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Multi-objective path finding in stochastic time-dependent road networks using non-dominated sorting genetic algorithm

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ABSTRACT

In this paper, a new multi-objective path-finding model is proposed to find optimal paths in road networks with time-dependent stochastic travel times. This study is motivated by the fact that different travelers usually have different route-choice preferences, often involving multiple conflicting criteria such as expected path travel time, variance of path travel time and so forth. However, most of the existing studies have only considered the expected value of path travel time as the sole decision criterion. In order to solve the multi-objective model, the non-dominated sorting genetic algorithm is employed and its parameters are tuned by the Taguchi method. Moreover, a dynamic n-point crossover operator is developed to enhance the search capability of the genetic algorithm. Experimental results on a grid network demonstrate that the proposed approach is able to provide a set of non-dominated paths from which travelers can choose their paths based on their attitudes toward travel time uncertainty. Statistical analysis confirms that the dynamic n-point crossover operator outperforms the traditional one-point crossover operator.

1. Introduction

Optimal path finding undoubtedly lies at the heart of many optimization problems in the field of transportation engineering such as vehicle routing problem and transit network analysis. This has motivated both practitioner and academic interest in the development of more realistic models. On this basis, the last three decades have witnessed a broad spectrum of research on this interesting topic. The earliest studies have tended to regard the road network as a deterministic network where the travel time (cost) of each link is assumed to be a constant value. Consequently, optimal path finding in a deterministic network can be reduced to the classical shortest path problem. In real-life situations, however, the transportation network is usually stochastic and time-dependent. In fact, a traveler traversing a link daily may experiences different travel times on that link due not only to the fluctuations in travel demand (origin–destination matrix) but also due to such incidents as work zones, bad weather conditions, accidents and vehicle breakdowns. As a result, a stochastic time-dependent (STD) network is a more realistic representation of an actual road network compared with the deterministic one.

Optimal path finding is also a multi-objective problem in which several different, and often conflicting, objectives of interest are required to be optimized. This means that travelers tend to make a compromise between several indicators such as expected path travel time, variance of path travel time, path length and so forth.

Despite the importance of the path finding problem, there exist only very few studies presenting a multi-objective model for this problem in stochastic and time-dependent networks. These few studies, however, have some limitations, which are discussed in the next two sections. Therefore, one of the motivations behind our study is to overcome some of these limitations and propose a more realistic model.

In this paper, we suggest a model aiming to find a multi-objective optimal path in stochastic and time-dependent networks. In order to solve the proposed model, we employ the well-known non-dominated sorting genetic algorithm (NSGA-II). This type of genetic algorithm (GA) has been widely used for solving multi-objective problems.

The rest of this paper is organized as follows. The next section reviews the literature on the path finding problem in stochastic networks. This is followed by a section that describes the research

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gaps and the contributions of this research. Then, some definitions and concepts related to multi-objective optimization are briefly described in Section 4. The non-dominated sorting genetic algorithm is then outlined in Section 5. The proposed model for finding an optimal path in a stochastic and time-dependent network is presented in Section 6. Section 7 is concerned with the implementation of NSGA-II to solve the proposed model. The results of the implementation of the proposed method are discussed in Section 8. Finally, the last section concludes the paper with a summary and suggestions for future research.

2. Literature review

Several attempts have been made over the last two decades to capture the stochastic and time-varying nature of road networks in the context of the path-finding problem. Many of these studies have spearheaded their efforts to find an optimal path with either the stochastic or time-dependent nature of travel times rather than capturing both. In this paper, we undertake a selective review of those prior studies that have considered at least the stochastic nature of the network to address the optimal path finding problem.

Despite considerable progress during the course of the past decade, it remains a controversial question how an optimal path should be defined and identified in stochastic road networks. In other words, there is no unique definition of an optimal path under uncertainty. One possible and common answer to this question is to find a path with the minimum expected travel time (Chen, Lam, Qingquan, Sumalee, & Ke, 2013; Dong et al., 2013; Fu & Rilett, 1998; Gao & Chabini, 2006; Miller-Hooks & Mahmassani, 2000; Nielsen, Andersen, & Pretolani, 2014; Yang & Zhou, 2014). The main advantage of using this approach is that efficient shortest path algorithms introduced for the deterministic networks can be readily employed to identify the path with the minimum expected travel time in a stochastic network. However, the resulting optimal path identified by this approach may not be reliable, because this approach fails to address travel time variability. It should be noted that the concept of *travel time reliability* is used interchangeably with *travel time variability* in the transportation research literature, so that, in general, one can say that the higher the variability in travel time, the lower the reliability would be, and vice versa.

It has been revealed from the research on travelers' behavior that travel time reliability has considerable influence on their route choice (Carrion & Levinson, 2012; Khademi, Rajabi, Mohaymany, & Samadzad, 2014). Thus, travel time reliability is indispensable for finding optimal paths. Based on this idea, several different approaches have been pursued. Sen, Pillai, Joshi, and Rathi (2001), Zhang, Jun, Wei, and Wu (2010) and Ji, Chen, and Subprasom (2004), for example, proposed a mean–variance model to find an optimal path in a stochastic network, where the variance of the path travel time was considered as a measure of travel time variability. Both of these studies established a multi-objective framework in which the mean of path travel time along with its variance was minimized.

As indicated by previous research (Taylor, 2013; Van Lint, van Zuylen, & Tu, 2008), variance of path travel time tells only the half of the story and it does not appropriately address travel time variability due to the high skewness observed in travel time probability distribution. For example, suppose there exist three non-overlapping paths (*path A*,*path B* and *path C*) between a given origin and destination. Fig. 1 depicts the travel time distributions of these paths. As shown in this figure, all paths have the same mean travel time. Based on the expected travel time criterion, one cannot draw a distinction between these paths, suggesting that travelers do not have any preferences between these paths. Intuitively, it appears certain that *path C* cannot be preferable to the two other paths, owing to its higher variability. In addition,

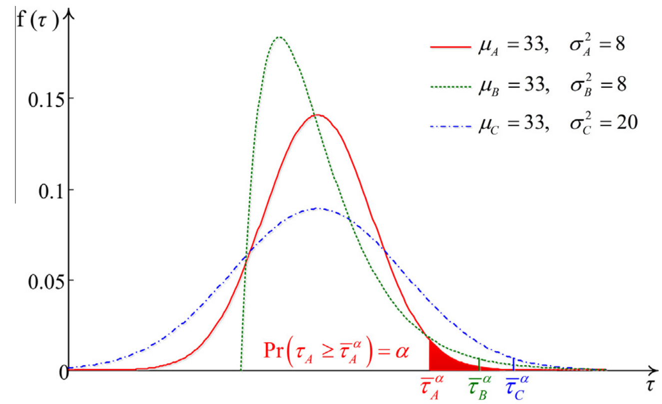

Fig. 1. Probability distribution of path travel time.

although the mean and variance of the travel time of *path A* are equal to those of *path B*, risk-averse travelers may choose *path A* because the travel time budget required to ensure a pre-specified on-time arrival probability $(1-\alpha)$ for *path A* is less than that of *path B* $(\bar{\tau}_A^\alpha < \bar{\tau}_B^\alpha)$.

In order to account for travel time reliability more accurately, two common alternative definitions for an optimal path under uncertainty have been suggested. Some have introduced the concept of *the most reliable path*, aiming to maximize the probability of arriving on time or earlier than a given travel time budget (Chen & Ji, 2005; Fan & Nie, 2006). Others, alternatively, have put forward the concept of an α-*reliable path* based on which they intended to minimize the travel time budget required to ensure a pre-specified on-time arrival probability (Chen, Lam, Sumalee, Li, & Tam, 2014; Ji, Kim, & Chen, 2011; Nie & Wu, 2009; Wu, 2013; Wu & Nie, 2011). Moreover, to evaluate paths in a stochastic and time-dependent network, Huang and Gao (2012) defined a disutility function for path travel time, and a path associated with the minimum expected disutility was considered as the optimal path. In order to capture the reliability and unreliability aspects of travel time variability simultaneously, Zhou, Martimo, and Chen (2010) proposed a path-finding model to determine an optimal path with the minimum mean-excess travel time required to satisfy a pre-specified on-time arrival probability.

Table 1 summarizes the studies described above in terms of their objective functions and whether or not they take the time dependency of travel time into account. In this table, the objective functions are abbreviated as follows:

- *E(TT)*: expected value of path travel time.
- *V(TT)*: variance of path travel time.
- *P(LA)*: probability of path travel time exceeding a pre-specified travel time.
- *P(OA)*: probability of arriving on time or earlier than a given travel time budget.
- *TTB*: travel time budget required to ensure a pre-specified on-time arrival probability.
- *ED*: expected disutility.
- *METT*: Mean-excess travel time required to satisfy a pre-specified on-time arrival probability.

As seen in Table 1, although several studies have attempted to solve the optimal path finding in stochastic road networks, few studies have simultaneously taken the stochastic and time-dependent nature of travel time into account. These studies are single objective and mainly aim to minimize only the expected value of path travel time. However, as discussed earlier, path finding is a multi-objective problem. As a result, there exists a need