. Ref. [5] considers driving time as a pure loss, and then changes it into benefits from roads using cost. As a result, the most advanced social optimization would be accomplished through the dynamic charge. Ref. [6] builds a bi-level programming of maximizing the social welfare as the upper planning target and a general multi-time multi-user equilibrium road network model.

Generally, these existing studies about road pricing are based on the fixed service level of urban public transport. It actually would reduce the vehicle crowded roads flow by charging on private car, because the increasing of travel costs by private cars makes of part travelers to use bus. However, the increasing of bus users would make the bus service level drop unless the condition of bus service is improved. Considering road pricing as one measure of improving the traffic, the charge should also be used to perfect traffic. This paper aims to reduce the bus travel cost, to make more private car travelers turn to bus system, and to relieve urban road congestion using charge amount on road pricing to enhance the departure frequency of bus lines.

2 Road pricing analysis with variable bus frequency

Suppose there are two traffic ways of bus and private car in the city. Road pricing could collect much income from private car travelers, though it may turn part private car travelers to the bus, and then use this income to increase buses so as to dramatically improve the bus service. Assume that the current bus network is good enough; it is only considered to increase more buses of existing bus lines. The process consists of two aspects of decision: road pricing and ascertain of increasing

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bus numbers, both are conditioned by each other. On the one hand, the road pricing decides the traffic flow of private cars on road network, and further influences the road pricing. Meanwhile, the income to increase buses comes from the road pricing. On the other hand, increasing buses of several bus lines could improve bus service level and make more travelers turn to bus, which would reduce the private cars flow in crowded roads and thus influence road pricing. Issue of road pricing with variable frequency of bus considers influence of enhancement of the bus frequency and road pricing to urban road traffic flow, the road pricing and the numbers of increasing buses as well as bus lines are decided in order to dramatically improve the travelers' service level of urban road network.

2.1 Notation

Road network $G=(N, A)$, where N is a set of road network node, which includes bus stops and road intersection; A refers to road network section set, and at the same time the changed road sections are given; γ_a refers to road section attribute, and when road section $a \in A$ is toll road section, $\gamma_a=1$, otherwise $\gamma_a=0$; the decision variable u_a ($a|\gamma_a=1$) refers to the charge of one private car. $U=\{u_a\}$ refers to fee set of all the charged road sections. v_a^l ($a \in A$) refers to the flow number of travelers when choosing traffic mode l, where l is the type of traffic mode, when $l=c$, it means using private cars traveling, and when $l=b$, it means using bus traveling; W is the set of OD in network, K_w^l is the set of travel path among OD $w \in W$, q_w is the total traffic demand among OD $w \in W$, q_w^l is the traffic demand among OD w when l is chosen, f_w^{lk} is the traffic flow among OD w when l is chosen on path k, Q is the set of bus lines on road network, λ_s is the original departure number of bus line $s \in Q$ during research period, decision variable y_s is the added number of bus line $s \in Q$. Define $Y=\{y_s\}$ as the set of added bus number of each bus line, F_s is the average fee of increasing per bus for bus line $s \in Q$; the average passenger capacity of private car is τ (person/per car), the average passenger capacity of bus is η (person/per bus); T is the research period.

2.2 Travel cost analysis by different travel modes

(i) The generalized travel cost of private car

The generalized travel cost of private car includes driving time, road pricing, travel congestion fees coming from internal crowded space of private cars, and other fees. Driving time is the total time of driving all the way. Travel congestion fees are the uncomfortableness brought about by overload, and it makes 0 because private cars commonly do not overload; other fees include fuel fee cost by traveling, depreciation fee, parking fee, and other additional charges. If the entire road conditions are unchanged, the fee has something to do with the added bus number Y and crowded fee U. For travelers taking travel path k by private cars among OD w, the generalized travel cost t_w^{ck} could be shown as Eq. (1).

$$t_w^{ck} = \xi \sum_{a\in k} t_a(x_a^c, x_a^b) + \frac{1}{\tau}\left(\sum_{a\in k}\gamma_a \cdot u_a + \sum_{a\in k} l_a \cdot \sigma\right) \quad (1)$$

where ξ is the value of time of travelers; $t_a(x_a^c, x_a^b)$ is the function relation of driving time with car flow on section a, it could be embodied by the BPR function provided by American Highway Administration; x_a^c, x_a^b is the standard car numbers changed from private cars and buses on road section a, its representation is

$$x_a^c = v_a^c / \tau, \quad x_a^b = \sum_{s\in Q \text{且} a\in s} \lambda_s'$$

where λ_s' is the current departure number of bus line $s \in Q$ during research period, $\lambda_s' = \lambda_s + y_s$; l_a is the length of road section a; σ is the other per traveling fees for private car.

(ii) The generalized travel cost of bus

The generalized travel cost of bus mainly includes waiting bus time during traveling, traveling time on bus, bus ticket prize, and travel congestion fees coming from internal crowded space in bus. The waiting bus time of traveling is related to the frequency of bus taken. The larger the frequency, the less the average time travelers spend on bus stop; travel congestion fees are related to the actual passenger capacity and allowance. Suppose the flow distribution of bus traveler is uniform during research period, then it can be believed that bus allowance is the summation of all the bus allowances on this bus line. In the same way, the fee has something to do with the added bus number Y and crowded fee U. Suppose bus line S is the k path of bus path set K_w^b among OD w, the travel cost t_w^{bk} on this k path could be shown as:

$$t_w^{bk} = \xi\left(t_w^s + \sum_{a\in k} t_a(v_a^c, v_a^b)\right) + t_s + \mu \sum_{a\in k} g(\lambda_s', v_a^b) \quad (2)$$

where t_w^s is the traveling waiting bus time, the value of t_w^s is $T/(2\lambda')_s$; t_s is bus ticket prize and is fixed here; μ is weight of bus travel congestion fees in total travel cost; $g(\lambda_s', v_a^b)$ is the function of travel congestion fees in bus, $B_s = \eta_s \lambda_s'$ is the total passenger capacity of bus line $s \in Q$. Ref. [7], on road section a, shows the function of travel congestion fees in bus using B_s, the total passenger capacity of bus line and v_a^b, the actual passenger capacity of bus is shown as:

$$g(\lambda_s', v_a^b) = \begin{cases} 0 & v_a^b \le B_s \\ \alpha\left[\dfrac{v_a^b}{B_s}\right]^\beta & v_a^b > B_s \end{cases}$$

where α and β are undetermined parameters.

3 Road pricing model with variable bus frequency

The traffic flow in the urban road network is a result of combined action of the transportation planners and the travelers. The transportation planners first make road pricing strategy as well as increase the bus number of partial bus lines, while the travelers determine their traveling behavior according to the road pricing strategy and the traffic condition