Spatial Refueling Patterns of Alternative-Fuel and Gasoline Vehicle Drivers in Los Angeles

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Abstract

The lack of refueling stations is a major barrier to adoption of alternative fuels and vehicles, but little is known about how early adopters deal with the sparseness of the station network and where they choose to refuel or recharge. In this study, we surveyed about 50 consumers at each of five compressed natural gas (CNG) stations in the greater Los Angeles region, and at five nearby gasoline stations as a control group. We surveyed drivers at the stations while they refueled, and asked them for their previous and next stops, the type of activities they engaged in before and after refueling, where they live, and other questions about themselves, their vehicles, and why they refueled where they did. Using GIS, we calculated trade areas for each station, distance from home, and the degree to which they deviated from their shortest paths in order to refuel. Results confirm the willingness and/or necessity of early adopters of CNG vehicles to refuel farther from home and more frequently in the middle of a trip, and detour farther off their least travel-time routes, than gasoline drivers. In particular, CNG drivers showed a willingness to deviate up to 6 minutes from their routes. CNG drivers in Los Angeles also refuel more on work-based trips and less on home-anchored trips than gasoline drivers. These results have major implications for planning future networks of alt-fuel stations to serve early adopters.

Keywords: Alternative fuels, Spatial refueling patterns, Fuel choices, Hybrid electric vehicles

Highlights

- We surveyed 518 drivers of CNG and gasoline vehicles at 10 stations in Los Angeles.
- We used GIS to measure trip length, travel time, detour, and distance from home.
- CNG drivers refuel farther from home, with fuller tanks, and more often mid-route.
- CNG drivers refuel more on work trips and detour 5-6 minutes from shortest paths.
- Results are useful for planning and modeling station networks for early adopters.

1. Introduction

Most countries around the world have several alternative transportation fuels that can be produced domestically and offer varying degrees of environmental benefits by reducing local smog and global CO_2 emissions. The major alternatives include ethanol (usually sold as E85, with 15% gasoline), biodiesel, compressed or liquefied natural gas (CNG or LNG), propane (LPG), battery electric vehicles (EV), plug-in hybrid electric vehicles (PHEV), and hydrogen. Flex-fuel vehicles can use gasoline or E85, and diesel cars can burn diesel or biodiesel. Many studies have emphasized the importance of locating the initial networks of stations conveniently to maximize the potential for consumers to adopt alternative-fuel vehicles (AFVs) and for station owners to see some return on investment (Greene et al., 2008; Melaina and Bremson, 2008; Flynn, 2002; Yeh 2007; Melendez 2006). Unfortunately, very few researchers have studied where AFV drivers actually choose to refuel and what their choices say about where new alt-fuel stations should be deployed.

This type of research was pioneered by Sperling and Kitamura, who collaborated on three papers on refueling decision-making. Sperling and Kitamura (1986) interviewed 1,528 drivers of gasoline vehicles in California and compared them to 107 drivers of diesel vehicles as a proxy for future AFV adopters. They concluded that the predictability of diesel locations somewhat compensates for the sparser networks, so that a network one-tenth the size of the gasoline station system might be large enough to satisfy diesel drivers. Kitamura and Sperling (1987) focused solely on gasoline drivers, while Dingemans, Sperling, and Kitamura (1986) collaborated on a survey of 309 drivers in Davis, California with a focus on the mental maps of drivers. Kitamura and Sperling (1987) found that 7% of gasoline drivers refueled on a single-purpose "unlinked" trip from home, while Dingemans, Sperling, and Kitamura (1986) reported 10%. In addition, Kitamura and Sperling (1987) found that three-quarters of refueling trips were made on the way to and from home, while drivers refueled on the way to or from work only 29% of the time, and that 72% of drivers refueled within 5 minutes of their origin or destination, with a bias towards origin locations. Sperling and Kitamura (1986) also considered the willingness of drivers to detour off their shortest routes, as did Lines et al. (2008).

Plummer, Haining, and Sheppard (1998) surveyed households in St. Cloud, MN about which gasoline stations they consider first for refueling, known as "choice sets." While most drivers considered their nearest station as part of their choice set, not all did, and many included stations far from their homes. They speculated that the divergence of choice sets of similarly located residents is due to differing commuting and shopping patterns. The most frequently considered stations were generally at highly accessible sites "at intersections or along principal routeways" (p. 78).

There is a compelling need to update and expand on these pioneering studies by surveying the revealed choices of an actual population of consumers driving AFVs and dealing with limited station availability. Sperling and Kitamura (1986) specifically mentioned that their findings for the drivers of gasoline vehicles "cannot easily be extended to situations where only a sparse retail fuel network is in place." Some recent studies have looked at recharging behavior of pure EV drivers

(Idaho National Laboratory, 2012; CABLED Consortium, 2012), but because of the restrictions imposed by long EV recharging times, these findings cannot be extended to the refueling patterns of CNG, hydrogen, or other types of fast refueling. It is important to understand how early adopters of AFVs actually use the initial network of stations, and what their refueling patterns suggest about their decision-making criteria.

This information can be valuable to researchers in choosing the type of optimal facility location model for planning new networks of stations. For instance, several studies (Greene et al., 2008; Nicholas, Handy, and Sperling, 2004) have been based on the assumption that drivers prefer to refuel near home, and therefore stations should be planned using models such as the *p*-median to minimize the distances from residential populations to their nearest station. This approach contrasts with the flow-based approach to facility location, which aims to maximize the number of trips that can be served en route between origins and destinations and implicitly assumes that drivers stop along their way to refuel rather than make a special-purpose trip. Flow-based models include: the flow-capturing or intercepting model, in which a facility anywhere on a shortest path can serve the origin-destination demand (Berman, Larson, and Fouska, 1992; Hodgson, 1990); the flow-refueling location model (Kuby and Lim, 2005; Capar, Kuby, Leon, and Tsai, 2013), which adds a maximum vehicle driving range and the resulting need for multiple stations on longer paths; and versions of both models that allow trips that deviate from the shortest paths in order to access a facility (Berman, Bertsimas, and Larson, 1995; Kim and Kuby, 2013). Other papers have proposed hybrid approaches recognizing that both home locations and road segment traffic volumes generate refueling demand (Goodchild and Noronha, 1987; Lin, Ogden, Fan, and Chen, 2008; Nicholas, 2010). Given that government agencies and private industry are beginning to use these modeling approaches to plan station networks, it is important to ascertain which underlying behavioral assumptions are most consistent with driver behavior (see also Kelley and Kuby (in press); Pearre, et al., 2011).

This paper compares the spatial refueling patterns of CNG and gasoline drivers in the Los Angeles area. We used a control group of gasoline stations located close to the studied CNG stations. Between the two fuels, we statistically compare distances from home, pre-refueling tank levels, deviations from their least-travel-time paths, and other trip metrics. We map the trade areas of the two types of stations, develop matrices for the types of activities at the stops immediately before and after their refueling trips, and compute percentages of home-anchored and work-anchored refueling trips.

2. Research Design

2.1 Study Area and Fuel Type

For several reasons, the greater Los Angeles region and CNG represented the best present opportunity to study refueling behavior of early AFV adopters in the United States. First, a fairly large population of *consumer* AFV drivers was required, and in Southern California, Honda® has sold original-equipment-manufactured Civic® GXs to consumers since 1998. Second, it was important to conduct this study on a single-fuel vehicle in order to assess how drivers adapt to a very limited refueling network—unlike hybrid, flex-fuel, and (bio)diesel vehicles, which drivers can fill up with gasoline or diesel when running low on fuel. Third, the vehicles should primarily be refueled away from home, in order to study how early adopters adapt to a sparse public station network. Fourth, refueling must be relatively quick, within the same relative duration as gasoline or diesel refueling, to hold the effect of refueling time relatively constant. Even fast charging (480V) of EVs takes 20-30 minutes or longer for a less-than-100% charge, which can dramatically alter if, where, and when EV drivers use public recharging. Los Angeles was suitable for this study because there were 60 CNG stations open to the general public, representing only 0.02% of the 3200 gasoline stations in the same region at that time (US Census Bureau, 2006).

Five CNG stations were purposefully selected in order to represent a variety of geographic settings and types of consumer usage. Each station was located at a fleet depot, which generally had pumps both inside their gates for their own vehicles and outside their perimeter for consumers and other companies' vehicles. The locations are prototypical of the types of location often considered for the first wave of AFV station infrastructure. Airport shuttle, taxi, bus, and baggage cart fleets have been early adopters of alternative fuels, and these types of sites are represented by the station serving the John Wayne Airport in Santa Ana and the Burbank station 2.6 miles from Bob Hope Airport. Downtown stations are often among the first sited in order to serve commuters, taxis, buses, and for demonstration purposes, and also recommended by flow-based location models because of the large volume of trips starting, ending, or passing through downtown freeway interchanges; our study includes a station in the Los Angeles central business district (CBD). Major trip generators and attractors are also a focus of early infrastructure, and the location in Anaheim has several major attractions nearby, as well as three different freeways. The Burbank location is just behind a suburban shopping area two blocks from the I-5 freeway. The Santa Monica station is on an arterial street in a more diverse urban area about 0.5 mile from the I-10 freeway. Clean Energy Fuels built and currently operates all of these stations except for Trillium's Anaheim station. None of the stations fit the typical consumer model of being at a major arterial intersection leading to or from a residential or shopping area or directly at a freeway exit.

Once these five stations were selected, we obtained permission to survey customers at the nearest possible gasoline station. The control gasoline stations were located on average 0.49 miles from the CNG station, and a maximum of 0.81 miles away. Generally, the control gasoline station was located in an equally or more accessible and visible location than the corresponding CNG station.

2.2 Sampling and Survey Design.

This study followed Sperling and Kitamura's intercept methodology of interviewing drivers at stations while they refueled, both to maximize response rates and minimize inaccurate memory of trip details. Two undergraduate students interviewed 50-55 drivers per station, with roughly equal sampling (15-20 drivers) during the morning rush hour (7-11 am), midday (11 am-2 pm), and afternoon peak period (2-7 pm). Interviews were conducted from June 27 to July 27, 2011, with additional surveys collected August 15-17 and December 19-21, 2011 to fill in certain time periods that were under-represented at certain stations. A total of 254 CNG drivers and 264 gasoline drivers are included in this study.

The survey comprised 18 questions and took about five minutes to complete. The most important questions focused on the approximate locations of the driver's home and trip anchor points, and the trip purpose. Other questions related to tank levels, reasons for and frequency of refueling where they did, socio-demographic factors about their households, other household vehicles, and reasons for purchasing a CNG vehicle.

2.3 GIS and Statistical Analysis

Each respondent's important locations—immediately preceding and following stops, fueling station, and home location—were stored in ArcView® 10.0. Using Network Analyst®, we computed least-travel-time paths between stops, both to and from the station, and from home to station. Travel time was based on posted speed limits and road lengths and then calibrated to match travel times provided by common web-mapping applications such as Google Maps®. Though factors such as congestion, accidents, and familiarity with the street network could lead to variation in the actual route taken, these shortest paths are reasonable estimates. Driver deviations were estimated by computing least travel time routes from their previous stop to the following stop, with and without the refueling stop in between. Using the estimated route via the station, we also calculated where along the route the driver refueled, with 0% representing a station at the preceding stop, 50% representing a station half way in between, and 100% representing a station at the following stop.

Using ArcMap's Business Analyst®, we generated the trade area of each station, defined as the smallest polygon containing at least 65% of the home locations of customers, thus ignoring outliers arriving from atypically long distances (Applebaum, 1966;Thrall, 2002).

We computed a variety of descriptive statistics (means, medians, standard deviations, histograms) for the parameters measured in the GIS analysis and reported directly by respondents. In addition, we conducted t-tests of the statistical significance of differences between conventional and AFV drivers, and computed several types of distance-decay curves. Finally, we created trip-purpose matrices for AFVs and conventional vehicles.

3. Results

3.1 Comparison of Sampled Drivers

Some socio-demographic characteristics of the sampled CNG drivers differed significantly from the drivers at gasoline stations (Table 1). CNG drivers were generally older, better educated, more often from smaller households, but with a higher percentage of households with more vehicles than drivers. The latter difference is consistent with Melendez and Milbrandt (2008), in which an NREL focus group considered multi-vehicle households to be "the most important factor in predicting hydrogen vehicle demand" (p. 5).

CNG drivers were also asked to rank their top three reasons for owning a CNG vehicle. Overwhelmingly, the most important reason was for use of the HOV lanes (32.3%), far outstripping environmental concerns (7.3%) and lower fuel prices (5.2%).

Table 1. Sampled Drivers

	CNG Stations	Gasoline Stations	t-statistic	sig.
Ages 32-71[a]	76.6%	54.1%	5.32	.001
Female[a]	39.4%	38.8%	.243	.808
High School or Less	4.1%	12.7%	3.43	.001
College Degree or higher	89.7%	74.3%	-4.50	.001
Employed[a]	94.6%	90.9%	-1.62	.107
Household Size 3 or more[a]	63.4%	71.3%	1.93	.054
Drivers in Household 1-2[a]	70.9%	66.4%	-1.09	.275
Households with More Vehicles than Drivers	19.7%	11.7%	-2.51	.013

[a]These categorical variables were divided into only two categories, so the t-test for the second category has the same absolute value and exactly a 100-X% share. In each case, the table lists the category with the higher percentage for CNG drivers than for gasoline drivers.

3.2 Self-Reported Refueling Behavior

As hypothesized, CNG drivers less frequently allow their tanks to go to empty: only 26.6% vs. 39.5% for drivers at gasoline stations. The percentages who filled at 1/8 tank and at 1/4 tank were about the same, but the percentage of CNG drivers who refueled with 3/8 or more left in their tanks (16.6%) far exceeded the share of gasoline station customers who did so (4.9%). The average tank levels of the two samples were significantly different ($p<.001$).

Not surprisingly, 74.4% of CNG drivers cited "convenient location" as their primary reason for choosing which station to visit, significantly higher ($p<.001$) than the 55.1% for gasoline station patrons. This was expected, as gasoline station customers have many more similarly located stations from which to choose. Consistent with the tank level results, more gasoline station customers reported running out of fuel as their primary reason for station selection, by a margin of 18.4% to 12.0% ($p<.001$). Low fuel price was cited by exactly 11.6% of both groups, but brand loyalty and convenience stores played a significantly larger role ($p<.001$) for gasoline station customers than for CNG customers.

CNG drivers show far more loyalty to the station at which they were surveyed than the gasoline station customers (Figure 1), consistent with Sperling and Kitamura (1986). Geographically, the stations in downtown Los Angeles stand out as major exceptions to the general pattern in Figure 1. While drivers of both CNG and gasoline vehicles were generally infrequent users of the downtown stations, 12% of CNG drivers refueling downtown were still willing to rely almost exclusively (>80% of the time) on that station.

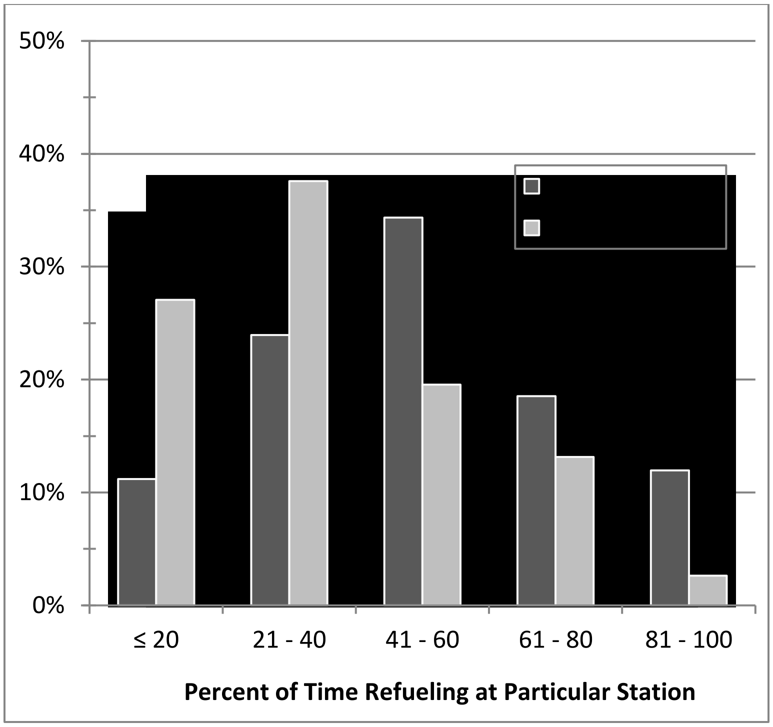

Figure 1. Frequency of refueling at chosen station (i.e., habituality or loyalty).

Somewhat surprisingly, the far smaller number of CNG stations did not have much impact on the drivers who had to turn left to enter the station. Conventional wisdom holds that drivers prefer to turn right to avoid dangerous left turns, yet CNG drivers only lagged their conventional counterparts by 68% to 70%, which was not significant at the .05 level.

In contrast, far more CNG drivers reported detouring out of their way to refuel, by a margin of 46.7% to only 19.1% for gasoline station customers ($p<.001$). This expected finding was hypothesized due to the sparseness of the CNG refueling network; we later compare these self-reported deviations to detours calculated objectively using GIS.

3.3 Trip Purpose Matrices

Transportation modeling and planning are moving increasingly towards activity-based approaches generally (Pendyala, Yamamoto, and Kitamura, 2002) and for vehicle ownership and station location specifically (Paleti, 2011; Kang and Recker, 2013). Therefore knowing what activities drivers were engaged in before and after refueling is useful in locating stations where (and implicitly, when) drivers tend to stop to refuel. Tables 2 and 3 provide matrices of the activities drivers engaged in immediately before and after refueling, for CNG and gasoline customers respectively. Kitamura and Sperling (1987) produced a similar matrix for gasoline customers only, but they did not collect similar data for diesel drivers, so these results offer the first such comparison between drivers of AFVs and conventional vehicles.

Table 2. Trip purpose matrix for CNG station customers.

ORIGIN	Home	Work	Social/ Dining	Shopping	School	Other	TOTAL
	DESTINATION						
Home	1.2	27.2	7.1	5.1	1.2	2.4	44.1
Work	20.9	10.6	6.3	0.8	0.0	0.0	38.6
Social/ Dining	3.9	1.6	0.0	0.0	0.0	0.8	6.3
Shopping	3.9	0.0	1.2	0.4	0.0	0.0	5.5
School	3.2	0.0	1.2	0.0	0.0	0.4	4.8
Other	0.4	0.4	0.0	0.0	0.0	0.0	0.8
TOTAL	33.5	39.8	15.8	6.3	1.2	3.5	100.0

Table 3. Trip purpose matrix for gasoline station customers.

ORIGIN	Home	Work	Social/ Dining	Shopping	School	Other	TOTAL
	DESTINATION						
Home	1.1	26.5	12.1	5.3	2.66	4.2	51.9
Work	15.5	5.3	6.1	1.1	0.0	0.0	28.0
Social/ Dining	7.2	0.8	0.8	0.0	0.0	0.0	8.7
Shopping	6.1	0.0	0.0	0.0	0.0	0.0	6.1
School	2.7	0.0	0.0	0.00	0.0	0.0	2.7
Other	2.3	0.4	0.0	0.0	0.0	0.0	2.7
TOTAL	34.8	33.0	18.9	6.4	2.7	4.2	100.0

In both matrices, the most common type of trip to refuel on is the home-work trip, with about 27% of refueling stops for both types of stations. Work-home ranks second in both matrices, but the 20.9% of CNG refueling stops is substantially more than the 15.5% of gasoline station stops. Ranking third for gasoline refueling stops are home to social/dining trips, while work-station-work trips rank third for CNG.

Overall, trips anchored at home either immediately before or after refueling accounted for 85.6% of gasoline stops compared with 76.4% of all CNG stops. For CNG refueling, home-anchored trips (76.4%) led work-anchored trips (67.7%) by 8.7%. For gasoline refueling, the gap between home-anchored (85.6%) and work-anchored (55.7%) refueling was a much larger 29.9%.

Cells on the diagonals of Tables 2 and 3 represent there-and-back trips or trips between two locations for the same activity. The home-station-home trips are a consistently small percentage: just over 1% for both types of fuel, meaning drivers rarely make a single-purpose trip from home solely to refuel their vehicle. Single-purpose trips from work, however, are far more frequent, and twice as commonly done by CNG drivers (10.6% of their stops) than gasoline station customers (5.3%). In contrast, Kitamura and Sperling (1987) found that 7% of refueling trips in 1983-84 in Northern California were single-purpose home-station-home trips, and 2.6% work-station-work trips. These results, of course, may reflect the particular locations of the five pairs of stations at or near fleet-based CNG stations.

3.4 Trip Lengths

CNG drivers consistently refueled their vehicles on longer trips ($p < .07$) than drivers of conventional vehicles (Table 4). Some of the stations (Anaheim, Downtown, Santa Monica) showed significant differences in distance and travel time, while Burbank did not. The downtown stations had the longest trip distances and travel times for both fuels, and Santa Ana had the shortest.

Table 5 shows the distances from stations to the drivers' homes for all drivers. For all trips, CNG drivers refueled at a station located an average of 13.9 miles from home, compared with only 9.2 miles from home for gasoline customers ($p < .08$). The difference is even more exaggerated for *median* distances from home, especially at the Santa Monica locations. Even looking only at the subset of home-anchored trips (home as the previous or next stop), the CNG drivers refueled farther from their homes (14.8 miles on average) than the gasoline drivers (9.4 miles), significant at the .08 level. Hence, it appears that most CNG drivers need to and/or are willing to refuel 8 or more miles from home, even if they are traveling to or from home.

Table 4. Trip lengths in travel time and distance[a]

CNG Station	Travel Time (minutes)		Distance (miles)		Gasoline Station	Travel Time (minutes)		Distance (miles)		Difference of means p-value:	
	Mean	Med	Mean	Med		Mean	Med	Mean	Med	Time	Distance
Burbank	55.9	32.9	42.9	20.4	Burbank	45.4	14.7	36.5	6.4	.60	.75
Santa Ana	21.8	22.9	10.3	9.8	Santa Ana	15.2	11.3	7.5	4.3	.02	.10
Santa Monica	31.9	24.8	18.3	10.6	Santa Monica	18.5	14.4	9.9	5.9	.01	.01
Downtown	42.6	34.5	28.0	19.8	Downtown	23.6	21.4	13.2	11.5	.01	.01
Anaheim	30.7	28.5	17.7	15.1	Anaheim	18.7	16.7	9.3	7.0	.01	.01
TOTAL	36.5	27.6	23.4	14.6	TOTAL	24.6	15.9	15.6	6.9	.01	.06

[a]Not including origin-station-origin trips.

Table 5. Travel times and distances from stations to home

CNG Station	All Trips Distance (miles)		Home-Anchored Trip Distance (miles)		Gasoline Station	All Trips Distance (miles)		Home-Anchored Trip Distance (miles)	
	Mean	Med	Mean	Med		Mean	Med	Mean	Med
Burbank	22.1	10.8	23.4	12.2	Burbank	20.8	2.2	23.5	2.0
Santa Ana	7.9	5.9	7.2	5.2	Santa Ana	7.2	5.4	5.8	4.2
Santa Monica	11.2	4.8	12.8	7.4	Santa Monica	2.5	2.4	2.4	2.4
Downtown	16.0	12.2	17.1	12.7	Downtown	8.7	7.7	8.4	6.9
Anaheim	12.4	7.9	11.2	7.7	Anaheim	5.8	3.5	5.7	3.5
TOTAL	13.9	8.3	14.8	8.3	TOTAL	9.2	3.5	9.4	3.3

3.5 Trip Detours

Researchers increasingly recognize the necessity for early AFV adopters to deviate (detour) from their shortest routes in a sparse public refueling or recharging infrastructure (Kim and Kuby, 2013; Kelley and Kuby (in press); Araz, Capar, Palmer, and Kuby, 2013; Kang and Recker, 2013). The hypothesis that mean deviations for CNG drivers would be greater than for gasoline drivers was significant at the .01 level for each individual station pair and <.001 for all stations combined. Most gasoline station customers detoured by a trivial amount to reach their station, while the median deviations for CNG drivers were between 3.1 and 6.5 minutes (0.8-1.3 miles) across the five stations—a surprising degree of consistency. CNG drivers were hypothesized to make larger deviations because fewer stations are directly on the way and because the CNG stations are located at fleet bases, which tend to be slightly off arterial roads.

While the deviations for CNG and gasoline customers confirm that CNG drivers make larger detours to refuel, they do not tell us how much of a detour is too much. To address this question, we estimated their actual detours based on their previous and next stops and combined that with the responses from the survey question about whether the drivers subjectively felt that they detoured from their preferred route to their final destination to refuel (Figure 2). These diagrams give us two ways to assess how much detour is too much.

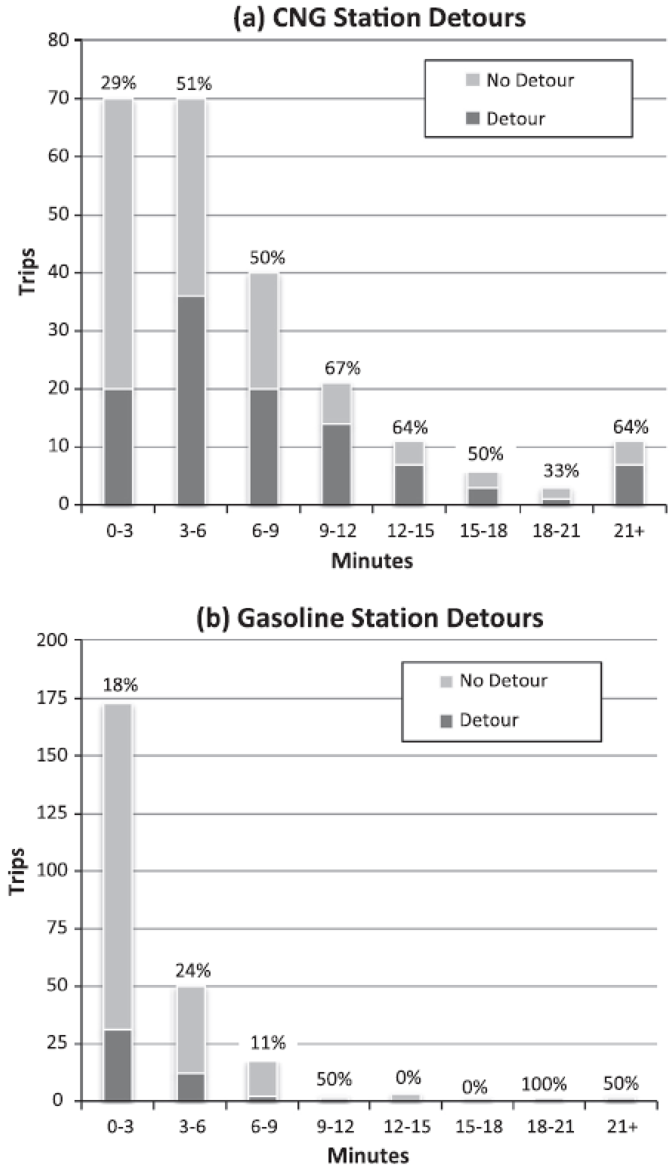

Figure 2. Length of detours (in minutes of extra driving time) for refueling at (a) CNG and (b) gasoline stations. Numbers above bars show percentage of respondents who felt they detoured from their preferred route to their final destination to visit this station. These histograms omit origin-station-origin single-purpose trips.

First, looking at the overall functional shapes, the distribution of detours to gasoline stations shows an immediate exponential decline, whereas CNG drivers detoured at about the same frequency up to about 5-6 minutes, after which a notable decay occurs suggesting an indifference to detouring among the CNG customers up to about 5-6 minutes (see Discussion).

Second, Figure 2 merges the objectively computed detours with the subjective survey responses. Consistent with their smaller detour sizes, only 19.2% of gasoline drivers reported that they detoured from their preferred route, compared with 46.6% CNG drivers. Yet CNG drivers appeared more sensitive to detouring, with a consistently higher percentage claiming to have detoured for the same objective number of minutes. Using this combined subjective/objective approach, the point at which about half of the CNG respondents felt that the detour required to refuel is cumbersome falls somewhere between 3 and 9 minutes.

3.6 Beginning, Middle, or End of Trips

Kitamura and Sperling (1987) found that gasoline drivers tend to refuel most often at the beginning or end of their trips rather than in the middle. We expected to find a similar pattern for gasoline customers but less so for CNG. To our surprise, no U-shaped pattern is apparent for the gasoline station respondents, while a reverse-U shape is apparent for CNG drivers (Figure 3). While this pattern does not mean that CNG drivers would have preferred mid-route refueling had stations been more available at the start or end, it does indicate a willingness by early adopters to refuel mid-route if it is the only—or most convenient—station available en route.

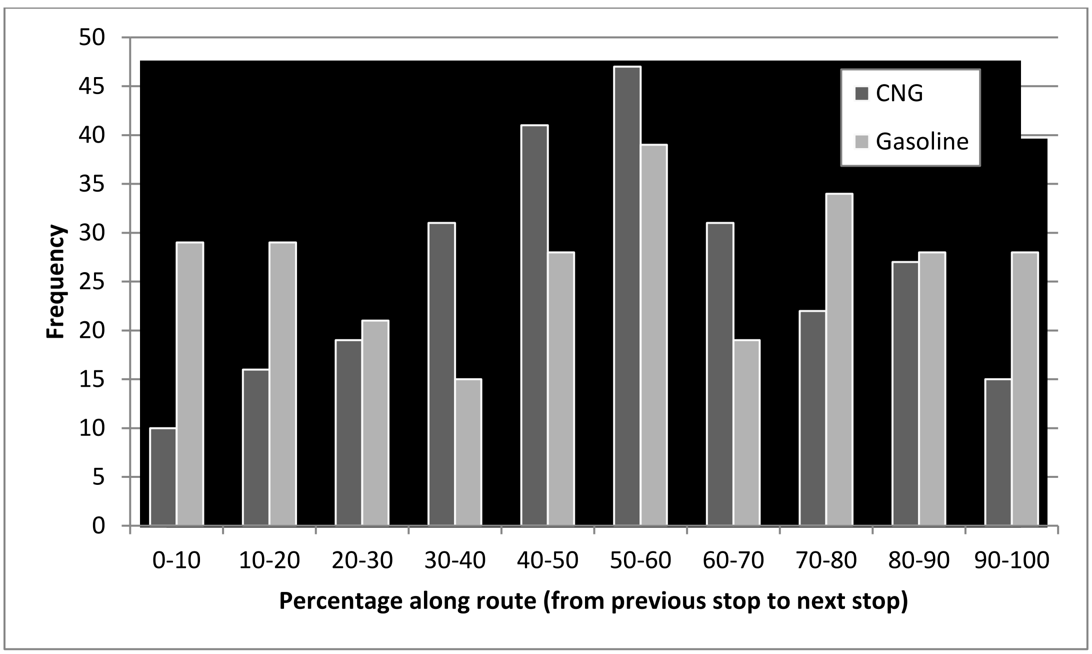

Figure 3. Histograms for (a) CNG and (b) gasoline station customers showing where along their route, from origin (0%) to destination (100%) they stopped to refuel.

3.7 Trade Areas

Figure 4 shows the estimated trade areas for the CNG stations and nearby gasoline stations. The CNG trade areas are generally larger than their gasoline counterparts, which is consistent with the average and median distance from home calculations presented earlier and indicates the willingness and/or necessity of CNG drivers to refuel farther from home.

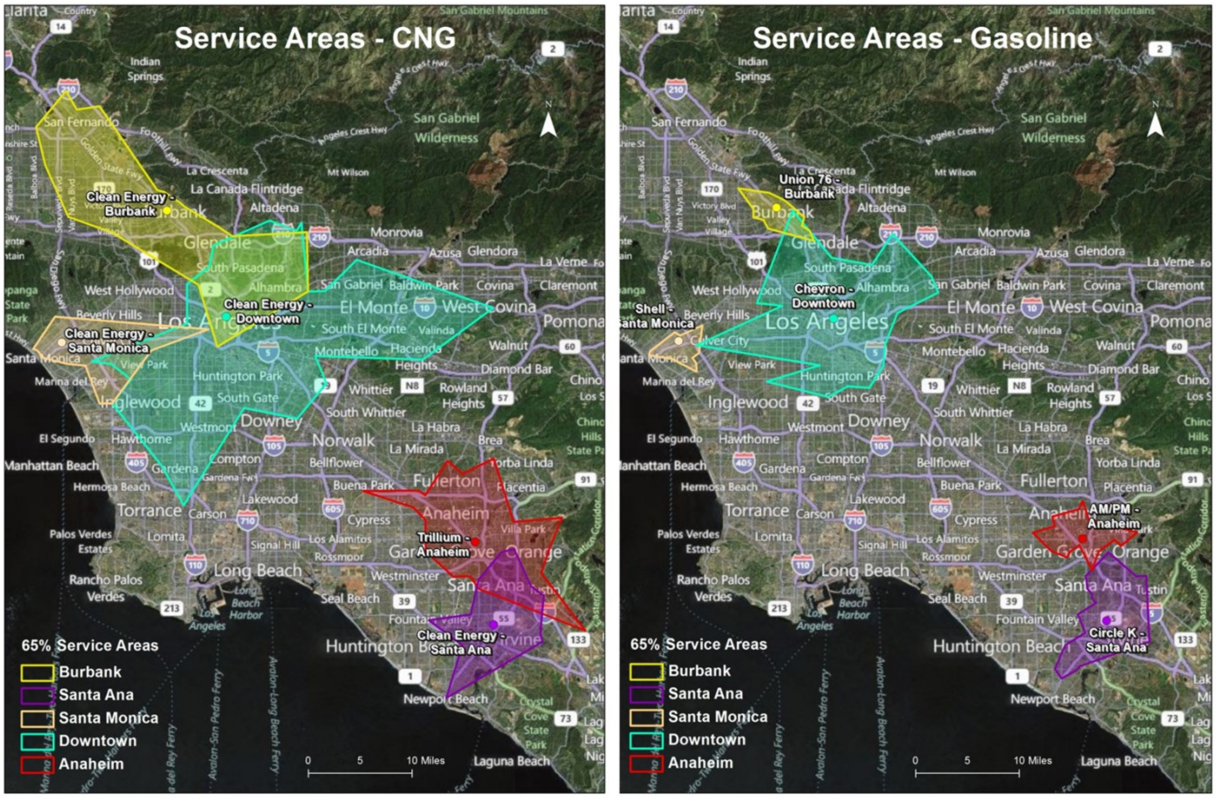

Figure 4. Trade areas containing 65% of home locations of customers of each station.

4. Discussion

Although the trade areas in Figure 4 are subject to interpretation, we offer the following additional observations. First, three of the pairs of trade areas (Burbank, Santa Monica, and Santa Ana) are oriented in similar directions, suggesting that they are capturing similar types of refueling trips across both fuels, and confirming that highways enable fuel stations to draw customers from farther away. In contrast, the downtown and Anaheim CNG stations have different orientations than their gasoline counterparts, which may indicate that if AFV stations are located near freeways, they can serve customers via freeway travel from greater distances than gasoline stations in similar locations.

Second, the downtown station has by far the largest trade area for gasoline drivers, followed by the station near the Santa Ana airport. For CNG, the downtown station once again has the largest trade area, but Burbank, which is also near an airport, has the second largest. This is not surprising given that CBDs and airports serve entire urban areas or large urban realms. The suitability of downtown stations is an important question for the AFV industry. Because freeway networks often converge in or pass through the CBD, downtown stations are uniquely positioned to intercept sizable flow volumes—*if* drivers are willing to refuel there. Nicholas (2010) found that vehicle-kilometers traveled (VKT) is a good predictor of gasoline demand *except* for stations in the downtown area, where high VKT did not translate to high sales. The larger trade area for the downtown *gasoline* station in Figure 4, as well as the earlier finding that half of their customers refueled there less than 20% of the time, are consistent with Nicholas's results. This conclusion for gasoline drivers, however, may not be transferable to AFV drivers, since five of the six CNG drivers who refueled downtown over 80% of the time live on or beyond the border of its trade area, demonstrating that some AFV drivers are willing to depend on a downtown station far from home on a regular basis.

Another important finding for station infrastructure providers and location analysts is the miniscule frequency (about 1%) with which drivers *of both types of vehicles* made single-purpose trips from home to a station and back (Section 3.3). It is often assumed that, because consumers prefer familiar gasoline stations close to home and most frequently refuel on the way to or from home, that stations *must* be close to home in order to be convenient to consumers. Our findings that gasoline customers refueled at stations located a median distance of 3.5 miles from home, deviated from their least travel-time path by a median of 1.76 minutes, and refueled 85.6% of the time on their way to or from home support this conventional wisdom. Given the ubiquity of gasoline stations, most drivers of conventional vehicles will be able to refuel close to home *and* on their way to or from home. For early AFV adopters dealing with a sparse refueling network, however, a station that is both on the way and close to home is a luxury that will not often exist. Even for the small population living near one of these stations, it may be located in the opposite direction from the way they are going. When faced with a choice between a facility on the way or near home because no station satisfied both metrics of convenience, CNG drivers chose the former by an overwhelming 10:1 margin (Kelley and Kuby, in press). This conclusion is bolstered here by our finding that half of all CNG drivers refueled at stations 13.8 miles or more from home, and yet detoured only 5.6 minutes out of their way, and did so nearly as often on work-anchored trips (67.7%) as home-anchored trips (76.4%).

Putting these statistics together with the finding that only 1% of drivers made single-purpose home-station-home trips liberates infrastructure companies from the impossible task of trying to "cover" all residential areas with nearby stations in the initial rollout of infrastructure, because it is only these particular types of single-purpose refueling trips from home that cannot be conveniently served by stations farther from home. Stations can be on the way to or from home without actually being near home. The revealed willingness of CNG early adopters to behave in this manner opens up numerous candidate facility locations within any large metropolitan area—locations through which hundreds of thousands of trips pass by (or nearby) on a daily basis. In contrast, stations placed in residential zones are doubly convenient (close to home *and* on the way), but only for a much smaller number of potential customers. If a convenient location can be provided on the way but far from home, far fewer stations are necessary to provide an entire metropolitan area with a minimal level of convenience.

This finding also supports the use of flow-based optimal facility location models that aim to refuel trips between origins and destinations rather than minimize distances from neighborhoods to their closest stations. While it may seem obvious that most drivers do not refuel their vehicles on there-and-back trips, it is important to keep in mind that there are many types of facilities that *are* often visited in that manner, such as grocery, drug, and home-improvement stores; medical offices; schools, libraries, and social service agencies; and restaurants. Thus, there are many kinds of facilities for which the more widely used point-based location models are more behaviorally realistic, but early stage alt-fuel stations may not be one of them.

The deviation analysis (Figure 3) indicates a threshold of around 5-6 minutes within which detouring was fairly uniform, beyond which detouring falls off exponentially. This shape stands in sharp contrast to the "deviation decay" curve for the gasoline drivers, which resembles a typical exponentially declining distance decay curve. The CNG deviation decay curve actually resembles a modified distance decay curve with a "frictionless zone" before distance decay occurs. While not a popular functional form for spatial interaction modeling, the zone of indifference was included in some early human geography books (Fellmann, Getis, and Getis, 1997) and is also an available option in ESRI's (2013) Spatial Statistics toolbox. A reverse S-curve could also describe this functional form (Kim and Kuby, 2012).

Given the greater ubiquity of gasoline stations, one might have expected that gasoline customers would refuel on a wider variety of types of trips (Tables 2 and 3), but the opposite was found to be true: 19 of the matrix cells were empty for gasoline stations, compared with only 15 for CNG stations. Three factors may be contributing to this. First, CNG drivers may need to avail themselves of the chance to refuel whenever it presents itself. Second, this particular control group of gasoline stations located near fleet depots may be less convenient than others for serving certain types of activities. Finally, gasoline customers can eschew refueling on their less-favored types of trips because of the availability of a gas station on their way to and from home.

The greater "habituality" of CNG drivers is consistent with Sperling and Kitamura (1986), who found that the refueling behavior of gasoline drivers was more "ad hoc" or opportunistic than for diesel customers. In addition to avoiding running on empty, we suspect that another factor contributing to the higher habituality of CNG refueling is the aforementioned tendency for CNG drivers to be members of multi-vehicle households who own conventional vehicles for trips across a much larger activity space. In our study, only 18 out of 253 CNG drivers did *not* have a second vehicle in their household, of whom 13 lived alone.

The most common reason cited for purchasing a CNG vehicle is for gaining access to the HOV lanes in the highly congested Los Angeles road network. The motivation to use the HOV lanes could bias our sample towards freeway drivers and contribute to our finding that CNG drivers refuel on longer trips and farther away from home than gasoline station customers. We would argue that our sample is representative of the target population identified by Melendez and Milbrandt's (2008) study of consumer hydrogen demand, which used variables such as multi-vehicle households, higher education, and commutes greater than 20 minutes to identify likely early fuel cell vehicle adopters. Also, HOV access is a common inducement offered to early AFV adopters, and longer commutes are known to incentivize hybrid buyers. The predilection for gaining access to freeway HOV lanes for longer trips in congested areas may in fact be representative of early adopters in other regions and of other technologies, and could help inform station placement accordingly. Thus, results of this study may point to a coordinated strategy for conquering the chicken-and-egg dilemma: incentivize early consumer adopters with HOV access and build a relatively smaller number of stations at fleet bases located close to busy freeways and situated between or at major trip generators and attractors.

5. Conclusions

This study measured the extent to which CNG drivers deviate from their shortest paths, refuel on non-home-based trips, refuel mid-route, and rely on downtown stations. The findings indicate that some of the conventional wisdom on what drivers consider convenient may not apply to early AFV adopters. Through their revealed behavior, early CNG vehicle adopters in this study appear willing, either by necessity or indifference, to stop at stations in ways that their gasoline counterparts are not. Our descriptive statistics of basic refueling behavior and statistically significant differences between CNG and gasoline customers should provide useful guidelines for companies, governments, and researchers planning the alt-fuel networks of the 21st century.

The research also informs the choice of models for locating alt-fuel stations. The results suggest that a greater emphasis should be placed on locating stations on the way to destinations (as in the flow-based models) or on the way to freeway entrances (Nicholas 2010) rather than median and covering models that place stations "close to home." However, the results also emphasize the shortcomings of the flow-based models that count trips as covered only if stations are located directly on the shortest paths. Small detours are common even for gasoline drivers, and early CNG adopters appear to be indifferent to deviations less than 5-6 minutes, which argues for increased usage of models that allow for driver deviations (Kim and Kuby, 2012, 2013). Various results presented here may prove useful in determining the inputs or assumptions for modeling, planning, and decision-making, such as assumptions about the behaviorally realistic driving range of vehicles, the shape of deviation penalty functions, and distances and travel times from homes to stations.

In addition, these findings may prove useful not only in modeling *where* to locate alt-fuel stations but also *how many* stations are needed for the transition to AFVs. Given that billions of dollars will be spent on new station infrastructure in the coming decades, it is important to provide the industry with current analysis so the decisions can be made based on current evidence from actual AFV drivers adapting to sparse networks. If early adopters do not rely primarily on stations close to their homes, perhaps fewer stations are needed to launch a new fueling infrastructure than previously thought.

Finally, we emphasize that the findings from this study are based on a particular technology at a particular stage of its transition process in a specific geographic region with specific incentives in place. The stations studied here were located in different kinds of locations than in Sperling's and Kitamura's studies. The findings from this study must be applied cautiously to other types of alternative fuels, and are probably most transferable to other fast-filling, single-fuel AFVs with limited home refueling, such as hydrogen. Plug-in EVs with switchable batteries also can be "re-energized" quickly en-route, but due to the unknown effect that home-recharging ability might have on the behaviors measured here, we hesitate to extend our results to this platform. The findings are increasingly less consistent with constraints and options for biodiesel, E85, and plug-in hybrid charging stations, due to the greater flexibility offered by being able to fill up at gasoline and diesel stations. Similar studies need to be conducted for other types of AFVs, at different geographic scales, in different geographic settings, and at different levels of station availability and market penetration.

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