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Modeling the Scheme Combined with Traffic Restriction and Special Lane Utilization

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Abstract

Traffic restriction scheme and special lane utilization are two normal measures in urban traffic management. This paper models the scheme combined with traffic restriction and special lane utilization on a traffic network. A variational inequality is adopted to describe the travelers' mode and route choice on the equilibrium condition. The model can be used for the determination of implementing the combined scheme for the better performance of traffic system in the process of traffic management.

Keywords

Urban Traffic Management; Traffic Network; Traffic Restriction; Special Lane Utilization; Model.

1. Introduction

Traffic congestion has been an obstacle for the development of the society due to the problems that traffic congestion brings, such as time waste, emission pollution, traffic accident, etc. Various measures have been emerged for mitigating congestion. For example, Beijing and Chongqing city use plate-number-based restriction in peak hours, and Stockholm and London use congestion pricing to adjust the travel demand and flow patterns. Special lanes have also been implemented in many cities. The common special lane is HOV (High Occupancy Vehicle) lane, which originated from the USA and has been adopted by many cities. Nevertheless, the measures always have superiority and drawbacks simultaneously. Thus, road managers still proceed on detecting how to alleviate congestion. Although many studies have devoted to the research of traffic restriction and special lane utilization respectively, few literatures have explored the effects of the scheme combined traffic restriction and HOV lane utilization.

There is a growing body of literatures in the filed of traffic restriction, including investigations of the performance on traffic networks within given restriction scheme (Han et al., 2010; Wang et al., 2010), and the design of optimal restriction scheme for the whole network (Shi et al., 2014; Chen et al., 2020). Bi-level programming is used to determine the optimal restriction scheme with the optimal restriction area and the proportion. (Nie, 2016) demonstrates that traffic restriction is not always valid since some population would buy two or more private vehicles to avoid the restriction.

As a special lane, HOV lanes are widely utilized all around the world while a large number of studies focus on it. With the regulation rejecting solo-driving vehicles to enter it, HOV lanes received positive effects in encouraging carpooling and thereby alleviating congestion (US Census Bureau, 2004). However, in some cases HOV lanes do not bring time saving. For instance, in California the HOV lanes lose its superiority on time saving (Plotz et al., 2010; Kwon and Varaiya, 2008). The reason is that number of the vehicles on the HOV lanes are insufficient. Therefore, the researches on better measures are still in the process.

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This paper devotes to the model the scheme combined traffic restriction and HOV lanes. With this model the road managers are able to determine the scheme to mitigate congestion. Section 2 describes the model formulation. And the model is discussed in Section 3.

2. Model Formulation

2.1. Cost Function

Consider a general network (G, A), where G is the set of the nodes and A is the set of the links. Assume A is the set of general purpose lanes and $\bar{A}$ is the set of HOV lanes. the set of OD pairs is W. d_w is the travel demand between OD pair w. The population travel by two modes: solo-driving s and carpooling h, and the set of travel mode is M. For simplicity, we assume that the HOV lanes have limited access. Namely, the travelers are forbidden to change lanes in the mid-way, which means we could describe the HOV lanes and general purpose lanes on one link as individual links. To be specific, the HOV lanes on link a is an individual link, and so it is the same with the general purpose lanes on link a.
The travel cost function of the two modes on a link is that:

$$t_a = t_a(v_a, C_a), \quad a \in A + \bar{A} \tag{1}$$

The cost on path l are:

$$c_{w,l}^{s} = \rho \sum_{l \in L} t_l \cdot \delta_a^l, \quad a \in A + \bar{A}, \mathrm{w} \in \mathrm{W} \tag{2}$$

$$c_{w,l}^{h} = \Delta + \rho \sum_{l \in L} t_l \cdot \delta_a^l, \quad a \in A + \bar{A}, \mathrm{w} \in \mathrm{W} \tag{3}$$

where ρ is the value of time, and Δ is the carpooling cost, including waiting time, extra fuel consumption, out-of-pocket cost, etc. δ_a^l is a binary variable. If link a is on path l, $\delta_a^l = 1$, and 0 otherwise.

2.2. Traffic Restriction

The solo-driving travelers are influenced by traffic restriction scheme. The solo-driving travelers who are restricted have to bypass the restriction area. If there is no alternative path, they have to convert the travel mode to carpooling. We use W^u and W^r to denote the OD pair in which the solo-driving travelers have and have no alternative path respectively. Then the minimal cost of the solo-driving travelers is expressed as:

$$\mu_w^s = \begin{cases} (1-\gamma)\mu_w^{su} + \gamma \mu_w^{sr}, & w \in W^u \\ (1-\gamma)\mu_w^{su} + \gamma \mu_w^{h}, & w \in W^r \end{cases} \tag{4}$$

where γ is the restriction proportion. μ_w^{su} is the minimal cost of the solo-driving travelers who are not restricted, and μ_w^{sr} is the s the minimal cost of the solo-driving travelers who are restricted with alternative paths. μ_w^h is the minimal cost of carpooling travelers.
The minimal cost of carpooling travelers is denoted as:

$$\mu_w^h = \min\left(c_{w,l}^h\right) \tag{5}$$

Therefore, the travel demand of mode m is that

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$$d_w^m = d_w \cdot P_w^m \tag{6}$$

Then we understand the travel demand with traffic restriction scheme. The travelers firstly decide to drive alone or carpool. The solo-driving travelers can be divided into two categories: the solo-driving travelers with and without accesses to the restriction area. The carpooling travelers and the solo-driving travelers without restriction are not influenced. The solo-driving travelers without accesses to restriction area are divided into two sub-categories: the solo-driving travelers who have alternative paths and those who have no alternative paths. The population without alternative paths have to choose carpooling. It means the carpooling travelers consist of two parts of travelers: the travelers who decide carpooling firstly and the travelers who have to choose carpooling with their initial willingness of solo-driving. The travel demand determination process is illustrated in Fig. 1.

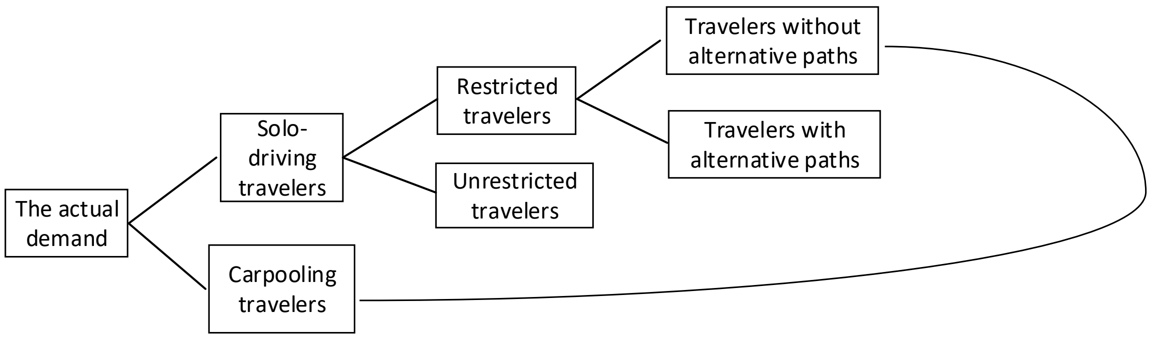

Figure 1. The travel demands

Fig. 1. illustrates that traffic restriction scheme affects the travel demand primarily. Then it impacts to traffic assignment through demand patterns and the restriction regulation, which implies that traffic restriction affects the network performance.

2.3. HOV Lanes

HOV lanes allows carpooling vehicles to enter and rejects solo-driving vehicles. In this paper we regard the HOV lanes and the general purpose lanes as individual links. It means the carpooling vehicles travel on the whole network and the solo-driving vehicles travel on the sub-network without HOV lanes. Therefore, the travel time of solo-driving vehicles on link a is expressed as:

$$t_a = t_a(v_a, C_a), \quad a \in A \tag{7}$$

And the travel time of carpooling vehicles on link a is:

$$t_a = t_a(\overline{v_a}, C_a), \quad a \in \bar{A} \tag{8}$$

where v_a is the vehicle flow on general purpose lane link and $\overline{v_a}$ is the vehicle flow on HOV lanes link. Note that the travel demand is individuals instead of vehicles. Let n be the average occupancy of a carpooling vehicle, then the vehicle flow on general purpose lane link is:

$$v_a = v_a^s + v_a^h, \quad a \in A \tag{9}$$

and the vehicle flow on HOV lane link is that:

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$$v_a = \frac{v_a^h}{n}, \quad a \in \bar{A} \tag{10}$$

where v_a^s and v_a^h are solo-driving vehicle flow and carpooling vehicle flow. It satisfies the relationship between the link vehicle flow and the path flow:

$$v_a = \sum_{w \in W} \sum_{l \in L} (f_{w,l}^s + \frac{f_{w,l}^h}{n}) \cdot \delta_a^l, \quad a \in A \tag{11}$$

$$v_a = \sum_{w \in W} \sum_{l \in L} \frac{f_{w,l}^h}{n} \cdot \delta_a^l, \quad a \in \bar{A} \tag{12}$$

where $f_{w,l}^s$ and $f_{w,l}^h$ are path flow on path l between OD pair w. Note that the flow is the individual flow instead of vehicle flow.

3. User Equilibrium of Traffic Assignment

After deciding travel mode, travelers start route choice. With the development of theories and technologies, travelers are able to obtain sufficient information about the state of the network, and the travel cost, etc., in an idea situation. Then all travelers would choose the route with minimal travel cost, and no one is able to receive lower cost by changing another route. This is user equilibrium (UE) state on the network. we use the following formulations to express UE:

$$c_{w,l}^m = \mu_w^m, \quad w \epsilon W, l \epsilon L, m \epsilon M, \text{if } f_{w,l}^m > 0 \tag{13}$$

$$c_{w,l}^m \geq \mu_w^m, \quad w \epsilon W, l \epsilon L, m \epsilon M, \text{if } f_{w,l}^m = 0 \tag{14}$$

The flow conservation follows:

$$\sum_{l \in L} f_{w,l}^s = (1-\gamma) d_w^s, \quad w \in W^u \tag{15}$$

$$\sum_{l \in L} f_{w,l}^s = \gamma d_w^s, \quad w \in W^r \tag{16}$$

$$\sum_{l \in L} f_{w,l}^h = d_w^h, \quad w \in W \tag{17}$$

$$d_w^s + d_w^h = d_w, \quad w \in W \tag{18}$$

$$f_{w,l}^m \geq 0, \; m \in M, \; w \in W, \; l \in L \tag{19}$$

The model above includes travel demand and flow. We can use Gauss-Seidel decomposition algorithm to capture the demand and flow patterns. Specifically, the procedure is illustrated in Fig. 2.

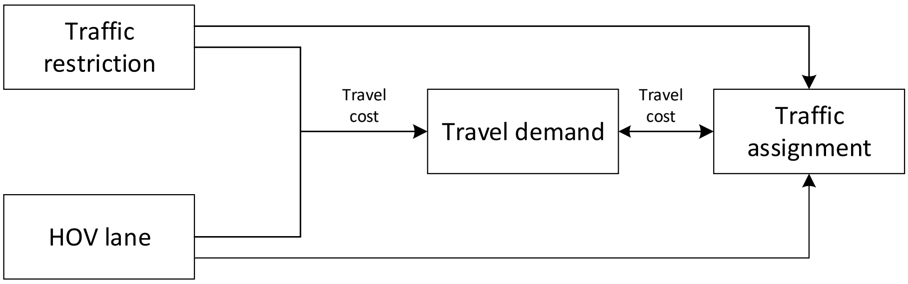

Figure 2. The algorithm procedure

The design of traffic restriction and HOV lane affects travel demand through travel cost, and traffic restriction scheme, HOV lane deployment and travel demand determine traffic assignment. Traffic assignment affects travel demand by travel cost simultaneously. Therefore, we use iteration approach to solve the model by capture the minimal travel cost, and then the travel demand and flow patterns.

4. Conclusion

This paper propose model to describe the scheme combined traffic restriction and HOV lane. We demonstrate the calculation of travel demand in the condition of traffic restriction and HOV lane deployment, and adopt a variational inequality to model the traffic assignment on UE. Then we describe the process of using Gauss-Seidel algorithm to solve the model. If the road managers intend to implement traffic restriction scheme and HOV lane scheme to manage traffic congestion, it is an preferable model to choose.

In this paper we just propose the model without the application. Real data is supposed to be applied to this model. Meanwhile, the optimal scheme with optimal traffic restriction and HOV lane deployment need to be detected to capture the optimal restriction area, proportion and the deployment of HOV lanes.

Acknowledgments

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