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On the stochastic network equilibrium with heterogeneous choice inertia

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ABSTRACT

As an alternative effort for quantifying recurrent traffic dynamics caused by network variations and analyzing the impact on the network performance from information provision, we describe in this paper a new equilibrium modeling scheme for stochastic networks with a finite number of states, which takes into account the behavioral inertia. A finite-dimensional variational inequality model is formulated to describe the cross-state equilibrium conditions among heterogeneous travelers with different inertial degrees and knowledge structures. Our model allows for traveler's partial understanding and inertial effect in perceiving varying network conditions and provides a different perspective (from existing stochastic and Markovian network equilibrium approaches) to describe traffic flow variations across multiple network scenarios. A disaggregate simplicial decomposition algorithm is suggested to solve the variational inequality problem. Numerical results from a few stochastic network examples demonstrate the validity and effectiveness of our methodology in modeling the inertia phenomenon within route choice behavior and the efficacy of using traveler information systems to eliminate the inertia effect.

1. Introduction

The descriptive principle by Wardrop (1952) has been widely accepted as a standard theoretical basis for characterizing the traffic equilibrium on road networks. This principle states such an individual self-optimal, non-cooperative routing behavior that every traveler selects a route with minimizing his own travel cost and no one can improve his travel cost by unilaterally changing routes. In the literature of transportation research, we often coin it user equilibrium (UE). The classic UE models for describing deterministic networks have been well investigated as a mathematical program, variational inequality, complementarity system, or fixed-point problem (see Patriksson, 1994; Florian and Hearn, 1995).

Traffic equilibrium models and methods for stochastic networks, however, are seemingly more complex but often highly preferable in many cases. Uncertainties or variations associated with both network supplies and travel demands seem inherently natural and may arise in infinite varieties. Road capacity may be altered by various unpredictable and predictable events, such as traffic accidents, weather conditions, road maintenance activities, traffic control strategies and special events.

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Travel demand varies with the society's productive and leisure activities. Numerous evidences show that traffic flows and congestion conditions in a traffic network vary with the changing capacity levels and demand rates over time.

Despite the resulting traffic flow patterns in a network vary from one scenario to another (or from one period to another), they are not mutually separate and uncorrelated, since the traffic flow entities—individual travelers—experience multiple network scenarios (or periods) and their routing decisions are in general a synthetic result of their long-term learning process over different network states (Horowitz, 1984; Fudenberg and Levine, 1998). Understanding the underlying correlation through varying traffic networks is critical to describing and evaluating traffic dynamics caused by scenario-to-scenario (or period-to-period) system supply and demand variations.

Stochasticity has been explicitly or implicitly specified in many existing traffic equilibrium models in a number of different ways. The stochastic sources may be either exogenous or endogenous. A common premise implied in these models is that travelers on some degree face an uncertain traffic environment or perceive the traffic environment in an uncertain way. To the authors' knowledge, Burrell (1968) and Dial (1971) appear to be the first ones who investigated stochastic traffic assignment problems, using simulation-based and analytical methods, respectively. Without considering traffic congestion, however, their models can only be used as a pure route choice device of the random-utility-maximization type, particularly for an uncongested network in which the traffic equilibrium is not of significant importance. The first attempt of incorporating the Wardrop equilibrium principle into a stochastic network is attributed to Daganzo and Sheffi (1977) and Sheffi and Powell (1982), who formulated a stochastic user equilibrium (SUE) model that explicitly treats the individual travel cost perception stochastic and so the individual routing behavior. Mirchandani and Soroush (1987) assumed both the travel cost and traveler's perception on travel cost to be random variables, resulting a generalized traffic equilibrium problem for stochastic networks, in which the stochastic equilibrium condition implies a disutility minimization rationale that considers both the travel cost mean and variance (or risk). Hazelton (1998), assuming that the traffic flow stochasticity is a result of travelers' stochastic route choices, devised a conditional stochastic user equilibrium model that may be regarded as an alternative generalized version of the SUE model with stochastic flows. The conditional stochastic model converges to the SUE model when its demand goes to infinity. Another effort to extend a fixed-point solution of the early SUE model to a probability distribution is due to Watling (2002), who presented an alternative generalized SUE model that correlates the traffic flow and travel cost variations in their first two orders (i.e., mean and variance). Following the assumption that travelers are highly pessimistic about travel time reliability, Watling (2006) also derived a risk-averse user equilibrium model, which considers stochastic travel costs and penalizes late arrivals (i.e., unreliable travel costs), in contrast to the classic UE or SUE models that implicitly imply a risk-neutral routing behavior. Connors and Sumalee (2009) constructed a prospect theory-based network equilibrium model that takes into account the individual perception of travel times and their probabilities in the form of nonlinear transformation. It is noted in many of these models that stochastic network equilibrium problems is closely associated with the concept of network reliability (particularly travel time reliability), by which the focal point and the modeling feature in these models are the behavior assumption about how individual travelers deal with travel time uncertainties in their route choice process.

While it is convenient to treat travel costs and traffic flows as self-explanatory stochastic variables, it is argued that all random occurrences in traffic networks inherently arise from two sources: randomness in network supplies and variations in travel demands (Nicolson and Du, 1997). The occurrence of stochastic network capacity degradations were discussed and introduced into the traffic equilibrium analysis by Arnott et al. (1991) and Chen et al. (2002). In two relevant studies, Lo and Tung (2003) and Lo et al. (2006) proposed a probabilistic user equilibrium model to characterize the network equilibrium conditions in the face of travel time uncertainties caused by network capacity variations. These models have a similar disutility structure to Watling's (2006) model in that all the models accommodate travel cost variations as a risk measure in route choice. A specific equilibrium assignment problem with risk-averse behavior due to capacity uncertainty is also examined by game theory approaches in Bell (2000) and Bell and Cassir (2002). In these studies, a Nash equilibrium model is formulated as a game joined by uncoordinated travelers who aim to minimize their individual expected travel costs and a demon player who tries to maximize the total expected travel cost.

On the other hand, an alternative research track was also developed by taking into account the demand uncertainty that causes traffic flow and travel cost variations (see Asakura and Kashiwadani, 1991; Clark and Watling, 2005). Given an assumption of the negative-binomial distributed demand pattern, Nakayama (2005) derived an analytical relationship between route flow randomness and travel demand randomness and formulated a stochastic demand-based user equilibrium model under the classic random utility framework without risk consideration. Shao et al. (2006) considered the traffic flow and travel cost variations caused by normally distributed travel demand fluctuations and formed a demand-driven user equilibrium model that connects the variations of travel costs and trip rates and incorporates the resulting travel cost variation into the route choice process. In a similar modeling fashion, Zhou and Chen (2008) combined both the reliability and unreliability modeling mechanisms, including, namely, the reliability-based routing rule in Lo et al. (2006) and Shao et al. (2006), and the unreliability-based routing rule in Watling (2006), to form a so-called mean-excess network equilibrium model. Of course, both supply and demand uncertainties impact route choice and network equilibrium and may be considered simultaneously in a network equilibrium model. For example, Lam et al. (2008) proposed a risk-averse network equilibrium model in the fixed-point problem form, which incorporates both the roadway performance and travel demand uncertainties caused by adverse weather conditions. Zhang and Chen (2008) and Zhang et al. (2011) recently formed a robust traffic equilibrium problem for networks with stochastic supplies and demands based on the notion of expected residual minimization.