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Estimating the value of travel time and of travel time reliability in road networks

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ABSTRACT

This study proposes two network models which simultaneously estimate the value of travel time and of travel time reliability based on the risk-averse driver's route choice behavior. The first model is formulated as a utility maximization problem under monotonic and separable link travel times, whereas the second model is formulated as a utility maximization problem under non-monotonic and non-separable link travel times. The proposed models have the same structure as a user equilibrium (UE) traffic assignment problem with elastic demand. It is shown that the first model, which addresses independent stochastic capacity, is formulated as an optimization problem with a unique solution and is solved by using an algorithm for a UE traffic assignment problem with fixed demand. The second model, which addresses both stochastic Origin–Destination (O–D) flow and stochastic link capacity, is formulated as a nonlinear complementary problem. O–D demand functions formulated in the proposed models are derived from the utility maximization behavior of the driver in the network. Therefore, the network models proposed in this study are consistent with those of studies that address the value of travel time and of travel time reliability based on utility maximization behavior without considering the driver's route choice. Numerical experiments are carried out to demonstrate the models presented in this study.

1. Introduction

In light of the need to evaluate travel time reliability in terms of its effect on mobility in transport networks, many studies have developed models that address uncertainties in the network. Uncertainties in the network can be categorized into the three main factors of supply, demand and travel behavior. Studies on travel time reliability in the network began with those that address stochastic Origin–Destination (O–D) demand flow. By assuming O–D demand flow that follows normal distributions, Asakura and Kashiwadani (1991) solved User Equilibrium (UE) traffic assignment problems several times by using a set of O–D demand flows that were sampled from normal distributions for the purpose of estimating travel time reliability. Clark and Watling (2005) proposed an equilibrium model that calculates travel time reliability under stochastic O–D demand flow when that flow follows a Poisson distribution. They employed probit-based Stochastic User Equilibrium (SUE) for the driver's route choice behavior. They applied a method proposed by Isserlis (1918) for the purpose of calculating travel time reliability, i.e., variance of stochastic travel time. Nakayama and Takayama (2003) proposed an equilibrium model which assumes that O–D demand flow follows a binomial distribution. UE traffic assignment was employed for expressing the driver's route choice behavior. They calculated travel time reliability by applying a moment-generating function. Zhou and Chen (2008) proposed an equilibrium model which assumes that O–D demand flow follows a lognormal distribution. The

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driver's route choice behavior based on UE was employed. Shao et al. (2006) proposed an equilibrium model which assumed an O–D demand flow that followed a normal distribution. The driver's route choice behavior based on logit-based SUE was employed. They evaluated travel time reliability from the viewpoint of safety margin.

Many studies have addressed stochastic link capacity. Cascetta (1989) and Cascetta and Canterella (1991) developed dynamic traffic assignment models by using a Markov chain. The models developed in their studies calculated drivers' equilibrium states under stochastic link capacity. Bell et al. (1993) proposed a method that estimated travel time reliability under stochastic link capacity by applying sensitivity analysis for logit-based SUE. Cassir and Bell (2002) applied the same method as proposed in Bell et al. (1993) and calculated the travel time reliability by assuming both stochastic O–D demand flow and stochastic link capacity. Chen et al. (1999) analyzed network capacity reliability under stochastic link capacity. They applied the Monte Carlo simulation technique for calculating the network capacity reliability. Chen et al. (2002) analyzed network capacity reliability under both stochastic link capacity and stochastic O–D demand flow by applying the Monte Carlo simulation technique. Lo and Tung (2003) proposed an equilibrium model in which link capacity was assumed to follow a uniform distribution. Stochastic link travel time under stochastic link capacity was calculated by applying a Mellin transform. Uchida and Munehiro (2010) proposed a method that estimated stochastic link capacity from observed traffic data, i.e., density and velocity. They also proposed an equilibrium network model under stochastic link capacity that followed an independent normal distribution. For the purpose of calculating travel time reliability, they applied a method proposed by Bras and Georgakakos (1989) which approximated the first negative moment of a normal distribution by a linear function of the normal distribution and its mean.

It is natural to consider both stochastic O–D demand flow and stochastic link capacity in calculating travel time reliability. Lam et al. (2008) proposed an equilibrium model under stochastic O–D demand flow that considered the influence of adverse weather on link capacity. They assumed that the rate of decrease in link capacity followed a normal distribution. Shao et al. (2008) extended the model proposed by Lam et al. (2008) to a model under a multi-user-class network. Sumalee et al. (2011) extended the same model to a model under a multi-modal network.

Watling (2006) proposed an equilibrium model under stochastic travel time that followed a normal distribution. The driver's route choice behavior was expressed by using a probit-based SUE that also considered arrival penalty. Wu and Nie (2011) proposed a unified approach to modeling heterogonous risk-taking behavior in route choice based on the theory of stochastic dominance (SD). They analyzed the relationship between an SD-based approach and other route choice models that considered risk-taking behavior. In these studies, travel time was expressed by a stochastic variable without identifying the source of uncertainties in a network. These studies focused on the driver's risk-taking behavior. Ng et al. (2011) proposed a methodology to assess travel time reliability under unknown travel time distribution. The method proposed in their study is useful when we do not have enough data to calibrate the travel time distribution. Chen et al. (2011) extended the α-reliable mean-excess traffic equilibrium (METE) model proposed in Chen and Zhou (2010) by explicitly modeling the stochastic perception errors within the travelers' route choice decision processes. Ng and Waller (2010) presented a methodology based on the theory of Fourier transforms to assess travel time reliability in a transportation network, when the source of uncertainty is given by random road capacities.

For the purpose of measuring the benefits from traffic measures in road networks in terms of travel time and travel time reliability, the value of travel time and of travel time reliability need to be estimated. These can be estimated by using empirical models (e.g., Lam and Small, 2001; Brownstone and Small, 2005). Hensher et al. (2011) modified a random utility model to include attribute-specific extended expected utility forms incorporating decision weights and risk in the context of willingness to pay for travel time variability for car commuting travel. Börjesson et al. (2012) estimated the value of travel time variability by applying both a scheduling model and an implied reduced-form model, using stated-choice data. Studies that addressed the value of travel time based on a utility maximization problem without considering the traveler's route choice behavior in the network began with Becker (1965) and DeSerpa (1971). Recently, some analytical models that address the value of travel time and of travel time reliability based on utility maximization principle have been proposed. Fosgerau and Karlström (2010) presented a model that estimates the value of travel time variability based on scheduling preferences. Fosgerau and Engelson (2011) considered the value of travel time variability under scheduling preferences that were defined in terms of linearly time-varying utility rates associated with being at the origin and at the destination. They have shown that a measure related to travel time variability is variance of travel time.

Studies that address travel time reliability based on equilibrium network models have not discussed how to estimate the value of travel time and of travel time reliability. The value of travel time and of travel time reliability were given assumed values in the studies. On the other hand, studies that addressed the value of travel time and of travel time reliability as a utility maximization problem have not addressed the traveler's route choice behavior in the network, even though this is an essential factor in estimating these values. The present study proposes two network models that estimate the value of travel time and of travel time reliability. The models are derived from a utility maximization problem under budget constraints. The models are finally formulated as UE traffic assignment problems with elastic demand that express the risk-averse driver's route choice. By applying the network models proposed in this study, the value of travel time and of travel time reliability consistent with observed link flows can be estimated. One advantage of the models proposed in this study over utility-maximization-based models is that the value of travel time and of travel time reliability are estimated by taking account of the risk-averse driver's route choice behavior in a road network that is not considered in the utility-maximization-based models. However, the value of travel time and of travel time reliability determined by the models proposed in this study need to be numerically estimated, whereas the values determined by utility-maximization-based models can