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Deviation-flow refueling location problem with capacitated facilities: Model and algorithm

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ABSTRACT

At the beginning of the period of transition from petroleum-based fuels to alternative green fuels, determining the optimal location of alternative fuel stations (AFSs) would be an important task. This paper addresses this issue under two main assumptions. First, the capacity of AFSs is limited and each AFS can only serve a number of vehicles up to its capacity. Second, drivers may have to deviate from their pre-determined shortest path to get refueling services. This problem is formulated as a mixed integer linear programming (MILP) model and a heuristic algorithm is developed to solve it. The heuristic method involves solving small and easy to solve linear programing (LP) models, embedded within a greedy approach, and hence, it requires an LP software. Although the proposed MILP model requires that the set of deviation paths be pregenerated with respect to the maximum tolerated deviation distance, the heuristic uses only a restricted set of such paths. The performance of the proposed model and algorithm is evaluated on some randomly generated instances.

1. Introduction

In the last few decades, the domination of petroleum fuels in the transportation sector has led to serious environmental damages such as climate change, urban air pollution, greenhouse effects, and global warming (Melaina and Bremson, 2008). An effective approach to cut back the greenhouse gas emissions is the use of alternative fuel vehicles (AFVs) running on cleaner sources of energy such as ethanol, biodiesel, electricity, and hydrogen. However, there are several obstacles to adapting the AFVs on a mass scale. Constructing alternative fuel stations (AFSs) in the transportation network is the most important step toward the promotion of AFVs. Many economically and technically feasible alternative fuels have lower energy density causing the vehicle to have a shorter driving range. This leads to an increase in the number of times that a vehicle needs refueling. Since infrastructure development is expensive and slow, there is a need to direct investments towards the establishment of AFSs in those locations covering maximum traffic flow in the transportation network (Shukla et al., 2011).

Although the main assumption in the traditional network location theory is that demands originate from customers existing at network nodes, in the studies addressing the problem of locating AFSs, the usual node-based models cannot depict the problem characteristics very efficiently, because people commonly will not make a trip to the AFSs only for the purpose of refueling (Jung et al., March 2014). Therefore, in the literature of locating AFSs, it is usually assumed that demands happen in a flow of trips. A comparison of the two approaches (i.e. node-based and flow-based strategies) has been reported in Upchurch and Kuby (2010).

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In flow-based models, the traffic flow is demonstrated as an origin-destination (OD) matrix each element of which represents the number of vehicles moving from a given origin to a given destination. Therefore, the facilities should be located in such a way that these flows are covered as much as possible. Hodgson (1990) and Berman et al. (1992) are the first researchers that addressed flow-based demands and developed flow intercepting location model (FILM). The aim of FILM is to locate a given number of facilities so as to maximize the number of customers who encounter at least one facility along their predetermined path.

FILM assumes that if a flow visits just one facility along its path, it is covered. This assumption may be impractical for the problem of locating AFSs because of the limited driving range of vehicles. Indeed, a traffic flow is said to be refueled if it starts from origin, moves to destination and then returns to origin without running out of fuel. Typically, the vehicles driving range is limited per refill that makes vehicles to refuel more than once on their path. This is an important fact which is left out in FILM (Melaina, 2005). To address the limited driving range of vehicles, the flow refueling location problem (FRLP) has been introduced and deals with the establishment of a given number of AFSs on the network so as to maximize the number of round-trip travels that can be refueled. Kuby and Lim (2005) formulated FRLP as an MILP model. However, their model needs a preprocessing phase to pregenerate all combinations of facilities that can refuel each round-trip path. This requirement makes their model intractable even for medium-sized networks. To overcome this shortcoming and to eliminate the need of pregeneration of valid combinations, Lim and Kuby (2010) proposed three heuristic algorithms. Additionally, Capar and Kuby (2012) and Capar et al. (2013) provided efficient reformulations for FRLP based on covering the arcs of paths. Wang and Lin (2009) studied the concept of set cover to formulate the uncapacitated problem as an MILP model based on vehicle-routing logic. This formulation for a real-life large-scale problem contains many constraints and is not easy to solve using an exact algorithm. MirHassani and Ebrazi (2012) proposed a reformulation of FRLP based on expanded networks that is computationally more efficient than previous models. Different extensions of FRLP have been provided in the literature. For example Kuby and Lim (2007) extended FRLP by allowing the dispersion of candidate sites on arcs. Moreover, Yang and Sun (2015) considered FRLP and vehicle routing problem simultaneously within a single optimization model. For a comprehensive overview of the literature of the refueling location problem, see Ko et al. (2016).

The main focus of aforementioned studies is on two following assumptions: first, customers receive services only from the AFSs located along their pre-planned shortest path. Second, AFSs have enough capacity to serve all passing flows. However, in practice, particularly at the beginning of the period of transition to AFVs, due to the scarcity of AFSs, drivers may have to deviate from their pre-determined shortest path to get refueling services (Kim and Kuby, 2012, 2013) and hence, by allowing deviation from the shortest path, FRLP can become more realistic (Kim and Kuby, 2012). Additionally, some AFSs such as the ones providing hydrogen have very small capacities (Upchurch et al., 2009); thus, the capacity limitation of AFSs, is another critical characteristic that must be considered. Therefore, by considering above facts, directors will be able to make better and more realistic decisions on the location of AFSs. One question arising here, is that at what stage during the transition period, the issues of deviations and station capacities become important factors to consider. It can be said that deviation might be important from the very beginning, because the fewer stations there are, the more drivers will need to deviate. But capacity may not be a concern initially because there are so few vehicles, but as adoption increases capacity quickly becomes an issue.

Berman and Bertsimas (1995) developed several models to generalize FILM assuming that flows are allowed to deviate from pre-determined shortest paths. Kim and Kuby (2012) relaxed FRLP to consider the willingness of drivers to deviate from their shortest path to visit refueling stations assuming that stations have unlimited capacity. However, their model needs a preprocessing phase to generate the valid combinations of stations over all possible deviation paths. This phase makes the model intractable for large-sized networks and to overcome this shortcoming, Kim and Kuby (2013) presented a heuristic algorithm based on the network transformation. Huang et al. (2015) addressed the problem of locating AFSs assuming that AFV users can utilize multiple deviation paths between all OD pairs on the network and an OD pair is considered as covered if there is at least one path available between the OD pair through which drivers can complete a trip without running out of fuel. They proposed a flow-based set covering model to minimize the cost of locating AFSs while satisfying travel demands between all OD pairs. Yildiz et al. (2016) addressed an extension of FRLP by considering routing aspect of the individual drivers. They developed a mathematical model and solved it by a branch and price algorithm that implicitly takes into account deviation tolerances without the pregeneration of the routes.

Upchurch et al. (2009) extended FRLP to address the capacity limitation of refueling stations. Furthermore, Hosseini and MirHassani (2015a) presented a flexible formulation for capacitated FRLP and solved it by a heuristic method based on Lagrangian relaxation. Moreover, a stochastic version of capacitated FRLP was addressed by Hosseini and MirHassani (2015b). They assumed that the volume of the traffic flow on the network is uncertain and formulated the problem as a two-stage stochastic programming model where the first stage locates permanent stations and the second one locates portable stations. Additionally, Hosseini and MirHassani (2015c) considered electric vehicles and addressed the location of recharging stations with limited capacity assuming that if the capacity is occupied, the vehicles must wait in queues. They proposed an MILP model and a heuristic method to solve the problem. Miralinaghi et al. (2016) incorporated demand patterns over multiple periods and considered a staircase function representing marginal operational cost, and accordingly, addressed the problem of locating capacitated AFSs with the aim of minimizing the cost of AFS construction and the customers travel costs. They provided a mathematical model and solved it by using branch-and-bound and Lagrangian relaxation algorithms.

As mentioned earlier, the capacity limitation of AFSs as well as the fact that drivers may have to deviate from their predetermined shortest path to get refueling services are two important aspects in the problem of locating AFSs. Therefore, in order to get a more efficient plan, it is valuable to consider these two aspects simultaneously within a single optimization