Decentralized refueling of compressed natural gas (CNG) fleet vehicles in Southern California

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Highlights

- Anchor fleets with central refueling help launch initial public refueling networks
- 133 fleet drivers were surveyed while refueling away from their fleet base
- Drivers with central refueling filled farther from their base than those without
- Drivers favored stations on their way over stations close to their fleet base
- Results varied somewhat by vehicle and route type

Abstract. While some compressed natural gas (CNG) vehicle fleets have a station at their base for central refueling, others lack refueling capability at their fleet depot and must rely on publicly available stations. To understand this kind of decentralized refueling behavior, we surveyed 133 drivers of CNG fleet vehicles at six public stations across the Los Angeles region. Nearly one-third of CNG fleet drivers were solely reliant upon public refueling for their operations. For each driver's refueling trip, we used GIS to compare the chosen station's proximity to the driver's fleet base and their deviation from the shortest path between their previous and next stops relative to all other stations they could have chosen. This revealed-preference approach shows that fleet drivers chose the station with the smallest deviation over the station closest to base by a 6:1 ratio, though this ratio varied by the driver's availability of central refueling and type of vehicle and route. Given that public stations remain essential to meeting decentralized refueling demand for other fleets as well as consumers, these findings have important implications for fleets that are both considering the adoption of CNG vehicles and the additional investment of hosting central refueling infrastructure at their base.

Keywords: alternative fuel, station, infrastructure, fleet, deviation, central refueling

1. Introduction

In the United States, the nearly singular reliance on petroleum fuel in the transportation sector carries a host of environmental, economic, and social issues. Major automakers now produce vehicles capable of operating with electricity, hydrogen, compressed natural gas (CNG), and biofuels, offering potential economic stability, improved air quality and health, carbon emissions reductions, and domestic energy production. From a policy standpoint, commercial vehicle fleets are often recommended as a more promising initial market for AFV adoption than personal vehicles for several reasons (Nesbitt and Sperling 2001, Melendez 2006, Zhao and Melaina 2006, Corts 2010), although the universality of some of these generalizations have been questioned (Nesbitt and Sperling 1998):

1. government incentives and mandates are more easily implemented with private and government fleets
2. auto manufacturers can work directly with fleets
3. in-house maintenance staff can be trained and equipped for the new vehicle technologies
4. central refueling can ease range anxiety
5. commercial vehicles, which typically drive twice as many miles and get fewer miles-per-gallon, use more fuel per year

The focus on fleets has been especially important to researchers and policy makers in the context of "energy transition" analysis, which emphasizes the process of and barriers to shifting away from the current petroleum-based system to one based on alternative fuels (Ogden 1999, Greene et al. 2008). This transition requires many essential parts of the "business ecosystem"—vehicle production, fuel production, fuel distribution, laws, standards, taxes, insurance, education—to evolve in a coordinated fashion (Melendez 2006, Lu et al. 2014). At the core of the transition problem is the so-called "chicken and egg" problem, the phenomenon of hesitancy that exists between AFV manufacturers and AFV station owners in which each is reluctant to invest before the other does (Melaina and Bremson 2008). A key strategy for breaking this cycle has been to develop large anchor fleets of private, state, or federal vehicles co-located with a depot-based fuel station (Melendez 2006). The "fleets-first" strategy is for anchor fleets to provide an initial market for AFV manufacturers, and for central refueling by the fleet to provide stable demand for the first fuel stations. By placing pumps "outside the fence," anchor fleet stations help to seed an initial publicly available refueling infrastructure for other fleets and eventually consumers. In surveys conducted by Melendez (2006), experts at National Renewable Energy Laboratory and Clean Cities Coordinators viewed the fleet introduction strategy as critical, though not sufficient by itself to spur widespread consumer adoption.

Legislation geared toward increased AFV adoption in the United States began with the Alternative Motor Fuels Act of 1988, which provided incentives to manufacturers to produce the vehicles. The Energy Policy Act of 1992 (EPACT) then required federal and state fleets to deploy certain numbers of AFVs. Some 13 years later, Section 701 of the Energy Policy Act of 2005 (EPAct § 701) stipulated that federal agencies with dual-fuel vehicles should operate with an alternative fuel when stations are accessible and the fuel is not unreasonably more expensive than gasoline. These and other policies, combined with heightened air quality standards and increasing availability, variety, and competitiveness of vehicles, have led to an increase in AFV fleets operating in recent years.

Nearly 23% of the national bus fleet now operates with natural gas, an increase of about 5% since 2010 (American Public Transportation Association 2016). Total U.S. natural gas vehicle fuel consumption has increased 44% since 2010, with 2016 representing the highest total volume of natural gas used in transportation on record (EIA 2017). In California, there are now approximately 24,600 natural gas vehicles in operation, half of which are classified as medium- or heavy-duty vehicles that belong to vehicle fleets (Schroeder 2015). Although CNG vehicles are not often dual-fueled, some fleets have turned to natural gas in particular because of its relatively low cost, lower price volatility, reduced maintenance, competitive driving range, familiar technology, lower emissions relative to liquid petroleum-based fuels, and in many regions, high-occupancy vehicle lane access (AFDC 2017, NGV America 2017, Questar 2017).

The recent proliferation of CNG vehicles in operation has been supported by a corresponding increase in stations nationwide from 841 in 2010 to 1,700 as of April 2017 (AFDC 2017), many of which were largely built to facilitate CNG fleet travel. Of the 1,700 CNG stations nationwide, 55% are available for public use. Nearly one-third of these 942 stations are owned by state and local governments or utilities. The other two-thirds of the public CNG stations are owned by private developers, and may or may not have a fleet anchored at the station. These public stations support decentralized refueling for a variety of fleets, though it remains unclear to what degree fleets rely upon them for their daily operations. The remaining 45% of U.S. CNG stations are not open to the general public, and instead are dedicated to specific users.

This study aims to address the gap in knowledge about where CNG fleet drivers refuel when they do so away from their fleet base. Based on intercept surveys of 133 CNG fleet drivers using the public CNG refueling infrastructure in the greater Los Angeles area, we ask the general research question: how do AFV fleet drivers access public CNG refueling stations in Southern California? Specifically, to what degree do fleet drivers prioritize such stations near their fleet base, and are there differences in this behavior between drivers without central refueling compared to those that have it? Additionally, are there variations in how drivers access these stations based on the nature of the vehicle or route type? Buses, taxis, delivery shuttles, municipal vehicles (such as those for trash collection), and mail and parcel distribution routes all differ in daily travel patterns and trip frequency.

The purpose of our study is to analyze the differences in usage patterns for fleet drivers that rely on public AFV stations in large cities, which is an important topic for location modellers, station developers, fleet operators, and policy-makers. Results from this analysis have relevance to current policies regarding the use of alternative fuels in government vehicle fleets, along with commercial considerations important to deciding the locations of CNG stations. We then discuss the relevance of such public AFV stations that allow for fleets to operate with alternative fuels in an urban environment. This is of particular importance because city and regional governments consider AFVs to be a critical means to comply with air quality standards and greenhouse gas emissions policies.

2. Literature Review

With the increase in fleet adoption of AFVs, several studies have analyzed AFV fleet travel patterns and driver and fleet manager perceptions and practices. Nesbitt and Sperling (1998) critically examined seven myths associated with the fleets-first strategy. In contrast to traditional perceptions, they found that very few fleets relied exclusively on central refueling at their base. Heterogeneity of fleets has been another theme: Nesbitt and Sperling (1998) highlighted the diverse nature of fleets and the types of routes driven, while Nesbitt and Sperling (2001) contrasted different organizational decision-making structures for fleet purchases. Flynn (2002) found that limited refueling infrastructure was the biggest barrier to CNG fleet development in Canada in the 1980s. According to Golob et al. (1997), fleet operators in Southern California considered off-site refueling to be a critical factor in their willingness to invest more aggressively in AFVs. Johns et al. (2009) studied bi-fuel vehicles operated by a county forest preserve and found that the vehicles were often filled with conventional rather than alternative fuels, depending on refueling convenience.

These few studies on AFV refueling by fleets suggest that: central refueling cannot satisfy all fleet refueling needs, convenience of public refueling infrastructure is important, and usage of the public stations may vary by type of vehicle, route, and company. To construct an effective refueling infrastructure for fleet AFVs, a deeper understanding is needed of refueling patterns by fleet drivers and, specifically, which stations drivers choose when they refuel away from their base. A limited amount of research along these lines has been conducted on consumers driving private automobiles.[1] In two pioneering intercept surveys at diesel and gasoline stations by Sperling and Kitamura (1986) and Kitamura and Sperling (1987), consumers cited proximity to home and lower fuel price as reasons for choosing a refueling station, although they stated that high-traffic commuting routes between home and work locations could be good candidate sites for early refueling infrastructure because a high percentage of drivers refueled on commuting trips. Plummer et al. (1998) also conducted revealed preference surveys of gasoline refueling in Minnesota, showing that consumers rely on a set of several stations, some of which are not near their homes. Bunzeck et al. (2010) found that 74% of consumers in Netherlands fill at gasoline stations within 10 minutes from the start of their trips. They also asked about their preconditions for refueling availability for switching to hydrogen fuel-cell vehicles, with nearly half stating that stations would have to be sufficient to travel abroad or at least travel across the Netherlands.

Two papers report on the revealed preference for refueling station choice by consumers driving CNG vehicles. First, Kuby et al. (2013) conducted intercept surveys at CNG and nearby gasoline stations in Southern California and found that CNG drivers refuel farther from home, farther off their shortest travel-time paths, and more frequently during the middle part of a trip than drivers of gasoline vehicles. In the second paper, Kelley and Kuby (2013) further investigated the behavior of these CNG drivers to determine what a driver's choice of refueling station on a given trip indicates about what they considered more convenient: a station close to home or one on their way. They used GIS to estimate the distance and travel time from home and the degree of detour off the fastest origin-destination route for all possible stations a driver could have chosen. The analysis showed that when no station existed that satisfied both criteria and drivers are thus forced to choose between these two definitions of convenience, consumers chose the CNG station on the way over the station closest to home by a 10:1 ratio. Only ten drivers chose the station closest to home when it was not also most on the way, and for all of these, the station was second or third most on the way. For the 102 drivers who chose the station with the shortest deviation, however, the station was not one of the three closest to home for half of them. The findings indicate that, for repeated use, a station close to home but in the wrong direction is not considered convenient, whereas a station farther from home but on the way is. These findings have important implications for developing an initial refueling infrastructure for the convenience of the early adopters. The transferability of these findings to other kinds of AFVs, to other regions, and to fleets, however, remains unknown.

[1] In this paper, we use the term "consumer" to indicate individuals driving a household vehicle, in contrast with fleet drivers driving commercial or government vehicle.

We know of only two other studies of revealed refueling behavior by AFV fleet drivers—though neither assesses CNG fleets. First, Daley et al. (2014) analyzed whether drivers of federally owned dual-fuel vehicles (i.e., flex-fuel vehicles or FFVs) filled with gasoline or E85 (85% ethanol, 15% gasoline). Although EPAct § 701 stipulates that federal FFVs fill with alternative fuel when such stations are accessible, the Federal Energy Management Program (FEMP) grants waivers to this requirement if no alternative-fuel station lies within 5 miles or 15-minute driving time of the base. Using GIS and vehicle-level data on fuel purchases from the US Department of Energy's Fleet Sustainability Dashboard (FleetDASH) program, they analyzed whether drivers with and without waivers missed opportunities to refuel at an E85 station within 5 miles of where they refueled with gasoline. They confirmed that most federal FFV drivers do not refuel with E85 even when it is available, though completed opportunities improved nationally from 19% to 25% over their 4-year study, and compliance is even better when fleets are ineligible for waivers.

The second revealed-preference study of the refueling behavior of fleet drivers is for mid-trip fast charging by consumer and fleet EV drivers in Japan (Sun et al. 2015, 2016). The 2015 paper focused on the state of charge (SOC) upon beginning a recharge event, and found that half of commercial drivers charged at SOC 60-70% or higher and often could have charged safely farther along their route. The 2016 paper used GPS tracking data to estimate driving distances, and highlighted drivers who charged at a station that was in the wrong direction from where they were headed, as evidenced by the origin-station or station-destination distances being longer than the direct distance from origin to destination. Such refueling events, however, were a small minority of the total and tended to add only a few km to the trip. They found that fleet drivers detour less (under 1 km) to recharge than consumers and recharge earlier on their routes.

With no revealed preference surveys of the refueling station choices by CNG commercial and government fleet vehicle drivers, this study aims to address this gap in the literature about their use of public stations away from their home fleet base.

3. Methodology and Data

3.1 Sampling Procedure.

Using an intercept survey methodology, undergraduate research assistants asked drivers to respond to questions while they refuelled their fleet vehicles at CNG stations. This is the same method employed by Kitamura and Sperling (1987), and was applied because it ensures relatively reliable responses by interviewees.

This survey of CNG fleet drivers was administered alongside the consumer surveys collected in Kelley and Kuby (2013) and Kuby et al. (2013) in the summer of 2011, with some additional surveys in the winter months. The survey is random in the sense that, while waiting for drivers of private automobiles to arrive at the station, student interviewers were instructed to ask all fleet drivers to participate. Although the number of surveys of fleet drivers varies by station, they are representative of the time it took to accumulate at least 50 consumer surveys per station and the frequency of fleet driver arrivals.

3.2 Questionnaire

To collect spatial information on driving and refueling patterns, drivers were asked to provide locations of stops immediately before and after refueling, along with the approximate location of their fleet base. These data enabled us to both interpolate the driver's actual route that included the public CNG station and a potential route from the fleet base to the station. The survey also collected information about frequency of refueling at the station in question and frequency of refueling at public stations away from the fleet base. Although we did not ask explicitly about availability of central refueling at the fleet base, if a driver answered that they refuel 100% of the time away from their base, we inferred that central refueling was not available.

Fleets vary both in vehicle and route types, and these differences are not trivial for the purposes of analyzing fleet driving and refueling behavior. To explore this variation, we asked drivers to identify the type of route that best represented their travel out of five choices:

- "Regular Route, All Streets" – A regular route covering every street in a service area (mail, trash, meter reading)
- "Regular Route, Back-and-Forth" – A regular, back-and-forth route to a regular set of stops (bus route, etc.)
- "Two Unique, One-Way" – A refueling stop in between two unique, one-way trips (between taxi fares, etc.)
- "Multi-stop" – A multi-stop, return-to-base route to a set of unique or regular stops (deliveries, pickups, repairs, airport shuttle)
- "Single-stop" – A single-stop, return-to-base route from an origin to a destination and back (single delivery or service call)

We also asked drivers to identify their fleet vehicle type from the following choice set: car, bus, delivery van, passenger van, minivan, pickup truck, and specialty truck.

3.3 CNG Stations and Study Area

The greater Los Angeles region has 76 public CNG stations, of which 30% are owned by state or local government agencies, 12% by public utilities, and 56% by private station developers (AFDC 2017). These 76 stations are available to both consumers and fleets for refueling, and we consider two unique categories of their general operation: those located on the property of a fleet base, and those without an anchor fleet on-site. In the former case, which we refer to as "fleet-based stations," the public CNG pumps are in a visible and accessible location on the fleet's property but "outside the fence" near a public right-of-way, with another set of pumps "behind the fence" for the host fleet's private use. The public CNG stations without an anchor fleet on-site are in various locations, such as truck stops and convenience stores that also sell other fuels, or at CNG-only stations located strategically in business districts, industrial parks, or near busy freeways where they can serve multiple fleets and/or consumers. We examined aerial imagery of the 76 stations in greater Los Angeles and estimate that 55 are fleet-based stations while 21 are CNG stations without an anchor fleet on-site.

We conducted the intercept survey at six public CNG stations operated by private station developers Clean Energy Fuels and Trillium CNG (Table 1). Four are fleet-based stations, while the other two have no on-site anchor fleet, which is consistent with the 55:21 region-wide ratio. Table 1 describes the variety of fleet travel data from across the study area that we attempted to capture at each station.

Table 1. Station summary table.

Station	n	Pumps	Owner	On-Site Anchor Fleet	Comments
Anaheim	29	1	Trillium	Southern California Gas Company	Public access outside the fence of SoCal Gas facility. Close to major freeways. Convenient for vans and taxis moving tourists to and from nearby Angel Stadium and Disneyland.
Burbank	39	2	Clean Energy	None	Owned by City of Burbank. Near a freeway entrance/exit along a high-volume commuting route. Near Burbank Airport.

Downtown Los Angeles	25	2	Clean Energy	None	Located in the central business district and used by a wide variety of vehicles and fleets conducting business here.
Pomona	15	1	Clean Energy	Foothill Transit	Public access outside the fence of a bus depot. Situated in the "Inland Empire" in a more suburban location than the others.
Santa Ana	8	2	Clean Energy	Southern California Gas Company	Public access outside the fence of SoCal Gas facility. Near John Wayne Airport and in a commercial and industrial area.
Santa Monica	17	1	Clean Energy	Southern California Gas Company	Public access outside the fence of SoCal Gas facility. This station is nearly a mile from the nearest freeway exit, and is close to both residential and commercial areas on an arterial street.

3.4 Route Calculations

To locate the survey respondents' stops immediately before and after refueling and analyze route time, distance, and deviations from shortest paths in order to refuel, we geocoded the cross-streets or exact locations provided by drivers. Using a script that accessed ArcGIS's Network Analyst extension, we computed shortest paths using travel time as the primary unit of impedance, based on arc lengths, speed limits, and global turn penalties. We then calibrated the network by comparing route times against popular web mapping platforms. To compute the route deviation required to refuel, we first calculated and stored the travel time and distance of the direct path between the stated locations immediately before and after refueling, and compared this result to the travel time and distance of the route that also included the stop at the CNG refueling station. These calculations provided us with a deviation metric, a key consideration when employing station location models (Hodgson 1990; Berman et al. 1992; Kim and Kuby 2012). To analyze the differences of driving and refueling behavior between route types and vehicles, a series of statistical tests were performed.

Following the methodology in Kelley and Kuby (2013), proximity to the fleet base and deviations from shortest paths were calculated not only for the station chosen by the driver, but for all possible stations open to the general public at that time. Drivers could have refueled at any of the open stations, so their preference is revealed by the station at which they were surveyed while refueling. By comparing the proximity and deviation of their chosen station with the same metrics for the stations not chosen, we are able to determine if they chose to refuel at the station closest to their base or most on their way between their previous and next stops. We categorize these convenience criteria in a 2x2 matrix, and, similar to Kelley and Kuby (2013), we focus on the drivers who chose a station maximizing one or the other of these two criteria but not both.

4. Results and Discussion

A total of 133 surveys were collected from respondents at the six public CNG stations. In total, 39 responses were collected from the Burbank station, 29 in Anaheim, 25 Downtown, 17 in Santa Monica, 15 in Pomona, and 8 in Santa Ana. The response rate of fleet drivers who refueled at these stations at the time of our study was just below 50% 134 fleet drivers either declined to participate or were not surveyed because the survey worker was busy interviewing another respondent.

4.1 Vehicle and Route Types

The most common route types across all surveyed drivers were unique one-way route types (36%), such as those completed by taxi drivers and mostly by car, followed by multi-stop route types (31%) such as those completed by delivery or shuttle drivers, which included a greater mixture of vehicle types. Vans were the most common vehicle type observed for multi-stop route drivers, but this group also included eight heavy-duty vehicles. Multi-stop trips were the only route type to include at least one response from each vehicle category (Table 2). The higher relative prevalence of unique one-way stops and multi-stop routes could be explained by the uncertain and dispersed nature of this type of fleet travel compared to the other types of fleet behavior. Taxi, delivery, or shuttle drivers do not always know the exact way in which their travel will develop throughout the day, as demands for their services can be spatially and temporally unpredictable. This uncertainty may require them to refuel more often and opportunistically at these public stations, either in anticipation of or reaction to unplanned trips away from their base. There are relatively few single-stop return-to-base routes observed, which could be explained by the predictable nature of that type of trip and greater potential reliance on central refueling.

Table 2. Route Type by Vehicle Type.

	VEHICLE TYPE					
ROUTE TYPE	Bus	Car	Van[a]	Pickup Truck	Specialty Truck	**TOTAL**
Regular Route, All Streets	0	5	2	3	13	**23**
Regular Route, back-and-forth	9	2	1	1	1	**14**
Two Unique One-way Trips	1	40	5	0	1	**47**
Multi-stop	1	7	22	3	7	**40**
Single-stop	0	0	3	3	1	**7**
TOTAL	**11**	**54**	**33**	**10**	**23**	**131[b]**

[a] "Van" includes passenger vans, delivery vans, and minivans. [+]2 drivers did not provide an answer for vehicle type.

[b] Two respondents did not provide an answer to the question about vehicle type

Light-duty vehicles, including cars, vans, and pickup trucks, accounted for 74% of the surveyed vehicle types. This is a noteworthy finding for station developers in the region, given that 52% of the total registered natural gas vehicles in California were heavy-duty vehicles as of 2013 (Schroeder 2015). Of note, 63% of the surveyed drivers of heavy-duty vehicles that did refuel at one of the public CNG stations indicated that they did have central refueling, which is a similar percentage (57%) to those drivers of light-duty vehicles. This means that the higher observed rate of light-duty vehicles using the public refueling stations cannot be explained by the presence or absence of central refueling alone.

4.2 Central Refueling and Habituality

The use of these public CNG stations by those fleets that lack central refueling is of particular interest for both station developers and fleet operators who are considering whether or not to invest in the construction of their own station at their base. In total, 47 respondents indicated that they did not have central refueling (Table 3), which means that of the drivers who provided an answer to the question, 40% were reliant upon the public refueling infrastructure to complete their trips at the time of the survey. These drivers refueled more frequently at public stations without an anchor fleet on-site, while drivers with central refueling tended to refuel more at fleet-based stations, even if it was not their own base.[2]

[2] The Chi-Squared analysis of this deviation from expected percentages is significant at the $\alpha = 0.1$ level.

Table 3. Public CNG station type chosen by fleet driver with or without on-base refueling.

	Not a fleet-based station	Fleet-based station	**TOTAL**
Station at driver’s fleet base	32	38	**70**
No station at driver’s fleet base	28	19	**47**
TOTAL	**60**	**57**	**117[a]**

[a] 16 respondents did not provide an answer as to whether or not they had central refueling.

Beyond the single refueling event captured by the intercept survey, drivers were asked how frequently they refueled at *any* station away from their base, and how frequently they refueled at *this* particular station where they were being surveyed (Table 4). Of the 115 drivers who provided an answer to both questions, 66% of CNG fleet drivers indicated that they were reliant on public refueling stations away from their base for at least half of their refueling needs, and 41% reported that they refueled away from the base at any station frequently (75% of the time or more). In contrast, 30% indicated that they rarely refueled (<25% of the time) away from their fleet base. In general, respondents frequented the station where they were surveyed: 91% of drivers refueled at the surveyed station 50% of the time or more. Out of 133 respondents, 21 (15.8%) refueled at the surveyed station 100% of the time, and eight of these also stated that they refueled away from base 100% of time, which means that 6% of respondents relied on a single public station for all of their refueling needs. Thus, this observed population of fleet drivers refuels frequently at public CNG stations away from their home base, and for many, the station at which they were surveyed is the public station on which they rely most.

Table 4. Habituality of refueling, by stated frequency of refueling at this station and stated frequency of refueling away from base.

	% At This Station					
% Away from Base	**0-25**	**25-49**	**50-74**	**75-99**	**100**	**TOTAL**
0-25	2.3%	2.3%	1.5%	11.3%	8.3%	25.6%
25-49	0.0%	0.0%	3.8%	0.0%	0.0%	3.8%
50-74	0.8%	2.3%	14.3%	3.8%	0.0%	21.1%
75-99	1.5%	0.0%	0.8%	0.0%	0.0%	2.3%
100	0.0%	0.0%	10.5%	17.3%	6.0%	33.8%
No Answer	0.0%	0.0%	4.5%	7.5%	1.5%	13.5%
TOTAL	4.5%	4.5%	35.3%	39.8%	15.8%	100.0%

4.3 Travel time and Deviations

Given the much smaller number of CNG stations relative to gasoline stations, it is not surprising that fleet drivers often have to deviate from their fastest routes to refuel. As Figure 1 shows, 58% deviated less than 6 minutes in order to refuel. Beyond 6 minutes, there is an observed sharp decrease in willingness and/or need to deviate, with a slight secondary increase around the 8-10 minute interval. This roughly S-shaped deviation decay curve exhibited by CNG fleet drivers is very similar to the one observed in a companion study of consumer CNG refueling (Kuby et al. 2013), which is noteworthy given the differing nature of fleet routes and consumer trips.

The median trip distance for all fleet drivers is 8.7 miles with a travel time of 18.6 minutes (Table 5), though there is variation by vehicle type. Buses refuel on shorter trips and farther from their fleet base than other vehicle types, and they also have shorter deviations. Drivers of fleet cars refuel on longer trips by distance, but not by travel time, while van drivers make longer trips by travel time and make greater deviations to refuel than those driving other vehicle types. Most of the surveyed drivers of cars were taxi drivers, who are possibly responding to longer-distance trips requested by customers who are dispersed throughout the region, allowing them more flexibility in choosing a station with a minimal deviation. In contrast, many of the van drivers are those operating shuttles between more predictable, fixed locations such as between airports and hotels and tourist centers, and assuming that they do not refuel with passengers on board, they have very limited opportunity to choose when they refuel. They likely must refuel when their tank is low and they have dropped off their last passenger, even if it requires a large deviation from the best route to where they are going next. Comparing drivers of light-duty and heavy-duty vehicles, we observe that those driving heavy-duty vehicles refuel on shorter trips, but deviations and distances from the station to the fleet base do not significantly differ.

Table 5. Median travel times, distances, deviations, and distance to fleet bases for fleet drivers at surveyed CNG stations.

Station	n	Trip Distance (miles)	Trip Distance (minutes)	Deviation to refuel (minutes)	Distance from Fleet Base to Station (miles)
Bus	11	6.9	12.5	3.5	6.2
Car	54	11.3	20.8	4.1	2.8
Van	33	8.7	21.4	6.3	2.8
Pickup Truck	10	8.6	18.7	4.8	4.4
Specialty Truck	23	6.1	15.1	4.8	2.4
TOTAL	**131**	**8.7**	**18.6**	**4.8**	**2.8**

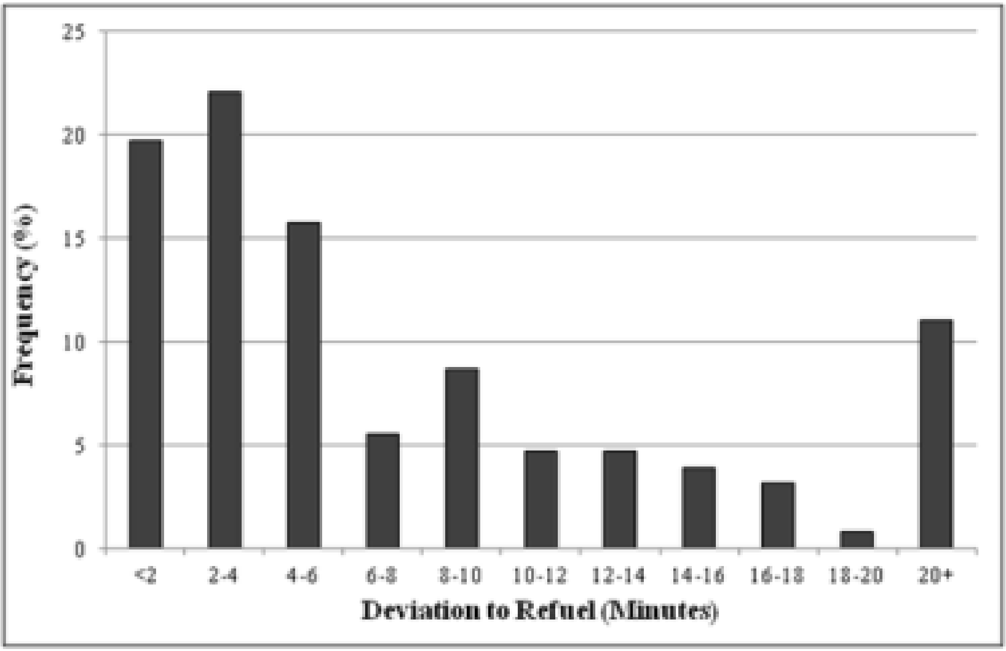

Figure 1. Deviation decay of CNG fleet drivers.

4.4 Proximity to Fleet Base

The map in Figure 2 and the histogram in Figure 3 demonstrate the spatial variability in how fleet drivers refuel at the surveyed stations, and there is noticeable variation in how drivers with and without central refueling access these stations. There is a cluster of fleet bases reported by survey respondents that lack central refueling near the Burbank and Santa Ana stations (Figure 3), and there are clusters of drivers with central refueling near both the Santa Monica and Downtown stations. Only 16% of the total respondents who refueled Downtown lacked central refueling, in contrast to the 62% observed at Burbank. The Burbank station was the only one of the six CNG stations where more drivers without central refueling accessed the station than those that did have it.

The Downtown Los Angeles station in particular served a relatively high volume of drivers from distant fleet bases (Figures 2 and 3), and these were dispersed throughout the metropolitan area. Of the 25 respondents who refueled Downtown, 56% indicated that their fleet base was greater than 10 miles away. Each of these drivers with distant and dispersed fleet bases had central refueling, meaning that these fleets were able to extend their activity space through the use of this centrally located public CNG station. A high percentage of drivers surveyed in Pomona (67%) also had distant fleet bases with central refueling, though the extent of observed fleet bases was confined to the extent of the Inland Empire. The geographic extent of customer bases was generally more closely centered around the remaining stations. There is a notable cluster of fleet bases around the Santa Monica CNG station, each of which had central refueling capability, and many of those who refueled at the station indicated their fleet bases were nearby. Only one respondent in Santa Monica lacked central refueling, so this station largely served nearby fleets that already had the ability to refuel at their base. No driver who refueled at the Santa Ana station had central refueling, and its set of customers generally had fleet bases greater than two miles away. The Anaheim station was used equally by those with or without central refueling, with the majority of respondents reporting fleet bases between five and ten miles away, largely from the same area.

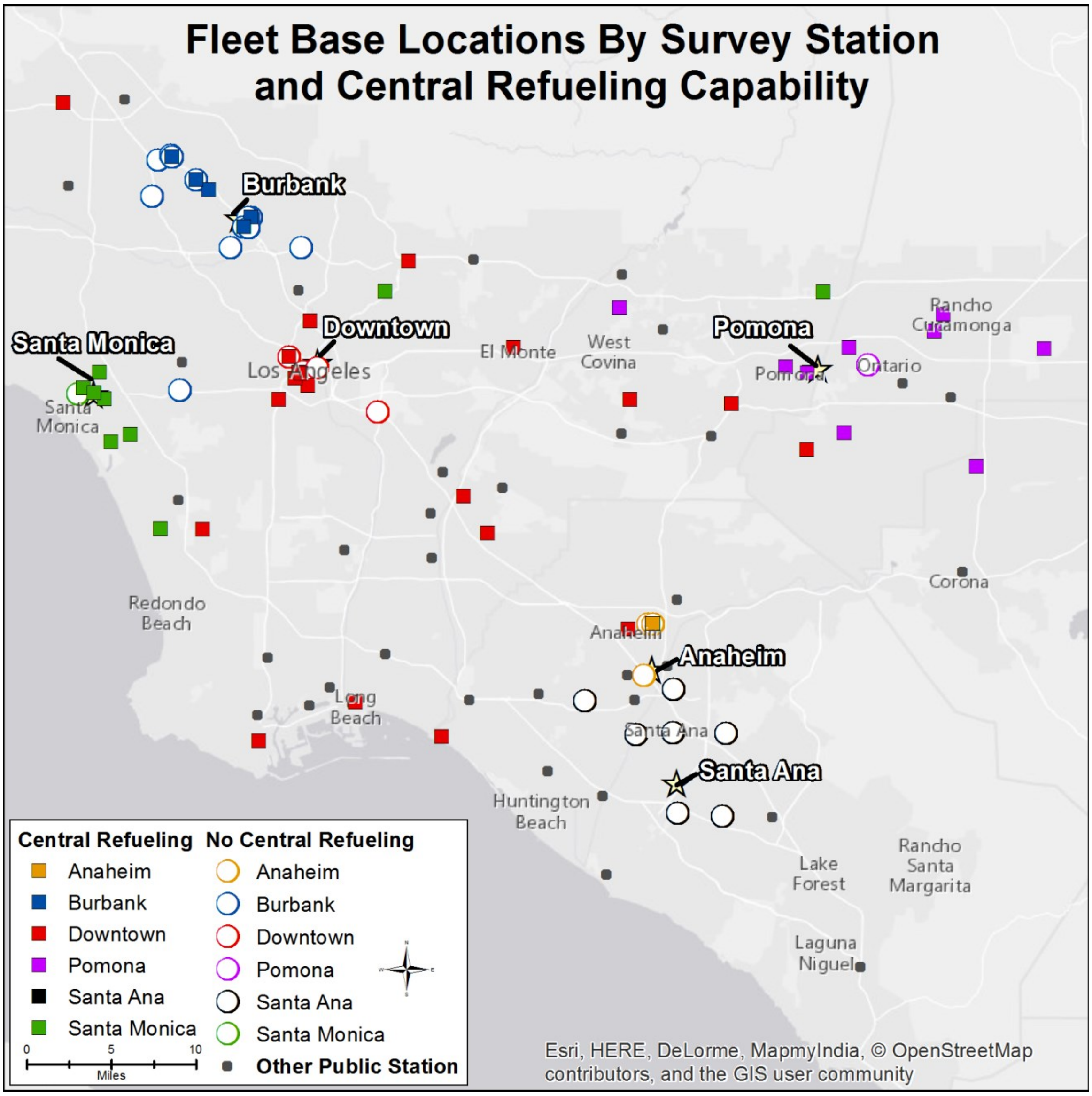

Figure 2. Spatial distribution of fleet bases, symbolized by presence or absence of central refueling. Other stations that were open to the public when surveys were conducted are also shown, since drivers also could have chosen to refuel at them.

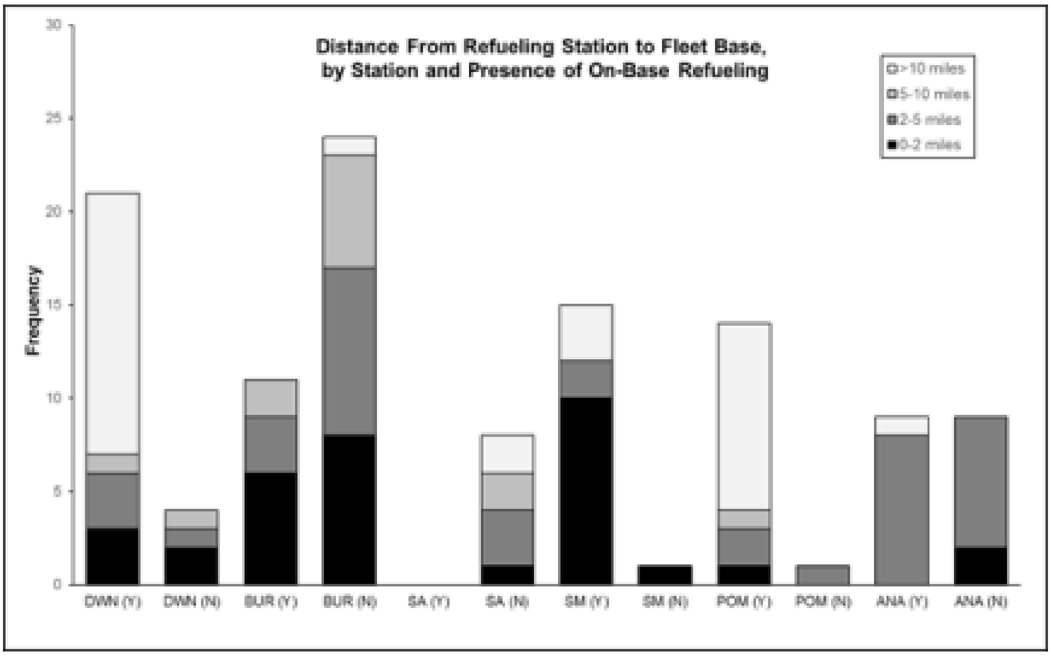

Figure 3. Use of CNG stations by fleets with central refueling (Y) or not (N), and by distance from base to station.

Using the distances from all fleet depots to the surveyed refueling station, we tested for significant differences in driving characteristics of those drivers both with and without central refueling. We find that drivers without central refueling chose to refuel significantly closer to their base, in terms of both time and distance, than those drivers with central refueling, and with significantly shorter deviations (Table 6).

Table 6. Two-sample difference of means tests of decentralized refueling behaviors between drivers with and without central refueling

Trip Attribute	Without Central Refueling	With Central Refueling	t	*p*
Base to station distance (miles)	4.1	9.5	3.87	<0.01
Deviation (minutes)	6.5	12.3	2.43	0.02
Trip distance (miles)	8.0	14.9	3.33	<0.01

It is possible that fleets may have been more willing to transition to CNG as their primary transportation fuel if a public station were located nearby, which is one explanation for why drivers without central refueling choose to refuel significantly closer to their base. When considering the application of popular station location models that recommend optimal CNG station sites in a region, this possible explanation becomes important. Some station location models inherently assume that drivers will choose to refuel at the station closest to a home location, or in the case of fleets, the fleet's base. This assumption may be appropriate when considering those fleets that lack central refueling, who may frequently use the public station closest to their base. It may be less appropriate for drivers with central refueling, as they would have little reason to refuel at the station closest to their base and are more likely to expand their activity space with a set of stations distant from their base that are along frequently-traveled routes.

4.5 On the Way or Close to Base?

To test if these assumptions were observed in the surveyed fleet drivers, we determined the rank of the chosen public CNG station in terms of both its proximity to the fleet base and its proximity to the shortest travel path route between the drivers' stated previous and next stops. The results are displayed in a 2x2 matrix. Of particular interest is whether or not the chosen station met one or the other of the criteria (the shaded boxes in Table 7 and Figure 4), not both, as these are the two most common definitions of "convenient location" assumed in the AFV station location modeling literature. This approach is the same as that employed in Kelley and Kuby's 2013 study of private CNG vehicle owners. Figure 4 shows examples of routes that would be categorized in each of the cells in the 2x2 matrix.

Figure 4. Illustrations of chosen refueling stations to demonstrate each behavior in the 2x2 matrix. In these examples, the fleet base (B) is the trip origin, and the route shown is the

least-travel-time direct route to the destination (D) with no stop at any station. The highlighted circle is the station where the driver was surveyed while refueling, while the other circles are publicly available stations that the driver did not choose. Note that station locations may vary between maps to better illustrate each case.

Table 7. 2x2 Matrix of station choice by proximity to base and efficiency of route.

	Closest to Base	Not Closest to Base	TOTAL
Least Deviation	64	**37**	101
Not Least Deviation	**6**	26	32
TOTAL	70	63	133

For the sample as a whole, 64 chose a station that was both closest to their fleet base and most on the way between their previous and next stops (Table 7). This choice, however, reveals little about their preference, since they (a) had a station that optimized both criteria, and (b) chose to refuel there. Likewise, 26 drivers chose a station that maximized neither of the convenience criteria, for what could be any number of reasons not considered in this analysis. Focusing on drivers who chose a public station satisfying one or the other definition but not both, 37 drivers refueled at the station most on the way between their previous and next stops but not closest to base, while only 6 drivers chose the station closest to base but not most convenient to their travel path, which is roughly a 6:1 ratio. This is not quite as extreme as the 10:1 ratio in Kelley and Kuby's (2013) study of consumers, but it still means that 86% of the fleet drivers who chose a station satisfying only one of the two criteria chose the station with the least deviation off their most direct route. Table 8 examines this relationship separately for fleets with and without central refueling. Of the drivers with central refueling at their base who optimized one criteria or the other but not both, 19 refueled at the station most on the way while no drivers chose the station closest to base. Drivers with central refueling likely start out each day with a full tank, reducing the need to fill at the closest station to the base. Refueling close to base appears to be more attractive to drivers lacking central refueling at their own base. Although they still favor minimizing deviation over refueling closest to base, the ratio falls to 2:1. This still indicates a strong preference to refuel along a shortest travel path rather than near the fleet base when no station meets both criteria. Similar analyses were conducted for other subcategories of drivers by route and vehicle type and answers to other survey questions (Table 9). Regardless of whether or not drivers said the primary reason the drivers chose the station was "convenient location," the sub-sample matched the overall ratio of 6:1. There was some variation by vehicle and route type. Cars overwhelmingly refueled at the station most on the way instead of the closest station to base (11:1), but heavy-duty vehicles did not. Out of the 9 bus drivers interviewed, none occurred at a station that fit only one criteria of convenience, and only two of the specialty trucks did. Drivers completing unique one-way trip or multi-stop route types also appear to favor stations along the way rather than those close to base. These are the two route types that would seem to offer drivers the most opportunities to refuel between stops, and therefore the most flexibility for choosing where and when it is most convenient to refuel. That their ratios are the highest of all route types is therefore consistent with the idea that refueling on the way saves drivers the most time and is usually preferred when it is feasible to do so. Though the sample size is small, it is also interesting to note that drivers along regular routes that cover all streets in a service area also refueled along the way but not at the station closest to base by a margin of 5:0. These drivers do not carry passengers, so it stands to reason that they have flexibility to refuel at any time and location along their route, and because the route is repeated regularly, they learn to refuel as efficiently as possible.

Table 8. Station choice relative to fleet base and most efficient travel path, for drivers (a) with and (b) without central refueling at their base[a]

Table 8a: With Central Refueling	Closest to Base	Not Closest to Base	TOTAL
Least Deviation	32	**19**	51
Not Least Deviation	**0**	19	19
TOTAL	32	38	70

Table 8b: Without Central Refueling	Closest to Base	Not Closest to Base	TOTAL
Least Deviation	28	**11**	39
Not Least Deviation	**5**	3	8
TOTAL	33	14	47

[a] The number of drivers in these two tables is less than the total reported in Table 5 because 16 drivers did not answer the question that indicates whether their fleet has central refueling.

Table 9. Summary of Ratio Between the Two Main Definitions of Convenience, for Various Subsamples

Category	Subcategory	Ratio of "Least Deviation But Not Closest" to "Closest But Not Least Deviation"	Sample Size in the Two Cells
All	None	6:1	43
Central Refueling	With	19:0	19
	Without	2:1	16
Primary Reason: "Convenient Location"	Yes	6:1	29
	No	6:1	14
Type of Vehicle	Bus	0:0	0
	Car	11:1	25
	Van	4:1	14
	Pickup Truck	2:0	2
	Specialty Truck	1:1	2
Type of Route	Regular Route, All Streets	5:0	5
	Regular Route, back-and-forth	1:0	1
	Two Unique One-way Trips	3:1	24
	Multi-stop	6:1	14
	Single-stop	1:1	2

5. Discussion

While this study is based on a sample of the use of public CNG stations by different fleets and vehicles in a metropolitan area and finds notable differences between those drivers that have central refueling compared to those that do not, it is important to note that it is not necessarily representative of all CNG fleet activity in the region. There were a number of stations that were not open to the public at the time of the study that some fleets may have had access to, and that may have included those fleets without central refueling. It is also possible that some CNG fleets with dedicated refueling infrastructure never needed to use these publicly available stations, and were therefore not sampled in this study, which is also a possible explanation for why there was a relative lack of heavy-duty vehicles observed in this study. Limited observations of particular sub-categories of the sample, including specific route types or types of vehicles, make generalizations of their refueling behavior difficult without further research. The total population of fleets or fleet vehicles in the region that rely on public CNG refueling infrastructure is also unknown, which also warrants further investigation.

We cannot make any claims regarding the interaction between the decision to place a station in a certain area and the decision of a fleet to locate a base of operations in the area. It is possible that some or all of these stations were strategically placed by Clean Energy or Trillium to provide a convenient refueling station for a set of fleets that expressed interest in having a nearby station, with the understanding that this public station would serve as a "home station" for a number of fleets. Conversely, it is possible that certain fleets located their base of operations at a site convenient to a public CNG station instead of investing in central refueling. There is evidence of variability in how each of the stations are being used by fleets, with the Downtown and Pomona stations largely serving distant customers who have central refueling, Santa Monica generally serving nearby fleets that have central refueling, and Burbank and Santa Ana largely serving fleets without central refueling. The interaction between the location decisions of CNG stations and both nearby and distant fleet base locations will be an interesting topic to consider in future research.

That deviation times vary somewhat between heavy and light-duty vehicles is important to note for station location models that incorporate deviation when optimally placing stations at a regional scale for fleet use. It is also worth noting that the general deviation decay across all fleet drivers is similar to that of the private vehicle driver population sampled in Kelley and Kuby's (2013) study, but given that many of the stations are the same between the two studies, this may be attributable to the physical arrangement of the road network rather than simply a reflection of driver choices and behavior alone. Should this consistency in deviation decay continue to be found in other geographic areas across drivers of both private and fleet vehicles, a single deviation threshold could be assumed for all vehicle types in an area when employing popular station location models. Further validation of the consistency between fleet and consumer drivers in other geographies will determine how transferable this result is. Studies have also demonstrated that AFV drivers do consider other factors beyond deviation minimization when selecting a refueling station, including fuel price, accessibility, and perceived convenience and safety, (e.g., Carley et al. 2013), and future research should consider how these factors influence station choice for fleet drivers.

This variety of vehicle and route types of fleets using a set of public CNG stations includes some complexities that must be considered before generalizing these results. While the stations were built primarily to serve the variety of fleets and vehicle types discussed throughout this study, these stations also serve private CNG vehicles. This led to interactions at these public stations that are largely uncommon at most traditional gasoline stations. Each of the six stations had a limited number of pumps available at the time of the survey, and some of the vehicles that arrived at the stations could only use a subset of these, depending on the architecture of the vehicle's fuel tank and pressure requirements. For example, if a heavy-duty vehicle such as a bus or a refuse truck arrived at a station to refuel, its size would make it impossible for a driver of another vehicle to park and access an unused pump at the station. Heavy-duty vehicles also took considerably longer to refuel compared to light-duty vehicles, which led to frustration among light-duty vehicle drivers when they arrived at the station and saw a heavy-duty vehicle at the pump. Likewise, heavy-duty vehicles occasionally had to wait for a large area near the pumps to be clear before they could refuel, which led to frustration on their part when one light-duty vehicle would arrive and use one of the pumps. Since no station had an on-site station attendant, there was no moderator available in case conflict arose. These types of interactions might lead drivers to forego a station that might be the most convenient station relative to a shortest travel path or a fleet base location in favor of one that conflicting classifications of drivers do not frequent as often. Further investigation into the impact of shared use on driver behavior may also be an area of investigation that needs more emphasis when constructing an effective set of initial AFV stations for both fleet and private vehicle drivers, and for design of station layouts.

Finally, the opportunistic sampling of fleet drivers without stratification controls does introduce a possible source of potential bias in the results. The results are representative, though, of the relative use of these stations by fleet drivers, given that roughly equal amounts of time were spent at each station by survey workers.

6. Conclusions and Policy Implications

A relatively robust public CNG refueling infrastructure has been constructed in Southern California in order to serve a variety of fleet operations. While greater than half of the operating CNG fleet vehicles in California at the time of the study were heavy-duty vehicles, in this survey conducted at six of the region's public CNG stations, the majority were light-duty vehicles such as taxis, shuttles, and delivery and service vans. Future fleet-based public station arrangements, then, should consider locations convenient to these more dispersed routes, which may not be as predictable as fixed routes served by some heavy-duty vehicles. Public CNG stations simultaneously allow fleets without central refueling at their base to conduct their operations while also encouraging those with central refueling to expand their activity space and complete more distant trips. This means that public CNG stations do not have to rely solely on fleets that lack central refueling, but can expect as much or more demand from fleets that have central refueling but maximize efficiency by not returning to base to refuel.

The key finding of this paper is that fleet drivers as a whole refuel more frequently at the station most directly on the way between their previous and next stops, as compared with the station closest to their fleet base. The overall ratio for this revealed preference for what constitutes a convenient location is 6:1 in favor of station on the way, though the ratio varies by subcategory. Fleets with central refueling presumably start most travel with a full tank and thus overwhelmingly (19:0) favored the station that minimizes deviation over the one closest to their fleet base. More surprisingly, drivers without central refueling do so as well, although at a lower ratio of 2:1. Heavy-duty vehicles do not refuel at public stations that fit either criteria, though, which warrants further investigation. When considering light-duty vehicle fleet travel use of public stations, companies and government agencies interested in developing a system of refueling stations in other metropolitan areas or regions to serve fleet travel should build or encourage public CNG stations across the metropolitan area to allow more widespread travel along frequently traveled paths that minimize deviation. Station developers should select final station sites by considering the fleet base locations of smaller fleets that have not yet transitioned to alternative fuels, providing a local, reliable customer base while serving more remote travel that passes by the area.

In terms of policy implications, our results suggest that the waiver criteria in the 2005 EPAct that exempt federal fleets lacking a station within 5 miles of their base are not fully aligned with the fact that most fleet drivers refuel at a station on their route rather than near their base, and that fleet drivers rely on multiple stations. The expectation that drivers could have refueled at an E85 station if it was within 5 miles or 15 minutes of where they filled with gasoline is fairly consistent with the behavior we observed, though deviations of that magnitude were rarely necessary by Southern California CNG fleet drivers. In fact, when station density reaches that of CNG stations in the Los Angeles region, even single-fuel AFVs of various types can be conveniently refueled most of the time with alternative fuel, even by fleets without central refueling.

While Southern California's large population of CNG fleets and stations provides an excellent laboratory for studying the revealed refueling preferences of single-fuel, fast-filling, range-limited alternative-fuel fleet vehicles in real-world usage, the ability to generalize these findings is unknown. The Los Angeles region is sprawling, heavily congested, and freeway-centric, with high-occupancy vehicle lane access available to single-occupant CNG vehicles on many of the region's freeways. This type of intercept survey and GIS network analysis bears repeating at other stations in other regions for other types of fleets for CNG and other fuels, and could be extended by analyzing the data in discrete choice models. Other criteria besides proximity to base and least deviation should be explored, such as freeway access, perceived neighborhood safety, congestion, conflicts among user types, and varying levels of compression. The refueling behavior of CNG drivers may also serve as a valuable proxy for the behavior of drivers of hydrogen fuel-cell vehicles, which have similar range and refueling characteristics. While this study provides initial insights into how fleets access public CNG refueling stations, it is only a first step in filling the knowledge gap about how AFV drivers adapt to the scarcity of refueling and recharging stations.

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