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Robust solutions to the pollution-routing problem with demand and travel time uncertainty

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ABSTRACT

Freight transportation activities could potentially lead to detrimental effects on the natural and built environments and pose health risks. The importance of the present study is to consider demand and travel time uncertainty in green transport planning by proposing several robust optimization techniques; soft worst case, hard worst case and chance constraints. These techniques provide the most reliable solutions with very limited increase in the objective function related to fuel consumption and CO_2-equivalent emissions.
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1. Introduction

Transportation has detrimental effects on the environment such as resource depletion, land use, acidification, toxic effects on ecosystems and humans, noise and the impacts induced by Greenhouse Gas (GHG) emissions (Knörr, 2009). The emissions of CO_2 are directly proportional to the amount of fuel consumed by a vehicle, which is in turn dependent on a variety of vehicle, environment and traffic-related parameters, such as vehicle speed, load and road gradient (Demir et al., 2011, 2014). The carbon dioxide equivalent (CO_2e) measures how much global warming a given type and amount of GHG may cause, using the functionally equivalent amount or concentration of CO_2 as the reference.

The Vehicle Routing Problem (VRP) is a well-known NP-hard problem which was introduced by Dantzig and Ramser (1959). Since then, VRP has been a topic of numerous studies in the literature of operations research. The traditional VRP is to find a set of vehicle routes for a set of customers with known demands. The literature on VRP and its variants are very widespread and involve many different aspects and decisions (see, for example, the latest surveys of Golden et al. (2008), Eksioglu et al. (2009), De Jaegere et al. (2014)). Also, various exact (see, e.g., Baldacci et al., 2012; Almoustafa et al., 2013) and heuristics algorithms (see, e.g., Demir et al., 2012; Kramer et al., 2015) are suggested to solve such operational-level routing problems.

The traditional objective in the standard VRP is to minimize the total distance traveled by all vehicles, but this objective can be enriched through the inclusion of terms related to fuel consumption (Bektaş and Laporte, 2011). Recent developments in Green Vehicle Routing Problems (GVRPs) have heightened the importance of operations research techniques in this area. One of the successful applications in GVRP is due to Bektaş and Laporte (2011) who introduced the Pollution-Routing Problem (PRP), which is an extension of the VRP with time windows (VRPTW). In this paper, we consider a special case of the PRP where the objective function solely depends on the total fuel consumption rather than a weighted sum of fuel consumption and total driving time as in the PRP.

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Demand uncertainty is one of the most common variants in non-deterministic (stochastic) VRPs. However, to the best of our knowledge, it has not been studied in the domain of GVRPs. Travel time uncertainty has been also investigated to see the impact of congested travel speeds on fuel consumption. The contributions of the paper are twofold: (i) we investigate the previous robust VRP models with stochastic demand and illustrate their weakness for the PRP, and (ii) we reformulate the PRP with several well-known robust approaches.

The remainder of this paper is organized as follows. In Section 2, a literature review on both VRPs and GVRPs is provided. In Section 3, the mathematical formulation of the PRP is presented. Section 4 introduces the proposed robust optimization approaches along with their formulations. Extensive numerical experiments and comparative analysis are provided in Section 5 to show the powerfulness of the proposed robust optimization models. Finally, Section 6 concludes the paper and introduces relevant future research directions.

2. Literature review

This section reviews the existing research literature on both VRP with uncertain data and green vehicle routing problems.

2.1. VRP with uncertain data

Nondeterministic VRP refers to situations that all information about the vehicle routing is not deterministic before the start of the planning, and some of the information may be uncertain, ambiguous, or even unknown (Chen et al., 2013). In the real world applications, the input data of VRP is highly tainted with uncertainty. This has triggered the development of several techniques to handle the imprecision of uncertain data in VRPs. In the literature, VRP with uncertain data has been studied in four groups; namely *stochastic VRP*, *dynamic VRP*, *fuzzy VRP*, and *robust VRP*.

Stochastic VRP (SVRP) has been extensively applied in the condition that the probability distribution of the uncertain parameter is available according to sufficient and reliable historical data (see, e.g., Li et al., 2010; Faulin et al., 2011). Generic variants of SVRP are VRP with stochastic customer demands (see, e.g., Novoa et al., 2006; Smith et al., 2010), VRP with stochastic customers (Bertsimas and Van Ryzin, 1991), VRP with stochastic customers and demands (Gendreau et al., 1995), and VRP with stochastic service times (Laporte, 1992). Interested readers are referred to Berhan et al. (2014) for a survey on different types of SVRP and its solution methodologies. The first study on *dynamic VRP* (DVRP) is done by Wilson and Colvin (1977). The authors investigated a single vehicle dynamic arc routing problem. We refer to Pillac et al. (2013) for the DVRP and its solution methods. Fuzzy number, or *Fuzzy VRP* (FVRP), is one of the most common approaches for modeling optimization problems which have one or more uncertain data with vagueness or ambiguity. Chen et al. (2013) categorized related works in three groups; namely VRP with fuzzy demands (Chen et al., 2006; Peng and Qian, 2010), VRP with fuzzy due times (see, e.g., Zhang et al., 2008; Jun, 2009) and VRP with fuzzy travel times (Brito et al., 2010).

Robust VRP (RVRP) was introduced by Bertsimas and Simchi-Levi (1996) for the SVRP and is applied when the probability distribution of uncertain parameter is unknown (i.e., deep uncertainty). Sungur et al. (2008) introduced a robust optimization approach to solve the capacitated VRP with demand uncertainty and compared the performance of robust solutions with deterministic ones. In a related work, Lee et al. (2012) addressed the VRP with deadlines which involves demand and travel time uncertainty. Adulyasak and Jaillet (2015) described models and algorithms for SVRP and RVRP with deadlines. The authors proposed new mathematical formulations to solve these problems based on a branch-and-cut framework.

Table 1
Selected studies on VRP with uncertain data.

Reference	Uncertain parameters			Type of VRP	Modeling approach
	Demand	Traveling time/cost	Service or due time		
Novoa et al. (2006)	✓			CVRP	SVRP
Chen et al. (2006)	✓			CVRP	FVRP
Sungur et al. (2008)	✓			CVRP	RVRP
Zhang et al. (2008)			✓	VRPTW	FVRP
Jun (2009)			✓	VRPTW	FVRP
Brito et al. (2010)		✓		VRPTW	FVRP
Peng and Qian (2010)	✓			CVRP	FVRP
Smith et al. (2010)	✓			CVRP	SVRP
Li et al. (2010)		✓	✓	VRPTW	SVRP
Faulin et al. (2011)	✓			CVRP	SVRP
Lee et al. (2012)	✓	✓		VRPTW	RVRP
Agra et al. (2013)		✓		VRPTW	RVRP
Adulyasak and Jaillet (2015)		✓		VRPD	RVRP/SVRP
Solano-Charris et al. (2014)		✓		CVRP	RVRP

VRPTW: Vehicle Routing Problem with Time Windows; CVRP: Capacitated Vehicle Routing Problem; VRPD: Vehicle Routing Problem with Deadline; RVRP: Robust Vehicle Routing Problem; FVRP: Fuzzy Vehicle Routing Problem; DVRP: Dynamic Vehicle Routing Problem; SVRP: Stochastic Vehicle Routing Problem.

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