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Modeling distribution tail in network performance assessment: A mean-excess total travel time risk measure and analytical estimation method

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ABSTRACT

Risk measures are often used by decision makers (DMs) as a scalar risk characterization by integrating the statistical characteristics of risk as well as the DMs' risk strategy towards uncertainty. A good risk measure typically needs to have a risk preference control mechanism, a complete uncertainty characterization, and a practical implementation strategy. Total travel time reliability (TTTR) and total travel time budget (TTTB) are two risk measures recently proposed for assessing transportation network performance under uncertainty. In this paper, we propose the mean-excess total travel time (METTT) as an *alternative network-wide risk measure* to more cost-effectively capture the *distribution tail*, and develop *an analytical method* to estimate risk measures without knowing the explicit distribution form of TTT uncertainty. Methodologically, the METTT measure characterizes the distribution tail of exceeding the TTTB via the conditional expectation without requiring an extraordinary reliability level. It is able to account for the tradeoff between planners' risk-aversion attitude and the unacceptable risk, which avoids the need of setting a too conservative reliability requirement in the TTTB to reduce the unacceptable risk. The explicit distribution tail consideration in the METTT could lower the construction cost and substantially reduce the unacceptable risk of network capacity enhancement under uncertainty. To enhance the practicality of METTT, we develop an analytical estimation method to efficiently calculate the METTT by using the first four TTT moments as well as the planners' risk attitude. The TTTR and TTTB measures can also be analytically estimated as a byproduct of the proposed method for assessing the METTT. The analytical feature of the proposed method avoids the burdensome computation of simulation method and also circumvents the need of fitting the explicit TTT distribution form. Numerical results indicate that the proposed method has a desirable and comparable estimation quality in comparison with the theoretical derivation and curve fitting methods.

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1. Introduction

1.1. Network performance assessment under uncertainty

Total travel time (TTT) is one of the most widely used measures for assessing transportation network performance and design (Yang and Bell, 1998; Clark and Watling, 2005; Chen et al., 2011a; Farahani et al., 2013). Due to the existence of

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uncertainties in transportation systems, both link and route travel times are uncertain, which aggregately result in the uncertainty of TTT. Probability is the most widely used uncertainty modeling philosophy. It handles uncertain variables such as random variables with probability distributions. With the probability distributions, we are able to conduct the reliability analysis of transportation networks. In the literature, estimation methods of the TTT distribution can be broadly categorized into two groups: simulation and numerical approximation.

The ***simulation method*** (e.g., Chen et al., 2007, 2010) samples the uncertainty source (e.g., travel demands) from a given distribution with a specified number of samples. For each sample (i.e., an O–D demand pattern), a traffic equilibrium problem (TEP) is solved to obtain an equilibrium flow pattern and the corresponding TTT. These TTT samples are then collected to estimate the TTT distribution and its statistics. The advantage of the simulation method lies in its flexibility. No strong assumption is needed. However, the main drawback is the intensive computation required to conduct the simulation. The main reason is that the TEP needs to be solved for many times. The high computational burden may prevent its applications in network optimization, which typically needs to evaluate the TTT distribution or its statistics. Due to the stochastic nature of simulations, how to interpret the non-reproducible simulation results also deserves cautions (Bell et al., 1999). Furthermore, it is not trivial to specify a minimum number of samples *a priori* required to obtain stable results for a given network. An intuitive improvement is that we only need to solve the TEP once and then use some analytical methods to obtain the whole TTT distribution function and its statistics.

For the ***numerical approximation*** method, Clark and Watling (2005) proposed a *two-stage process* (i.e., *moment analysis and curve fitting*) to estimate the whole TTT distribution. The moment analysis stage computes the TTT moments under the Poisson distributed demand uncertainty and multivariate normal distributed link flows, while the curve fitting stage fits the obtained moments to a family of probability density functions (PDF). As is well known, Poisson distribution assumes the variance equals the mean. This assumption may not be realistic in representing the transportation systems. It is also worth noting that the curve fitting stage (i.e., estimating the whole distribution) does not make use of the moment information to calculate some risk measures for designing reliable networks. In addition, Ng and Waller (2010) developed an efficient *Fourier transform* technique for numerically approximating the entire PDF of TTT uncertainty incurred from independent link capacity degradation. They derived the theoretical bounds of approximation errors, and suggested ways to ensure the approximation accuracy by refining computational grids.

On the other hand, most of the existing studies on travel time reliability estimation need the complete probability distributions (e.g., distribution type and parameters) of uncertainty sources, and then calculate the exact travel time reliability. Ng et al. (2011) recently developed an alternate method without the complete distribution for quantifying the bound of total travel time reliability (TTTR). This alternate method requires the first N order moments of link travel times and its support to compute the bound of TTTR.

The above methods indeed provide an *intuitive picture* of the TTT distribution under uncertainty. Meanwhile, risk measures are often used by planners as a *quantitative characterization* of TTT uncertainty. Compared to the probability distribution function, risk measures can be considered as a *scalar* risk characterization. However, this scalar form typically integrates the statistical characteristics of a probability distribution as well as the planners' risk strategy towards network uncertainty. A good risk measure typically needs to have a risk preference control mechanism, a complete uncertainty characterization, and a practical implementation strategy. Total travel time reliability (TTTR) and total travel time budget (TTTB) are two risk measures recently proposed for assessing transportation network performance under uncertainty. TTTB is defined as the minimum TTT threshold that satisfies a reliability requirement specified by decision-makers (DMs) using a confidence level, while TTTR is the probability that TTT will not exceed a threshold value specified by DMs. Conceptually, both measures capture the acceptable risk under a specified reliability requirement. However, besides the acceptable risk consideration, we observe that it is also important to explicitly model the unacceptable risk lie in the *distribution tail* when assessing and designing network under uncertainty, and to develop the mean-excess total travel time (METTT) as an *alternative network-wide risk measure* to more cost-effectively capture the *distribution tail*.

1.2. Motivations

1.2.1. Empirical observations

Recently, several empirical studies have revealed that the positive skew with a long upper tail was a basic characteristic of observed travel time data. For example, Fosgerau and Karlström (2010) found that the empirical travel time data at a congested radial road in the Greater Copenhagen exhibit a fat right tail. Susilawati et al. (2011) analyzed the longitudinal travel time data for two major urban arterial road corridors in Adelaide, Australia, and found the data also exhibit a strong positive skew, very long/fat upper tail, and bimodality. Bogers et al. (2006) conducted a large-scale laboratory experiment with 2500 respondents to study the effect of travelers' extreme experiences (i.e., extremely long travel times on a route) on their route choice. They found that the most extreme travel time experiences influence their perception on the route attractiveness and route swapping. van Lint et al. (2008) used empirical data from a densely utilized freeway in The Netherlands to identify the characteristics of day-to-day travel time distribution. They observed that the travel time distribution is not only very wide but also heavily skewed with a long fat tail. Also, the economic consequences of these right-skew travel time distributions are substantial. The strong positive skew and long/fat upper tail suggest that the travel time distribution tail may have a significant impact on investment evaluations and decisions. The bimodality in travel time distributions further makes it