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# A threshold covering flow-based location model to build a critical mass of alternative-fuel stations

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ABSTRACT

To facilitate the transition to alternative-fuel vehicles (AFVs), researchers have developed models for optimally locating an initial refueling infrastructure for AFVs with limited driving range. Recently, clustering of stations has emerged as a strategy to encourage consumers to purchase AFVs by building a critical mass of stations. Clustering approaches, however, have focused on serving demands represented as nodes or arcs rather than origin-destination (O-D) trips. This study proposes a Threshold Coverage extension to the original Flow Refueling Location Model that focuses on the percentage of a zone's O-D trips that can be successfully completed given a typical driving range and location of stations. It is motivated by the idea that drivers in an area will not purchase an AFV unless a critical mass of the trips they regularly make can be completed. Therefore, the new model optimally locates $p$ refueling stations on a network to maximize the sum of weighted demand of covered origin zones, where "covered" means that the zone exceeds a specified threshold percentage of their total outbound round trips that are refuelable. The model is tested on networks for Orlando and the state of Florida. As the threshold percentage is raised, fewer zones can surpass the threshold. Covered nodes increasingly cluster together, as do stations for serving their O-D flows. The model's policy implementation will provide managerial insights for some key concerns of the industry, such as geographic equity vs. critical mass, from a new perspective.


## 1. Introduction

The dominance of petroleum-fueled vehicles in the road transportation sector has long raised concerns about energy security, sustainability, environmental protection, and public health. Commercialization of alternative-fuel vehicles (AFVs), such as compressed natural gas (CNG), liquefied petroleum gas (LPG, or propane), hydrogen, biodiesel, ethanol, and electricity, is gaining speed. Lack of refueling infrastructure has been identified by many as one of the most formidable barriers to the large-scale transition to AFVs (Melaina et al., 2012; Melendez, 2006; Romm, 2006). A national-scale study (Melaina, 2003) suggested that successful penetration of the household vehicle market will need initial hydrogen refueling stations numbering at least 15% of the existing gas stations. Therefore, the underlying chicken-and-egg problem makes the initial locations of AFV refueling stations critical to a successful transition process.

Researchers have developed a wide variety of optimal location models for planning an AFV fueling infrastructure for maximum convenience. Two popular approaches are the flow refueling location model (FRLM), which maximizes the origin-destination (O-D) trips that can be refueled given a vehicle driving range (Kuby and Lim, 2005), and the $p$-median model, which minimizes the travel costs to the stations (ReVelle and Swain, 1970). To help determine which approach represents driver behavior most realistically, Kelley and Kuby (2013) surveyed early CNG vehicle adopters in Southern California at CNG stations while they refueled their cars. Their revealed preferences indicate that, when no station exists that is both closest to home and most on their way, CNG drivers overwhelmingly chose the station with the least deviation from their shortest routes over the station closest to home. This finding suggests that to best serve the early adopters, AFV refueling infrastructures should be located on or near the routes that drivers frequently travel, regardless of whether the stations are near to home or not. It is possible, however, that the station locations that existing AFV owners find convenient (based on their experience of repeated trips and refueling stops with their AFVs in the face of a sparse refueling infrastructure) may not be the best geographical arrangement of infrastructure for attracting new AFV buyers in the first place.

Some recent papers have argued that the best way to attract early adopters is to deploy clusters of stations in pre-determined areas where residents fit the classic profile of early AFV adopters: high purchasing power, well-educated, and owning more than one vehicle (Melendez and Milbrandt, 2008; Tal and Nicholas, 2013; Turrentine and Kurani, 1995). The idea of planning to achieve a critical mass of stations to convince potential buyers to purchase a new AFV is promising, because locally abundant AFV stations will increase public awareness and reduce range anxiety of potential buyers (Neubauer and Wood, 2014). Another reason for clustering stations—and the one that is the

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focus of this paper—is the concern that potential buyers might not purchase an AFV if the refueling infrastructure only enables them to complete a small fraction of the trips they regularly make.

Based on this key idea, this paper extends the FRLM by locating stations to enable as many zones as possible (weighted by their trip volumes) to surpass a given threshold for the percentage of their trips that can be completed, considering where the residents of that zone travel to and from on a regular basis and the limited driving range of AFVs. The objective is to cover as much zonal demand as possible with the given station-building budget, considering that trips from each zone go to other zones near and far, and that a zone's threshold can be achieved by covering a combination of short trips that may need only one refueling stop and longer trips that may require two or more stops. In this approach to clustering stations, the neighborhoods served are not pre-determined, but emerge from the structure of the network and the traffic flows on it.

## 2. Literature review

A wide variety of models have been developed to locate a network of fueling stations optimally. One common way to classify them is by the spatial units of demand to be served: nodes, arcs, paths (or routes, flows, trips), and tours (i.e., trip chaining or space-time path). Following that, we review “clustering” approaches.

Nodes are the most commonly used spatial units in optimal station location models, where the nodes are centroids of geographic zones. The *p*-median model (Hakimi, 1964; ReVelle and Swain, 1970) locates *p* facilities and allocates demand nodes to facilities to minimize total distance traveled to facilities. Because of its minimal data requirements, and because early empirical studies showed driver preference to refuel near home (Kitamura and Sperling, 1987), the *p*-median model has been an appealing choice for station location models (Goodchild and Noronha, 1987; Greene et al., 2008; Nicholas et al., 2004; Nicholas and Ogden, 2006), including variants that weight nodes by the quantity of fuel consumed on nearby road segments (Lin et al., 2008). Covering models (Church and ReVelle, 1974; Toregas et al., 1971), which count a demand node as covered if a facility is located within a given distance or travel time, have also been used for station location (Stephens-Romero et al., 2010).

A second group of models locates stations on high-traffic arcs to maximize passing traffic and capture drivers en route. Melendez and Milbrandt (2005) considered only roads with at least 20,000 vehicles per day in a GIS analysis of hydrogen station corridors. Boostani et al. (2010) developed an arc demand coverage model, while Goodchild and Noronha (1987) combined an arc-flow objective with a *p*-median in a multi-objective model. Brey et al. (2016)'s arc-based approach included a constraint to discourage multiple locations on high-volume arcs. While traffic volume data for arcs are widely available, arc-based approaches cannot evaluate whether a driver's entire path can be refueled.

A third category locates refueling stations to serve demands consisting of shortest (or least travel-time) paths for flows defined by an O-D trip matrix. The first flow capturing or intercepting models were developed for locating facilities such as gasoline stations, automatic teller machines, and vehicle inspection stations (Berman et al., 1992; Hodgson, 1990; Mirchandani and Rebello, 1995), which customers tend to access by stopping en route to somewhere else. The basic flow-capturing model locates *p* facilities to intercept as many trips as possible; trips are “captured” if a facility is located anywhere on their shortest path. For longer round trips using AFVs, however, one fuel station may not be enough to make the trip possible without running out of fuel. To address this, Kuby and Lim developed the Flow-Refueling Location Model (FRLM), which counts a flow as refueled only if one or a series of stations exists on a path sufficient to complete the round trip between the origin and destination, given the driving range of vehicles (Kuby and Lim, 2005). Upchurch and Kuby (2010) demonstrated that path-based models tend to produce a more robust set of locations than median models, in the sense that locations that are optimal for small *p* more frequently remain optimal as more stations are added. The FRLM has been extended to full covering versions (Wang and Wang, 2010), deviation paths (Kim and Kuby, 2012), and capacitated stations (Upchurch et al., 2009). Solution methods for path-based approaches have been evolving as well (Capar et al., 2013; Lim and Kuby, 2010; MirHassani and Ebrazi, 2012; Wang and Wang, 2010). While path-based models are behaviorally realistic and explicitly guarantee that covered trips can be completed, challenges include the lesser availability of O-D flow data, the tendency for the model to choose high-volume freeway-interchange nodes, and the assumption that drivers are equally willing to refuel at any distance from home (Kuby et al., 2013).

A newer category of models uses demand consisting of tours (trip chains on space-time paths), because drivers do not really have to refuel on every O-D trip (Andrews et al., 2013; Ji et al., 2015; Kang and Recker, 2014). This approach typically requires travel diary data obtained from regional household travel surveys.

The strategy of clustering stations in and near “lighthouse regions” has been gaining ground in the hydrogen fuel-cell vehicle (FCV) industry in the US (California Fuel Cell Partnership, 2012), Europe (Garche et al., 2009) and China (Weinert et al., 2007). The California Hydrogen Highway Network Blueprint Plan (California Environmental Protection Agency, 2005) was one of the first to focus on certain metropolitan areas, and it was followed by other proposals to micro-target certain communities within those cities with concentrated populations of potential AFVs buyers. Socioeconomic data and hybrid/plug-in vehicle sales are often used to target regions of likely adopters (Melendez and Milbrandt, 2008). The rationale for clustering is to provide a higher level of service, reliability, and public awareness by building a critical mass of stations to serve targeted communities.

Only a few optimal location models, however, have been designed specifically for clustering stations for lighthouse regions. Stephens-Romero et al. (2010) developed STREET, a node-based model for hydrogen stations in California. They first identify hotspots of early adopters based on a survey of automakers and stakeholders, and then use a set-covering formulation to minimize the number of stations needed to achieve an acceptable travel time to stations in the targeted communities. Traffic volume is incorporated by eliminating candidate sites with low weekday travel density.

Ogden and Nicholas (2011) developed a method for locating two kinds of stations for the same set of targeted California communities as Stephens-Romero et al. (2010). Stations for *local* usage were located using a *p*-median model minimizing travel time to population centers, with candidate sites restricted to freeway exits, based on (Nicholas, 2010). Connector stations for serving *regional* trips to destinations outside the clusters were located using a *p*-median model minimizing travel time to vehicle-miles traveled (VMT), which was calculated by isolating the flows in an O-D flow matrix originating from targeted communities and aggregating the VMT to census tracts through which the paths travel. They combined these in a hybrid approach that specified different numbers of local freeway stations and connector stations to build. Brey et al. (2014) developed a sequential roll-out strategy that integrates concepts of main nodes, clusters, and interconnection nodes. Clusters are groups of main nodes that exceed given thresholds of proximity and population, while interconnection stations connect main nodes to clusters when they are too far away.

Kuby et al. (2009) also recommended a strategy of “clustering and bridging” for rolling out an initial refueling infrastructure for metropolitan Orlando and Florida in tiers. They applied the FRLM using sociodemographic data to give greater weight to trips from hotspots. The concepts of clustering and critical mass, however, were not explicit parts of the model, but emerged from maximizing the volume of trips or VMT that could be covered.

Based on this review of the station location literature, a need remains for an efficient clustering approach to facilitate AFV infrastructure