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Adaptive vehicle routing for risk-averse travelers ☆

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ABSTRACT

This paper develops an adaptive navigation approach for risk-averse travelers in a stochastic network while considering on-time arrival reliability, in which travelers' final utility is measured with the prospect theory. Instead of finding a route or a policy that simply minimizes the expected travel time or maximizes the on-time arrival reliability, this model optimizes the expected prospect of potential routing alternatives while ensuring that both the expected en route travel time and resultant on-time arrival reliability are acceptable to the traveler. Moreover, the formulation is designed to incorporate various sources of information and real time traffic states in an adaptive routing framework, offering flexibility to incorporate different information types deemed useful in future extensions.

1. Introduction

1.1. Background

Transportation networks are by nature stochastic due to the underlying uncertainties in demand and supply. Vehicle routing in a stochastic network hence is an important part of the analysis to meet the different optimality conditions for which the routing objective is defined. A common optimality condition is defined as the least expected en route travel time. Such an effort can be traced back to at least 1958 (Dijkstra's shortest path algorithm). In this context, researchers have been proposing many different approaches to achieve this objective. For instance, Hart et al. (1968) proposed the goal-directed search algorithm which is also known as the A* algorithm. Eppstein (1998) extended the single shortest path to a set of alternative paths and developed k-shortest path algorithm. More recently, Bell (2009) developed an algorithm which generates a set of attractive paths (hyperpath) as a modification of the classical A* algorithm. Another optimality condition considering travel time reliability has been proposed recently (Lo and Tung, 2003; Lo et al., 2006; Azaron et al., 2005; Siu and Lo, 2008, 2009, 2013; Chen and Zhou, 2009, 2010). Besides, Fan and Nie (2006) modeled how to determine a most reliable route; and Opasanon and Miller-Hooks (2005) incorporated the condition of first-order stochastic dominance (SD) in the optimal routing decision procedure. Chen et al. (2013) proposed the method of finding a reliable shortest path in a time-dependent network. Connors and Sumalee (2009) developed a network equilibrium model in terms of travelers' perception of path travel time. The objective there was to determine a path to ensure certain on-time arrival reliability or reduce the risk of being late.

The objective of finding the shortest path with the minimum expected en route travel time may not be desirable to a risk-averse traveler who is sensitive to on-time arrival reliability (e.g. in attending an important meeting), since it may lead to a path with a low probability of on-time arrival despite that it may be a path with the minimum expected travel time. Opposite

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to this case, the path with the highest on-time reliability may lead to a long expected travel time as compared with other choices. The obvious consequence resulted from this drawback is that a path with high reliability may not be desirable for trips sensitive to the average travel cost. Considering both aspects, which sometimes are in conflict with each other, a multi-objective linear program (MOLP) is typically formulated to provide a set of solutions which forms the so-called Pareto frontier. For instance, Corley and Moon (1985) formulated a bi-objective shortest path algorithm using vector weights; Brumbaugh-Smith and Shier (1989) implemented several bi-objective algorithms on large network; and Hamacher et al. (2006) developed a bi-objective shortest path searching algorithm producing a set of Pareto optimal paths. A review on this can be found in Hamacher et al. (2007). Basically, a MOLP requires an explicit estimation of the linear objective matrix/vector such that a new criterion taking the form of a weighted sum of pertinent objectives can be derived. However, it is laborious, if feasible at all, to calibrate all the objective matrices or to produce the Pareto frontier relevant to each individual. In addition, the solution from typical MOLP methods is a set of Pareto paths, rendering the need to prune down the set to a single path eventually for the traveler.

1.2. Contributions and highlights of the proposed approach

Different from proposing a single criterion which is typically taken to be the weighted sum of some objectives, this paper proposes a way to include the two criteria discussed above, namely, travel time/cost and on-time reliability, in determining the optimal routing policy by making a feasible and reasonable tradeoff between them. The tradeoff between the two criteria is necessary since they are sometimes in conflict with each other. By "tradeoff", we imply that the approach does not optimize for one criterion exclusively, but optimizes one criterion, e.g. expected travel cost or prospect as much as possible, while ensuring that the alternatives are admissible or acceptable for the other criterion of on-time arrival reliability. We then formulate this problem through an adaptive optimal routing approach for risk-averse travelers. Such "short" and also "reliable" route guidance helps travelers with different trip purposes and preferences to better plan their schedules.

This approach is developed for a specific group of travelers who are risk-averse such that their common features can be exploited. In terms of methodology, besides dynamic programming (Bertsekas, 1987, 1995), we combine the prospect theory (Kahneman and Tversky, 1979) and the concept of stochastic dominance (SD) (Hadar and Russell, 1969) in formulating this problem. In fact, both of them are not new in economics and transportation. Sumalee et al. (2009) modeled network equilibrium under the cumulative prospect theory for stochastic demand; and Nie and Wu (2009) discussed the implementation of SD for minimizing late penalty and travel time related cost. Wu and Nie (2011) proposed means of determining paths for travelers with different risk-taking preferences. Nie et al. (2012) discussed optimal paths with SD constraints. One salient feature of this proposed approach is that we introduce the reflection effect to account for the behavior of risk-averse travelers for negative payoffs while considering SD. Furthermore, we capture the measure of on-time arrival reliability through a dynamic programming approach, and formulate the adaptive optimization problem with finite stages and finite states in each stage subject to SD and reliability constraints. The end result produces a routing policy with low expected travel time or high prospect while capturing on-time reliability considerations.

1.3. Fundamental concept of adaptive vehicle navigation

For readability, in this section, we briefly explain the formulation of adaptive vehicle navigation for general navigation purposes. More details can be found in Xiao and Lo (2010). The adaptive vehicle routing problem is formulated via probabilistic dynamic programming (PDP). In addition to offering a way to formulate the problem, PDP possesses the advantage of allowing for efficient numerical solution methods to be developed. Another advantage of PDP is that it provides a more transparent exposition of the problem formulation. The routing problem can be formulated as a finite horizon adaptive routing problem with finite discrete stages and finite states in each stage.

The output of the approach is an adaptive routing policy rather than a complete path (or a set of paths) which is fixed once the problem is solved. This routing policy, in the form of a decision matrix, depicts at each decision point the 'best' link or sub-path to enter in accordance to the current traffic condition encountered, as well as to other related restrictions. For example, at each intersection, the policy depicts the next step to be taken based on the travel time encountered in the current link so as to achieve the desired routing objective.

Before discuss the formulation, certain terms should be defined in advance:

Stage	To set up the problem as a dynamic programming formulation, we divide the routing problem into a finite number of stages or decision points. Meanwhile, in urban areas, transportation networks are typically segmented by intersections/junctions. Thus, a stage is defined as a location at which link switching is possible, for example at an intersection or exit or entrance of a freeway. In this paper, we define each intersection (presented by a node in graph) in the traffic network as a stage. Therefore, in the following, to make the formulation succinct, we will not distinguish between the notation of stage, intersection and node

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