RESEARCH ON APPLICATION PROSPECT OF TOLL BUS LANE IN CHINA

PAN Dawei, School of Transportation, Southeast University, Nanjing 210096, China; PH: 15850539537; email: pandaweijt@yahoo.com.cn

DENG Wei, School of Transportation, Southeast University, Nanjing 210096, China; PH: 13705150697; email: dengwei@seu.edu.cn

SHAO Fei, Engineering Institute of Corps of Engineers, PLA Univ. of Sci. & Tech., Nanjing 210096, China; 13951798458，email: shaofeiriver@163.com

ABSTRACT

In the Metropolitan of China, the situation of the general-purpose lane congested while the bus lane relatively idle is often occurred during the time of peak hour, the excess capacity of the bus lane doesn't effectively used. Making use of the excess capacity by opening them to car pools is a method that can effectively mitigate traffic jams and improve the operating efficiency of the road. In order not to influence buses' operation in bus lanes, the congestion pricing is needed to regulate the volume of car pools in bus lanes. The paper illustrate the condition and the method for implementation of the toll bus lane, analyze travelers' travel choice mode which is affected by the toll rate, and then proposes bi-level model, in which the lowest average people cost and maximum road operating efficiency are the upper-layer objective model and the user equilibrium is the lower-layer objective model. The objective function of the model was solved by an advanced heuristic solution algorithm based on sensitivity analysis.

Key words: excess capacity; toll bus lane; bi-level model; heuristic solution algorithm; sensitivity analysis

1. INTRODUCTION

In the face of growing urban congestion, the range of strategies to maintain and improve highway service is also increasing. The traditional approach has been the addition of general-purpose lanes. However, because of the high costs and impacts of creating new capacity, increasing attention is also being given to strategies that make the maximum use of existing highway capacity. One such strategy, bus lanes, reserves existing or new highway lanes for the exclusive use of buses. The strategy is very helpful to alleviate congestion during peak hours, but the excess capacity of bus lanes is not being fully used when the situation of fewer buses in bus lanes while excessive private vehicles in general-purpose lanes happened. The paper expand the strategy of bus lanes to a new management concepts of toll bus lanes—combines bus lanes and pricing strategies by allowing carpool vehicles to gain access to bus lanes by paying a toll during peak hours(peak periods). The paper introduces the utility, technical and operational issues of the strategy, and proposes a bi-level model to analyze the relationship between the demand and the toll rate.

2. UTILITY ANALYSIS OF THE STRATEGY

The method of carpool vehicles using excess capacity of the bus lanes combines bus lanes and pricing strategies by allowing carpool vehicles carrying more than two passengers to gain access to bus lanes by paying a toll during rush hours. The combined ability of toll bus lanes to introduce additional traffic to existing bus lane facilities, while using price and other management techniques to control the number of additional motorists and maintain high service levels, renders the concept a promising means of reducing congestion and improving service on the existing highway system. Figure 1 and Figure 2 illustrate the excess capacity of bus lanes which can be used to manage overall roadway congestion from the aspect of time and space respectively, the gap between the curve line and the top of figure 1 represent the excess capacity. The key to effective use of this strategy is to actively managed, using dynamic toll collection, what time and how many vehicles can use the excess capacity. The traveler has the option of paying for a congestion-free restricted freeway lane or traveling freely on a congested general purpose freeway lane.

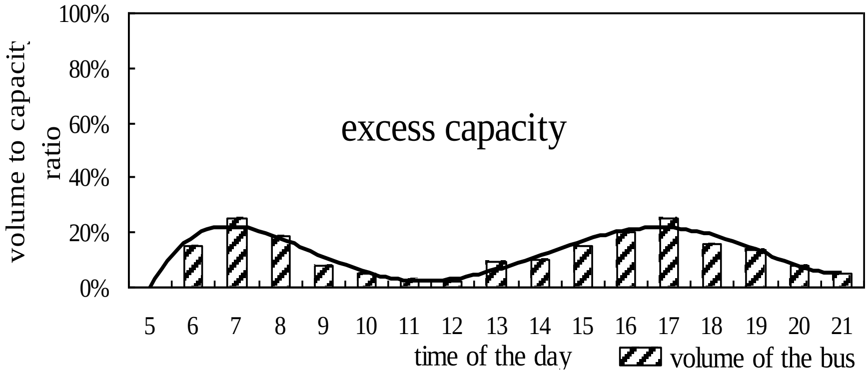

Fig 1. The excess capacity of bus lane (from the aspect of time)

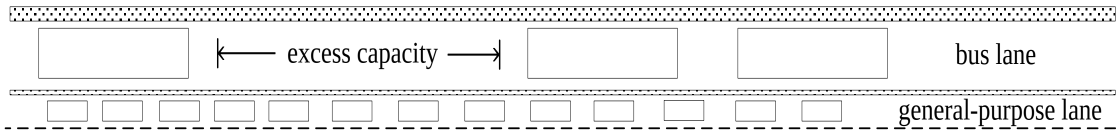

Fig2. The excess capacity of bus lane (from the aspect of space)

When the method is applied, the toll-paying carpool vehicles move into bus lanes and the demand on the mixed flow lanes is reduced, as shown in Figure 3. The initial maximum delay is the upper dashed horizontal line. After the carpool vehicles move to the bus lanes, the maximum delay is reduced to a portion of that line. The total delay is reduced by the area between the initial and final demand, and the traffic congestion disappeared earlier than ever (Pan 2009).

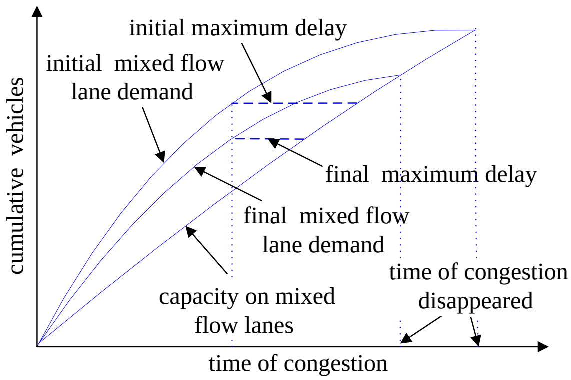

Fig 3. The utility of the method for reducing the traffic congestion

The appeal of this concept is as follows:

1. Optimization of the traffic time: providing incentives for motorists to shift some trips to a congestion-free, dependable and faster trip
2. Optimization of the traffic routes: providing incentives for motorists to shift some trips to less congested routes
3. Optimization of the traffic mode: providing incentives for motorists to shift some trips to alternative modes, such as shift from single-occupant vehicles to carpool vehicles or from cars to mass transit
4. Optimization of the traffic efficiency: optimizing the efficiency by offering potential users the choice of using general-purpose lanes or paying for premium conditions on

the toll bus lanes, which can save trip time, improve travel time reliability , enhance mobility.

3. IMPLEMENT TIME OF THE STRATEGY

In order to find the implement time of the strategy, the paper classified the change of the volumes of the vehicles into three stages

Stage 1: during non-crowded hours, it is fluent for travelers to travel in the general-purpose lanes ($t \le t'$), the travelers have no requirements of using the bus lanes, so it is not necessary to open the bus lanes to the cars; (t is the travel time in general-purpose lanes, t' is the travel time in bus lanes before the carpools entered the bus lanes)

Stage 2: the number of cars in general-purpose lanes increased to some extent ($x_0 \le x \le x_1$), the road became congested to some degree, and the traveling time in the general-purpose lanes is larger than the use of excess capacity of the bus lanes ($t \ge t'$), the travelers have requirements of entering the bus lanes but the number of cars which is willing to enter the bus lanes has no effect on the traveling of the bus ($t' = t'_+$), in this situation it is necessary to open the bus lanes to the cars but doesn't need to toll (x is the volume of the vehicles in general-purpose lanes, x_0, x_1, x_2 are numerical values which is the key change point of the traveling time, t'_+ is the travel time in bus lanes before the carpools entered the bus lanes)

Stage 3: the number of cars in general-purpose lanes increased to a further extent ($x \ge x_1$), on the one hand, the carpool vehicles have the requirements of entering the bus lanes for decrease their travel time, on the other hand, the increased carpool vehicles in bus lanes affect the traveling of the bus ($t' < t'_+$), so it is necessary to take proper charge policy to regulate the number of carpool vehicles in bus lanes which has beneficial to reduce bus delays and maximize the operation efficiency of the traffic system. In this stage, when the volume of the vehicles no less than the road capacity ($x \ge x_2$), it would a better choice for travelers to change travel time or traffic mode to bus.

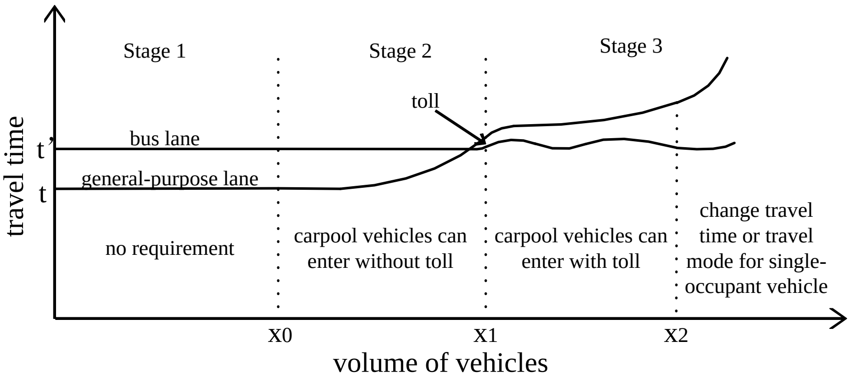

Fig 4. The different stages of the traffic condition

4. VEHICLE REQUIREMENT AND TRAVEL CHOICE MODE

The demand for using the toll bus lanes is affected by the toll rate, vehicle occupancy and the time can be saved. The table below shows how the different scenarios affected the demand (the blank with gray shading) during the peak hour. The survey showed that the demand is proportional to the time can be saved, and inversely proportional to the toll rate, when the toll rate increased, the demand of the two-occupancy vehicles decreased obviously. The table also showed that the vehicle with more occupancy is more inclined to choose the toll bus lanes. In order for the two-occupant vehicles can be regulated effectively by the toll rate, and the vehicles with more occupancy can be encouraged, the requirement of the toll bus lane may be the vehicles with no fewer than two occupants per vehicle.

Table1. Demand variations with different scenarios

toll rate (yuan/km)	vehicle occupancy	time saved		
		10%	20%	30%
0.1	2	387	512	963
	⩾3	163	278	489
0.2	2	315	425	647
	⩾3	156	242	435

This paper put forward disaggregate model-split model considering the influence of the congestion pricing and the analysis method considering passenger's behavior, analyzed the relationship between traffic mode split rate and congestion toll rate. $U^* = U^*(x_i, E)$ is the utility function of the travelers' traffic mode choice, it is inverse ratio function of the toll rate, x is the attribute variables of the traffic mode; E is the social and economy characteristics variable of the traveler. And there are four types of traffic mode: single-occupancy vehicle travel in general purpose lane (i=1), carpool vehicle travel in general purpose lane (i=2), carpool vehicle travel in bus lane (i=3), bus travel in bus lane (i=4). The probability of the traveler to choose traffic mode i is as (Xu 2008):

$$p(i) = p\{(U^*(x_i, E) > U^*(x_j, E)), \forall j \neq i, j = 1,2,\cdots\}$$
$$= \frac{e^{U_i}}{\sum_{i=1}^{4} e^{U_i}} = \frac{e^{\xi_i + mF_i^* + nB_i^* + kT_i^*}}{\sum_{i=1}^{4} e^{\xi_i + mF_i^* + nB_i^* + kT_i^*}} = \frac{e^{-\theta' t_{kg}}}{\sum_{k\in K}\sum_{g\in G} e^{-\theta' t_{kg}}} \quad (1)$$

Where F is the cost can be saved under the condition of traffic congestion toll; B is the ratio between economic profit and personal income, that is the reflect of the utility of the social and economy characteristics; T is the cost can be saved when choose one type of traffic modes; ξ_i is the constant of stochastic properties, namely the constant for model adjustment; m, n, k denote respectively the constant of toll rate, economic benefits, and travel time; θ' is an nonnegative constant, represent the travelers' comprehensive degree of travel cost.

5. TOLL RATE OF THE STRATEGY

Toll rate will influence the demand during the peak hour and the traffic flow will be optimized by reasonable toll. In the paper, the vehicle are classified into three types, single-occupancy vehicle (represent by g1), carpool vehicle (represent by g2) and bus (represent by g3), they travel on the general purpose lanes (represent by k1) or the bus lanes (represent by k2), and the travel time of one type of the vehicles may influenced by the flow of the other type of the vehicle (represent by f_{kg}) and the toll rate (represent by u_{kg}), so the travel time should represent by $t_{kg}(f_{kg}, f_{kg}, u_{kg})$. A bi-level model is proposed as follow, in which the lowest average people cost and maximum road operating efficiency are the upper-layer objective model and the user equilibrium is the lower-layer objective model.

Upper Model (P1)

$$\min F(u) = \lambda_{g1} f_{k1g1} t_{k1g1}(f_{k1g1}, f_{k1g2}, u_{k1g1}) + \lambda_{g2} f_{k1g2} t_{k1g2}(f_{k1g1}, f_{k1g2}, u_{k1g2})$$
$$+ \lambda_{g2} f_{k2g2} t_{k2g2}(f_{k2g2}, f_{k2g3}, u_{k2g2}) + \lambda_{g3} f_{k2g3} t_{k2g3}(f_{k2g2}, f_{k2g3}, u_{k2g3})$$
$$= \sum_{k\in K}\sum_{g\in G} \lambda_g f_{kg}(u) t_{kg}(f_{kg}, u) \quad (2)$$

$$s.t. \quad u_{kg} \geq 0; \quad \sum_{k\in K} d_g f_{kg} \leq C_k; \quad f_{bus}^{\min} \leq f_{k2g3} \leq f_{bus}^{\max} \quad (3), (4), (5)$$

Where λ is weight coefficient, it is proportional to the average number of passengers of the vehicle type g; t_{kg}^0 is free flow time of the traffic mode type g in lane type k; d_g is equivalent conversion factor to standard vehicle of the traffic mode type g vehicle; $f_{bus}^{\min}$ is lower limit of the volume of the buses for open bus lanes; $f_{bus}^{\max}$ is upper limit of the volume of the buses considering the capacity and the service level of the bus lanes.

Lower Model (P2)

$$\min Z = \frac{1}{\theta}\left\{\sum_{k\in K}\sum_{g\in G}[\Gamma_g f_{kg}(\ln f_{kg}-1)] - \sum_{g\in G}[\Gamma_g q_g(\ln q_g - 1)]\right\} + \sum_{g\in G}\Gamma_g \Phi_g(u_g + y_g)q_g$$

$$-\sum_{g\in G}\Gamma_g \int_0^{q_g}[D_g(f)]^{-1}df + \int_0^{q} t(f)df \tag{6}$$

$$s.t.\quad \sum_{g\in G} q_g = \sum_{k\in K}\sum_{g\in G} f_{kg}\ ;\quad q_g \ge 0;\quad f_{kg} \ge 0 \qquad (7), (8), (9)$$

The Kuhn-Tucker condition of the lower model can be represented as:

$$\ln f_{kg} + \theta\Phi_g(u_g + y_g) + \int_0^{q_g} t(f)df - m_k - l = 0,\quad k\in K, g\in G; \tag{10}$$

$$-\ln q_g - \theta[D_g(w)]^{-1} + l = 0;\quad \sum_{g\in G} q_g = \sum_{k\in K}\sum_{g\in G} f_{kg}; \qquad (11), (12)$$

$$m(C_k - \sum q_g) = 0,\quad m \le 0;\quad \sum_{g\in G} q_g \le C_k \qquad (13), (14)$$

Where Γ_g is the influence coefficient of the vehicle of the traffic mode type g compared with standard car to traffic flow; q_g is the volume of the vehicle of the traffic mode type g; Φ_g is conversion factor between toll and time value of the vehicle of the traffic mode type g; y_g is the sum of travel cost and individual preference cost of the vehicle of the traffic mode type g; D_g is travel demand function of vehicle type g.

Heuristic Algorithm Base on Sensitivity Analysis

For the obtained solution $\mathbf{u}^0$,solve the lower-level problem and get the corresponding solution $v(\mathbf{u}^0)$,then linearize the upper-level problem at $\mathbf{u}^0$ and get the linear programming problem as (LP1),

$$\min\left|\frac{\partial \mathbf{F}(\mathbf{u}^0)}{\partial \mathbf{u}} + \frac{\partial \mathbf{F}}{\partial f}\,{}^{u}_{\Delta} f(\mathbf{u}^0)\right|^T (\mathbf{u} - \mathbf{u}^0) \tag{15}$$

s.t. $\mathbf{u}^{\min} \le \mathbf{u}$ (16)

Solve the linear programming problem above and get the optimal solution $\mathbf{u}'$, the $\mathbf{u}' - \mathbf{u}^0$ is the feasible descending direction. Finally, get the heuristic algorithm of bi-level programming problem, the algorithm steps are as:

Step 1 Give a initial structure of congestion pricing u which is feasible;

Step 2 Solve problem (P2) with u, then we can get f ;

Step 3 Calculate the sensitivity analysis information ${}^{u}_{\Delta} f$;

Step 4 Linearize the problem (P1) at u, we can get the problem (LP1);

Step 5 Calculate $\mathbf{u} := \mathbf{u} + \alpha(\mathbf{u}' - \mathbf{u})$, which α is the step size in search;

Step 6 If the u is closed enough at two adjacent times, iterative is end; if not, return back to step2.

From the model above we can simulate the relationship between the volume ratio of different vehicle types and different toll rate as follow:

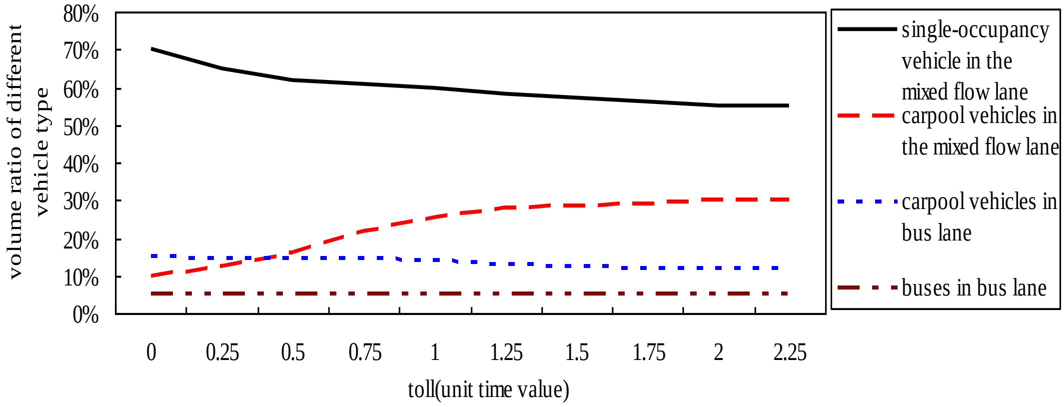

Fig 5. The volume ratio of different vehicle types with different toll rate

From the figures above, it is clear that: with the increment of toll, the number of carpool vehicles converting to the bus lanes reduced, when the toll decreased the situation is the opposite, so the toll is an effective way to regulate the number of carpool vehicles in bus lane.

6. OTHER ISSUES

Toll Collection Procedures

In order to avoid the delays associated with manual toll collection, HOT lanes rely on electronic payment systems or paid monthly passes during test pilot periods. Therefore, only those vehicles equipped with a transponder tag or valid permit may use the lanes.

Access Points

HOT lane facilities are normally separated from general-purpose travel lanes by physical barriers or lane markings. Access to the lane may be provided at intermittent points, but in many cases there may be only single entry and exit points. Barrier separation and the limited number of access points are important tools for managing traffic flows on HOT lanes.

7. CONCLUSION

In this paper, the method of excess capacity of bus lanes being used by carpool vehicles and congestion pricing being used to regulate the volumes of carpool vehicles in bus lanes is proposed. And analyzing the time and the qualified vehicles of the strategy, then put forward bi-level programming model, using advanced heuristic solution algorithm based on sensitivity analysis to solve the model .The method and the model proposed by the paper is practical to solve the problem of the congestion.

Acknowledgement

This work is supported by the National Natural Science Foundation of China (50908051).

References

Pan Dawei, Deng Wei, Qian Renjie.(2009). Study on congestion pricing model of bus lane mixed use by carpool vehicles. 9th International Conference of Chinese Transportation Professionals, 2900~2905

XU Wang-tu, HE Shi-wei, SONG Rui, LI Jua.(2008). Disaggregate Modal-split Model Considering Congestion Pricing.Journal of Transportation Systems Engineering and Information Technology, 8(3):96~102

Wu Jian-guo, Huang Jie-feng, Liu Ming-yuan, An Na.(2008). Double-mode modeling for the traffic congestion toll. Journal of ChangSha Communications University, 24(2):54~59

Zhou Jing, Sheng Zhao-Han, He Jian-Ming. (2001). Optimal fare design for public transport networks with elastic demand. Acta Automatica Sinica, Sept,27(5):637~643

Tobin R L, Friesz T L.(1988). Sensitivity analysis for equilibriumnetwork flow. Transportation Science, 22(3):243～250