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A game-theoretic model of car ownership and household time allocation

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ABSTRACT

The explosive growth of private cars in China and other developing countries has attracted a great deal of renewed research interest in car ownership. This paper investigates households' car ownership decision-making process from the perspective of household time allocation. Applying the game-theoretic approach to capturing household members' interactive decision-making mechanism, we propose a two-stage model that links household members' short-term time allocation decisions to long-term car ownership decisions. The first stage models the bargaining of household members (e.g., husband and wife) over the car ownership decision, taking into consideration of government policies for regulating car ownership; and the second stage is a generalized Nash equilibrium model for activity-travel pattern analysis incorporating individuals' interactions concerning activity participation. The existence and uniqueness of the generalized Nash equilibrium solution is examined, and a heuristic procedure that combines backwards induction and method of exhaustion is adopted to solve the two-stage game. The proposed model is applied to an empirical case study in Beijing, which demonstrates the applicability of the model in predicting car ownership and examining interactions between car ownership and household time allocation. The empirical model is applied to assess the impacts of plate-number-based vehicle usage rationing policies on car ownership and time allocation to travel and daily activities. Results show that the model can be applied to evaluate the car ownership impacts of car usage rationing policies.

1. Introduction

1.1. Background and motivation

The fast economic growth has greatly contributed to the rapid pace of motorization in developing countries in recent years. Taking China as an example, it experienced an exponential growth in total number of private cars in less than a decade, from 18.5 million in 2005 to 88.4 million in 2012. In the same period, the number of private cars in Beijing, the capital of China, nearly tripled from 1.5 million (14.1% household car ownership) to 4.1 million (42.3% household car ownership) .[1] The fast growth in vehicle ownership has resulted in serious traffic congestion and air pollution problems. As a

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[1] Information source: National Bureau of Statistics of China. http://www.stats.gov.cn/.

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response, since 2008, the transportation authority in Beijing has been implementing the plate-number-based vehicle usage rationing policy with the objectives of mitigating traffic congestion as well as discouraging car ownership. The policy stipulates the usage of cars with certain plate numbers on specific workdays.[2] This policy intervention may have helped in restraining people's desire to buy cars, but it may also turn out to motivate financially well-off people to buy additional cars in order to maintain access to cars (Goddard, 1999). Therefore, research efforts are needed to investigate the real effects of policy measures such as the vehicle usage rationing policy on car ownership. Further, the interrelationship between car usage and time allocation have been revealed in the literature (e.g., Golob et al., 1995; Ding et al., 2014), it is thus worth noting that car ownership plays an important role in facilitating household members' engagement in daily activities and associated travel (Li et al., 2010). Although previous studies have made significant contributions to acknowledging the influence of car usage on time allocation patterns and investigating the decision mechanism of household car ownership, they can hardly tackle questions regarding how household members make tradeoffs regarding spending money on cars to save travel time for activity participation, to what extent car usage influences the daily time allocation to activities, and how the vehicle usage rationing policies impact car ownership decision and the resultant time allocation decision, etc.

1.2. Previous studies on car ownership

With respect to static modelling, there are in general two approaches to modelling car or auto ownership in the existing studies. The first approach applies the computationally efficient aggregate models that predict car ownership at zonal, regional or national level (see Jong et al., 2004 for a detailed review); the second approach makes use of the disaggregate models (often at household level), which treat single household as a decision making unit and examine the determinants of household car ownership such as household social-economic variables and built environment attributes (Bhat and Pulugurta, 1998). By dealing with individual households separately, some researchers argued that the disaggregate modelling approach was demonstrated to be more appropriate and preferable to car ownership modeling in terms of reducing aggregation bias, estimating high precision model parameters, and addressing human behavior (Potoglou and Kanaroglou, 2008).

When addressing household car ownership problem itself or the interrelation between household car ownership and other long-term/short-term choices at a disaggregate level, disaggregate car ownership models in literature usually take the form of discrete choice because car ownership is a categorical variable (Li et al., 2010; Pinjari et al., 2011). Depending on whether the ordinal nature of car numbers is utilized in the modeling mechanism or not, the discrete choice over car ownership alternatives can be further divided into ordered-response models represented by ordered-response logit and ordered-response probit (Golob and Van Wissen, 1989; Bhat and Koppelman, 1993; Kim and Kim, 2004), and unordered-response models including multinomial logit (MNL) and multinomial probit (MNP) models. Ordered-response structure has the advantage of discerning unequal differences between ordinal categories in a dependent variable, but Bhat and Pulugurta (1998) empirically demonstrated that unordered-response structure could more closely represent car ownership decision-making behavior. Within unordered-response models, multinomial logit was most frequently used for car ownership study (e.g. Lerman, 1976; Purvis, 1994; Ryan and Han, 1999; Potoglou and Kanaroglou, 2008), and it has been applied to different geographical areas since its first introduction by Lerman and Ben-Akiva (1976). As an extension structure of the MNL model, the nested logit model was also used for multidimensional cases when jointly dealing with car ownership choice and other possible choices such as mode (Train, 1980) and vehicle type (Mannering and Winston, 1985). Besides, the MNL model was combined with group decision theoretic approaches to examine interactions among household members on car size choice (Zhang et al., 2009). Another representative type of unordered-response model, the multinomial probit model was also applied by Bunch and Kitamura (1989) to auto ownership prediction. But as they stated, MNP is less commonly used due to its various computational difficulties associated with parameter estimation.

Apart from these static models, researchers have begun to model car ownership from a dynamic perspective recently. Roorda et al. (2009) proposed an integrated model of dynamic vehicle transactions (change car ownership by purchasing, disposing or replacing vehicles) and activity scheduling/mode choice, where intra-household interactions of vehicle allocation, ridesharing, and drop-off/pick-up of household members were considered. More choice dimensions were addressed by embedding a discrete-continuous choice model into a dynamic programming framework, which allowed a joint modelling of transaction type, annual driving distance, fuel type, car ownership status and car state relative to each car in a household's fleet (Glerum et al., 2013). The existing dynamic discrete choice models based on pure dynamic programming perspective were improved by Cirillo et al. (2015) in the aspects that the optimal time of purchase must be decided and quality of different vehicles types changed stochastically over time.

However, the above-mentioned methodologies of disaggregate modeling employed in car ownership research generally ignore the individual differences and interactions within a household in reaching an agreement on car ownership decision (in terms of number of cars to own). They usually treat a household as if it were an individual, despite the fact that intra-household interactions in decision making have gained research attention in recent decades (Bhat and Pendyala, 2005; Timmermans and Zhang, 2009; De Palma et al., 2016). Indeed, male head, female head, children and other household members with different car ownership or car usage preferences may interact with each other by means like bargaining to reach a final agreement. Roorda et al. (2009) and Meister et al. (2005) dealt with intrahousehold interactions of vehicle allocation

[2] Information source: Official website of Beijing Traffic Management Bureau. http://www.bjjtgl.gov.cn/jgj/95332/127211/index.html