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The dynamic shortest path problem with time-dependent stochastic disruptions

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ABSTRACT

The dynamic shortest path problem with time-dependent stochastic disruptions consists of finding a route with a minimum expected travel time from an origin to a destination using both historical and real-time information. The problem is formulated as a discrete time finite horizon Markov decision process and it is solved by a hybrid Approximate Dynamic Programming (ADP) algorithm with a clustering approach using a deterministic lookahead policy and value function approximation. The algorithm is tested on a number of network configurations which represent different network sizes and disruption levels. Computational results reveal that the proposed hybrid ADP algorithm provides high quality solutions with a reduced computational effort.

1. Introduction

The growth in economic output influences the volume of transportation activities. Within the EU-28 (European Union's 28 countries), about 2200 billion ton-kilometers of goods were transported in 2014, with road transportation accounting for about three quarters (i.e., 74.9%) of this volume (Eurostat, 2016). The growing volumes of road freight transportation contribute to congestion on road, which leads to delay, disruption, and other negative impacts on the reliability of transportation. The direct impact of congestion, as transportation externality, refers to increased travel times to other entities in the transportation system. Moreover, congestion could indirectly result in increased fuel costs, air pollution, noise pollution and stress levels (Demir et al., 2015).

Congestion can be measured as the sum of recurrent and non-recurrent delay in a traffic network (Skabardonis et al., 2003). The first category depends on the fluctuations in demand and the physical capacity of the road. The second category depends on the nature of the incident, such as breakdowns, and accidents. As the uncertainty in traffic networks increases due to recurrent and non-recurrent delays, a driver needs to take into account the congestion by considering all traffic states that change the travel time with respect to disruption level.

Having real-time traffic information from Intelligent Transportation Systems (ITS) and taking into account the stochastic nature of disruptions can significantly reduce time delays, congestion and air pollution. As a trade-off, for networks with many disruption levels, computing dynamic routing decisions takes very long computational time. In order to improve the speed of computation, real-life applications (e.g., navigation devices) require fast and high quality algorithms as we intended to propose one in this paper. The

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problem at hand is named as dynamic and stochastic shortest path problem in the literature and has been the topic of extensive research over the last decades (see, e.g., Flatberg et al., 2005; Kumari and Geethanjali, 2010). The existing models in the literature can be categorized into two: Adaptive routing recourse policies (see, e.g., Polychronopoulos and Tsitsiklis, 1996; Fu, 2001) and a Markov decision process (MDP) (see, e.g., Kim et al., 2005a; Thomas and White, 2007; Güner et al., 2012).

In the domain of vehicle routing, the dynamic shortest path problem with anticipation using the MDP is first studied by Kim et al. (2005a). Whenever there is a new information about disruption, their proposed model considers the congestion dissemination and anticipates the route accordingly. For larger networks, as the formulation becomes intractable, Kim et al. (2005b) proposed state space reduction techniques where the authors identified the traffic data that has no added value in the decision making process. In another study, Güner et al. (2012) considered the non-stationary stochastic shortest path problem with both recurrent and non-recurrent congestion using real time traffic information. The authors formulated the problem as the MDP that generates a dynamic routing policy. To prevent the state explosion, the authors limited the formulation to two-links-ahead formulation where they only retrieve the state information for only two links ahead of the current location. At last, Sever et al. (2013) formulated the dynamic shortest path problem with travel time-dependency using the MDP formulation. The authors reduced the computational time by using different levels of real-time and historical information.

For large-scale traffic networks with many disruption levels, obtaining the optimal solution faces the curses of dimensionality, i.e., states, outcomes, and decisions (Powell, 2011). In order to deal with dimensionality problem, we propose Approximate Dynamic Programming (ADP) approach for the investigated problem (see, e.g., Powell et al., 2002; Powell and Van Roy, 2004; Simão et al., 2009). ADP is widely used in other applications and interested readers are referred to Lam et al. (2007), Cai et al. (2009), Medury and Madanat (2013) and Hulshof et al. (2016). The current empirical studies on traffic congestion show that highways can have more than two levels of disruption which are specified according to the speed level and possible spill-back (Helbing et al., 2009; Rehborn et al., 2011). However, increase in disruption levels leads to an exponential state- and outcome-space growth causing the well-known curses of dimensionality. Therefore, it is necessary to propose efficient approximation techniques to deal with many disruption levels in traffic networks.

In this paper, we formulate the dynamic shortest problem with time-dependent stochastic disruptions as the MDP and propose the hybrid ADP algorithm with the clustering approach. The algorithm uses both a deterministic lookahead policy and a value function approximation. To our knowledge, the hybrid ADP algorithm with the clustering approach has not yet been thoroughly investigated for the dynamic shortest path problem. We propose and compare several variations of ADP algorithms for networks with many disruption levels which are similar to real-life traffic situations.

The scientific contribution of this study is twofold: (i) to propose the hybrid ADP with the clustering approach for solving the dynamic shortest path problem in traffic networks with many disruption levels, and (ii) to test various algorithmic variations of the hybrid ADP algorithm. The remainder of this paper is organized as follows. Section 2 presents a mathematical foundation of the investigated problem. Section 3 introduces the MDP model followed by the introduction of the proposed ADP algorithm. Section 4 discusses the computational results when applying the proposed algorithms to generated instances. Conclusions are stated in Section 5.

2. Mathematical formulation

Consider a traffic network represented by a directed graph consisting of a finite set of nodes and arcs. This network can be represented as $G = (N,A,A_v)$, where $N = \{0,...,n\}$ is the set of nodes (or intersections), $A = \{(i,j): i,j \in N \text{ and } i \neq j\}$ is the set of directed arcs, and finally A_v is the set of vulnerable arcs (i.e., $A_v \subseteq A$). The number of vulnerable arcs is defined as R: $R = |A_v|$. Each vulnerable arc, namely $r \in A_v$, can take any value from the disruption level vector, U^r, whose dimension depends on a specific vulnerable arc. The travel time on an arc (i,j) is assumed to follow a discrete distribution function on the positive integers based upon historical data and the disruption level of the arc (i,j). The real-time information about the disruption statuses of all vulnerable arcs is obtained when reached at the next node. The objective of the investigated problem is to minimize the expected travel time between an origin and a destination. The resulting problem is a finite horizon stochastic dynamic optimization problem, which can be formulated as a MDP. In the following subsections, we describe the key elements of the mathematical model, using the notations of Powell (2011).

2.1. State

Stage t represents the number of nodes that have been visited so far from the origin node. The system state S_t at stage t is represented by the following two components, $S_t = (i_t,\widehat{D}_t), t = 0,...,T$:

i_t The current node at stage t ($i_t \in N$)
$\widehat{D}_t$ The disruption status vector which gives disruption statuses of all vulnerable arcs at stage t.

The terminal stage T can be reached by arriving at the destination. Note that, at each stage, a realization of the disruption vector $\widehat{D}_t$ is used. For each vulnerable arc, there can be K_r different types of disruption levels: $\widehat{D}_t(r) \in U^r$: $U^r = \{u^1,u^2,...u^{K_r}\}$,$\forall\ r \in A_v$.

Moreover, the initial state is defined as $S_0 =$ (origin node,$\widehat{D}_0$), and the final goal state is defined as $S_T =$ (destination node,$\widehat{D}_T$), where $\widehat{D}_0$ and $\widehat{D}_T$ are the realizations of the disruptions for all vulnerable arcs at the initial and final stage, respectively. We note that the goal state is absorbing and cost free.