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A continuous network location problem for a single refueling station on a tree

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ABSTRACT

This article considers the continuous version of the refueling station location problem on a tree network, which is a common structure in numerous toll roads worldwide, so as to locate a single alternative-fuel refueling station to maximize the traffic flow covered in round trips/day. Two reduction properties regarding the problem size and some optimality conditions are derived. Based on these conditions, an exact polynomial algorithm is developed to determine the set of optimal locations for the refueling station. A small tree network example is solved to illustrate the algorithm.

1. Introduction

By 2040, the Federal Highway Administration in the U.S. Department of Transportation expects that freight trucks on arterial roads including interstate and major highways will travel 662 million miles per day, which is an increase of 66% with respect to 2002 [13]. Currently, freight trucks are mainly powered by conventional fossil fuels such as gasoline or diesel. In order to respond to environmental and economic sustainability in the transportation sector, many logistics companies have a considerable interest in a transition to alternative-fuel (AF) trucks powered by natural gas, electricity, or hydrogen [6,10,14,33]. For example, Fedex, one of the major logistics companies, plans to replace 30% of their long-distance trucks with natural gas trucks over the next 10 years [11]. They expect that refueling stations for natural gas vehicles will soon become ubiquitous on their primary supply chain routes. The availability of an AF refueling infrastructure on transportation networks is a key issue for logistics companies that want to bring in non-conventional or AF vehicles [29].

Transportation networks have two basic structures: circuit networks and branching networks [18,39]. They can be distinguished by their cyclomatic number which indicates the number of circuits in the network. A circuit or directed cycle is defined as a closed path (with no less than three edges) that begins and ends at the same vertex. While circuit networks have a positive cyclomatic number, branching networks have a zero cyclomatic number. Branching networks are characterized by their tree-like structures, which consists of sets of connected line segments without any complete circuit. A graph without cycles is called a forest and a connected forest is a tree [38].

Although highway systems in most countries form circuit networks, we can observe that quite a few toll roads consisting of highway segments constitute tree or tree-like networks. For example, in the U.S., the Maine and Ohio Turnpikes, and the Indiana Toll Road have a single path structure, and the two main lines in the Pennsylvania Turnpike (East–West mainline and Northeastern extension) define a tree network. Furthermore, the entire turnpike network in states such as Pennsylvania and Oklahoma, which include a number of independent roadway segments or expressways, can be represented as forests [16]. In addition, there exist other countries, such as Chile, Indonesia, Malaysia, Philippines, Slovakia, and Spain (excluding the Catalan region), where toll roads also form trees or forests [1,12,28,37]. Moreover, in the U.S., when ignoring beltways and cycles within metro areas or collapsing them into single vertices, the portions of interstate highways within certain states, such as Georgia, North Dakota, South Dakota, and Montana, can be represented as trees [15,17].

In traditional facility location models, such as the median, center, and covering problems, demand is usually considered a weight at vertices. Alternatively, people tend to stop by service areas or facilities just to rest, eat, or refuel on the way to their homes or work places. Obtaining this type of service is not the main purpose of a trip, so we refer to it as a discretionary activity. Considering that this discretionary activity for a driver (vehicle) is a unit of demand, the demand along a pre-planned path can be covered by a service facility located at any vertex on the path. Hodgson [19] and Berman et al. [5] were the first to propose a basic flow-capturing location model (FCLM) for locating p service facilities with the objective of maximizing the passing flow rate captured by the facilities. Hodgson et al. [20] applied the model to

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a real-world transportation network with over 20,000 flow pairs representing the morning-peak traffic in the Edmonton Metropolitan Area in Canada. The model was extended to consider derivations from pre-planned routes to visit service facilities by Berman et al. [4]; to consider multi-counting by Averbakh and Berman [2], where customer service level is based on the number of facilities that customers encounter on their pre-planned tours; to incorporate customer preferences by Zeng et al. [40]; and to take into account facilities of different sizes by Tanaka and Furuta [34], where deviations from pre-planned routes depend on the facility size. Berman [3] proposed four new flow-demand location models, in two of them the objective was to maximize the coverage of potential customers whereas in the other two the emphasis was to maximize the number of potential customers that can become users. Furthermore, based on the distribution of the deviation distances to visit a facility from preplanned routes derived in [31], Miyagawa [32] developed an analytical model for determining the adequate density of AF refueling stations to achieve certain level of service.

By incorporating the key aspect that vehicles may need to refuel or recharge multiple times along their paths due to the limited driving range in the FCLM, Kuby and Lim [24] developed the flow-refueling location model (FRLM) to locate AF refueling stations that maximize the total path-flow that can be covered by combinations of refueling stations. Upchurch and Kuby [35] compared the performance of the *p*-median and FRLM for locating AF refueling stations, and verified that the FRLM has a better performance in locating the stations, especially for inter-city trips. The FRLM, however, requires a pre-step for generating all valid refueling station combinations for each path, which results in high complexity. Thus, to apply the FRLM to large real-world networks, Lim and Kuby [27] proposed three heuristic algorithms, and Kuby et al. [26] applied the heuristic algorithms to determine locations for hydrogen stations in the Orlando metropolitan area and the State of Florida. Also, for generation of optimal solutions and elimination of the feasible facility combinations step, Capar and Kuby [7] developed an efficient formulation of the FRLM by introducing decision variables that indicate whether a vehicle at a particular candidate site has enough fuel remaining to get to the next open refueling station. In a similar manner, Capar et al. [8] resolved the complexity issue by developing a compact model with “cover sets” that cover the entire distance between any pair of nodes when a vehicle is filled up at a candidate site in the set. Also, on an expanded network with dummy supply and demand nodes, MirHassani and Ebrazi [30] proposed a set covering version of the FRLM to determine a set of candidate locations that minimize the cost of building AF refueling stations on the paths that are generated by the flow-conservation property. While the original FRLM assumed that all refueling stations have sufficient capacity to meet any refueling demand, Upchurch et al. [36] developed the capacitated FRLM that limits the number of vehicles that can be refueled at each station. Also, while the original FRLM did not allow to deviate from preplanned trips for refueling, Kim and Kuby [21] proposed the deviation version of the FRLM with five types of distance decay functions to model the fraction of drivers that are willing to deviate from their shortest path. Their approach, however, is too computationally intensive when applied to real world transportation networks, because it requires the pre-generation of all possible deviation paths for each origin/destination pair and all combinations of refueling stations that provide refueling coverage for each path. Accordingly, Kim and Kuby [22] developed two heuristic algorithms to overcome the computational burden of their deviation-FRLM through network transformation. They use a feasible network, the nodes of which represent candidate locations, origins, and destinations, and the arcs represent feasible paths between two nodes given the assumed vehicle driving range.

In this article, we introduce the continuous location problem for a single refueling station on a tree network. Considering the infinite number of candidate sites on the network, the objective is to place a single refueling station at a point that maximizes the traffic flow in round trips/day that can be covered by the station. In general, the existing location models for refueling stations only consider the nodes of the network as potential station locations, but the optimal station locations may occur at points along the edges of the network due to a vehicle driving range. Kuby and Lim [25] pointed this out and used three methods for generating additional candidate sites. The first method adds a candidate site in the middle of some arc segments where a single station could refuel a path that would otherwise require two stations. The other two methods, developed by Kuby et al. [23], use the added-node dispersion problem to disperse nodes along the arcs of a network with the objective of minimizing the maximum separated arc length or maximizing the minimum separated arc length. While none of these methods can guarantee the generation of a set of dominating candidate sites, two dispersion methods produce better solutions than the mid-path method or considering only the original set of nodes as candidate sites.

By considering the location of a single refueling station on a tree network, we first prove two properties regarding the reduction of the problem size. Then, we identify a segment of candidate sites on each path of the reduced network. Later, we prove that some of the endpoints of these segments are optimal station locations and propose a polynomial time algorithm to identify the set of optimal endpoints that maximize the traffic flow in round trips/day covered by the station. These optimal endpoints are finally used to generate the entire set of optimal station sites. This work is intended to provide a theoretical foundation for more general versions of the continuous network location problem with multiple AF refueling stations to be located on a general transportation network.

The remainder of this article is organized as follows. In Section 2, we first provide the theoretical background needed to solve the problem and then propose a polynomial algorithm to find the set of optimal locations for the refueling station. A small test problem is solved in Section 3 to illustrate the algorithm. In Section 4, we provide conclusions and suggest topics for future research.

2. Single refueling station location problem on a tree network

2.1. Problem statement

This research work aims at locating a single AF refueling station on a tree network. The following assumptions, which are consistent with related work in the literature [7,24–27], are made in order to precisely formulate and solve the problem:

Assumption 1. All vehicles have the same safe travel distance, denoted as *R*. That is, a vehicle with a full fuel tank can travel a distance *R* before refueling.

Assumption 2. Vehicles make a complete round trip between their corresponding entrance and exit points on the road network.

Assumption 3. The fuel tank of a vehicle is at least half full when it enters and also has to be at least half full when it exits the road network.

Assumption 4. A driver cannot deviate from its original simple path to refuel.

Assumption 5. A refueling station provides refueling service to vehicles traveling in both directions of the road segment where the station is located.