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Itinerary planning with time budget for risk-averse travelers

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ABSTRACT

Itinerary planning problem (IPP) in public transport networks has witnessed to be a fundamental and important problem in public transport operations management. Although empirical studies show that time budgets are usually prescribed by travelers, the time budget is rarely considered in literature related to IPP under stochastic travel times. In this paper, we study the IPP with time budget (IPPB) in public transport networks with stochastic travel times, which consists of planning an itinerary from an origin to a destination that helps risk-averse travelers mitigate uncertainty and effectively meet their time budgets. A mathematical model (MRHA-IPPB) is developed for the IPPB, in which we use the utility theory to characterize travelers' risk-averse behaviors. Since minimizing the lateness probability or the expected lateness duration is intractable, we propose a new decision criterion, maximizing risk-hedging ability (short for MRHA hereafter) while guaranteeing that the corresponding certainty equivalent of itinerary travel time would not exceed the time budget. The model MRHA-IPPB is shown theoretically and numerically to consider both the lateness probability and the lateness duration. We show NP-completeness of the IPPB with fully correlated arc travel times and study two tractable scenarios, i.e., the IPPB with independent arc travel times and that with partially correlated arc travel times. We decompose an IPPB as a two-stage problem and efficiently solve it through a binary search scheme with a label-setting algorithm embedded. We demonstrate the effectiveness of the MRHA-IPPB model through an illustrative example and show that the MRHA-based decomposition approach requires only less than one second per query over a real-world public transport network.

1. Introduction

Itinerary planning problem (IPP) in public transport networks has witnessed to be a fundamental and important problem in public transport operations management. This problem includes determining an optimal public-transport itinerary from an origin to a destination. The findings could i) help passengers better arrange their travels, ii) enable managers to understand travelers' route choice behaviors and facilitate efficient operations and management of public transport, iii) help the government raise the attractiveness of public transport systems and thus ease congestion, reduce emissions, etc., and iv) contribute to further studies of, for instance, transit assignment and transit network design.

In itinerary planning, travelers would usually prescribe travel time budgets prior to starting travels. In some cases such as attending a job interview, deadlines are imposed at the destinations that should be met almost surely. In other cases such as participating in a party, deadlines are expected to be met but can be slightly violated. Even if no exogenous deadline is imposed, empirical studies show that target times to arrive may be scheduled artificially (Stopher, Ahmed, & Liu, 2017). A risk-averse traveler in such situations would prescribe a departure time. The time budget, which is the scheduled travel duration from the departure time to the deadline, is usually longer than the expected shortest travel time. Despite its importance, the itinerary planning problem with time budget (IPPB) under stochastic travel times is rarely studied in literature. The work of Häme and Hakula (2013) is the only one to our knowledge, and due to the inherent complexity of solving the IPPB, they proposed an approximation algorithm to achieve the computational efficiency.

Solving the IPPB efficiently is not an easy task. The IPPB with deterministic arc travel times (i.e., vehicular travel times and transfer waiting times) amounts to finding the minimum travel time itinerary without time budget, which is well studied. However, uncertainty exists ubiquitously in travel times and cannot be ignored. Travelers usually address this issue through the following heuristic approach: traveling along the itinerary with the mini-

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mum deterministic travel time but departing earlier. This approach is computationally efficient, but may perform badly in decreasing lateness probability and lateness duration. Considering uncertainty and time budget explicitly, the stochastic programming approach that minimizes the lateness probability or the expected lateness duration seems to be a natural approach, but the resultant problem is generally NP-hard (Nemirovski & Shapiro, 2006) or #P-hard (Hanasusanto, Kuhn, & Wiesemann, 2016), respectively. Hence, it can be impractical to solve real-world (and often large-scale) IPPBs. Motivated by both the technical difficulty and the practical importance, we aim at developing an alternative approach that is both computationally efficient and theoretically effective to solve the IPPB under stochastic travel times.

In this paper, we contribute to the literature by providing a new approach to solve the IPPB. We characterize the risk-averse travelers' route choice behaviors through the utility theory (Von Neumann & Morgenstern, 2007), based on which, we propose a new decision criterion, i.e., maximizing risk-hedging ability (MRHA). The basic idea is to maximize a traveler's risk-hedging ability (or risk-averse level), while guaranteeing that the corresponding certainty equivalent of itinerary travel time would not exceed the time budget. The resultant model for the IPPB, called the MRHA-IPPB model, is shown theoretically and numerically to have the ability of involving both the lateness probability and the lateness duration into consideration. The MRHA-IPPB model also turns out to be efficiently solvable. Incorporating the correlation in each bus trip's vehicular travel times would keep the tractability of the IPPB and make the solutions more precise.

1.1. Previous related work

The itinerary planning problems, typically modeled as enhanced shortest path problems, are extensively studied, either separately or integrated in, for instance, transit assignment problems (De Cea & Fernández, 1993; Spiess & Florian, 1989; Szeto & Jiang, 2014; Verbas, Mahmassani, & Hyland, 2016) and transit network design problems (An & Lo, 2016; Bagloee & Ceder, 2011; Guihaire & Hao, 2008; Yao, Hu, Lu, Gao, & Zhang, 2014). Regarding modeling the underlying public transport network, we follow Androutsopoulos and Zografos (2009) and distinguish the difference between the headway-based model and the schedule-based one. In the headway-based network, each transit line is associated with a constant headway and the transfer waiting time is considered random. Typically, the expected transfer waiting time is assumed to be a half of the headway of the to-be-transferred line (Dial, 1967; Peng & Huang, 2000). Chriqui and Robillard (1975) studied a so-called "common bus line" problem, which indicates that, with multiple headway-based transit lines serving a single bus stop, a traveler waiting at this stop might apply the strategy of choosing a set of attractive lines and boarding the first arriving vehicle in that set in order to minimize the expected travel time to the destination. A sequence of such strategies at transfer stops is called the hyperpath by Nguyen and Pallotino (1988). See Li, Chen, and Nie (2015) for a review of hyperpath finding problems in headway-based networks. In the schedule-based network, each transit line is with a fixed timetable that specifies the arrival and departure times for the stops to serve. A transfer waiting time is then determined by both the time a traveler arrives at a stop and the timetable of the to-be-transferred line, and thus it is time-dependent. The path-finding problems in schedule-based networks were typically treated as time-dependent shortest path problems (de Jonge & Teunter, 2013; Delling, Pajor, & Werneck, 2014; Khani, Hickman, & Noh, 2015). Pyrga, Schulz, Wagner, and Zaroliagis (2008); Tong & Richardson, 1984 demonstrated through computational experiments that, modeling the schedule-based network as a time-dependent network is more computationally efficient than modeling it as a time-expanded network.

To incorporate more real-world concerns in the itinerary planning problems, extensions of considering multiple transport modes, using multiple criteria to evaluate itineraries, and finding k-th shortest itineraries were investigated in the literature. Multiple transport modes under consideration, apart from walking and headway- or schedule-based transit lines (buses, metros, trains), may also include taxis, cars, bikes, flights and ferries, among others (Canca, Zarzo, González-R, Barrena, & Algaba, 2013; Delling et al., 2014; Dibbelt, Pajor, & Wagner, 2015; Horn, 2003; Lozano & Storchi, 2002). Arcs are usually added to connect different transport modes, where each arc cost corresponds to a transfer penalty, and thus the multimodal issue is circumvented. Besides the total travel time, travelers may also care about the criteria of the number of transfers, the monetary cost, etc. To handle these possibly conflicting criteria, some studies transform all the criteria into monetary costs so as to construct a so-called generalized cost function to minimize, and thus change the multi-objective problem to a single objective problem (Horn, 2003; Noh, Hickman, & Khani, 2012; Verbas & Mahmassani, 2015). Yang, Zhang, Li, and Gao (2016) minimized the total travel time plus the penalty cost incurred by transfers. Another popular way is to identify a set of Pareto optimal (or non-dominated) itineraries and provide all of them to the travelers to choose (Androutsopoulos & Zografos, 2009; Delling et al., 2014; Dibbelt et al., 2015). Alternatively, Zografos and Androutsopoulos (2008) proposed optimizing lexicographically over several criteria. Xu et al. (2012) and Canca et al. (2013) developed labeling algorithms to determine not only the shortest travel time itinerary, but also the k-th shortest itineraries, and hence more options are provided to the travelers.

Most above studies implicitly assume risk neutrality of travelers and minimize the expected total travel time (or together with other criteria to optimize), which would potentially result in unreliable solutions when uncertainty occurs. Indeed, uncertainty is ubiquitous in travel times and risk-averse travelers value the travel time reliability (Nie & Wu, 2009), but this is rarely considered in the context of itinerary planning problems. Palma and Picard (2005) demonstrated through their empirical study that there is a certain portion of travelers who are risk-averse. Goerigk, Schmidt, Schöbel, Knoth, and Müller-Hannemann (2013) studied the itinerary planning problem in a train network where delays may occur and the planned transfers may fail. Using robust optimization, they assumed an uncertainty set of scenarios of the train delays and identified risky transfers, which are excluded in the itinerary planning. Li, Chen et al. (2015) also introduced an uncertainty set to characterize the uncertainty in travel times along arcs; their objective is to determine the itinerary with the minimum travel time under the worst-case scenario occurring within the uncertainty set. It has been emphasized that risk-averse travelers tend to reserve buffer times in their route choices to safeguard against the uncertainty in travel times (Hall, 1983; Lo, Luo, & Siu, 2006; Stopher et al., 2017; Wu & Nie, 2011). The time budget is then defined as the mean travel time plus the buffer time. Considering traveler's time budget in the itinerary planning problem in schedule-based public transport networks, Häme and Hakula (2013) adopted Markov decision process to model the problem, which yields a set of policies at stops aiming at maximizing the on-time arrival probability. Since the exact algorithm is computationally demanding, they solve the problem approximately by posing the assumption of independence between the current state and historical states. To our knowledge, no other works have explicitly considered the aspect of time budget in the itinerary planning problem in public transport networks with stochastic travel times. In this paper, we aim to fill the gap and develop a computationally