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RESEARCH

Comparative Analysis of Transportation Network Design Problem under Stochastic Capacity

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Abstract: The method to accurately simulate users travel behavior in the network design problem (NDP) is one of the most crucial problems. Most researches in the network equilibrium based approach to model NDP ignore the unreliability aspect of travel time. The uncertain events result in the spatial and temporal variability of network travel times, which directly contributes to the crucial decision of NDP. Specifically, the mean travel time (MTT), the travel time budget (TTB), and the α- reliable mean-excess travel time (METT) are employed in the transportation network design problem under uncertain environment due to stochastic link capacity. Numerical results are presented to examine how these models affects decisions under the condition of travel time variability. The comparative analyses show that the performance of DRUE and METTUE is better than DUE which is employed in network design problem under variation degrees because of considering travel time variability.

Key words: urban traffic; transportation network design; link capacity variation; travel time reliability; particle swarm optimization

1 Introduction

Transportation network design problem is to make a crucial decision of the network construction. The decisions are allocation of a limited financial budget to enhance the existing links and/or to the addition of new candidate links. The aim is to cope with the rapidly growing travel demand and the congestion problem[1].

NDP is firstly proposed by Morlok in 1973 has been continuously studied during the last five decades. The number of related publications has grown over time. In 1975, Leblanc[2] firstly studied the urban traffic network design problems and formulated the problem with a mixed integer optimization model. In recent years, the study of urban traffic network design problem has made great progress.

Recent empirical studies[3 4] revealed that travelers actually consider the travel time variability as a risk in their route choice decisions. They are interested in not only travel time saving but also the risk reduction. However, the traditional user equilibrium (DUE) model[5] neglects travel time variability in the route choice decision process. It uses only the expected travel time (Mean Travel Time-MTT) as the criterion for making route choices, which implicitly assumes all travelers to be risk-neutral.

Uncertainty is unavoidable in real life. Various uncertainty factors can contribute to the travel time variability, such as nature disaster, traffic accident, and recurrent congestion. These uncertain events result in the variations of traffic flow, which directly contributes to the spatial and temporal variability of network travel times. Such travel time variability introduces uncertainty for travelers such that they do not know exactly when they will arrive at the destination. Lo et al.[6] proposed a key concept adopted in models is the travel time budget (TTB), which is defined as the average travel time plus an extra time as an acceptable travel time, such that the probability of completing the trip within the TTB is no less than a predefined reliability threshold (or a confidence level α). The concept of TTB is analogous to the Value-at-Risk (VaR), which is by far the most widely applied risk measure in the finance area.

Furthermore, in order to describe travelers' route choice decision process under travel time variability, it is not adequate to describe travelers' risk preferences only considering the reliability aspect. On the one hand, the FHWA report[7]

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documented that travelers, especially commuters, do add a 'buffer time' to their expected travel time to ensure more frequent on-time arrivals when planning a trip. It represented the reliability aspect in the travelers' route choice decision process. On the other hand, the impacts of late arrival and its explicit link to the travelers' preferred arrival time were also examined in the literature [8]. It represented the travelers' concern of the unreliability aspect of travel time variability in their route choice decision process[9]. Recently, Zhou and Chen[10] proposed a new model called the α -reliable mean-excess travel time (METT) user equilibrium model or the mean-excess travel time user equilibrium (METTUE) model for short that explicitly considers both reliability and unreliability aspects of travel time variability in the route choice decision process.

Recent empirical studies on the value of time and reliability reveal that travel time variability plays an important role on travelers' route choice decision process. It can be considered as a risk to travelers making a trip. Therefore, travelers are not only interested in saving their travel time but also in reducing their risk. The uncertainty events from supply side sources (stochastic link capacity variations) typically lead to uncertainty of network travel times. It could influence the travelers' trip decision, including their departure time, destination, mode, and route choice, which consequently affect the flow pattern. MTT, TTB, and METT are employed in the transportation network design problem under an uncertain environment due to stochastic link capacity. Numerical are presented for the comparative analysis to examine how these models affects decisions under the condition of travel time variability.

2 Route choice formulation under stochastic link capacity

Consider a strongly connected network $G=(N,A)$, where N and A denote the sets of nodes and links, respectively. Let R and S denote a subset of N for which travel demand q^{rs} is generated from origin $r\in R$ to destination $s\in S$, and P^{rs} denote the set of paths from origin r to destination s . Since link capacity is random, and assumes it follows to uniform distribution $u_a \sim B(\theta_a(\overline{C_a}+y_a),(\overline{C_a}+y_a))$. Therefore, the travel time on path p T_p is also a random variable. The travel time on each link is depicted by $t_a(x_a)=t_a^0\times\left[1+\beta(x_a/u_a)^n\right]$. Similar to Lo et al.[6], all travelers are assumed to have knowledge of the variability of path travel time acquired from past experiences and incorporate this information along with their risk-preferences into their route choice decisions. Therefore, to study the user equilibrium problem under an uncertain environment, a key factor is to understand the travelers' route choice decision process under travel time variability.

Definition 1: (MTT) In the traditional DUE model, travelers are assumed to be risk-neutral since they make their route choice decisions based on the expected travel time[6]. Expected travel time variability is induced by stochastic link capacity noted in Eq.(1).

$$E(T_p)=\sum_a\left\{\delta_{a,p}\left[t_a^0+\beta t_a^0(x_a)^n\frac{1-\theta_\alpha^{1-n}}{\overline{C_a}^n(1-\theta_\alpha)(1-n)}\right]\right\}\quad(1)$$

where, T_p is the random travel time on path p ; $E[T_p]$ is the expected travel time; x_a is the flow on link a ; α is confidence level; θ_a is the degree of degraded capacity for link a ; $\overline{C_a}$ is the design capacity of link a ; $\delta_{a,p}$ is link-path incidence parameter, 1 if link a is on path p , zero otherwise; t_a^0 is free-flow travel time on link a ; β and n are the parameter in BPR function, respectively.

Definition 2: (TTB) Link capacity degradations cause link and route travel time variability. Travelers, therefore, do not know their exact travel times. Most travelers would depart earlier to allow for additional time, or add a travel time margin to the expected trip time, to avoid late arrivals[6]. In other words, travelers allow for a longer travel time budget to hedge against travel time variability. We define the travel time budget as Eq.(2).

$$B_p=E(T_p)+\lambda\sigma_{T_p}\quad(2)$$

Where, B_p is the travel time budget; σ_{T_p} is the extra time added to the mean travel time as a 'buffer time' to ensure more frequent on-time arrivals at the destination under the travel time reliability requirement; λ is degree of risk aversion; σ_{T_p} is noted in Eq.(3).

$$\sigma_{T_p}=\sqrt{\sum_a\delta_{a,p}\beta^2(t_a^0)^2(x_a)^{2n}\left\{\frac{1-\theta_a^{1-2n}}{\overline{C_a}^{2n}(1-\theta_a)(1-2n)}-\left[\frac{1-\theta_a^{1-n}}{\overline{C_a}^{n}(1-\theta_a)(1-n)}\right]^2\right\}}\quad(3)$$

Definition 3: (METT) By considering the travel time reliability requirement, travelers are searching for a path such that the corresponding travel time budget allows for on-time arrival with a predefined confidence level α . Meanwhile, they are also considering the impacts of excessively late arrival (i.e., the unreliable aspect of travel time variability) and its explicit link to the travelers' preferred arrival time in the route choice decision process. Therefore, it is reasonable for travelers to choose a route such that the travel time reliability is ensured most of the time and the expected unreliability impact is minimized. This trade-off between the reliable and unreliable aspects in travelers' route choice decision process can be represented by the mean-excess travel time (METT)[10]. It is defined as Eq.(4).

$$\eta_p(\alpha)=E[T_p\mid T_p\geq B_p(\alpha)]\quad(4)$$

where, $B_p(\alpha)$ is the minimum travel time budget on path p with a predefined confidence level α defined in Eq.(5).

$$B_p=\min\{B\mid \Pr(T_p\leq B)\geq\alpha\}\quad(5)$$

The mean-excess travel time $\eta_p(\alpha)$ for a path p with a predefined confidence level α is equal to the conditional

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