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Optimal toll of new highway in the equilibrium framework of heterogeneous households' residential location choice

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ABSTRACT

Because of limited budget and the consideration of transportation demand management, most of the new highways will be tolled after putting them into use. Meanwhile, lots of people belonging to different sectors of society flocked to city to search for jobs and better living each year. Therefore, for the government departments, one of most important issues is to determine the optimal toll of new highway under the background of ever-increasing households. This paper proposes an optimal toll model in the equilibrium framework of heterogeneous households' residential location choice. It is formulated as a bi-level program. In the upper-level subprogram, government departments determine an optimal toll of new highway in order to minimize urban system's total travel time. However, the construction and toll charge of the new highway will totally change urban traffic condition, and thus under the assumption of a complete market economy it will further affect the new households' location and commute behavior. Here, new households' location choice behavior has been modeled based on reference-dependent theory and household balance model. And their route choice behavior has been formulated as the multi-class multi-criteria stochastic user equilibrium model. This combined residential location choice and traffic assignment problem has been formulated by fixed point theory as the lower-level program. Finally, a genetic algorithm based solution approach is used to solve this optimization problem. In addition, a set of numerical experiments has been conducted to demonstrate the properties of this problem and the performance of our proposed model. And some interesting conclusions have been given.

1. Introduction

Nowadays, lots of people belonging to different sectors of society have flocked to city to search for jobs and better living. Depending on the latest statistics, in the past year, the populations of Beijing and Singapore increased by approximately 200 thousand and 72 thousand, respectively. Meanwhile, government departments make new highway construction plan to release traffic congestion. Numerous highways[1] will be built in metropolitans all over the world. Because of limited budget and the consideration of transportation demand management, most of them will be tolled after putting them into use. According to the latest report by the Beijing Transport Institute (BJTI, 2016), approximately 886.1 km, 90.2% of Beijing highway mileage, is tolled. Therefore, for the

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[1] We use highway (in the broad sense) represents those large-scale construction projects of transportation infrastructure, such as subsea tunnel, cross-sea bridge, etc. They all have the characters as mentioned in Section 2.

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management department, one of most important issues is to determine the optimal toll of new highway under the background of ever-increasing households.

For this kind of infrastructure construction, it has the following two characters: (1) It belongs to large-scale construction projects of transportation infrastructure which will totally change the urban traffic condition. (2) It will be tolled after putting them into use. And once the fee charge standard is made, it will be adopted for more than ten years or several decades. Thus the construction and toll charge of new highway will significantly change residents' commuting cost for a long period of time, and thus further affect the new households' residential location behavior (Vega and Reynolds-Feighan, 2009; Tillema et al., 2010; Ibeas et al., 2013). Namely, it has a significant effect on urban spatial distribution. Therefore, determining where those new residents will choose to live when the city reaches to a new equilibrium is the key issue need to be solved before determining toll of new highway. However, the complex interrelationship between transportation and households' location choice, commute behavior makes it difficult to determine an optimal toll of new highway with respect to the whole urban system.

In fact, the optimal toll design problem has been studied for quite a long time. It is well known that a first-best marginal cost toll is charged on each link to drive a user equilibrium flow pattern toward a system optimum in a general network (Yang and Huang, 1998; Yang and Zhang, 2003). Because of its high operating cost and poor public acceptance, the second-best road pricing problem is proposed (Verhoef, 2002; Yang and Huang, 2005). It is assumed that only some of its major congested links charged rather than the entire road network. In addition, based on the consideration that traffic cost between different OD pairs will affect their traffic demand, the first-best marginal cost pricing and second-best road pricing problem have been extensively studies with the assumption of elastic demand (Sumalee and Xu, 2011; Verhoef, 2002). However, commuting is a kind of indispensable travel, total traffic demand will not change no matter how the travel cost it is. Therefore, the assumption of elastic demand isn't suitable for this case. The effect of toll charge on the travelers' route choice has been explicitly studied in previous studies. But once traffic toll charge has been taken as a long-term strategy, it will affect households' daily commuting cost and further affect households' location choice behavior (Waddell, 2011; Su et al., 2014; Ng and Hong, 2015; Zhong et al., 2015). Recently, based on the studies of transportation and land use (Li et al., 2012, 2013), Li has detailedly studied the effects of vehicle emission taxes on residential segregation based on the classical monocentric city model (Li and Peng, 2016), which was proposed by Alonso (1964), Muth (1969) and Mills and Hamilton (1972). It is found that different vehicle emission taxes will lead to the totally different layout of heterogeneous households. However, the classical monocentric city model is assumed that the workplace is exogenous or located at a CBD that does not occupy any land but employs the city's entire labor force (Alonso, 1964; Waddell, 1993; Li et al., 2012, 2013). Many researchers believe that those models become more realistic if this assumption (monocentric city) is relaxed, producing results consistent with empirical evidence in terms of several aspects of urban form (Ogawa and Fujita, 1980; Waddell, 1993).

The effect of construction of new road on the traveler's route choice behavior has been detailedly studied in the traditional network design problem (NDP). But it always neglected further changes in land use (Yang and Huang, 1998; Gao et al., 2005). The residential location and transportation cycle is a well-known phenomenon for urban planners and transportation engineers, which is important for the formulation of effective urban or traffic planning strategies (Anderstig and Mattsson, 1991; Yim et al., 2011). Levinson et al. (2007) firstly proposed a co-evolution model of land use and transportation. In their model, road agents of each individual road toll each link and use the money for improving the corresponding link capacity. Then the improvement of traffic condition will further cause redistribution of population and employment in the city. In 2016, Li expanded this co-evolution model into a new integrated co-evolution model of land use and traffic network design. They simplified that government department made road investment from the perspective of the whole traffic network but not the single road (Li et al., 2016). Besides, from the point of view of government planning, Yim proposed a problem considering a set of budgets for the residential and employment development and network enhancement in an urban system. In his model, the government makes the decision regarding the number of households and companies in every zone (Yim et al., 2011). However, as for the modeling of distribution of households, they (Levinson et al., 2007; Yim et al., 2011; Li et al., 2016) all belong to the aggregate level modeling not from the individual behavior's point of view. Based on the assumption of a complete market economy, from the individual behavior's point of view, Li studied households' residential location choice behaviors based on Alonso's household balance model (Alonso, 1964). It established the relationship between housing pricing and commuting costs, which is directly correlated with transport infrastructure conditions. It was then used as an integrated model of rail line design and property development in a linear monocentric city (Li et al., 2012). In 2013, they proposed an analytical urban system equilibrium model to optimize the density of radial major roads in a two-dimensional monocentric city (Li et al., 2013). However, for the convenience of continuous modeling, their work is all based on the classical monocentric city model. Compared to the continuous modeling approach, the discrete modeling approach better captures the realistic characteristics of transportation networks, and is thus more appropriate for the detailed planning and design of transportation systems (Li et al., 2014). More recently, based on the discrete modeling approach, a nested multinomial logit model combined with the bid-rent process was formulated to model residents' location and travel choice, with the problem of housing supply integrated into the framework (Ma and Lo, 2012; Ng and Hong, 2015). As for the new households' location choice behavior, based on the assumption of a complete market economy and the individual behavior's point of view, there are few researches in this area.

For the household residential location choice behavior, each household of the urban system chooses the residential location to maximize his/her household utility. When household residential location choice equilibrium state is reached, all households belonging to the same income class have the same utility regardless of their residential locations. And no one can increase his/her household utility by unilateral action. This theory has been proposed and widely studied by many previous literates (Alonso, 1964; Li et al., 2012, 2013, 2016). Obviously, new residents' location choice behavior also obeys the rule as described above. Furthermore, from the individual behavior's point of view, it found that, in reality, people exhibit a natural tendency to compare themselves with their peers and take others' choice as a reference point when they make a choice decision. In addition, people care more about the