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A decision support system of vehicle routing and refueling for motor carriers with time-sensitive demands

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ABSTRACT

Given the recent trend of raising fuel cost and the increased time-sensitiveness of shippers, an extensive pressure is placed on the motor-carrier industry to meet the time-constrained customer demands at minimum fuel cost. We propose a decision support system that allows motor carriers to route each vehicle such that the vehicle not only visits all the customers in time (without violating time windows), but also utilizes the "cheapest" gas stations (cheapest truck stops in the region) as refueling points during the tour. While this approach does not necessarily minimize a vehicle's fuel consumption, as it often suggests using non-shortest routes with cheap gas stations (truck stops), it allows the vehicle to reduce the unit cost of buying fuel. Computational testing shows that the proposed approach may attain up to 4.29% savings in fuel cost for motor carriers.

1. Introduction

U.S. motor carriers, including the asset-based third-party logistics companies (3PLs) and the shippers with private fleets, are currently facing a challenging business environment for two reasons. The first is the raising fuel cost. It is well known that, during the last few years, fuel prices have increased dramatically by more than 100%, and that thousands of U.S. motor carriers went bankrupt because of such price hikes (Transport Topics [13]). The second is the increased time-sensitiveness of customers. Because of the growing use of lean and just-in-time operations in the manufacturing sector (a major customer segment for motor carriers), many shippers are now imposing time-window constraints on their demands (Ohlmann and Thomas [9]). Hence, an extensive pressure is placed on motor carriers to dispatch their pickup and delivery vehicles in such a way that they can meet the time-sensitive customer demands at minimum fuel costs.

Many carriers are using the following two strategies to cope with these challenges. The first is to reduce the fuel consumption of each vehicle by scheduling the customer visits such that the total travel distance during a tour can be minimized without violating time windows. This can be accomplished by using the techniques (and the software products) that solve the time-constrained vehicle routing problems (Bell and Griffis [1]). The second is to reduce the unit-cost of buying fuel (cost per gallon). This is usually accomplished by using the "purchase contract" strategy, in which a carrier makes a commitment to buy certain amounts of fuel from a specific truck stop (typically located near the company depot) to obtain price discounts. Many carriers believe that the joint use of these two strategies would minimize their fuel costs in the long run.

In theory, however, the use of these two strategies may not necessarily minimize the fuel cost of carriers. The reason is that, while the price discounts the motor carriers obtain by using purchase contracts typically range from ¢3 to ¢5 per gallon, the difference (variance) of fuel price among truck stops in the same region often goes beyond ¢10 per gallon (see, e.g., Transport Topics [14], or any publicly available fuel-price data). This pattern implies that carriers may attain larger discounts in fuel price by refueling their vehicles at "cheap" truck stops along the route (during the tour) than by using the conventional purchase-contract strategy, which limits the choice of truck stops. From the fleet managers' standpoint, therefore, it may be more logical to use an alternative refueling strategy in which each vehicle is routed such that: (*i*) the vehicle not only visits all customers in time (without violating time windows) but also finds cheap truck stops along the route, so that (*ii*) the vehicle can be asked to refuel at these "cheap" truck stops.

This paper describes the work being carried out to develop a decision support system for motor carriers that is designed to address the following two questions jointly: (*i*) "Which route should a truck use to minimize fuel consumption", and (*ii*) "Where (at which fuel station) should a truck buy fuel to minimize the fuel-procurement cost". We develop a technique that seeks to minimize the fuel cost of operating a vehicle by jointly making the routing and refueling decisions, while enforcing the time-window constraints. This method allows carriers to consider the trade-off between using the shortest route

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(which can minimize the fuel consumption) and using non-shortest routes with cheap truck stops (which can minimize the unit cost of buying fuel). To the best of our knowledge, no study has considered this type of problem in the past.

The contribution of this paper is threefold. First, we present a problem (model) that jointly addresses the time-constrained single-vehicle routing problem, known as the *traveling salesman problem with time windows* (TSPTW), and the vehicle-refueling problem. This model, which is denoted hereafter as the *traveling-salesman problem with time windows and refueling* (TSPTWR), was developed by working closely with motor carriers to maximize its workability in the field. Second, we propose a metaheuristic method for the TSPTWR. Our method seeks both the route and the sequence of truck stops, which (in combination) minimize the fuel cost of operating a vehicle. Third, we apply our method to both the actual and hypothetical instances, and test its effectiveness. We show that our method provides considerably lower fuel costs than the conventional method, which combines the “shortest-route” and “purchase contract” strategies.

2. Literature review

Since the vehicle-routing studies are reviewed extensively elsewhere (see, e.g., Figliozzi [3]), this section reviews only the studies that considered the vehicle-refueling problem, or those that jointly considered the vehicle-routing and vehicle-refueling problems, for motor carriers. Studies which proposed the vehicle-refueling methods for other modes of transportation, or those which proposed the methods of finding the best locations of fuel stations, are not reviewed. We refer the readers who are interested in these “other” refueling studies to Besbes and Savin [2], Suzuki [12], Wang and Lin [15], Huang et al. [4], and Nourbakhsh and Ouyang [8].

The simplest, and the earliest, form of the vehicle-refueling problem is the *fixed-route vehicle refueling problem* (FRVRP). The FRVRP seeks the optimal *refueling policy* which indicates the best sequence of truck stops to use, along with the best refueling quantities at the chosen truck stops, for a given (fixed) origin–destination route. The FRVRP and its solution techniques were pioneered by practitioners (consulting firms) in the mid-1990s. The idea was to develop software products for motor carriers that allow them to buy more gallons at cheap truck stops and buy fewer gallons at expensive truck stops. Today, several software products exist that can solve the FRVRP to near-optimality, which are often called *fuel optimizers* by fleet managers. These products (fuel optimizers) typically work in conjunction with truck-routing software products, so that carriers can first compute the shortest route for a given origin–destination, and then find a refueling policy for this route. Fuel optimizers also work in conjunction with fuel-price databases (which are updated daily), so that carriers can always utilize the latest fuel price.

Recently, several scholarly works have been conducted that proposed the exact (optimal) solution techniques for the FRVRP. Lin et al. [7] proposed a linear-time greedy (but an exact) algorithm for the FRVRP by modifying the technique widely used in the inventory-capacitated lot-sizing literature. Khuller et al. [5] also proposed a relatively simple algorithm that solves the FRVRP to optimality by employing a dynamic programming technique. Suzuki [11] proposed a mixed-integer linear programming approach to the FRVRP, and empirically showed that, for relatively small problems, the optimal refueling policies can be obtained in a straight-forward fashion by using the simplex algorithm, in conjunction with the branch-and-bound technique.

Some scholarly works have considered more complex forms of refueling problems that jointly address the shortest-route problem and the FRVRP. The motivation behind these studies is that, if the routing and refueling problems are solved sequentially (independently), we will ignore the impact of routing decisions on refueling performances, so that the resulting solutions may not be optimal (near optimal). Both Lin [6] and Khuller et al. [5] proposed exact algorithms that jointly solve the shortest-route problem and the FRVRP. These two methods find the route and the refueling policy which, in combination, minimize the fuel cost of operating a vehicle from origin to destination. It is to be noted, however, that these methods both assume that the origin and the destination represent two distinct points in a graph. This implies that they may not be applied directly to the TSP (traveling salesman problem) type instances. (Note that the TSP, which is NP-hard, and the shortest route problem with distinct origin and destination, which is not NP-hard, are intrinsically different problems that cannot be solved by the same technique).

Perhaps the work that is most relevant to this study is Khuller et al. [5]. They considered the problem that jointly addresses the TSP and the FRVRP, and proposed a heuristic method. In our view, however, their study (method) seems to suffer from limited practical values for the following two reasons. First, it does not consider some “real-world” issues and constraints that are considered by all commercial fuel optimizers. These constraints include: (*i*) the minimum purchase quantity per fuel stop (which prohibits “small-purchase” fuel stops and/or too many fuel stops), and (*ii*) the maximum distance a vehicle is allowed to travel “off the route” to reach a fuel station (which forbids a vehicle to divert excessively from the route). Second, it does not consider the customer time windows (delivery or pickup). As we had discussed previously, this constraint is increasingly recognized as an important customer-service element by motor carriers.

3. The decision support system

The proposed decision support system is composed of three parts; i.e., inputs, decision model, and outputs (see Fig. 1). The inputs include: (*i*) the set of customers to service (along with their time windows), (*ii*) the geographical data of the covered area, and (*iii*) the data on truck-stop attributes. The geographical data are readily available from many truck-routing software products (e.g., *PC Miler*), and the truck-stop attributes (of nearly all the truck stops in the U.S.) can be obtained from several fuel-price database products such as the *OPIS* (Oil Price Information Service) database. The outputs consist of the routing and refueling instructions for truck drivers. The former identifies the sequence (order) of customer visits, while the latter identifies the set of truck stops to use, along with the refueling quantity at each chosen truck stop.

The main focus of this paper is the formulation of the decision model (problem) and the development of the solution technique for the problem. In the paragraphs that follow we discuss: (*i*) the definition and the formulation of the problem, (*ii*) the computational complexity of the problem, (*iii*) the proposed solution approach to the problem, and (*iv*) the set of strategies that can be used to improve the CPU time of solving the problem when using the proposed technique.

4. Problem formulation

4.1. The TSPTWR instance

Consider a TSPTW delivery instance for day t. Let $G=(N, L)$ be a directed graph, where $N=\{0, 1, 2, \ldots, n, n+1\}$ is the finite set customers (nodes) that must be visited on day t, and L is the set of arcs connecting nodes (see Fig. 2 for a sample network). The depot is represented by two nodes; 0 (starting node) and $n+1$ (ending node). We assume that there exists an arc $(i, j) \in L$ for every $i \in N \setminus \{n+1\}$, $j \in N \setminus \{0\}$, $i \neq j$. The distance (miles) and travel time (minutes) of each arc (i, j) are denoted by d_{ij} and t_{ij}, respectively. Each customer i has a specific time window $[S_i, S_i+D_i]$ during which the customer must be served, where S_i and D_i denote the starting time and the duration, respectively, of the time window. The unloading time (duration) at each customer i is denoted by U_i. A visit to customer i must be scheduled such that both the time to begin unloading (B_i) and the time to finish unloading