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The heterogeneous green vehicle routing and scheduling problem with time-varying traffic congestion

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ABSTRACT

The green vehicle routing and scheduling problem (GVRSP) aims to minimize green-house gas emissions in logistics systems through better planning of deliveries/pickups made by a fleet of vehicles. We define a new mixed integer liner programming (MIP) model which considers heterogeneous vehicles, time-varying traffic congestion, customer/vehicle time window constraints, the impact of vehicle loads on emissions, and vehicle capacity/range constraints in the GVRSP. The proposed model allows vehicles to stop on arcs, which is shown to reduce emissions up to additional 8% on simulated data. A hybrid algorithm of MIP and iterated neighborhood search is proposed to solve the problem.

1. Introduction

Climate scientists undoubtedly point out that the concentration of greenhouse gases in the atmosphere, particularly CO_2 emitted by human activities, is the primary cause of global warming. The Keeling Curve (http://keelingcurve.ucsd.edu/) shows that the concentration of CO_2 in the atmosphere has been growing in the past half-century and even faster in the last decade. According to the US Environment Protection Agency (US EPA, 2014), transportation is one of the major sectors emitting CO_2, counting for 27% of the total US emissions in 2013, and almost three-quarters of these emissions from transportation were due to road transportation. Today, all large and growing urban areas experience high levels of road traffic congestion. Road traffic congestion, often companied with frequent acceleration and deceleration, contributes to CO_2 emissions significantly (Barth and Boriboonsomsin, 2008; Franceschetti et al., 2013). According to the International Road Transport Union (IRTU), road traffic congestion could increase CO_2 emissions by 300% and was responsible for 100 billion liters of wasted fuel, or 250 billion tons of CO_2 emissions in the U.S. (IRTU, 2012). In China, cars and trucks are also responsible for 40% of the $PM_{2.5}$ air pollution, which is caused by particles less than 2.5 micrometers in diameter, observed in many central Chinese cities such as Beijing where 175 days in 2014 were reported to have dangerous levels of $PM_{2.5}$ air pollution (Chai, 2015). Traffic congestion may be caused by various factors such as road capacities, rush-hour, school zones, road work, tidal roads, accidents, and traffic controls. Whatever the cause is, traffic congestion is almost always time dependent, which we refer to as *time-varying traffic conditions*, indicating that the average travel speed on a road may change from one period to another with predictable patterns. Considering time-varying traffic conditions in vehicle routes and schedules provides an

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opportunity for reducing vehicle emissions in logistic systems by implementing Operations Research techniques to avoid traffic congestion and meet delivery requirements at the same time. Several recent papers related to this issue can be found in the literature, including Figliozzi (2010, 2012), Kuo (2010), Franceschetti et al. (2013), Kwon et al. (2013), Gaur et al. (2013), Demir et al. (2014a, 2014b), Soysal et al. (2015), and Xiao and Konak (2015a).

In recent years, green logistics, which aims at improving environmental sustainability by reducing fossil fuel consumption in freight transportation systems, has been a subject undergoing intense study and attracted the attention of Operations Research professionals (Demir et al., 2014a,b; Rodrigue et al., 2013; Eglese and Bektaş, 2014; Bektaş et al., 2016). In the context of the vehicle routing problem (VRP), traditional logistics activities are often optimized in a way that customer requirements are met at minimum cost in terms of solely monetary measures. On the other hand, the green vehicle routing problem (GVRP) is characterized by the objective of balancing the environmental and economic costs by implementing effective vehicle routes and schedules. Considering the fuel consumption cost (or the CO_2 emissions cost) in the GVRP may lead to quite different logistic plans for customer assignments, route selections, and schedules than the traditional VRP (Lin et al., 2014; Xiao and Konak, 2015a).

In this paper, we present a comprehensive mixed integer linear programming (MILP) model to formulate the GVRP for a fleet of heterogeneous vehicles operating under time-varying traffic conditions. The formulated problem is referred to as Heterogeneous Green Vehicle Routing and Scheduling Problem (HGVRSP). In the MILP model, we use total CO_2 emissions as the objective function to be minimized by various operational decisions including customer-vehicle assignment, route selection, and travel time scheduling. The main advantages of our MILP model lie on three aspects: (1) idle/waiting times can be scheduled at any point during tours (i.e., the non-stopping assumption is relaxed), (2) heterogeneous vehicles are considered with individualized features including vehicle types, CO_2 emissions rates/models, load capacities, fuel tank capacities, and time availabilities, and (3) vehicle emissions are calculated by considering their dynamic payload weights and travel speeds. In addition, the model also considers general traffic congestion patterns with several periods and time windows dictated by customer requirements or the availability of vehicles. Therefore, the proposed model is very comprehensive and general. For the solution approach, we propose a hybrid algorithm of partial MIP optimization and iterative neighborhood search (P-MIP-INS) based on the concepts from variable neighborhood search. Comprehensive computational experiments with different problem sizes are carried out to study the effectiveness and efficiency of the P-MIP-INS algorithm with respect to several well-known construction heuristics from the literature.

The rest of the paper is organized as follows. In Section 2, we review the previous related work and point out the drawbacks of previous models with the *non-stop* assumption. In Section 3, we remodel the time-dependent travel and formulate a comprehensive model for the HGVRSP. In Section 4, we carry out computational experiments on 20 small-sized problems to compare the solutions found with three different objective functions—(1) the total travel distance, the total travel time, and the total CO_2 emissions. In Section 5, we develop a hybrid solution approach of partial MIP optimization and variable neighborhood search (P-MIP-INS) for the proposed HGVRSP model in this paper and introduce our modifications on the construction heuristics from the literature. In Section 6, computational experiments are carried out on 140 problem instances (small, medium, and large). Finally, we conclude the paper in Section 7.

2. Literature review

Since its introduction by Dantzig and Ramser (1959), the VRP has been extensively studied in the literature. Various versions of the VRP have been developed for different applications, such as pickup and delivery VRP, capacitated VRP, multiple depot VRP, VRP with time windows, split delivery VRP, and time-dependent VRP. Surveys on various VRP formulations and algorithms can be found in Laporte (1992), Laporte et al. (2000), Toth and Vigo (2002, 2014), Golden et al. (2008), and Eksioglu et al. (2009). In the following, we review the previous VRP work considering time constraints.

2.1. Vehicle routing and scheduling problems

The vehicle routing and scheduling problem (VRSP), first defined by Bodin and Golden (1981), refers to the case when customers have specific service time requirements. Therefore, a solution to the VRSP includes both vehicle routes and schedules. The route of a vehicle is defined by the sequence of pickup and/or delivery points which the vehicle visits, and the schedule of the vehicle indicates the associated arrival and departure times to and from these points. Solomon (1983) first presented an MIP formulation for the VRSP with time window constraints (VRSPTW) where some customers impose deadlines or earliest time constraints on their pickups/deliveries. Since then, the VRSPTW have been a subject of intensive research efforts for both construction heuristics (Solomon, 1987; Christofides et al., 1979; Van Landeghem, 1988; Malandraki, 1989; Ioannou et al., 2001) and meta-heuristics (Garcia et al., 1994; Thangiah, 1995; Vidal et al., 2013). Comprehensive surveys on the VRPTW can be found in Olli and Michel (2005a,b) and Desaulniers et al. (2014).

The time-dependent VRPTW (TD-VRPTW) is an extension of VRSPTW such that the travel time of an arc is considered as a function of the departure time. Malandraki (1989) and Malandraki and Daskin (1992) first formulated the TD-VRPTW as a MIP model and proposed a greedy nearest-neighbor heuristic as the solution approach. Malandraki and Dial (1996) proposed a restricted dynamic programming heuristic for constructing the route for a time-dependent traveling salesperson problem. Chen et al. (2006) studied the real-time TD-VRPTW. Maden et al. (2010) proposed a heuristic algorithm for the single-depot