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Discrete Optimization

Integrating stochastic time-dependent travel speed in solution methods for the dynamic dial-a-ride problem

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ABSTRACT

In urban areas, logistic transportation operations often run into problems because travel speeds change, depending on the current traffic situation. If not accounted for, time-dependent and stochastic travel speeds frequently lead to missed time windows and thus poorer service. Especially in the case of passenger transportation, it often leads to excessive passenger ride times as well. Therefore, time-dependent and stochastic influences on travel speeds are relevant for finding feasible and reliable solutions. This study considers the effect of exploiting statistical information available about historical accidents, using stochastic solution approaches for the dynamic dial-a-ride problem (dynamic DARP). The authors propose two pairs of metaheuristic solution approaches, each consisting of a deterministic method (average time-dependent travel speeds for planning) and its corresponding stochastic version (exploiting stochastic information while planning). The results, using test instances with up to 762 requests based on a real-world road network, show that in certain conditions, exploiting stochastic information about travel speeds leads to significant improvements over deterministic approaches.

1. Introduction

Most published articles related to vehicle routing problems assume travel speeds that are constant over time (e.g., Muelas, LaTorre, & Peña, 2013;; Paquette, Cordeau, Laporte, & Pascoal, 2013; Parragh and Schmid, 2013). In reality, travel speeds rarely are constant but instead depend on factors such as traffic congestion caused by rush hours, accidents, construction sites, or bad weather conditions. An example in Fig. 1 reveals the average travel speeds observed on a specific road segment in the city of Vienna, by time of day. The morning and afternoon peaks (rush hours), which are typical for inner-city roads, are clearly visible. The comparison with the real (stochastic) travel speed observed during one specific day on the same road segment shows that travel speeds are highly sensitive to the time of day, with significant stochastic fluctuations caused by different effects. Therefore, assuming that travel speeds are non-stochastic or even time-independent often causes planned schedules to fail with respect to time windows or ride time limitations.

Some recent publications treat travel speeds as time-dependent, by dividing each day into discrete time intervals, each of which provides a characteristic travel speed for each road within a network (Ehmke, Steinert, & Mattfeld, 2012; Fleischmann, Gietz, & Gnutzmann, 2004; Ichoua, Gendreau, & Potvin, 2003; Kok, Hans, Schutten, & Zijm, 2010; Lorini, Potvin, & Zufferey, 2011; Potvin, Xu, & Benyahia, 2006; Schmid & Doerner, 2010; Xiang, Chu, & Chen, 2008). Even these approaches assume travel speeds to be deterministic though, with the assertion that travel speed, in terms of average values for each interval, is known a priori and not influenced by any stochastic effects. Some authors (Eglese, Maden, & Slater, 2006; Fleischmann, Gnutzmann, & Sandvoß, 2004; Maden, Eglese, & Black, 2010) use a different approach and incorporate time-dependent travel speeds in the process of calculating shortest paths. However, to the best of our knowledge, these algorithms do not take stochastic information about future travel speeds into account to obtain better solutions. Instead, these methods treat travel times as deterministic, so they are restricted to reacting to changes in travel speeds by recalculating the shortest paths.

Travel speeds should be treated as stochastic if we hope to represent reality more precisely. This approach would also improve the reliability and productivity of the planned schedules significantly (Fu, 1999, 2002; Nielsen, Andersen, & Pretolani, 2013; Taş, Dellaert, van Woensel, & de Kok, 2013; Taş, Gendreau, Dellaert, van Woensel, & de Kok, 2013). In this article, we present variants of stochastic solution methods that use a state-of-the-art, network-consistent, time-dependent travel time layer to take the stochastic influence of future traffic accidents into account while computing

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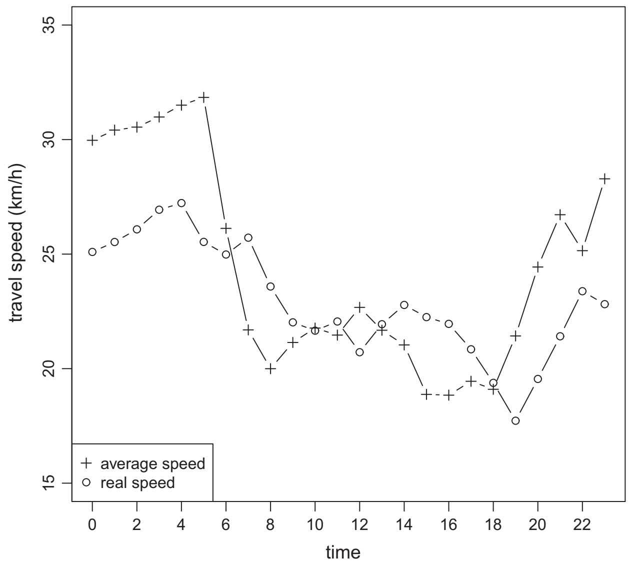

Fig. 1. Time-dependent average travel speeds and real (stochastic) travel speeds along a road segment in Vienna over 24 hour.

vehicle routes. The stochastic accident influence is estimated based on statistical parameters derived from historical, real-world information about accidents with physical injuries collected by different Austrian authorities. There are in fact several factors that can cause stochastic deviations from time-dependent average travel speeds: accidents, temporary construction sites, or large one-time events (e.g., sports games, fares) are just some possible examples. We decided to use data about accidents with physical injuries because of three reasons. First, the respective information is collected systematically by the authorities (and thus available). Second, the influence of major traffic accidents on travel speeds is strong enough to make a difference. Third, traffic accidents occur frequently enough to model them based on statistical information derived from historical data. The numerical results (see Section 5.2) show, that the severity of missed time windows and excess ride times caused by unexpected stochastic changes in travel speed can be reduced significantly by exploiting historical information about traffic accidents with physical injuries.

Especially when conveying passengers, missed time windows and excessive ride times due to changes in travel speeds have a strong negative effect on perceived service quality. This effect becomes even more important when the transported passengers are medical patients or elderly people. The challenge of transporting elderly or disabled people has been widely studied; it is usually modeled as a dial-a-ride-problem (DARP), as introduced in the early 1970s by Wilson and Colvin (1977), Wilson and Weissberg (1976), Wilson, Sussman, Wong, and Higonnet (1971). Healy and Moll (1995) showed that the DARP is NP-hard, and much effort has been dedicated to the development of (meta-)heuristic solution approaches for this problem class, especially in the form of real-world-motivated DARPs (Cordeau & Laporte, 2007; Parragh, Doerner, & Hartl, 2008). A recent review of articles covering the optimization for dynamic ride-sharing was presented by Agatz, Erera, Savelsbergh, and Wang (2012).

In this article, we study the effect of using information about stochastic deviations from time-dependent average travel speeds to plan vehicle routes for a dynamic DARP. This research offers four main contributions:

- We extend four metaheuristic solution approaches to handle stochastic, time-dependent travel speeds in the case of a dynamic DARP.
- We adapt a state-of-the-art, network-consistent, time-dependent travel time layer (i.e., a "method to generate time-dependent travel times that are guaranteed to be network-consistent" (Lecluyse, Sörensen, & Peremans, 2013)) and thereby estimate the stochastic effects of future traffic accidents.
- We propose a new scheduling algorithm for the DARP that is designed specifically to handle time-dependent travel speeds.
- We show that exploiting historical data about traffic accidents using a stochastic planning algorithm has beneficial effects on solution quality in certain conditions.

The remainder of this article is organized as follows. In Section 2, we provide a detailed problem description, followed by an overview of the simulation framework in Section 3 and the solution methods in Section 4. In Sections 5.1 and 5.2, we explain the used test instances and the corresponding computational results, respectively. This article concludes with a summary and short discussion of remaining research questions.

2. Problem description

The dynamic DARP with stochastic, time-dependent travel speeds is based on a (directed) real-world road network. Let d be the shortest path (with respect to distance, not travel time) between any two nodes in this network. Then $\widehat{T}(t,d) = \widehat{T}_{avg}(t,d) + \widehat{T}_{stoc}(t,d)$ is the time required to travel this path, starting at time t, and $\widehat{T}_{avg}(t,d)$ is the time required to travel the path given the departure time t, based on the average vehicle speeds along the path during the affected time intervals. The term $\widehat{T}_{stoc}(t,d)$ represents the stochastic influence on this travel time, which we assume is revealed the moment a vehicle starts traveling this path. Note that we also assume the shortest paths within the network are constant, not recalculated according to changing traffic situations, but evaluated using the time-dependent or stochastic travel speeds along each path. Although recalculating any single path is not very demanding, doing so for a large number of possible future travel speed scenarios would lead to significant performance problems for an online stochastic solution method. Furthermore, we denote by $\check{T}(t,d)$ the time required to travel along this path when the arrival time at the end of the path should be t.

Each transportation request r consists of two separate nodes $p_r, d_r \in N$, representing the pickup and delivery location, respectively. That is, N denotes the set of all customer locations in the graph. The time a_r represents the time the solution method (i.e., the dispatcher) is informed about transportation request r (e.g., by phone). Some requests are static ($a_r = 0$), but others are dynamic in the sense that they become known only as the day progresses ($a_r > 0$). For the dynamic DARP, a limited number of vehicles is available to service all requests. We assume that rejecting requests is not permitted (solution feasibility is guaranteed by the soft evening-depot time window, described subsequently).

Each node $n \in N$ is assigned a quantity of $q_n = 1$ for pickup locations and $q_n = -1$ for delivery locations, indicating that one passenger is boarding or leaving the vehicle. The depot node 0 is assigned a quantity of $q_0 = 0$. Each vehicle has a limited capacity of $Q_{max} = 3$, assuming a homogeneous vehicle fleet and homogeneous passengers. Each passenger occupies exactly one seat inside a vehicle, and each vehicle has exactly three seats installed. We do not differentiate between different modes of transportation in this work (interested readers should consult Parragh, Cordeau, Doerner, & Hartl (2012) for a heterogeneous DARP).

Each node n (both pickup and delivery) has a time window $[e_n, l_n]$. The depot node 0 has the time window $[0, T_{max}]$, which means that vehicles can leave the depot at any time $e_0 = 0$ or thereafter and should not return later than $l_0 = T_{max}$. Here, T_{max} is