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Modeling impacts of adverse weather conditions on a road network with uncertainties in demand and supply

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Abstract

This paper proposes a novel traffic assignment model considering uncertainties in both demand and supply sides of a road network. These uncertainties are mainly due to adverse weather conditions with different rainfall intensities on the road network. A generalized link travel time function is proposed to capture these effects. The proposed model allows the risk-averse travelers to consider both an average and uncertainty of the random travel time on each path in their path choice decisions, together with the impacts of weather forecasts. Elastic travel demand is considered explicitly in the model responding to random traffic condition in the network. In addition, the model also considers travelers' perception errors using a logit-based stochastic user equilibrium framework formulated as fixed point problem. A heuristic solution algorithm is proposed for solving the fixed point problem. Numerical examples are presented to illustrate the applications of the proposed model and efficiency of the solution algorithm.

Keywords: Stochastic network assignment model; Travel time reliability; Adverse weather; Weather forecast; Demand uncertainty; Supply uncertainty

1. Introduction

Traditionally, road traffic congestion has been usually expressed in terms of a simple average of travel time or duration of traffic delay. However, evaluating only the mean of the traffic condition may not be sufficient to capture the variability of travel time from day to day due to various uncertainties in the system. These uncertainties can be broadly categorized into two main groups: supply and demand uncertainties. The supply uncertainty is caused by different disturbances on the road (e.g. accident, road work, illegal parking, or rainfall) affecting the driving condition and hence the road capacity. The causes of the capacity variability can be

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further categorized as predictable and less-predictable one. The weather condition (i.e. rainfall or storm) or scheduled road work can be considered more predictable whereas the road accident, vehicle breakdown, or other forms of capacity degradation fall into the other category. On the demand side, a significant level of the day-to-day demand variation can be observed in most cities. The coupling of the demand and supply uncertainties results in the recurrent variability and unreliability of the travel time and traffic condition (Asakura and Kashiwadani, 1991). This issue has been gradually becoming a major concern for many countries (SACTRA, 1999).

To address this issue, different modeling frameworks have been proposed to explicitly incorporate demand and supply uncertainties into the analysis. On the demand side, Clark and Watling (2005) proposed a stochastic network model with the Poisson distributed origin–destination (O–D) demand based on the original model proposed by Watling (2002). Sumalee et al. (2006) applied this model to the reliable network design problem. Nakayama and Takayama (2003) applied a similar stochastic model but with the Binomial distribution of the travel demand. Shao et al. (2006) extended the Lo et al.'s study (2006) and presented a demand driven travel time reliability-based user equilibrium model to consider the effects of daily demand fluctuations. On the capacity side, most existing studies are concerned with the less-predictable disturbances. For example, Chen et al. (1999) proposed the concept of capacity reliability which explicitly considers the stochastic characteristics of link capacities subject to routine degradation due to physical and operational factors. Lo et al. (2006) proposed a model which considers the road capacity as a uniform distributed random variable subject to traffic incidents.

All of the studies mentioned above fall within the class of static model, in which equilibrium modeling approaches have been adopted while considering the effects of network uncertainties on long-run behavior of travelers. However, some non-equilibrium and modified equilibrium approaches have also been proposed to represent adaptive changes of traveler's behavior, such as the doubly dynamic equilibrium distribution model by Balijepalli and Watling (2005), the partial user equilibrium framework proposed of Sumalee and Watling (2008), and the modified user equilibrium model under given the possibility of an accident condition (Sanso and Milot, 1999).

The main focus on modeling the capacity variability in the literature has been mainly on the less-predictable causes by assuming some statistical distributions of the road capacities. For the more predictable causes, additional information of such events may be available and could be introduced into the model formulation explicitly. For instance, in Hong Kong the rainstorm can be forecasted by the Hong Kong Observatory with three levels of warning signals based on the levels of predicted hourly rainfall intensity: amber rainstorm signal (>30 mm/h), red rainstorm signal (>50 mm/h) and black rainstorm signal (>70 mm/h). In addition, estimated probabilities of different rainfall intensities can also be forecasted and disseminated to the travelers (see e.g. weather.yahoo.com). In turn, the information about the weather forecast may also have an impact on the travel decision (in terms of path, mode, and departure time choices) through expected (or uncertain) changes in the road condition.

This paper aims to propose a network modeling framework taking into account both less and more predictable causes of the capacity degradation. In particular, the focus is on the impact of the rainfall and adverse weather condition on the road performance. A generalized travel time function is introduced in which the level of the road capacity degradation is a function of the random rainfall intensity. The model proposed in this paper also considers the day-to-day demand variation by assuming the Normal distribution of the random demand.

The introduction of both demand and supply uncertainties in the model formulation also causes the travel time in the model to be a random variable. Given the travel time uncertainty, a traditional assumption on the drivers' path choice decisions which considers only the mean travel time (e.g. user equilibrium or stochastic user equilibrium) may no longer be appropriate. For instance, a driver may have to choose between a path with a lower expected travel time but less reliable (thus a higher risk of being late) and the other path with a higher expected travel time but more reliable. Under such a condition, the driver then has to trade-off between his value of time and the risk (and related penalty) of arriving the destination late.

Such a risk-averse behavior in the context of path choice model has been confirmed by several empirical studies (see e.g. de Palma and Picard, 2005; Bruinsma et al., 1999; Bates et al., 2001; Lam and Small, 2001). In particular, Lam and Small (2001), found that the travelers are likely to set up a travel time safety