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Travel mental budgeting under road toll: An investigation based on user equilibrium

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ABSTRACT

With the approach of introducing the conceptions of mental account and mental budgeting into the process of travelers' route choice, we try to identify why the usages of tolled roads are often overestimated. Assuming that every traveler sets a mental account for his/her travel to keep track of their expense and keep out-of-pocket spending under control, it addresses these questions such that "How much money can I spend on the travel?" and "What if I spend too much?". Route tolls that exceed the budget are much more unacceptable compared to those within budget due to the non-fungibility of money between different accounts. A simple network with two nodes and two routes is analyzed firstly, the analytical solutions are obtained and the optimal road tolls supporting the user equilibrium as a system optimum are also derived. The proposed model is then extended to a generalized network. The multiclass user equilibrium conditions with travel mental budgeting are formulated into an equivalent variational inequality (VI) problem and an equivalent minimization problem. Through analyses with numerical examples, it is found that the main reason that the usages of high tolled roads are often overestimated is due to the fact that travelers with low and moderate out-of-pocket travel budget perceive a much higher travel cost than their actual cost on the high tolled roads.

1. Introduction

Due to the perfect theoretical properties, the notion of user equilibrium (UE) has been used widely in the urban transportation planning and management studies, e.g., transportation network design problem, transportation demand modeling, and traffic congestion pricing. The UE conditions, given by Wardrop (1952), formulate that, when no individual traveler can improve his or her travel time by unilaterally changing routes. Later, Beckman et al. (1956) provided the formulations of the UE problem in the form of a mathematical program and LeBlanc et al. (1975) applied the Frank–Wolfe algorithm to solve the Beckmann model and made the traffic assignment of large network possible, practical implementation of UE in the traffic demand analysis has been progressed rapidly.

Although UE is very useful in transport studies, the assumptions are restrictive in the sense that it requires all drivers have perfect knowledge on traffic conditions, can calculate the travel cost of every route, and can make perfectly rational route choices. Traffic equilibrium models that can improve the realism of the assumptions have been studied extensively in recent years. Generally, these modified models fall into the following four groups. (1) The stochastic user equilibrium

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models. This kind of models is based on the assumption that all drivers try to minimize their perceived travel cost. In their assumptions, drivers do not know the actual travel cost exactly and they perceive their travel cost differently according to their degree of familiarity to the road network (e.g. Daganzo and Sheffi, 1977; Yu et al., 2014; Kitthamkesorn and Chen, 2014); (2) the travel time reliability models. The uncertain traffic environment is considered and travel time reliability is an important factor influencing travelers' route choice (e.g., Lo et al., 2006; Shao et al., 2006; Zhou and Chen, 2008; Chen and Zhou, 2010; Tan et al., 2014); (3) the schedule delay models with early/late arrival penalty. In this kind of models, drivers must suffer extra penalty if they are early/late, therefore their travel cost includes the early/late penalty (e.g. Alfa, 1986; Ben-Akiva et al., 1986; Vythoulkas, 1990; Watling, 2006); (4) the bounded rational user equilibrium models. This kind of models includes the BRUE model (e.g. Lou et al., 2010; Di et al., 2013), the prospect-based models (e.g., Avineri, 2006; Connors and Sumalee, 2009; Xu et al., 2010) and the reference-dependent model (e.g. Delle Site and Filippi, 2012; Bao et al., 2014). They all assume that travelers do not always make rational choices perfectly.

All these modified models show that it could be not enough if only the travel time and monetary cost (the road tolls) are considered in the route choice model. When considering the road tolls, another important question is that the usages of the tolled roads are often overestimated. Especially in the two routes (one tolled and the other not) network, as is often the case, the untolled routes is very congested while the flow on the tolled routes is very low. An important example of this is the highway road network consisting of the Capital Airport Express route and the Jingping Express – the Jingcheng Express route in Beijing. After the Capital Airport Express stopped charging travelers from the Capital Airport to the urban area (while the Jingping Express – the Jingcheng Express still charges 15 RMB), its flow increased forty percent, while the flow of the Jingping Express – the Jingcheng Express route is much lower (Deng, 2011). Another example of overestimation is the Fifth Ring Road in Beijing. When the Fifth Ring Road was tolled in 2003, the average flow is 200–300 veh/h while its capacity is 3000 veh/h. The usage of the road was far below the planners' estimation, as was the total revenue collected every day. Because the Fifth Ring Road is a BOT project, the low usage and revenue led to a very embarrassing situation. At last, the government had no choice but to stop the traffic charge. Through tough negotiations with the private firm, the government paid large amount of money and all sides suffered great losses (Zhang, 2004).

To approach this overestimation question, we introduce the conceptions of mental account and mental budgeting into the prediction of travelers' route choice. Mental account is an important conception of behavioral economics. It refers to the psychological separation of economic categories and has been applied in many fields, such as financial investment (e.g., Shefrin and Statman, 1987), and consumption (e.g., Shefrin and Thaler, 1988). Individuals and households use mental accounts to keep track where their money is going, and to keep spending under control (Thaler, 1999). For example, people may divide their income into different categories and group their expenditures into budgets (e.g. food, housing, travel, etc.). Mental accounting in this sense is called mental budgeting and violates the assumption of the fungibility of money (Thaler, 1990, 1999; Antonides et al., 2011). Hess et al. (2012) investigated the consistency and fungibility of monetary valuations in transport and suggested that the assumption of fungibility does not hold. Other studies about mental account and mental budgeting in traffic equilibrium models are rare. However, travelers may consider questions like "How much money can I spend on the travel?" and "What if I spend too much?" in their trip decision-making. It is necessary to adopt mental account and mental budgeting in travelers' route choice.

In this paper, we assume that every traveler sets a travel mental account to track and control the money spent in travel. With a travel mental account, travelers will be more prudent in choosing tolled routes. Once the road tolls exceed their out-of-pocket travel budget, travelers will perceive a much larger travel cost than their actual travel cost. To keep their spending within budget, travelers will try to choose routes with no or less toll charge. Only when the travel time savings are very large, travelers consider choosing routes charging more tolls than their budget. This explains why the usages of the tolled roads are often far below expectation.

The out-of-pocket travel budget is defined as the maximal money allocated to the trip in their travel mental account. It depends on travelers' socio-economic characteristics, especially the income levels. We assume that travelers' out-of-pocket travel budget is a continuous random variable, and follows a continuous probability distribution. When making route choices, the generalized travel cost perceived by travelers consists of three parts: (1) route travel time; (2) road tolls; and (3) over-budget penalty. If the route toll is smaller than travelers' budget, the over-budget penalty is zero. Route travel time is changed into monetary unit through travelers' value of time (VOT). Because travelers' VOT also depends on their socio-economic characteristics, we assume that it is the continuous function of the out-of-pocket travel budget. Therefore the VOT is also a continuous random variable.

The organization of this paper: we firstly propose the over-budget penalty function in Section 2. Then a two nodes two routes network is analyzed in Section 3 and some analytical results are obtained. In Section 4, the problem is extended to a general network and some theoretical analyses are presented. An equivalent variational inequality (VI) problem and its algorithm are proposed in Section 5. Section 6 presents two numerical examples to investigate how the travel mental budgeting affects the performance of the road network and travelers' welfare. The paper is concluded in Section 7.

2. Over-budget penalty function

People often divide spending into budget categories and track expenses against their budgets. Different from the traditional economic theory, money in mental budgeting is labeled for particular spending or saving categories, and the budgets