Journal of Transport Geography 18 (2010) 750–758

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

Comparing the *p*-median and flow-refueling models for locating alternative-fuel stations

Christopher Upchurch [a,*], Michael Kuby [b,1]

[a] Department of Geography, University of South Carolina, 709 Bull St., Columbia, SC 29208, USA
[b] School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ 85287, USA

ARTICLE INFO

Keywords:
Refueling facilities
Optimal location
Electric vehicle
Hydrogen
Biofuel
Natural gas

ABSTRACT

The *p*-median and flow-refueling models are two of the more popular models for optimal location of alternative-fuel stations. The *p*-median model, one of the most widely used location models of any kind, locates *p* facilities and allocates demand nodes to them to minimize total weighted distance traveled. In comparison, the flow-refueling location model (FRLM) is a path-based demand model that locates *p* stations to maximize the number of trips on their shortest paths that can be refueled. For a path to be considered refuelable, one or more stations must be located on the path in a way that allows the round trip to be completed without running out of fuel, given the vehicle driving range. In this paper, we analyze how well the facilities located by each model perform on the other's objective function on road networks in Florida. While each objective function degrades somewhat when facilities are located by the other model, the stations located by the flow-refueling model generally do better on the *p*-median objective than the stations located by the *p*-median model do on the flow-refueling objective. This difference between the two models is even more pronounced at the state scale than at the metropolitan scale. In addition, the optimal locations for the FRLM tend to be more much more stable as *p* increases than those located by the *p*-median model.

1. Introduction

Over the next several decades, as countries transition from gasoline and diesel to alternative fuels, they will need to invest heavily in new refueling station infrastructure. Many studies have emphasized the critical role that refueling stations play in facilitating the development of alternative fuels (California Environmental Protection Agency, 2005; Greene et al., 2008; Huleatt-James, 2008; Melaina, 2003; Melaina and Bremson, 2008; Ogden, 1999). The which-comes-first "chicken-and-egg" dilemma involving alternative-fuel (alt-fuel) stations and vehicles is widely acknowledged by researchers and industry representatives alike (Melendez, 2006; National Research Council, 2004; US Department of Energy, 2002). A common strategy for breaking this cycle and building towards necessary economies of scale involves government requirements for alternative-fuel fleets for government agencies, utilities, and other large organizations, plus government subsidies for depot-based fuel stations. However, recent studies have highlighted the difficulty of transitioning from fleets to consumers (Melendez, 2006). In the early stages of transition, when consumer demand for fuel may not be high enough to support private stations without subsidies, it is especially important that the initial networks of stations be located in a way that maximizes the potential for consumers to adopt alt-fuel vehicles.

In the literature, several approaches have been used to locate refueling stations optimally. One group of studies has employed variants of the *p*-median model, perhaps the most widely used model in the field of optimal facility location analysis. The *p*-median is a location-allocation model that locates a given number *p* of facilities, and allocates demand nodes *i* to facilities *j* to minimize the total distance traveled by consumers to facilities (Hakimi, 1964; Revelle and Swain, 1970). For locating alternative-fuel stations, the *p*-median model has the appeal of locating stations convenient to where people live. Several studies have demonstrated empirically that consumers generally prefer to refuel near their homes (Sperling and Kitamura, 1986; Kitamura and Sperling, 1987). The *p*-median model was first applied to fuel stations by Goodchild and Noronha (1987), who used it as one of the objectives in a multiobjective programming model for rationalizing stations from existing gas station networks. For alternative fuels, it has been used in studies by Nicholas et al. (2004) and Nicholas and Ogden (2006) and adopted for several major studies of the transition to hydrogen by Oak Ridge National Laboratory (Greene et al., 2008). Lin et al. (2008) developed what they called the "fuel travel-back" approach that is structurally

* Corresponding author. Tel.: +1 803 777 5867; fax: +1 803 777 4972.
E-mail addresses: chris.upchurch@sc.edu (C. Upchurch), mikekuby@asu.edu (M. Kuby).
[1] Tel.: +1 480 730 8457.

0966-6923/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jtrangeo.2010.06.015

similar to the p-median model but with nodes weighted by the quantity of fuel consumed on segments "pointing to" demand node i (instead of population) and with travel time between demand nodes i and candidate facility locations j substituted for distance. Essentially, this model uses vehicle-miles traveled (VMT) data to minimize the total travel time for all fuel (in gallon-minutes) to travel from where it is burned back to the nearest station. The p-median model has the additional advantage of having simple data requirements. Road network data and population data are widely available in GIS format from various sources (e.g., US Census Bureau, 2010), and inter-node distances can be easily computed using a custom program, in this case a script written in the Python programming language.

A second approach aims to locate stations on high-traffic routes. In addition to the p-median objective they used, Goodchild and Noronha (1987) employed a second objective that maximizes the traffic flows on the roads passing by a station. Melendez and Milbrandt (2005) considered only roads with at least 20,000 vehicles per day in their GIS analysis of a national hydrogen station network. This approach recognizes that many drivers refuel on their way to somewhere else, and tries to maximize the passing traffic. Nicholas (2010) operationalized a version of this criteria as the total vehicle-kilometers traveled within an aggregated zone. Bapna et al. (2002) introduced an objective that is a hybrid of the first two types, which maximizes the population on covered links. The potential problem with traffic-count methods, however, is they count the same trips by the same drivers more than once if the trip travels multiple links, even though drivers might refuel only once. As a result, the traffic-count or VMT methods could locate stations on several adjacent links of a high-volume freeway. These methods are therefore probably best suited as a secondary objective that competes with a primary objective that would spread the stations around, as in Goodchild and Noronha (1987), or as a "threshold"-type constraint guaranteeing a certain minimum potential demand for each station.

A third general approach to locating refueling stations maximizes passing flows without double counting. This approach originated with Hodgson's (1990) flow-capturing location model, later termed the flow-intercepting location model (FILM) by Berman et al. (1992). These models are classified as *path*-based or *flow*-demand models. The basic units of demand in these models are not points in space representing where people live (p-median models), nor network links (traffic-count models), but flows on paths across a network representing the routes people travel. The basic objective of the FILM is to locate p facilities to maximize the number of trips intercepted. A demand is considered captured or intercepted if there is a facility anywhere along the path. The standard FILM counts each flow intercepted only once, regardless of how many stations are along its route.[2] Behaviorally, the FILM is well-suited for facilities at which consumers stop along their way to somewhere else rather than making a special trip from home and back. Given that drivers rarely make special-purpose trips from home to stations and back solely to refuel their vehicles, it can be argued that flow capturing provides a behaviorally realistic basis for locating refueling stations.

There are two main problems, however, in applying the basic FILM to locating refueling stations. First, the model requires a matrix of traffic flows from origins to destinations, each of which must then be assigned to a particular likely path through the network. These "trip table" data are more challenging to work with than population data, and are not always available for all regions and geographic scales. The second problem is that, for longer inter-city trips, one station anywhere along the path may not be enough to enable a vehicle with a limited driving range to complete the trip without running out of fuel. This is especially a problem for battery-powered electric vehicles and hydrogen vehicles because of the limited energy storage capabilities of these technologies. To address this limitation, Kuby and Lim (2005) developed the flow-refueling location model (FRLM). The FRLM counts a flow as refueled only if a *combination of stations* exists on a path that can successfully refuel the round trip between the origin and destination, given the assumed driving range of vehicles. Like the FILM, the FRLM tries to maximize the number of trips that can potentially be refueled by p stations. The FRLM has been applied to real-world networks at both the metropolitan scale and state scale in Florida (Kuby et al., 2009) and Arizona (Kuby et al., 2004), and has been extended to stations with limited capacities (Upchurch et al., 2009), locations along arcs (Kuby and Lim, 2007), and maximizing trip-miles instead of trips (Kuby et al., 2009). At the metropolitan scale, if no round trips are longer than the assumed vehicle driving range, the FRLM reduces to the FILM.

In this paper, we compare the two main approaches—the node-based p-median model and the flow-based FRLM—in terms of how well each one does in satisfying the other's objective. Other researchers have combined traditional point-based demands with flow demands in several ways (Berman, 1997; Berman and Krass, 1998; Hodgson and Rosing, 1992), but using FILM rather than FRLM, and not applied to refueling stations. Using the Orlando metro area and statewide Florida networks developed in Kuby et al. (2009), we locate p stations to maximize the flows refueled, and calculate how well the solutions perform in minimizing the total weighted distance traveled from population nodes to stations, that is, the p-median objective. Then, we locate p stations to minimize the p-median objective and calculate how well the stations so located would be able to refuel the trips in the trip table. Our purpose here is not to assess which model more accurately represents typical consumer refueling behavior. Rather, assuming that both models capture an important aspect of refueling behavior—refueling near home (p-median) and refueling on the way (FRLM)—our goal is to assess which model does better in satisfying the other's objective. We also investigate which model provides more stable solutions in which locations that are optimal for smaller numbers of stations remain optimal when networks are expanded with additional stations.

2. Model descriptions

The p-median model minimizes the total distance between population and the closest facility. The formulation for the p-median model is as follows:

$$\text{Min} \sum_i \sum_j h_i d_{ij} Y_{ij} \tag{1}$$

Subject to :

$$\sum_j Y_{ij} = 1 \quad \forall\, i \tag{2}$$

$$\sum_j X_j = p \tag{3}$$

$$Y_{ij} - X_j \leqslant 0 \quad \forall\, i,j \tag{4}$$

$$X_j = 0,1 \quad \forall\, j \tag{5}$$

$$Y_{ij} = 0,1 \quad \forall\, i,j \tag{6}$$

where Y_{ij} is 1 if customer i is served by facility j, 0 if not; X_j is 1 if a facility is located at candidate site j, 0 if not; h_i is demand at location i; d_{ij} is distance from location i to location j; p is the number of facilities to be located.

[2] Extensions of the FILM have considered multiple exposures, such as to billboards or inspection stations, with diminishing benefits of subsequent exposures (Berman et al., 1995a,b; Zeng et al., 2008, 2010a,b; Berman, 1997).