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Locating alternative-fuel refueling stations on a multi-class vehicle transportation network

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ABSTRACT

The existing literature regarding the location of alternative fuel (AF) refueling stations in transportation networks generally assumes that all vehicles are capable of traveling the same driving range and have similar levels of fuel in their tanks at the moment they enter the network and when they exit it. In this article, we relax these assumptions and introduce a multi-class vehicle transportation network in which vehicles have different driving ranges and fuel tank levels at their origins and destinations. A 0-1 linear programming model is proposed for locating a given number of refueling stations that maximize the total traffic flow covered (in round trips per time unit) by the stations on the network. Through numerical experiments with the 2011 medium- and heavy-duty truck traffic data in the Pennsylvania Turnpike, we identify the optimal sets of refueling stations for AF trucks on a multi-class vehicle transportation network.

1. Introduction

Compressed natural gas (CNG) and liquefied natural gas (LNG) have recently been considered as candidate next generation fuels to improve fuel economy and produce lower greenhouse gas emissions than traditional fossil fuels, such as gasoline and diesel. In particular, LNG is the top alternative fuel (AF) for diesel-powered trucks, which move approximately 90% of the freight tonnage in the US, because LNG has higher energy density than other AFs (Whyatt, 2010). LNG engines are suited for mid- and heavy-duty trucks, which are classified by the Federal Highway Administration (FHWA) into classes 6–10 according to the number of axles and trailer units (Randall, 2012, Appendix A), as shown in Fig. 1. LNG-powered trucks can reduce up to 16% of greenhouse gas emissions and 73% of volatile organic compounds emissions compared to diesel-powered trucks (Tiax LLC, 2007). Furthermore, the low fuel price of LNG compensates for the high cost of purchasing LNG-powered trucks (Garthwaite, 2013). Myers et al. (2013, Appendix C) state that trucking companies can reduce operational costs if the LNG price is at least $0.52 per diesel gallon equivalent less than diesel price, given that trucks travel at least 120,000 miles annually over 6 years.

A proper AF refueling availability is necessary to encourage the use of AF vehicles, including LNG-powered trucks. There exists a variety of approaches to develop an AF infrastructure on a transportation network. Vehicles may need multiple refuelings for long-distance trips because fuel tank capacities are limited; the driving range of AF vehicles is, in fact, even shorter than that of traditional fuel counterparts. A set of refueling stations must be located along a path to cover the corresponding traffic flow when the path distance is longer than the driving range. Kuby and Lim (2005) develop the flow refueling location model (FRLM) to locate AF refueling stations on a transportation network with the objective of maximizing the total traffic flow covered by the stations. The FRLM requires a pre-generation stage to establish the combinations of refueling stations that can cover vehicles on each path for a given driving range. Evaluating the station combinations on all paths of a given network requires a large computational effort. To resolve the computational burden of the FRLM, Lim and Kuby (2010) suggest the use of three heuristics, namely greedy, greedy substitution, and genetic algorithms, and Kuby et al. (2009) integrate these heuristic algorithms to a geographic information system to analyze scenarios and evaluate the tradeoffs for the development of a hydrogen refueling infrastructure in Florida. As an alternative approach to reduce the complexity of the FRLM, Capar and Kuby (2012) propose an efficient formulation of the FRLM. Since their model does not need the pre-generation stage of feasible refueling station combinations, it is capable to efficiently find exact solutions for large-scale network problems.

While the FRLM mainly finds the locations of refueling stations that maximize the origin–destination (OD) flow refueled, a set-covering formulation of the problem can also be applied to locate the stations with the objective of minimizing the total

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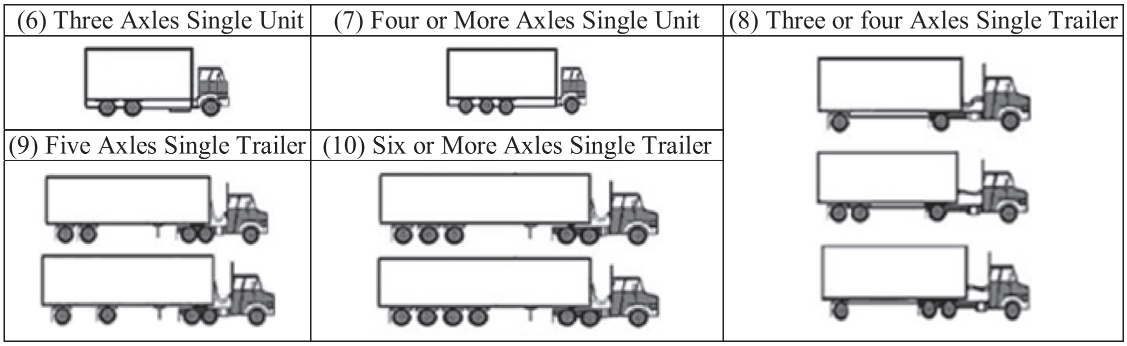

Fig. 1. FHWA vehicle classification scheme for mid and heavy duty trucks (Randall, 2012, Appendix A).

cost of building the refueling stations to cover all traffic flow on a given network. In general, the set-covering approach uses the OD distance matrix, instead of the OD flow volume matrix required by the FRLM. OD distances are easily collected, while OD flow volumes are usually estimated, as it is difficult to obtain their exact values or probability distributions. We note that the set-covering approach also requires the use of the OD flow volume matrix when the set-covering approach defines path coverage with respect to station capacity. Considering the advantage of the set-covering approach on collecting the OD distance matrix, Wang and Lin (2009) extend the basic concept of the set-covering problem to formulate a mixed-integer programming model that determines locations of AF refueling stations with the objective of minimizing the total building cost of the stations. The model evaluates whether a vehicle at a given site can arrive to the next site with the fuel remaining on the tank. This evaluation procedure for each path is, however, very computationally costly. To reduce the computational burden of the set-covering approach, MirHassani and Ebrazi (2012) provide a new reformulation of the set-covering model for AF refueling stations, which is able to solve large-scale set-covering problems much faster. Also, the new reformulation can be simply changed to a flow-base maximum coverage model.

In addition to the solution approaches for the AF refueling station location problem discussed above, there exist several extensions of the FRLM that consider additional situations. First, some drivers may be willing to detour from their pre-planned paths for refueling. According to a survey that compares spatial refueling behaviors between CNG and gasoline vehicle drivers, CNG vehicle drivers seem to detour more than gasoline vehicle drivers do for refueling services (Kuby, Kelley, & Schoenemann, 2013). In order to account for driver deviation behavior, Kim and Kuby (2012) propose the deviation version of the FRLM with the objective of maximizing the total traffic flow covered by the stations on deviation paths. Kim and Kuby (2013) then develop heuristic algorithms for the deviation version of the FRLM to solve large network problems. Second, external restrictions on setting up refueling stations can be considered in real-world networks. Upchurch, Kuby, and Lim (2009) consider capacity constraints that limit traffic flow volumes at the refueling stations, and Capar, Kuby, Leon, and Tsai (2013) consider a budget constraint to analyze the effects of different land values. Third, it may be possible to cover more traffic flow volume when refueling stations are able to be located along the arcs. Kuby and Lim (2007) propose an approach for adding a single site on the middle of paths and suggest two dispersions methods, one minimizes the maximum length of subdivisions of the original arcs and the other maximizes the minimum length of subdivisions of the original arcs. The FRLM with original and additional candidate sites can provide better optimal locations for AF refueling stations to maximize the traffic flow volume covered by stations. Ventura, Hwang, and Kweon (2015) introduce the continuous version of the refueling station location problem where a single refueling station can be located anywhere on a tree transportation network. Lastly, there are other station location network design studies considering different initial states of charge of electric vehicles at origins and integrated decision-making models for marketing, engineering, and operational decisions (Kang, Feinberg, & Papalambros, 2015; Lee, Kim, Kho, & Lee, 2014).

In order to invigorate the use of AF vehicles in intercity freight transportation, Hwang, Kweon, and Ventura (2015) propose a new mathematical model for developing AF infrastructures on directed (symmetric) transportation networks when vehicles traveling the network have the same driving range and similar fuel levels at ODs. A directed transportation network consists of two divided-pathways, which are separated by a traffic barrier, and is only accessible from entrance and exit ramps, so that vehicles can drive at high speed safely for long-distance travel without any interruption such as traffic signals and intersections. Such a transportation network is called a dual carriageway or a divided highway, and many countries apply this road system to motorways, freeways, expressways, and toll roads. In general, a directed transportation network has built-in service facilities that provide service such as travel information, restrooms, food, and fuel for drivers' convenience, so that drivers use these facilities on the network without deviating from their preplanned trips. Built-in service facilities are classified according to accessibility; a single-access service facility can provide refueling service only to vehicles in one driving direction, while a dual-access service facility can offer its service to vehicles in both driving directions.

This paper proposes a new mathematical model for a refueling station location problem on a directed transportation network where AF vehicles have different driving ranges and fuel tank levels at the entrances and exits. In general, some vehicles have higher fuel efficiency or carry a larger fuel tank than others, so that vehicles have different driving ranges depending on vehicle classes. The information on traffic flow distribution of the vehicle classes in a road system is easily obtained from federal agencies or related corporations. For example, in case of Pennsylvania, the information on the traffic flow distribution of vehicle classes is available from Pennsylvania Spatial Data Access (Pennsylvania Spatial Data Access, 2016). Korea Expressway Corporation (2014) also annually publishes a summary of the traffic flow statistics in South Korea.

Next, we consider that a vehicle has different remaining fuel tank levels at the entrances and exits of a transportation network. A vehicle would depart from its home location, such a transportation company, travel to a road network, go through a particular entrance and exit pair of the network, and then exit the network to reach a customer location. After that, the vehicle would return to the home location. During this round trip, the vehicle may be refueled outside the road network in or near its home location and customer locations, so that it is reasonable to consider

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