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Efficient frontier of route choice for modeling the equilibrium under travel time variability with heterogeneous traveler preferences

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ABSTRACT

Travelers consider the average duration and the reliability of travel time when choosing their route. However, the relative importance of average travel time and reliability not only depends on the purpose of the trip, but also varies from one person to another. Users seek to minimize their travel costs leading to an equilibrium condition in which they choose routes in such a way that they cannot reduce the general cost of their own trip. In this paper, we adopt the concept of the efficient frontier to represent the equilibrium route choice of the heterogeneous users in a network under travel time variability. Then, we use the primary properties of the efficient frontier to propose a mathematical formulation for the route choice problem for a discrete or continuous distribution of sensitivity of users to variations in route travel times. An analytical-based algorithm is designed to assign the heterogeneous demand to the network. Efficiency of the proposed algorithm in solving the route choice problem is also compared in a numerical example with a classic iterative method with a smoothing factor.

1. Introduction

The route choice decision-making procedure can be considered to have two separate stages. In the first stage, travelers need to observe different routes to collect information regarding the performance of different choices. In the second stage, this information is used to evaluate the available route choices. We seek to identify the equilibrium when a heterogeneous population of travelers simultaneously choose routes under travel time variability. Conventional traffic assignment models presume that the trip duration is the only important measure of route performance. With perfect information, users are assumed to be able to anticipate the exact trip durations for each route. The interaction between users that choose the route with the shortest travel time leads to the classic user equilibrium (UE) in which no one can improve his/her travel time by changing his/her own route. In the user equilibrium, all the used routes between the origin and destination have identical travel times while routes with longer travel times remain unused (Wardrop, 1952).

The accuracy of the equilibrium model can be improved by elaborating the underlying assumptions. First of all, there are aspects other than the duration of the trip that travelers also take into account in their choice evaluation. Secondly, heterogeneous users may have different characteristics and preferences for their trips in the network (Lindsey, 2012). In this case, the relative importance of such aspects varies among the travelers with heterogeneous tastes (preferences) and also with the purposes of their trips (Beckmann et al., 1956; Small, 1982). Accordingly, different people may choose different routes to travel from the origin to the destination which might be even different from the shortest path in the network (Jan et al., 2000; Lou et al., 2010). Furthermore, the network travel times cannot be anticipated with certainty, because the travel time is a stochastic process in nature. Travel time variability is due to two main factors: 1) variability of the capacity due to various types of incidents and 2) variability of demand flows (Siu and Lo, 2008; Lo and Tung, 2003; Jia et al., 2011; Adler et al., 2013; Shabanpour et al., 2017). So, a stochastic traffic assignment model that treats the travel time as variable and recognizes the taste variation among the users can improve the consistency of the route choice model with the reality of individual travel behaviors.

There is a large body of research on stochastic traffic assignment models that analyzes the route choice behavior of the users from different perspectives. The stochastic user equilibrium model (SUE), presented in Daganzo and Sheffi (1977), is one of the first models that proposes an extension to the user equilibrium by adding a random component to the travel cost functions. Such randomness can represent both errors in system performance and user perceptions. In the SUE model, the probability that a route is chosen by the travelers is determined based on the

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probability that the route is the shortest path (route with the lowest travel time). However, research shows that not only is there an uncertainty associated with route travel times in the network, but travelers are also unable to predict exact travel times in the network (Mirchandani and Soroush, 1987). In this regard, Watling (2006) proposes the late arrival penalized user equilibrium (LAPUE) as a general equilibrium model that also takes the schedule delay into account in the route choice problem. Levinson and Zhu (2013) also proposes a stochastic traffic assignment model considering that users tend to minimize the associated risk by choosing from a portfolio of routes. However, including the effect of heterogeneity in sensitivity of the users to different factors can reveal the unseen motivation of different drivers for taking different routes.

Route choice behavior of the travelers with heterogeneous preferences in the network can be also considered as a multi-criterion choice problem. Time and monetary costs have been traditionally conceived in the literature as the two main factors that users consider in their decision-making procedure. To account for the heterogeneity in value of time of users, Dial (1996) adopted the concept of the efficient frontier to generalize the Frank and Wolfe (1956) algorithm for solving the bi-criterion traffic assignment model that takes both the durations and the costs of the trips into account in forecasting travelers' route choices. To capture the effect of heterogeneity in the preferences of the users, Zhang et al. (2013) proposes a probit-based bi-criterion dynamic stochastic user equilibrium (BDSUE) model to account for heterogeneity of value of time of the users. Wang et al. (2014a) also assumes that travelers choose their routes among the first several choices with the lowest general disutility (travel time and cost), and proposes a rank-dependent bi-criterion equilibrium model for the route choice problem when there is stochasticity associated with both the criteria measurements and the subjective preferences. The heterogeneity in value of time of the users is taken into account in designing the optimal pricing strategies for urban networks by considering various classes of users with different values of time in the mathematical formulation of the problem (Yang and Zhang, 2002; Yang et al., 2002; Yang and Huang, 2004; van den Berg and Verhoef (2011); Amirgholy et al., 2015; Small, 2015).

Route choice modeling with travel time risk is another application of bi-criterion traffic assignment models. There are different approaches proposed in the literature to include the effect of risk in travel time in the route choice modeling of users. Lo and Tung (2003) assumes that the degradation in capacity of links due to incidents is the primary cause of travel time variations in the network. On this basis, the study proposes a probabilistic user equilibrium model to account for such uncertainty on long-term route choice behavior of the users in the network. In addition to uncertainty of capacity, the stochastic nature of the route choice decision of individual users on an aggregate level causes variations in travel times in the network. Chen and Zhou (2010) develops a mean-excess traffic equilibrium model that takes both reliability and uncertainty associated with travel time into account in route choice modeling. Wu and Nie (2011) also considers the heterogeneous sensitivity of users to risk for traffic assignment by linking the first-, second-, and third order stochastic dominance to concepts of insatiability, risk-aversion, and ruin-aversion within the framework of utility maximization. In another study, Nie (2011) considers travelers that choose routes to minimize the travel time budget required to guarantee their on-time arrivals with a certain level of confidence, and on this basis proposes a multiclass percentile user equilibrium traffic assignment model. Chen et al. (2011) proposes a solution algorithm for the multiclass reliability-based user equilibrium problem. Xiao and Lo (2013) studies route choice behavior of adaptive drivers in a stochastic network, and the proposed model optimizes the expected prospect of potential choices with acceptable travel time and arrival time. Wang et al. (2014b) proposes a general travel time reliability bi-objective user equilibrium model (TTR-BUE), which simultaneously incorporates the travel time budget model (Lo et al., 2006) and late arrival penalty model (Watling, 2006). This model has the advantage that it can identify a range of possible solutions based on the rational behavior of the users, regardless of the distribution of their preferences. Tan et al. (2014) assumes the link travel times are random variable functions of the link flows under the assumption that the variation in travel times are the result of certain exogenous factors. So, route choice behavior of the users has been studied for different types of general cost functions under travel time risk. The concept of the Pareto-efficient route flow pattern is then introduced to describe the equilibrium assignment of the users to the non-dominated routes in terms of the mean and standard deviation of travel time. The general geometric properties of the mean-standard deviation (ES) indifference curve has been related to the definition of the general cost function as a combination of the mean and standard deviation of the travel time. This body of work addresses the need to account for heterogeneity in networks with travel time variability, but there remains a need for an analytical approach to determine the assignment of traffic across routes in a network when travelers have heterogeneous preferences and the travel times on individual routes exhibit variability.

In this paper, we propose a traffic assignment model that accounts for the effect of travel time variability on the route choice behavior of the users in the network. In the proposed model, we consider a distribution of travel times for each route. The link generalized cost is expressed as a linear combination of the mean and standard deviation of the link travel time, regardless of the shape of the distribution (Fosgerau and Karlström, 2010; Fosgerau and Engelsson, 2011). Both the mean and standard deviation of the travel times are assumed to be functions of traffic flows on each link, which implies a relationship between the mean and standard deviation of the travel time (Noland et al., 1998; Fosgerau, 2010; Mahmassani et al., 2013). Network users are also assumed to be capable of estimating the mean and standard deviation of travel times based on their previous experiences in the network or a traveler information system, while the relative importance of these variables varies among the heterogeneous travelers with different trip purposes.

This research adopts the concept of the efficient frontier from portfolio theory (Markowitz, 1952) in finance, which accounts for the fundamental heterogeneity of preferences for risk among investors, to the traffic assignment problem in which travelers have fundamentally heterogeneous preferences for travel time risk. The concept of the efficient frontier can be easily adapted for the purpose of modeling bi-objective problems in transportation. In this respect, Anas (2012) uses a differentiable version of the efficient frontier to propose a core-periphery spatial model for the equilibrium allocation choices of the heterogeneous workers with a bi-criterion general cost function in the core and suburbs of a monocentric city. Amirgholy and Gonzales (2017) makes a use of the concept of the efficient frontier to propose an analytical solution for the morning commute problem when there is heterogeneity associated with schedule penalty preferences of the users. The concept of the efficient frontier is also used to model the bi-criterion route choice behavior of heterogeneous users in the network (Dial, 1996). In this research, we define the efficient frontier of the route choice (EFRC) to model the route choice behavior of the heterogeneous travelers that account for the trade-off between expected travel time and risk in their route choice decision-making procedure. By definition of the EFRC, each user can just choose a single route from a discrete set of choices for his/her trip, as opposed to the portfolio set of different choices in the investment problem. In view of that, we show that the EFRC has specific characteristics that support a new formulation and solution algorithm for the route choice problem. In this model, we take the heterogeneity in preferences of the users into account by considering a probability distribution for the risk sensitivity of the users to travel time, while the performance of the links is modeled as a function of the link flows.

The proposed model is based on the analytical results directly derived from the concept of the efficient frontier. Therefore, the model can provide intuition about the characteristics of the solution in the equilibrium condition. Moreover, the proposed model reveals the route choice ranking of the heterogeneous users according to their own preferences, which makes it possible to predict the effect of changes in the network on the route choice behavior of the users. The main advantage of