Infrastructure Development for Alternative-Fuel Vehicles on a Traffic Network

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Abstract

Reduction of greenhouse gas (GHG) emissions from ground transportation is increasingly becoming one of the most important issues for automobile manufacturers to achieve environmental sustainability in the transportation sector. As a result, recent research has paid considerable attention to the use of alternative-fuel vehicles (AFVs) that may help reduce GHG emissions. However, due to the lack of an initial infrastructure, which would include alternative-fuel refueling stations, the use of AFVs is still in their early stages. In order to commercialize AFVs in a given region, it is necessary to set up an initial set of refueling stations on the region’s road network. In this paper, we develop a mathematical model to determine optimal locations for a pre-determined number of refueling stations whose objective is to maximize the traffic flows covered on a tree network, which is a common structure of toll roads in many states. After collecting the necessary origin/destination traffic flow data, the model is applied to the Pennsylvania Turnpike network.

Keywords
Refueling Stations, Facility Location, Transportation Planning, Integer Programming, Alternative-fuel Vehicle

1. Introduction

In 2011, 1,876 million metric tons of carbon dioxide equivalents, accounting for 28% of the total greenhouse gas (GHG) emissions in the United States, came from the transportation sector [1]. As a result, reduction of GHG from ground transportation is increasingly becoming one of the important issues in automobile and heavy-duty vehicle manufacturers in the United States to achieve environmental sustainability in logistics. Vehicles using alternative-fuel (AF) such as biodiesel, hydrogen, electricity and natural gas help to cut down the emissions because they emit less GHG than vehicles by traditional fuels such as diesel or gasoline.

During the last decades, the United States has made many efforts to invigorate the use of alternative-fuel vehicles (AFVs). In spite of the efforts, only 0.3% of the total vehicle fuel consumption is merely derived from alternative-fuel, compared to the consumption of traditional fuels that are gasoline or diesel [2]. One of the top barriers to this marginal transition to the deployment of AFVs in the United States is the lack of refueling stations [3]. Refueling availability is a significant issue in the vehicle-purchasing decision before consumers buy AFVs [4]. Thus, to promote commercialization of AFVs, a sufficient number of initial AF refueling stations are necessary [5]. If a sufficient number of refueling stations for AFVs are properly located on a transportation network, demand of AFVs would gradually increase and consequently the impact of traditional fuel vehicle emissions on the environment would decrease.

Over the last few decades, a large number of papers have been published to locate refueling stations optimally in road transportation systems. Upchurch and Kuby categorize these papers into three classes [6]. The first class is related to the p-median model, one of the most popular models in facility location theory. Assuming that AF refueling stations can be located at existing gasoline stations in California, the p-median model is applied to minimize the average driving time to p-stations [7]. Also, under the notion “where you drive more is where you more likely need refueling”,

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Lin et al. present a model to locate $p$-refueling stations by minimizing the total refueling travel time that is calculated from sum of fuel demand on road segments toward a node and the average travel time from these segments to the node [8]. The second approach is to locate AF refueling stations on roads with high traffic flows. In order to place a certain number of refueling stations near high traffic nodes, Bapna et al. use the populations on covered arcs in one of their multi-objectives, which maximizes the total demand within a covering distance [9]. Given a limited vehicle travel range and a maximum distance between two refueling stations, Melendez and Milbrandt determine the station placements on interstate highways in areas with high traffic flows [10]. Nicholas considers a new variable in a regression analysis to explain that the fuel demand along routes from home towards freeways is an important factor as well as population [11]. Lastly, the third approach is to relate the demand of traffic flows between origins and destinations (ODs). By locating facilities along the OD paths, this approach is to maximize the path flows covered by them along the paths with a given number of the facilities [12, 13]. On the other hand, for AFVs with a short driving range, an adequate number of refueling stations along each path flow should be located to complete their trips between ODs. Kuby and Lim develop a model to maximize the total round-trip flows refueled by combinations of stations along the OD paths [14]. Their model is formulated in two steps to generate feasible combinations of refueling stations and then selects the optimal combination on the travel paths using a mixed-integer linear programming. Based on their model, Kuby et al. use heuristic algorithms to find near optimal locations of hydrogen stations in the Orlando metropolitan area and State of Florida because the original model requires too much computational effort to solve the real-world networks [15].

The objective of this paper is to develop a mathematical model to determine optimal locations of AF refueling stations on a tree network. In the next section, we describe the assumptions and the model that locates a given number of refueling stations optimally to maximize the number of vehicle (round) trips covered on a tree network. In section 3, we analyze a real-world road network, the Pennsylvania (PA) Turnpike. Next, our model is applied to the real network data of the PA Turnpike to set up initial AF refueling stations considering that all vehicles have the same limited range. The last section provides conclusion and directions for future research.

2. Methodology

This section presents a new model of locating AF refueling stations on a tree network. In most states of the United States, the interstate and major highways, including toll roads, are designed as a tree or tree-like network, focusing mainly on uninterrupted traveling for a high level of mobility [16]. Before describing the model, we first introduce the following assumptions, sets, and parameters [17]:

**Assumptions**
- The target road network has a tree structure. Thus, all OD pairs have a unique path.
- All vehicles have the same limited travel range, denoted as $R$, meaning the maximum distance that AFVs can travel without refueling.
- Entrances and exits of a traffic network are considered origins and destinations, respectively.
- The fuel tanks for all AFVs at the origin and destination are at least half-full.
- All vehicles make a complete round-trip between origins and destinations.
- The set of potential locations for AF refueling stations is given in advance.

**Sets**
- $P = \{p_1, \ldots, p_s\}$: set of all origins and destinations.
- $K = \{k_1, \ldots, k_h\}$: set of all candidate locations for AF refueling stations.
- $N = \{n_1, \ldots, n_l\}$: set of all nodes on $T$, i.e., $N = P \cup K$.
- $A$: set of arcs connecting any two nodes $n_i, n_j \in N$.
- $Q = \{(p_i, p_j) : p_i, p_j \in P, i < j\}$: set of OD pairs.

**Parameters**
- $m$: number of AF refueling stations located along a tree network.
- $f(p_i, p_j)$: traffic flows on a path from $p_i$ to $p_j$.
- $d(n_i, n_j)$: distance between two nodes $n_i$ and $n_j$. Note that $d(n_i, n_j) = d(n_j, n_i)$. 

Hwang, Kweon, and Ventura
For vehicles which have a limited fuel tank size, distance between OD pairs \(d(p_i, p_j)\) is an important consideration to deploy refueling stations on a network because the vehicles are able to travel a certain distance \(R\) with a single refueling. Multiple refuelings are necessary for vehicles traveling a long-trip whose distance is longer than \(R\). In this respect, we first consider short-trips whose travel distance is less than or equals \(R/4\) in Type 1. Since their distance is short, a single refueling is required during their round trip. On the other hand, other trips may need multiple refuelings depending on their distance. Type 2 trips are able to complete their round trip with a single refueling in each direction, \(p_i \rightarrow p_j\) and \(p_j \rightarrow p_i\), respectively, while Type 3 trips require refueling twice. Lastly, long-trips whose distance is greater than \(R\) are considered as Type 4 trips. Thus, four subsets of OD pairs \(Q\) are defined as follows:

**Four types of OD pairs**
- Type 1: \(Q^{(1)} = \{(p_i, p_j) \in Q: 0 < d(p_i, p_j) \leq R/4\}\)
- Type 2: \(Q^{(2)} = \{(p_i, p_j) \in Q: R/4 < d(p_i, p_j) \leq R/2\}\)
- Type 3: \(Q^{(3)} = \{(p_i, p_j) \in Q: R/2 < d(p_i, p_j) \leq R\}\)
- Type 4: \(Q^{(4)} = \{(p_i, p_j) \in Q: R < d(p_i, p_j)\}\)

Considering the complete round-trip between each OD pair, \((p_i, p_j)\), we define two different location sets for the path \(p_i \rightarrow p_j\) and \(p_j \rightarrow p_i\), respectively. Thus, the following sets have valid locations to cover round-trips of four types of OD pairs when a vehicle enters/leaves a road network with at least half of its tank full.

\[E_1^{(1)}(p_i, p_j) = \{k_u \in K: k_u \text{ is located on path } p_i \rightarrow p_j, \forall (p_i, p_j) \in Q^{(1)}\}\]
\[E_1^{(2)}(p_i, p_j) = \{k_u \in K: k_u \text{ is located on path } p_i \rightarrow p_j, \forall (p_i, p_j) \in Q^{(2)}\}\]
\[E_1^{(3)}(p_i, p_j) = \{k_u \in K: k_u \text{ is located on path } p_i \rightarrow p_j, d(p_i, k_u) \leq R/2, \forall (p_i, p_j) \in Q^{(3)}\}\]
\[E_1^{(4)}(p_i, p_j) = \{k_u \in K: k_u \text{ is located on path } p_i \rightarrow p_j, d(k_u, p_j) \leq R/2, \forall (p_i, p_j) \in Q^{(4)}\}\]
\[E_2^{(1)}(p_i, p_j) = \{k_u \in K: k_u \text{ is located on path } p_i \rightarrow p_j, d(p_i, k_u) \leq R/2, \forall (p_i, p_j) \in Q^{(1)}\}\]
\[E_2^{(2)}(p_i, p_j) = \{k_u \in K: k_u \text{ is located on path } p_i \rightarrow p_j, d(k_u, p_j) \leq R/2, \forall (p_i, p_j) \in Q^{(2)}\}\]
\[E_2^{(3)}(p_i, p_j) = \{k_u \in K: k_u \text{ is located on path } p_i \rightarrow p_j, d(p_i, k_u) > R, d(k_u, p_j) > R, \forall (p_i, p_j) \in Q^{(3)}\}\]
\[E_2^{(4)}(p_i, p_j) = \{k_u \in K: k_u \text{ is located on path } p_i \rightarrow p_j, d(p_i, k_u) > R, d(k_u, p_j) > R, \forall (p_i, p_j) \in Q^{(4)}\}\]

**Mixed Integer Programming Model**

Given the OD flows and sets of candidate locations on each path, the problem is formulated as a mixed integer programming (MIP), where the objective of the model is to determine optimal locations of AF refueling stations on a tree network for maximization of the number of (round) trips covered by the stations [17]. We first introduce two binary variables: (1) \(x_{k_u}, k_u \in K\), which equals 1 if Station \(k_u\) is selected, and 0 otherwise, and (2) \(y_{p,p',j}\), which equals 1 if the traffic flows of \((p_i, p_j), f(p_i, p_j)\) and \(f(p_j, p_i)\), are covered by sets of refueling stations, and 0 otherwise. The model is formulated as follows:

\[
\text{Max Refueled Traffic Flows} = \sum_{(p_i, p_j) \in Q} \{f(p_i, p_j) + f(p_j, p_i)\} y_{p,p',j},
\]

subject to

\[
\sum_{k_u \in E_1^{(1)}(p_i, p_j) \cup E_1^{(2)}(p_i, p_j)} x_{k_u} \geq y_{p,p,j} \quad \forall (p_i, p_j) \in Q^{(1)}
\]
\[
\sum_{k_u \in E_1^{(2)}(p_i, p_j)} x_{k_u} \geq y_{p,p,j} \quad \forall (p_i, p_j) \in Q^{(2)}
\]
\[
\sum_{k_u \in E_1^{(3)}(p_i, p_j)} x_{k_u} \geq y_{p,p,j} \quad \forall (p_i, p_j) \in Q^{(3)}
\]
\[
\sum_{k_u \in E_1^{(4)}(p_i, p_j)} x_{k_u} \geq y_{p,p,j} \quad \forall (p_i, p_j) \in Q^{(4)}
\]
The objective function (1) maximizes the traffic flows that can be covered by $p$ refueling stations located between all OD pairs. Constraint set (2) establishes conditions to determine the coverage of trips related to the OD pairs of Type 1. If at least one refueling station is selected on the path from $p_i$ to $p_j$, or on the path from $p_j$ to $p_i$, the trips between $p_i$ and $p_j$ can be covered. Note that we relax “at least half fuel tank” assumption in the direction where there is no feasible refueling station to consider a realistic refueling plan that some vehicles might be refueled once during their round-trip. Constraint sets (3) and (4) ensure that the trips for Type 2 are covered by two refueling stations of $E_1^{(2)}(p_i, p_j)$ and $E_1^{(2)}(p_j, p_i)$ in each direction. Constraint sets (5) and (6) represent that we need two refueling stations on the path from $p_i$ to $p_j$, and two refueling stations on the path from $p_j$ to $p_i$, respectively, to cover the trips for Type 3. Similarly to Type 3, Type 4 first requires constraint sets (5) and (6). Additionally, constraint sets (7) and (8) are used to identify the trips for Type 4. The coefficients of constraint set (7), $a_{k_u k_v}$’s, represent whether station $k_v \in L_2(p_i, p_j)$ is reachable from the other stations in $L_1(p_i, p_j)$. That is, $a_{k_u k_v} = 1$ if $0 < d(k_u, k_v) \leq R$ and $u < v$; otherwise 0, where $k_u \in L_1(p_i, p_j)$ and $k_v \in L_2(p_i, p_j)$. Similarly, this linkage relationship between refueling stations of $L_1(p_i, p_j)$ and refueling stations of $L_2(p_i, p_j)$ can be constructed for the trip from $p_j$ to $p_i$ in constraint set (8). Constraint (9) limits the total number of refueling stations to $p$ exactly. Lastly, all the decision variables are restricted as binary by constraint sets (10).

$$\sum_{k_u \in E_1^{(1)}(p_i, p_j)} x_{k_u} \geq y_{p_ip_j}, \quad \forall (p_i, p_j) \in Q^{(1)}; \quad t = 3, 4; \quad c = 1, 2,$$

$$\sum_{k_u \in E_2^{(2)}(p_i, p_j)} x_{k_u} \geq y_{p_ip_j}, \quad \forall (p_i, p_j) \in Q^{(1)}; \quad t = 3, 4; \quad c = 1, 2,$$

$$\sum_{k_u \in L_1(p_i, p_j)} a_{k_u k_p} x_{k_u} \geq y_{p_ip_j}, \quad \forall k_p \in L_2(p_i, p_j); \quad \forall (p_i, p_j) \in Q^{(4)},$$

$$\sum_{k_u \in L_2(p_j, p_i)} a_{k_u k_p} x_{k_u} \geq y_{p_ip_j}, \quad \forall k_p \in L_2(p_j, p_i); \quad \forall (p_i, p_j) \in Q^{(4)},$$

$$\sum_{k_u \in k} x_{k_u} = m, \quad \forall k \in K,$$

$$x_{k_u} \in \{0, 1\}, \forall k_u \in K; \quad y_{p_ip_j} \in \{0, 1\}, \forall (p_i, p_j) \in Q.$$
on, we call the two main segments the PA Turnpike in this paper. The PA Turnpike has 47 active interchanges/toll plazas with 17 open service plazas and some closed service plazas. In our model, 19 service plazas including 2 temporarily closed service plazas are our candidate sites for AF refueling stations. Especially, while three of them provide refueling service in both directions of the PA Turnpike, called a dual-access station, the others provide refueling service in only one direction, called a single-access station. Furthermore, the PA Turnpike does not allow U-turns. Thus, vehicles have no chance to stop by services plazas if they travel between certain pairs of successive interchanges where there does not exist any service plaza. These interchanges can be aggregated with a single interchange whose location is identified as the weighted traffic flow average of the consecutive interchanges. Figure 1 shows the simplified PA Turnpike with 19 (aggregated) interchanges and 19 candidate sites for AF refueling stations.

We run three scenarios determining initial locations of AF refueling stations on the PA Turnpike. The scenarios assume that all vehicles on the PA Turnpike have the same limited range (300, 450, 600 miles). When $R = 300$, five stations are capable of covering 60.56% out of the 11,552,000 trips that is the entire traffic flow on the simplified PA Turnpike (Figure 1). Next, with the longer ranges $R = 450$ and $600$, the each coverage as a function of the number of refueling stations shows strictly diminishing marginal returns, meaning that each additional station covers fewer flows than the previous one in Figure 2. However, the function of $R = 300$ has nearly a constant rate of increase in a certain section where the number of refueling stations increases from 3 to 8.

We could relax one of our assumptions, all vehicles have the same limited range. Instead, for example, we can analyze scenarios where some AFVs have the limited range, R, and the others have the double limited range, 2R. Based on the analysis of the mixed limited range, we could observe that the refueling station locations and refueled traffic flows are affected by the variations in limited ranges. A more detailed discussion of the analysis is presented in [17].

4. Conclusions
In this paper, we study the problem of setting up initial AF infrastructure on a traffic network. Unlike other location-allocation problems, relationship between OD distance and a vehicle limited range is a key issue that locates AF refueling stations to make successful round-trips of OD pairs without running out of fuel. In this respect, after constructing sets of feasible locations for each OD pair, we have developed a MIP model to determine a set of optimal locations of AF refueling stations by maximizing the total refueled round-trips. Using the presented model, we run two numerical experiments with a real data set regarding traffic flows of the PA Turnpike. Assuming that all vehicles have the same limited range, the result shows the impact of the different vehicle range on optimal locations.

Our current model of deploying AF refueling stations has been developed with the half-full assumption and the fixed transportation demand. The model could be extended by considering a variable amount of fuel tank at origins or destinations. Also, for uncertain transportation demand, the strategic decisions of robust locations could be developed.
References