Travel Behaviour and Society 1 (2014) 79–90

Contents lists available at ScienceDirect

Travel Behaviour and Society

journal homepage: www.elsevier.com/locate/tbs

# Applications of theories and models of choice and decision-making under conditions of uncertainty in travel behavior research

Soora Rasouli *, Harry Timmermans

*Eindhoven University of Technology, Urban Planning Group, Eindhoven, The Netherlands*

ARTICLE INFO

*Article history:*
Available online 27 January 2014

ABSTRACT

The overwhelming majority of models in travel behavior research assume implicitly or explicitly that individuals choose between alternatives under conditions of certainty. The validity of this assumption can be questioned as in reality urban and transportation networks are in a constant state of flux. It is important therefore that transportation researchers develop relevant approaches and models to analyze and predict decision-making under conditions of uncertainty. Transportation researchers have tended to adopt theories and models, originally developed in social psychology and decision sciences, and explore their applicability to travel choice behavior. This invited review paper summarizes the most important of these theories and models, and illustrates their application using examples of empirical research in travel behavior research. Arguing that some basic assumptions underlying these theories may not mimic the quintessence of day-to-day activity–travel behavior, the paper is completed by reflecting on the limitations of these models and identifying avenues of future research.



## Introduction

The analysis and modeling of human choice and decision-making has a long history in travel behavior research. This statement should not come as a surprise, considering that the essence of travel demand forecasting is how people choose to participate in activities, decide on the departure times for these activities, choose a transport mode, decide where to execute their activities, choose a route to arrive at the chosen destinations, etc. Moreover, modeling consumer response to exogenous policies is essential in assessing the impact and effectiveness of transportation policies, captured in terms of changing attributes of the choice alternatives of interest. Finally, understanding how choice behavior co-varies with genders, income categories, age groups and other socio-demographics is crucial in evaluating social effects and equity of transport investment and traffic management scenarios.

Over the last decades, the travel behavior research community has applied a variety of theories and modeling approaches to individual and household choice and decision-making processes. Until the mid 1970s, spatial interaction and entropy-maximizing models, based on the theory of social physics, dominated the field (Wilson, 1974; Batty, 1976). Later, random utility theory (McFadden, 1974) and psychological choice theory (Luce, 1959) led to the formulation and application of many discrete choice models (Hensher, 1981; Ben-Akiva and Lerman, 1985). Soon the multinomial logit model became the working horse of the profession, to be complemented by various more advanced, less stringent models, such as the nested logit model and generalized extreme value models, which avoided some of the rigorous assumptions underlying the multinomial logit model. Lately, the mixed logit model (Train, 2003), MDCV model (Bhat, 2005) and hierarchical choice models (Walker and Ben-Akiva, 2002) have become rather popular. In parallel, but less pertinent, researchers have also applied rule-based models to capture decision heuristics (e.g., Arentze et al., 2000).

Regardless of the modeling approach and the underlying theory of choice and decision-making, these models have in common the assumption that decision-makers have perfect knowledge about the attributes of their choice alternatives. At the moment of choice, the values of these attributes are invariant, while individuals are assumed to hold perfect and complete knowledge about these attributes. All these models relate to choice and decision-making under conditions of certainty.

In reality, however, the assumption that attribute values are certain is not very realistic. When leaving home, individuals will not be certain about their arrival time to the intended destination as travel times exhibit inherent fluctuation. When choosing public transport, travelers may not be sure whether they will have a seat as demand and therefore occupancy fundamentally varies on a day-to-day basis. When choosing a place to park their car, drivers may face unexpected queues, and parking garages may be full.

* Corresponding author. Tel.: +31 402474527.
*E-mail address:* s.rasouli@tue.nl (S. Rasouli).

http://dx.doi.org/10.1016/j.tbs.2013.12.001
2214-367X/

When choosing a route, drivers can never be sure about the congestion situation. Even if the chosen route is normally not congested, an accident or sudden adverse weather conditions may cause significant delays.

Thus, the state of the transportation system and the urban envelope are inherently uncertain. Consequently, decision-makers always face conditions of uncertainty when choosing departure times, activities, destinations, transport modes, routes, etc. In that sense, it is surprising that applications of theories and models of decision making under conditions of uncertainty are relatively scarce in travel behavior analysis. Moreover, the majority of studies, albeit also small in number, are concerned with uncertainty or variability in the transportation system (Rasouli and Timmermans, 2012a, 2012b), but do not address how individuals make decisions when facing such uncertainty and how it affects their activity–travel decisions. Considering the inherent uncertainty in the state of the transportation system, the formulation and application of (improved) models of decision-making under conditions of uncertainty should be a field of research of high priority in travel behavior research. This paper is meant to provide readers with some basic background information and a state of the art overview.

In particular, we will discuss the principles and applications of expected utility theory, (cumulative) prospect theory and regret theory as these models have dominated the scarce literature in travel behavior analysis on decision-making under uncertainty.[1] In each section, we will first discuss the basic assumptions and specifications of the model and some variations, and then discuss selected results of empirical studies. In addition to providing a state-of-the-art overview, we will also reflect on the appropriateness and limitations of these models to applications in transportation planning and management, and suggest some avenues of future research.

## Notation

Most models in travel behavior research on choice and decision-making assume that the probability of choosing a particular choice alternative is some function of the attributes of the choice alternatives and a set of socio-demographic variables. The position of the choice alternatives on these variables is represented by a single value. This represents choice and decision making under conditions of certainty. In case of choice and decision making under uncertainty, the characterization of the choice alternatives is captured in terms of probability distributions. It implies that individuals are or cannot be sure about the exact state of the choice alternative along these uncertain dimensions or about the outcome of his decisions. This is the realm of choice and decision-making under conditions of uncertainty.

To create an overall framework for the various models in an attempt to allow the researcher to compare the various approaches with classic discrete choice model, in this section we will first introduce some notation. Expanding the notation suggested by Liu and Polak (2007), assume that each decision maker $i$ is faced with a set $C = \{\mathbf{s}^n;\ C = \{\mathbf{S}^n \leq n \leq N\}$ of $N$ risky choice alternatives (prospects, lotteries).[2] Each choice alternative $\mathbf{s}^n$ in $C$ consists of a set of $J$ possible outcomes or states $\mathbf{s}^n = \{S^n_j; 1 \leq j \leq J\}$. Each outcome $j$ of the $n$th risky choice alternative is defined by a vector of observable attributes $X^n_j = \{x^n_{jk}; 1 \leq k \leq K\}$. Associated with each risky alternative is a set of given probabilities $\mathbf{p}^n = \{p^n_j; 1 \leq j \leq J\}$, such that $\sum_{j=1}^{J} p^n_j = 1$, where $p^n_j$ is the probability that outcome $S^n_j$ is realized in $\mathbf{s}^n$.

Choice under risk implies that a decision maker has to integrate (i) information about the attributes characterizing the risky outcomes, and (ii) information about the probability of each outcome. We assume that each attribute $k$ influencing outcome $j$ of prospect $n$ is valued according to mapping function $h$, which translates the values of the observable variables $x^n_{jk}; \forall j, k$ into valuation scores $v^n_{ijk}; \forall j, k$. In turn, the valued variables are integrated according to function $g$ to derive to arrive at an valuation $v^n_{ij}; \forall j$ of the $j$th outcome of the $n$th prospect. Thus,

$$v^n_{ijk} = h(x^n_{jk}); \forall\ i, j, k \tag{1}$$

$$v^n_{ij} = g(v^n_{ijk}); \forall\ i, j \tag{2}$$

or,

$$v^n_{ij} = g(h(x^n_{jk})); \forall\ i, j, k \tag{3}$$

Finally, we assume that the overall valuation (or utility) $u^n_i$ of prospect $\mathbf{s}^n$ by decision maker $i$ is a function $f$ of the valuations of the possible outcomes $j$ of the $n$th prospect, the given probabilities of these outcomes $\mathbf{p}^n$ and a set of model parameters $\boldsymbol{\varphi}_i = \{\varphi_{ir}; 1 \leq r \leq R\}$ that characterize the decision making process in risky situations. Hence,

$$u^n_i = f(v^n_{ij}, \varphi_i)p^n_j; \quad j = 1, \ldots, J \tag{4}$$

## Expected utility theory

### *Principles*

Expected utility theory can be traced back to the work of Bernoulli in 1738 to solve the famous St. Petersburg paradox. This paradox concerns the problem how much a single gambler should pay a casino to enter a game in which he would toss a fair coin, doubles a start gain of 1 unit every time a head appears, and the game ends the first time a tail appears. Thus, the gambler would win $2^{k-1}$ units if the coin is tossed $k$ times before the game ends. The expected payoff of this gamble is equal to $E = \sum_{k=1}^{\infty} \frac{1}{2} = \infty$ Consequently, the expected payoff for the gambler would be an infinite amount of money, implying that the gambler should play the game at any price. Yet, few people would consider paying any price, giving rise to the paradox: the discrepancy between what people seem willing to pay to play the game and the infinite expected value. The problem led to a considerable amount of work on decision making under uncertainty. Neumann and Morgenstern (1947) should be viewed as the basis of modern expected utility theory in that they provided a set of axioms (completeness, transitivity and continuity) to lay the foundation of modern expected utility theory.

The most basic version of expected utility theory (EUT), especially used in a normative context, is the expected value model, which states that the overall evaluation or utility $u^n_i$ of prospect $\mathbf{s}^n$ by decision maker $i$, given $\mathbf{p}^n$ can be derived by taking the expectation of the outcome evaluations $x^n_{ij} \forall j$ over the probability distribution $\mathbf{p}^n$. That is,

$$u^n_i = \sum_{j=1}^{J} p^n_{ij} x^n_{ij} \tag{5}$$

[1] These three theories are just a small subset of theories and models of choice behavior under uncertainty. For example, Hey and Chris (1997) list the following additional theories that were motivated by the inability of expected utility theory to explain observed behavior. Allais' (1952) theory, Anticipated Utility theory, Cumulative Prospect theory, Disappointment theory, Disappointment Aversion theory, Implicit Expected (or linear) Utility theory, Implicit Rank Linear Utility theory, Implicit Weighed Utility theory, Lottery Dependent Expected Utility theory, Machina's Generalised Expected Utility theory, Perspective theory, Prospective Reference theory, Quadratic Utility theory, SSB theory, and Yaari's Dual theory. Some of these theories are special cases or generalisations of those discussed in this paper; others are based on different concepts.

[2] Although there are differences between risk and uncertainty, we will use the terms interchangeably in the present paper.