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A Stochastic User Equilibrium Model and Optimal Congestion Pricing with Prospect Theory

Xiaofeng Pan, Zhi Zuo*

School of Transportation & Logistics, Dalian University of Technology, No.2 Linggong Road, Ganjingzi District, Dalian 116024, China

Abstract

In spite of the fact that expected utility theory is a main method to model people's travel choice behavior under uncertainty, the assumption that each decision maker (DM) is completely rational limits its wide application. This paper applies prospect theory, which can appropriately describe DMs' bounded rational behavior, to route choice behavior analysis and develops an improved stochastic user equilibrium model and finally analyzes optimal congestion pricing. We find that the prospect in prospect theory could be regarded as a special utility in some degree. Based on this result we assume that the prospect of each route is constituted by a fixed term and a random one, and then proposed the concept of perceived prospect. Further assumption is that the random variable follows some certain normal distribution and then a probit model is put forward. Considering the complexity of probit model, Monte Carlo simulation is brought into the solution algorithm of MSA. A numerical example is given to show the impact of uncertainty, including subjective and objective uncertainty that travelers have to deal with. Congestion pricing is also taken into account to express the influence of traffic management policy on traffic flow on a network. At last, an approximately optimal charging standard is proposed through comparing one-link charging and two-links charging. The results prove the effectiveness of congestion pricing. Further research shows that there are 1.91% and 2.71% drops of total travel time and total travel cost respectively when achieving the optimal charging standard.

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Keywords: urban transporatation; stochastic user equilibrium; prospect theory; probit model; congestion pricing

* Corresponding author. Tel.: +86-151-8403-8958; Fax: +86-(0)411-8470-9687.
E-mail address: zuozhi@dlut.edu.cn.

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1. Introduction

Traffic equilibrium models play an important role in travel demand analysis. Researches must consider the uncertainty of urban transportation system when analyzing and simulating travelers' route choice behavior. Conditionally, expected utility theory (EUT) is a main method to reveal the decision-making process under uncertainty. Whereas the weakness of rational agent hypothesis restricts is wide application. For instance, Allais Paradox and Ellsberg Paradox are two obviously famous exceptions of EUT.

To accommodate such violations, prospect theory (PT, Kahneman and Tversky, 1979, 1992) was proposed. It reflects DMs' bounded rationality and puts emphasis on their behavior from perspective of gain and loss, therefore is more appropriate and promising than EUT, especially when information is provided. It seems to be a trend to apply PT to transportation network analysis.

Sumalee et al. (2009) applied the decision framework of PT to capture the difference of decision making process between with and without uncertainty. Gao et al. (2010) dealt with route choice models capturing travelers' strategic behavior when adapting to revealed traffic conditions en route in a stochastic network. Xu et al. (2011) proposed a conjecture on travelers' determination of reference points and encapsulated it into the prospect-based user equilibrium conditions.

Generally speaking, each existed study has its own focus. However, in most studies travel time is the only influence factor and other factors are treated as additional that couldn't be taken into account in the models; most equilibrium would like to use logit loading model to assign traffic flow, which could lead to some absurd results.

This paper is organized as follows. Section 2 describes the basic concepts and ideas of PT. Section 3 presents how to apply PT to stochastic user equilibrium. Then in Section 4 a solution algorithm is proposed and a numerical example is given. In Section 5, congestion pricing is brought into the example network, and 2 cases are proposed. At last, an optimal charging standard is put forward.

2. Prospect Theory

From a historical perspective of its development, PT inherits and improves EUT. The utility function of EUT is replaced by value function, in which adds an important concept of reference point. The probability in EUT is replaced by probability weighting function. The probability weighting function is about the weighted cumulative probabilities, and can be regarded as a regression function of probabilities. Consequently, a reasonable conclusion will be conducted that the prospect in PT is a special utility.

2.1. Reference point

Reference point is an extremely important concept in PT. Due to the existence of bounded rationality, DMs choose alternatives that satisfy their needs instead of producing maximum profit or minimum cost. Take cost index as an example. If cost is less than the reference point, DM feels satisfied, otherwise, disappointed. Commonly, the reference point is exogenous and can't change with the decision-making environment which can't reflect decision making process perfectively in some special cases, thus in this paper we make use of an endogenous reference point.

2.2. Value function

Kahneman and Tversky (1979) found that the value function is (i) defined on deviations from the reference point; (ii) concave for gain and convex for loss. A value function which satisfies the properties is given by (Kahneman and Tversky 1992):

$$v(x)=\begin{cases}(x_0-x)^{\alpha} & x_0 \geq x \\ -\lambda(x-x_0)^{\beta} & x_0 < x\end{cases} \tag{1}$$

Where x means the deviation of cost; α, β and λ are parameters.