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Modeling traffic restriction scheme for e-hailing vehicles

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Abstract

This paper proposes a model to describe traffic restriction scheme for e-hailing vehicles. This paper used mathematical model to describe traffic restriction on e-hailing vehicles. Then similar to spatial model of taxi market, we propose ride-sourcing market with Logit split model and user equilibrium model of occupancy e-hailing vehicles and vacant e-hailing vehicles including the constraints in the condition of traffic restriction. Road managers are able to use this model to evaluate the impacts of traffic restriction on ride-sourcing market and determine the management.

Keywords

Urban traffic, traffic restriction, e-hailing vehicles.

1. Introduction

E-hailing vehicle is a type of burgeoning travel mode and has been focused on in an increasing number of studies. Travelers are able to apply vehicle transportation service via internet, and are assigned a vehicle. From the perspective of alleviating traffic congestion, it is like a double-edge sword. On one hand, it activates some idle vehicles for the purpose of satisfying travel demand, which increases social welfare. On the other hand, it leads to an increment of the number of vehicles on the network, which increases marginal cost of congestion and intensifies congestion. Therefore, it is necessary to use traffic management measures to manage e-hailing vehicle for better network performance.

As a common traffic management measure, traffic restriction has been utilized in many cities, e.g., Beijing, Chongqing, St. paul, Milan, etc., and received apparent effects. At present traffic restriction schemes are almost designed for all autos without classification. In the condition of marginal cost of e-hailing vehicles and the utilization of the idle vehicle, it is necessary to understand the impacts of traffic restriction on e-hailing vehicles. The first step is to model the equilibrium of the network on equilibrium in the presence of traffic restriction and e-hailing vehicles.

2. Literature Review

E-hailing vehicle has been paid a vast of attention since it emerged. In a transportation system, e-hailing vehicles consist of the ride-sourcing market, which normally includes the drivers, the passengers, the vehicle providers (the companies), etc. (Zha et al., 2016) used an aggregate model to analyze the economics of ride-sourcing market with the founding that the competition of ride-sourcing platforms may not bring higher social welfare. (Zha et al., 2018) proposed a framework to match the customers and drivers nearby and analyzed the effects of spatial pricing on equilibrium. (Ke et al., 2017) and (Ke et al., 2019) developed the deep learning approaches to forecast the e-hailing demand in a matching framework.

Many studies have focused on traffic restriction. The effects of the given restriction scheme are explored (Han et al., 2010; Wang et al., 2010). In addition, (Shi et al., 2014) proposed a bi-level

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programming for the optimal design of traffic restriction scheme. The restriction area and the proportion are taken as variables and captured from the bi-level model by genetic algorithm. (Chen et al., 2020) built a bi-level programming to optimize the restriction scheme from the perspective of one week, and captured the plate-end-numbers which are supposed to be restricted. However, (Nie, 2017) pointed out that traffic restriction is not always valid since some travelers would buy two or more vehicles to avoid the restriction regulation.

At present few literatures focus on the impacts of traffic restriction to e-hailing vehicles. This paper establishes a model to describe the equilibrium ride-sourcing market with a traffic restriction scheme. From the model the network performance can be captured.

3. Prelininaries

Consider a network (G, A), where G is the set of the nodes and A is the set of the links. The notations are listed as follows:

M the set of travel modes. In this paper there exists two modes: e-haling vehicle mode e and the alternative mode θ.

L the set of paths

R the set of origins

S the set of destinations

d_{rs} the e-hailing travel demand between OD pair rs

f_{rs}^{p} the e-hailing vehicle flow on path p between OD pair rs

t_a^0 Free flow travel time on link a

t_a travel time on link a

The generalized travel cost function of occupancy e-hailing vehicles on path l between OD pair w can be expressed as:

$$c_{rs,p}^{e} = \left(\lambda \cdot \sum_{l\in L} t_a \cdot \delta_a^p\right) + \rho \cdot l + \tau \cdot \sum_{l\in L} (t_a - t_a^0) \cdot \delta_a^p, \quad a \in A, r \in R, s \in S \tag{1}$$

where λ is the value of time. δ_a^p is a binary variable, which equals 1 when link a is on path p, and 0 otherwise. ρ is the unit price of length of path p, and l is the length. τ is the unit price per time, and t_a^0 is the free flow travel time on link a.

For simplicity, we assume the traffic restriction in this paper is cordon-based restriction. This is a widespread form of traffic restriction due to its convenience to implement. It includes two components: the restriction area and the restriction proportion.

4. Model Formulations

4.1. Traffic Restriction

In terms of a traffic restriction scheme, we set the proportion γ as the restriction proportion, which means $\gamma \cdot d_{rs}$ travelers are forbidden to enter the restriction area while $(1-\gamma) \cdot d_{rs}$ travelers have accesses to enter the restriction area. If the travelers who are in restriction have alternative path to bypass the area, they would choose it, and if not, they would convert to alternative mode. For simplicity, we assume the generalized cost of the alternative mode on path p is $\theta_w^p(d_p)$, which is an increasing function of the total demand of this mode. We use (R^u, S^u) and (R^{re}, S^{re}) to denote the origins and destinations in which travelers have or have no alternative paths. Therefore, the generalized minimal cost of e-hailing travelers is denoted as:

$$\mu_{rs}^{e}=\begin{cases}(1-\gamma)\mu_{rs}^{e,u}+\gamma\mu_{rs}^{e,r}, & r\in R^{u}, s\in S^{u}\\(1-\gamma)\mu_{rs}^{e,u}+\gamma\mu_{rs}^{e,\theta}, & r\in R^{re}, s\in S^{re}\end{cases} \quad (2)$$

where $\mu_{w}^{e,u}$ is the minimal cost of the travelers who are not restricted, and $\mu_{w}^{e,r}$ is the s the minimal cost of the travelers who are restricted with alternative paths. μ_{w}^{θ} is the minimal cost of the travelers with alternative mode, which is denoted as:

$$\mu_{rs}^{\theta}=\min\left(\theta_{rs}^{p}\right) \quad (3)$$

Logit model is adopted to describe the demand of each mode, which is denoted as:

$$d_{rs}^{m}=d_{rs}\cdot\frac{\exp(\mu_{rs}^{m})}{\sum_{m}\exp(\mu_{rs}^{m})}, \qquad r\in R, s\in S, m=e,\theta \quad (4)$$

4.2. Ride-sourcing market

E-hailing vehicles travel according to the orders. After arriving at the destinations, they will travel back to the origins to take other passengers. The spatial distribution of e-hailing vehicle market in a traffic system is very similar to that of taxi market. Thus, we are able to use the taxi model approach to describe the e-hailing vehicle market. It is worth noticing that e-hailing vehicles receive orders via internet instead of cruise, which implies that the searching time can be estimated precisely.

The demand distribution of e-hailing vehicles satisfies the following relationship:

$$\sum_{s\in S}d_{rs}^{e,o}=O_{r}^{e,o}, \qquad r\in R \quad (5)$$

$$\sum_{r\in R}d_{rs}^{e,o}=D_{s}^{e,o}, \qquad s\in S \quad (6)$$

$O_{r}^{e,o}$ and $D_{s}^{e,o}$ are the generation and attraction demands for the occupied e-hailing vehicle from origins to destinations respectively. The distribution of vacant e-hailing vehicle is based on the trips of occupied e-hailing vehicle, which can be expressed as follows:

$$\sum_{r\in R}d_{sr}^{e,v}=D_{s}^{e,o}, \qquad s\in S \quad (7)$$

$$\sum_{s\in S}d_{sr}^{e,v}=\sum_{s\in S}D_{s}^{e,o}\cdot\frac{\exp[-\sigma(\mu_{sr}^{e,v}+\lambda_{v}\cdot w_{r}^{e,v}]}{\sum_{r\in R}\exp[-\sigma(\mu_{sr}^{e,v}+\lambda_{v}\cdot w_{r}^{e,v}]}=O_{r}^{o}, \qquad r\in R \quad (8)$$

where $\mu_{sr}^{e,v}$ is the minimal travel cost of vacant e-hailing vehicles from destination s to origin r, and σ is the non-negative parameter. λ_{v} is the value of time of e-hailing vacant vehicle. $w_{r}^{e,v}$ is the searching time of a passenger. Comparing to taxis, the searching time of e-haling vehicle passengers is more precise since the drivers are able to know the exact position of the passengers from internet. Therefore, we set the searching time is a constant.

The following constraint is supposed to be satisfied in 1-h e-hailing vehicle market:

$$\sum_{r\in R}\sum_{s\in S}d_{rs}^{e,o}h_{rs}+\sum_{s\in S}\sum_{r\in R}d_{sr}^{e,v}(h_{sr}+w_{r}^{e,v})=N \quad (9)$$

where N is the fleet size of e-hailing vehicles in the market. Eq. 11 demonstrates the total number of e-hailing vehicles in one hour at this service level, which connect the service time to the fleet size of the vehicles. h_{rs} and h_{sr} are the average travel time of occupied and vacant e-hailing respectively, and can be calculated by:

$$h_{rs}=\frac{\sum_{p}\left(f_{rs,p}^{e,o}\cdot\sum_{a\epsilon A}t_{a}\cdot\delta_{a,p}^{rs}\right)}{\sum_{p}f_{rs,p}^{e,o}} \quad (10)$$

$$h_{sr} = \frac{\sum_{p_v}\left(f^{e,v}_{sr,p_v} \cdot \sum_{a\epsilon A} t_a \cdot \delta^{sr}_{a,p_v}\right)}{\sum_{p_v} f^{e,v}_{rs,p_v}} \tag{11}$$

where p_v is the path of vacant e-hailing vehicles from destination s to origin r.

4.3. Traffic Assignment

In an idle situation, travelers receive perfect information about the network so that they can choose travel route, and the network reaches equilibrium. In this paper we use user equilibrium (UE) to describe the state on the network. At UE, every traveler chooses the path with minimal cost, and no one can lower the cost via changing his/her path. It can be described as follows:

$$c^m_{sr,p} = \mu^m_{sr,p} \ \text{ if } f^m_{sr,p} > 0,\ m = e,\theta \tag{12}$$

$$c^m_{sr,p} \geq \mu^m_{sr,p} \ \text{ if } f^m_{sr,p} = 0,\ m = e,\theta \tag{13}$$

Meanwhile, the vacant e-hailing vehicle drivers also follow UE, which is expressed as:

$$c^{e,v}_{sr,p_v} = \mu^{e,v}_{sr,p_v} \ \text{ if } f^{e,v}_{sr,p_v} > 0 \tag{14}$$

$$c^{e,v}_{sr,p_v} \geq \mu^{e,v}_{sr,p_v} \ \text{ if } f^{e,v}_{sr,p_v} = 0 \tag{15}$$

The constraints is organized by:

$$\sum_{p\in P} f^{e,o}_{rs,p} = (1-\gamma)d^e_{rs},\ \ s \in S^u, r \in R^u \tag{16}$$

$$\sum_{p\in P} f^{e,o}_{rs,p} = \gamma d^e_{rs},\ \ \ s \in S^{re}, r \in R^{re} \tag{17}$$

$$\sum_{p\in P} f^{\theta}_{rs,p} = d^{\theta}_{rs},\ \ \ s \in S, r \in R \tag{18}$$

$$d^e_{rs} + d^{\theta}_{rs} = d_{rs},\qquad s \in S, r \in R \tag{19}$$

$$f^m_{rs,p} \geq 0,\qquad m = e,\theta \tag{20}$$

The constraint of vacant e-hailing vehicle can be formulated as follows:

$$\sum_{p\in P} f^{e,o}_{sr,p} = (1-\gamma)d^e_{sr},\ \ s \in S^u, r \in R^u \tag{21}$$

$$\sum_{p\in P} f^{e,o}_{sr,p} = \gamma d^e_{sr},\ \ \ s \in S^{re}, r \in R^{re} \tag{22}$$

The model above describes the traffic assignment of e-hailing vehicle and alternative mode with traffic restriction scheme. From the UE of occupancy e-haling vehicle assignment we know the distribution of the occupancy e-hailing vehicles, based on which we capture the distribution of vacant e-hailing vehicles. Gauss-Seidel algorithm can be utilized to solve the two variational inequalities. First of all, we set an initial feasible solution to compute the demands of occupancy e-hailing vehicles and the alternative mode. Then we obtain the demand of vacant e-hailing vehicles. After that we solve the variational equality by some existing approaches. Then we capture the flow patterns and to evaluate the effects of the scheme.

5. Conclusion

On the basis of the advantage that the e-hailing vehicle releases potential transportation capacity and the drawback that it brings marginal cost to traffic network, we propose that traffic restriction can be implemented for e-hailing vehicles. The variational equalities are established to describe the UE state on the network with traffic restriction. Gauss-Seidel algorithm is briefly introduced for the model. Built on that we are capable of obtaining the flow patterns and evaluating the network performance.

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In the future direction the measurement of network performance should be determined to apply the model to real cases. And the optimal traffic restriction scheme is worth being explored for better traffic management. In addition, some other assignments such as stochastic user equilibrium and that based on prospect theory can be considered.

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