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A simulating annealing algorithm to solve the green vehicle routing & scheduling problem with hierarchical objectives and weighted tardiness

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A R T I C L E I N F O

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A B S T R A C T

We present a green vehicle routing and scheduling problem (GVRSP) considering general time-dependent traffic conditions with the primary objective of minimizing CO_2 emissions and weighted tardiness. A new mathematical formulation is proposed to describe the GVRSP with hierarchical objectives and weighted tardiness. The proposed formulation is an alternative formulation of the GVRSP in the way that a vehicle is allowed to travel an arc in multiple time periods. The schedule of a vehicle is determined based on the actual distance that the vehicle travels each arc in each time period instead of the time point when the vehicle departs from each node. Thereby, more general time dependent traffic patterns can be considered in the model. The proposed formulation is studied using various objectives functions, such as minimizing the total CO_2 emissions, the total travel distance, and the total travel time. Computational results show that up to 50% reduction in CO_2 emissions can be achieved with average reductions of 12% and 28% compared to distance-oriented solutions and travel-time-oriented solutions, respectively. In addition, a simulated annealing (SA) algorithm is introduced to solve large-sized problem instances. To reduce the search space, the SA algorithm searches only for vehicle routes and rough schedules, and a straightforward heuristic procedure is used to determine near-optimal detailed schedules for a given set of routes. The performance of the SA algorithm is tested on large-sized problems with up to 100 nodes and 10 time periods.

1. Introduction

It is well recognized that carbon dioxide (CO_2) is the major contributor of the global warming effect of the Earth during the past decades. Since it was first measured in 1958, the concentration of CO_2 in Earth's atmosphere has been continuously increasing, recently at a rate of 1.7 ppm/yr for 1993–2004 and 2.3 ppm/yr for 2005–2014 (lively in http://keelingcurve.ucsd.edu/). According to the International Energy Agency (IEA), the transportation sector, after electricity generation and heating, was the second-largest contributor of CO_2 emissions, representing 22% of the global CO_2 emissions in 2010, and almost three-quarters of the emissions from transportation were due to road transportation [33]. Traffic congestion, which results in low speeds with fluctuations on roads, often companied with frequent acceleration and deceleration, had greatly contributed to CO_2 emissions [2,16]. According to the International Road Transport Union (IRTU), traffic congestion had increased CO_2 emissions by 300% and is responsible for 100 billion liters of wasted fuel, or 250 billion tons of CO_2 emissions in the United States alone [21]. Therefore, reducing fossil fuel consumption and CO_2 emissions due to road transportation is an important part of the efforts to control the global warming. The objective of this paper is to develop new mathematical models and optimization methods for reducing CO_2 emissions in the context of the Vehicle Routing Problem with traffic congestion considerations. We propose a new mathematical formulation for modeling the time-dependency in vehicle routing and scheduling problems. In the proposed formulation, the schedule of a vehicle is modeled using the total distance that the vehicle travels on each road segment in each time period. This approach is different from the literature where the schedule of a vehicle is generally determined by the time points when the vehicle departs from each node on its route. The main advantage of the proposed formulation is that more general time-dependent traffic patterns can be considered. In addition, the complexity of calculating CO_2 emissions within the model is eliminated, which leads to a linear mathematical formulation. The proposed formulation is appropriate for urban transportation

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networks where the travel speed of a vehicle depends on the road conditions and the time of the day.

The Vehicle Routing Problem (VRP) has been a classic and important optimization problem involved in road transportation applications since its introduction by [7]. In general, the VRP is concerned with the determination of the optimal routes used by a fleet of vehicles, stationed at one or multiple depots, with the objective of fulfilling customers' demands at minimum cost. Various versions of the VRP have been developed for different applications in the past half century, such as pickup and delivery VRP, capacitated VRP, multiple depot VRP, VRP with time windows, split delivery VRP, time-dependent VRP, etc. Surveys on various formulations and algorithms of the VRP can be found in [10,18,26,35].

Recently, the Green VRP (GVRP) [8,27], which is characterized by the objective of balancing environmental and operational costs, has attracted the attention of researchers in the VRP literature. Ericsson et al. [13] identified the impact of traffic disturbance events on fuel consumption and proposed a model for estimating the potential reduction in fuel consumption through route optimization. Kara et al. [23] proposed a cost function in terms of energy consumption for the VRP and named it as the Energy Minimizing VRP (EMVRP), which minimizes the total energy consumption in the route (instead of the total distance) to minimize fuel consumption. Reducing CO_2 emissions also helps to save the fuel cost because CO_2 emissions are usually proportional to the amount of the fuel consumption. The fuel cost accounts for more than 60% of the total transportation cost [30,31] of road logistic companies. Tavares et al. [32] considered the effect of both road inclination and vehicle load on the fuel consumption of waste collection vehicles. Kuo [24] proposed a mathematical model to calculate the total fuel consumption for the time-dependent VRP, considering both load weight and the "non-passing" property. Figliozzi [15] proposed a partial emissions minimizing VRP (EVRP) model to optimize the departure times of vehicles on the routes that are found by a time-dependent VRP algorithm. Xiao et al. [38] incorporated the fuel consumption rate resulted from vehicle's load (which is decreasing/increasing throughout the tour) into the Capacitated VRP (CVRP) and proposed a model considering fuel consumption rate for the CVRP. Erdogan and Miller-Hooks [12] presented a GVRP and developed solution techniques to aid organizations with alternative fuel-powered vehicle fleets working in large driving range in conjunction with limited refueling infrastructure. Kwon et al. [25] developed a Heterogeneous fixed fleet VRP model that considers the carbon emissions trade cost in the objective function. Gaur et al. [17] studied the cumulative VRPs with the objective to minimize fuel consumption and proposed an approximation algorithm for cumulative VRPs when vehicles have finite capacity and an arbitrary number of depot offloads are allowed. Demir et al. [8] proposed an adaptive large neighborhood search algorithm (ALNS) to minimize the fuel consumption and the driving time with Pareto optimality.

Traffic congestion usually causes road conditions to be time-dependent, and the VRP under this case is called the time-dependent VRP (TDVRP) [5,14,28,29]. Compared with the distance-based VRP, the node departure times of a vehicle are decision variables in the TDVRP. Because the total travel time depends on node departure times as well as routes, the TDVRP is usually studied with alternative objectives such as minimizing the travel time or the fuel consumption (or CO_2 emissions) [15,24]. The TDVRP is a more challenging problem to solve than the traditional VRP because the solution space is increased exponentially by the introduction of node departure time decisions.

Bektas and Laporte [4] presented the pollution routing problem (PRP) by extending the classical VRP with time windows (VRPTW) as well as with a more comprehensive objective function including fuel, emissions, and driver costs. In the PRP, the vehicle load and speed on each route segment are considered as decision variables. Demir et al. (2012) developed a two-stage heuristic algorithm to solve the PRP of large-size instances with up to 200 nodes. In this two-stage approach, a large neighborhood search (LNS) heuristic is used to solve traditional VRPTW in the first stage, and the optimal speed for each arc of the route is determined optimally in the second state. Franceschetti et al. [16] extended the PRP to Time-Dependent PRP (TDPRP) by considering traffic congestion. In their approach, the planning horizon is divided into two periods: (1) an initial period of traffic congestion with a lower and constant travel speed and (2) a period with a travel speed range where the travel time linearly depends on the departure time.

Table 1 summarizes and compares the formulations of the PRP in the literature and the proposed formulation. In this paper, we consider a general case of the time-dependency for vehicle routing and scheduling with the hierarchical objectives of the total CO_2 emissions, the total arrival time, the total travel time, and the total travel distance. A tardiness objective is considered for the first time in the context of the GVRP. Tardiness objectives are frequently used in the scheduling literature to model the timeliness of customer service when it is impossible to satisfy all customer orders on time due to capacity limitations. In a tardiness objective, the late service of a customer is penalized by a tardiness penalty coefficient that represents the loss of customer goodwill. The magnitude of the tardiness penalty depends on the relative importance of customers.

In this paper, the formulated problem is referred to as Green Vehicle Routing and Scheduling Problem (GVRSP). The proposed GVRSP formulation contributes to the existing body of the research on the green time-dependent VRP in several ways. While the existing time-dependent GVRP formulations assume that an arc is allowed to be traveled in only one time period, in the GVRSP herein an arc can be traveled in multiple time periods. We present an alternative formulation for modeling time-dependency using the total distance traveled on an arc in each period as the primary decision variable. Thereby, the proposed modeling approach allows to incorporate more general patterns of traffic scenarios in the formulation. The proposed GVRSP formulation is linear and can be solved optimally by the existing MIP solvers for small-sized problems. In this sense, the proposed formulation is a more general model for combined routing and scheduling decisions in the context of the GVRSP. We also propose a simulated annealing (SA) algorithm to solve medium & large-sized problems with near-optimal solutions. Computational experiments are carried out to examine the proposed MILP model and solution approaches using a large set of problem instances.

The rest of the paper is organized as follows. We first describe the GVRSP in Section 2. In Section 3, we present the MILP model with hierarchical objectives and develop a solution approach based on Pareto optimality for its real-life application under a carbon trading system. Computational studies are also carried out in this section. In Section 4, a SA algorithm is proposed and computational experiments are carried out to examine its effectiveness and efficiency. Finally, in Section 5 we conclude the paper.

2. Problem description

The GVRSP in this paper can be described as follows. A fleet of homogeneous vehicles is going to visit a set of customers randomly located in a region. The problem is formulated on a complete network $G(N, A)$ where N is the set of nodes representing customers and a depot, and A is the set of arcs representing the roads between the nodes. All vehicles are located in the depot and expected to return to the depot after completing their tours. Each customer i should be visited within the time-window $[0,T_i]$ where T_i is the due-time of the customer. A late visit results in a tardiness penalty