The Transition to Alternative Fuel Vehicles (AFVs):

an Analysis of Early Adopters of Natural Gas Vehicles and Implications

for Refueling Infrastructure Location Methods

by

Scott Kelley

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Graduate Supervisory Committee:

Michael Kuby, Chair
Ram Pendyala
Elizabeth Wentz

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ABSTRACT

Alternative fuel vehicles (AFVs) have seen increased attention as a way to reduce reliance on petroleum for transportation, but adoption rates lag behind conventional vehicles. One crucial barrier to their proliferation is the lack of a convenient refueling infrastructure, and there is not a consensus on how to locate initial stations. Some approaches recommend placing stations near where early adopters live. An alternate group of methods places stations along busy travel routes that drivers from across the metropolitan area traverse each day. To assess which theoretical approach is most appropriate, drivers of compressed natural gas (CNG) vehicles in Southern California were surveyed at stations while they refueled. Through GIS analysis, results demonstrate that respondents refueled on the way between their origins and destinations ten times more often than they refueled near their home, when no station satisfied both criteria. Freeway interchanges, which carry high daily passing traffic volumes in metropolitan areas, can be appropriate locations for initial stations based on these results. Stations cannot actually be built directly at these interchange sites, so suitable locations on nearby street networks must be chosen. A network GIS method is developed to assess street network locations' ability to capture all traffic passing through 72 interchanges in greater Los Angeles, using deviation from a driver's shortest path as the metric to assess a candidate site's suitability. There is variation in the ability of these locations to capture passing traffic both within and across interchanges, but only 7% of sites near interchanges can conveniently capture all travel directions passing through the interchange, indicating that an ad hoc station location strategy is unlikely to succeed. Surveys were then conducted at CNG stations near freeway interchanges to assess how drivers perceive and access refueling stations in these environments. Through comparative analysis of drivers' perceptions of stations, consideration of their choice sets, and the observed frequency of the use of a freeway to both access and leave these stations, results indicate that initial AFV stations near freeway interchanges can play an important role in regional AFV infrastructure.

DEDICATION

To my family and friends for their unwavering support throughout.

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Chapter 1. Introduction

1.1. Overview

Global energy consumption and production patterns are in a state of transition. Coupled with uncertainty about future supplies, decisions regarding energy are among the most important facing the international community. Petroleum supplies cannot meet the dramatic increase in global demand in perpetuity, much of which is occurring in China and India. Despite the highest level of domestic petroleum production in the country's history, drivers in the United States have experienced volatility in gasoline prices over the past decade, and the nation continues to require imports of petroleum from international sources to meet its demand. The nation is almost completely reliant upon petroleum for transportation, which represents an economic vulnerability and leaves the nation at geopolitical risk in the search for new reserves. Beyond the issue of fuel supply and demand, negative externalities caused by petroleum consumption in the transportation sector include citizens' health and safety, local water pollution, and its role in contributing to the highest levels of atmospheric carbon dioxide in Earth's recorded history.

Recommendations for transitions away from the reliance on the personal automobile and petroleum-based transportation have generally fallen into two categories: those that focus on changes in land use and on travel demand management (Cervero 1997, Ewing 1997), and those that argue for the widespread adoption of alternative fuel vehicles (AFVs) and AFV refueling infrastructure (Sperling and Gordon 2009). While investments in public transportation and changes in commuting patterns are suitable alternatives for some urban residents, passenger vehicles will continue to play an important role in transportation for the coming decades due to slow-changing consumer habits and a massive amount of sunk infrastructure for automobile travel. AFVs offer a potential avenue to allay many of the negative externalities of the current automobility paradigm while allowing people to generally maintain their current driving behavior. While this may seem to be a more palatable option than an overhaul of the built environment for some regional planning agencies, the transition to AFVs will be a difficult and expensive process.

1.2. Overview of AFVs and Key Issues

To assess the steps needed to produce an eventual transition to AFVs, Melendez (2006) surveyed academics, private sector stakeholders, and government experts, and the lack of a convenient refueling infrastructure was cited as the most critical barrier to AFV adoption. With this in mind, the United States Department of Transportation's Strategic Plan 2012-2016 includes a provision to "develop infrastructure and distribution systems for advanced transportation energy sources including electricity and alternative fuels (p.57)."

Though both AFV refueling station developers and AFV manufacturers are acutely aware that a functional and convenient refueling infrastructure is the best way to reduce consumer fears of range anxiety, neither group is rushing to invest the necessary capital until the other does so first because of the financial risks involved. This "chicken and egg problem" (Sperling 1990) has been a source of constant frustration for AFV adoption policy, and policy analysts are aware that AFVs and infrastructure are complementary goods that cannot succeed without a substantial presence of the other (Meyer and Winebrake 2009). Most government and industry experts argue that the most effective way to break this stalemate lies in first placing a minimally sufficient infrastructure of AFV refueling stations in order to stimulate vehicle sales (Melaina and Bremson 2008). From that point, it is possible that private station developers will construct the remainder of the necessary refueling infrastructure needed to sustain widespread adoption, once they are convinced that the market holds financial promise. The question of *where* to place the initial refueling stations, then, is a crucial step to the eventual success of any AFV adoption policy.

Infrastructure build-out carries inherent economic and political risk for those involved: investors stand to lose millions if consumers fail to adopt the technology. More importantly, the long-term skepticism and political damage could make future AFV policy more difficult to craft and implement (Peters von Rosenstiel et al. 2015), so effectiveness of the initially chosen AFV refueling station locations is of paramount importance (Struben and Sterman 2008; Flynn 2002). Some countries around the world (e.g., Argentina, Pakistan, Iran) have constructed relatively effective refueling infrastructures for AFVs, largely through government investment and lower fuel prices relative to gasoline (Collantes and Melaina 2011; Yeh 2007). Translating those policy instruments into domestic success will require effective locations that will be palatable to station developers and drivers alike.

Confounding the issue is the varied nature of AFVs: some are capable of running on multiple fuels, such as flex-fuel vehicles, which can burn either E-85 (an 85% ethanol, 15% gasoline blended fuel) or unleaded gasoline. Hybrid vehicles, with both an electric motor and an internal combustion engine (ICE), can operate either with electric power or gasoline, so that drivers enjoy some benefits of AFVs without the concerns of range anxiety. These vehicles are not as reliant upon an effective refueling infrastructure for a single alternative fuel, since drivers of these cars can always default to gasoline when running low on fuel.

Electric vehicles (EVs) are a classification of AFVs that have garnered the most amount of attention from the public with the recent releases of the Nissan Leaf, the Chevy Volt, and the Tesla Model S. EVs appear in both hybrid and all-electric forms, but are distinct from other AFVs in that recharging times are substantially longer than their fast-fueling AFV counterparts. Refueling infrastructure for these vehicles will differ from other AFV types in that relatively long recharging times restrict recharging locations to places where vehicles will stay parked, with the exception of fast-charging or battery switching stations. Even with fast-charging stations available in some parts of the United States, home recharging currently carries the bulk of the recharging load in the nascent EV infrastructure (Tal et al. 2013), while workplaces, shopping malls, and parking garages are frequent suggestions for charging locations (Nicholas et al. 2013). Recent studies on driver and refueling behavior of people who drive battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) have been conducted to assess the driving and refueling behavior of these early AFV adopters (Nicholas et al. 2013; Kurani et al. 2009; Kurani et al. 2008; Gonder et al. 2007).

While the conclusions drawn from these studies can help inform future EV policy, the locations of charging infrastructure were determined largely by an ad hoc process, driven by sales opportunities instead of through regional planning. Further, the refueling behavior of EV drivers is inherently very different than that of those who drive fast-fueling AFVs, since many EV drivers simply recharge their vehicles at home, even if public charging options exist (Tal et al. 2013). AFVs that operate on a single fuel and are not generally refueled at home, such as hydrogen, compressed natural gas (CNG), liquefied natural gas (LNG), propane, and biodiesel, represent a break from both the current transportation refueling network and EV charging infrastructure. They are classified as "fast-fueling" AFVs since they can be refueled in similar times to gasoline vehicles, and by fuel pumps at facilities that very closely resemble modern gasoline stations.

In contrast to hybrid vehicles or EVs, drivers of these fast-fueling AFVs will have to be reliant upon a public refueling infrastructure when completing the types of trips that they are accustomed to making. In the early stages of AFV adoption, there will only be enough of a budget to place a select number of stations across a given geographic area. This means that choosing the locations of initial refueling stations is a crucial decision that requires careful analysis of driving and refueling behavior, and more broadly, impacts how widespread AFV adoption may be across a given metropolitan area or region.

Researchers have developed a number of methods in the facility location literature that can be applied to the deployment of AFV refueling stations, but each general classification of location methods makes inherent assumptions about drivers' travel behavior and refueling preferences. For example, GIS analysis that identifies areas where vehicles will be stationary for long periods of time (Liu 2012) may be appropriate for the deployment of charging infrastructure for EVs, but cannot effectively meet the refueling needs of fast-fueling AFV drivers. In addition, modeling approaches that are appropriate for fast-fueling AFV station deployment (Capar et al. 2013; Kim and Kuby 2012;

MirHassani and Ebrazzi 2012; Wang and Wang 2010; Zeng et al. 2008; Wang and Lin 2009) currently have a number of crucial limitations, which must be addressed before they can be easily understood and applied by regional planners and stakeholders interested in building an AFV effective refueling infrastructure.

1.3. Research Objectives

One general research question that frames this dissertation research is: where are the best locations at which to place initial AFV refueling stations to encourage eventual widespread adoption at the metropolitan or regional scale? This question is inherently related to the types of AFVs for which a refueling infrastructure must be built, and the assumptions made about what drivers will consider to be effective and convenient locations. This dissertation research will specifically focus on the refueling needs of fast-fueling AFVs, with each chapter addressing an outstanding issue in the station location literature. A novel aspect of this dissertation research is that it relies largely on empirical data gathered from early adopters of AFVs. Virtually every previous study that recommended station locations for a region used theoretical data in their construction, since empirical data on AFV driver and refueling behavior were not available at the time.

The greater Los Angeles metropolitan is an ideal region in which to conduct this dissertation research for a number of reasons. First, it is the only American city with a high number of consumers who drive CNG vehicles, which are single-fuel, fast-fueling AFVs that are generally not refueled at home. Subsequently, Los Angeles has a high number of public CNG refueling stations. Data gathered from the driving and refueling behaviors of these drivers can also be extrapolated to other refueling technologies, such as hydrogen or biofuels. Secondly, because of the region's noted reliance on the personal automobile for transportation, it serves a test piece for other large, automobile-dependent cities such as Atlanta, Houston, Phoenix, or Dallas-Fort Worth that may eventually be interested in transitioning to alternative fuels. Finally, early adopters of CNG vehicles in Southern California enjoy incentives such as HOV lane access, tax credits, and lower fuel prices. These incentives may be of interest in certain other regions and are relatively easy for regional governments to implement, making the Los Angeles region an interesting early bellwether of a large city in transition away from petroleum for transportation.

The second chapter examines the applicability of existing AFV refueling facility location methods by testing how the observed behavior of early adopters of CNG vehicles in Southern California compares to the assumptions implicit in the two general classifications of station location models. This paper surveyed CNG drivers while they refueled their vehicles, asking them to provide approximate stops before and after the refueling station. From this information, drivers were isolated into categories to see whether they refueled at the station nearest to their homes or at stations on the way between their origins and destinations. Results showed that consumers exhibited a strong preference toward the latter behavior, indicating that one classification of methods, flow-based location models, is a more appropriate approach when locating early AFV infrastructure at a regional scale for fast-fueling AFVs. The details of the general classifications of station location models are explored in Chapter 2.

Chapter 3 is motivated by the conclusion of Chapter 2 that drivers prefer to refuel along their way on a given travel route. This requires a detailed analysis of the types of locations that perform well at capturing high volumes of passing traffic across an area of interest for station deployment. The emphasis on these types of locations is driven by the following logic:

1) Busy roads are good places for fuel stations because of the high traffic volume that passes the station location each day.

2) Busy intersections are better places than simply locating a station along a busy road because of the high passing traffic volume on *both* roads.

3) Logically, that means that intersections of freeways with arterial streets are even better sites because of the much higher traffic volume of freeways compared to even the busiest arterial street. Finding a site convenient to drivers along both the arterial street and the freeway is as simple as choosing one of the sites where an on-ramp or off-ramp from the freeway connects with an arterial street. These are the types of locations where gasoline stations are commonly found along highways and freeways.

4) Taking this logic one step further, intersections of two limited-access freeways see more passing traffic volume than the intersection of a freeway with any arterial road. Arterials can carry tens of thousands of vehicles each day, but freeways carry hundreds of thousands, meaning that one station located at that interchange could conveniently serve as a refueling station for far more people than any other location in a metropolitan area.

Placing stations across a metropolitan area at a few strategic freeway interchanges would conceivably capture the most passing traffic and associated AFV refueling demand with a minimal amount of investment, which would be of great interest to fuel station developers. These are also the locations that are targeted by flow-based location models. The difficulty with placing refueling stations at such sites is that freeway interchanges are often complex traffic structures with many subsidiary access points and connections between the freeway and the local roads around them. A station placed near a freeway interchange without convenient access for all drivers that pass by the station would compromise the location's ability to perform effectively.

To address this concern, in Chapter 3, a new network GIS algorithm is developed that measures the theoretical accessibility of potential AFV station locations near freeway interchanges in Southern California. The accessibility of these sites relative to freeway interchanges is measured using a travel time threshold that measures the difference between a shortest path through an interchange and a path that involves a station location as an intermediary stop, repeating this process for all possible travel directions through the interchange. Generalizations are then drawn between interchanges with a relatively high number of convenient sites for refueling stations and those without. Implications for the algorithm's future application are also addressed.

An empirical study in Chapter 4 specifically gathers data from drivers using existing AFV refueling stations near busy freeway interchanges in the Los Angeles area using an intercept travel survey. The objectives of this paper are both to compare the expected accessibility results from Chapter 3 to observed behavior, and to generate new insights into how such facilities are used and perceived by drivers. Survey questions consider factors that may influence a driver's decision to refuel at a station near interchanges aside from deviation reduction. These include the station's perceived convenience relative to a number of trip anchors, safety, and ease of access. This study also explores the "choice sets" of drivers, which is the subset of stations that an individual driver generally considers as his or her refueling options across the metropolitan area. The prevalence of other stations near interchanges in drivers' choice sets is of interest, in addition to some of the common factors of stations that are frequently cited.

This chapter also explores the types of trips that drivers take when accessing these stations through logistic regression analysis. Theoretically, stations near freeway interchanges will serve a mixture of uses, including both local and distant trips. It is unknown whether or not drivers typically exit a freeway to refuel at these stations and then return to the freeway to continue their trip without any other intervening stops, or whether they more often avoid travel along the freeway when accessing the station at all. The logistic regression model helps to explore the factors that significantly differ between drivers who leave and return to the freeway for refueling and those who do not. These are the types of trips that are assumed in the algorithm developed in Chapter 3, and a relatively high frequency of this observed behavior could indicate that drivers do consider freeway interchange stations as convenient refueling stops between origins and destinations from across the metropolitan area.

1.4. Significance

As cities around the world begin to explore the role of AFVs in their regional transportation plans, the results from this research can provide the theoretical foundation that supports the incorporation of busy areas that many people pass through each day as effective sites for initial infrastructure. From a practical standpoint, the algorithm developed in Chapter 3 can be applied as a stand-alone tool or integrated into models for planning a network of stations or other types of facilities that can be built at freeway interchanges to capture traffic from across a large geographic area. More broadly, the characteristics of interchanges that are more or less effective at capturing passing traffic will also be examined and compared, providing a useful categorization for future applications of interest to general traffic capture near freeway interchanges. Data gathered from the intercept travel survey of early adopters of AFVs using refueling stations in freeway interchange environments can inform effective future policy to deploy AFV infrastructure that will be useful to both station developers and drivers. The analysis of refueling trips that are completely freeway-anchored or not can be applied to any general study of travel behavior that requires a single stop in these types of locations.

Chapter 2. On the way or around the corner? Observed refueling choices of alternative fuel drivers in Southern California

2.1. Introduction

Alternative fuel vehicles (AFVs) are beginning to operate on American roadways at a time when conventional energy prices and supplies are uncertain. Economic, environmental, and social sustainability issues continue to build with the world's singular reliance upon petroleum fuel for transportation. Currently, 94% of all transportation energy consumed in the United States comes from petroleum sources (EIA 2011). A transition to AFVs for transportation offers many benefits, including improved air quality and health, and increased use of domestic energy resources. Light duty vehicles generate 89% of all vehicle-miles traveled in the United States, and automakers are producing or developing vehicles that run on compressed natural gas (CNG), electricity, hydrogen, propane, biodiesel, or E85 (an 85% ethanol-15% gasoline blend) (Davis et al. 2011).

While few would argue the long-term benefits of an AFV transportation system, construction of an effective infrastructure to refuel and recharge these vehicles represents a substantial investment in capital and carries financial and political risks. As a result, the industry has encountered the "chicken and egg" problem: automobile manufacturers hesitate to produce more AFVs without a basic refueling system in place, and station developers are reluctant to build stations without a substantial population of vehicles (Melendez 2006; Sperling 1990). Government and transportation industry leaders interested in breaking this cycle argue that a minimally sufficient network of refueling stations must accompany the introduction of vehicles to the consumer market (Melaina and Bremson 2008). To be effective, refueling infrastructure must be deployed in convenient locations so that drivers avoid “range anxiety,” or the fear that they will run out of fuel as result of inferior vehicle range. More importantly, the infrastructure must be functional and convenient in its early stages or the future technology may risk damaging long-term skepticism from the public (Struben and Sterman 2008; Flynn 2002).

Indeed, the lack of a convenient refueling infrastructure is consistently cited as the largest barrier to widespread AFV adoption and displacement of gasoline-powered vehicles (Johns et al. 2009; Zhao and Melainia 2006; Flynn 2002; Byrne and Polonski 2001). Dagsvik (2002) found that when AFV refueling infrastructure is competitive with that of gasoline stations available for conventional vehicles, consumers are more likely to consider purchasing an AFV. In order to reach this point, the task of initial infrastructure investment usually falls to the government (Collantes and Melaina 2011; Yeh 2007). Wise investments are necessary before the refueling infrastructure becomes viable, which makes the siting of initial stations a critical stage for AFV adoption.

To develop an effective location methodology for AFV refueling stations, an understanding of driver and refueling behavior is of paramount importance. Sperling and Kitamura (1986) and Kitamura and Sperling (1987) surveyed drivers of gasoline and diesel vehicles while they refueled at stations in Sacramento, Berkeley, and rural highway locations in Northern California, treating the diesel drivers as a proxy for future AFV drivers. These studies analyzed how early adopters of fast-fueling AFVs, such as those fueled by hydrogen or natural gas, might behave in an early infrastructure, noting in particular the types of trips on which drivers refueled, the trip lengths, and the distance from the driver’s home.

Since that time, more empirical studies of AFV driver behavior, perceptions, and adoption barriers have been conducted, largely on plug-in electric vehicles, as the vehicle population and recharging infrastructure have become more robust in specific regions of the United States, providing important insights into this type of early AFV adopter (Carley et al. 2013; Caparello and Kurani 2011; Kurani et al. 2009; Gonder et al. 2007). Transferability of these data to refueling infrastructure for fast-fueling AFVs is tenuous, however, since electric vehicles require long periods of charging, largely at home locations or other places where a vehicle remains stationary for many hours, with the exception of battery-switching stations. Empirical data remains sparse, though, for fast-fueling AFV driving and refueling behavior.

Thus, there are several compelling reasons to update the landmark studies of Sperling and Kitamura. First, at that time (winter of 1983-84), diesel station networks were already more well-established (1/10th as many stations as gasoline) than the infrastructure for today's alternative fuels. Second, the analytical tools available to researchers within the GIS environment have increased dramatically. Finally, in the three decades since Sperling and Kitamura conducted their surveys, few studies have focused on refueling station choice by fast-fueling AFV drivers, due to the scarcity of AFVs driven by consumers. In the absence of such a population, Nicholas (2010) made one such attempt, using gasoline sales to try to identify determinants of future alternative-fuel demand. He found that vehicle-kilometers traveled (VKT) was a better predictor of gallons of gasoline sold than population, although high VKT did not produce high gasoline demand near the central business district. Nicholas concluded that "the route between home and the nearest freeway entrance may help predict a large portion of refueling and merits further investigation” (p. 738).

At the time of the Kitamura and Sperling studies, it was widely assumed that proximity to home was among the most important factors in station choice (American Society of Planning Officials 1973), and consistent with that assumption, Kitamura and Sperling (1987) found that 75% of refueling trips were made on their way to or from home. Others have suggested that refueling infrastructure should be coupled to home locations in various ways, identifying areas where early adopters are likely to live and travel (Melendez and Milbrandt 2008; Lin et al. 2008; Nicholas and Ogden 2006; Nicholas et al. 2004; Goodchild and Noronha 1987). The common theme across this small body of literature is an attempt to measure or operationalize some meaning of “convenience” by analyzing travel times and distances for future AFV adopters. Only 9% of the home-anchored refueling trips in the Kitamura and Sperling study, however, traveled from home to station and back to home, meaning that 91% of the refueling stops were made between home and somewhere else. Plummer (1998) likewise found that special trips from home to the station and back are uncommon for gasoline drivers, and frequently are made as part of a multi-stop trip involving work or shopping. In addition, Kitamura and Sperling (1987) found that 29% of all refueling trips were work-anchored, leading them to conclude that “…commuting routes are perhaps an important consideration in designing an effective distribution network for new fuels” (p. 243). Activity-based approaches have become more common in transportation modeling (Pendyala et al. 2002), and even incorporate trip chaining explicitly in station location modeling (Kang and Recker 2013), signaling that refueling events may be linked to differing kinds of trips. Left unanswered was what AFV drivers considered to be *more* convenient: station proximity to home, or availability of refueling stations along their frequently traveled paths.

What fast-fueling AFVs drivers consider as convenient refueling locations carries some inherent ambiguity and also remains unresolved. In addition to station familiarity, comfort, and perceptions of safety and reliability, minimizing detours in order to refuel stands as an important metric (Kuby and Lim 2005; Kuby et al. 2009). Lines et al (2009) conducted surveys at the Orlando International Airport, finding that 80% of potential drivers of hydrogen rental cars stated they would detour more than one mile away in order to refuel, but these responses are stated preferences not corroborated by empirical data. Through analysis of revealed behavior of fast-fueling AFV drivers, we ask the following research question: based on observed data of CNG drivers in Southern California, what do early adopters of AFVs consider to be convenient locations for refueling? Specifically, when no station exists that is both closest to home *and* most on the way, do drivers choose the station closest to home or the one requiring the smallest deviation? We hypothesized that in an early refueling infrastructure, drivers faced with such a choice will more frequently refuel at the station that minimizes deviation, which has implications for station utilization by early adopters of AFVs.

Answers to these questions have important implications for future deployment of AFV refueling infrastructure and can help researchers decide which type of optimal facility location model to use for station network planning. Generally, these fall into two categories: 1) point-based models (Hakimi 1964; Revelle and Swain 1970; Church and Revelle 1974) and 2) flow-based models (Zeng et al. 2008; Hodgson 1990; Kuby and

Lim 2005; Kim and Kuby 2012). Point-based models site a number of facilities relative to their distances from the demand nodes, which represent zones where people live. The objective could be to minimize the average weighted distance from all demand nodes to their closest facility, as in the *p*-median model (Hakimi 1964; Revelle and Swain 1970), or serve as many customers as possible within a maximum distance or travel time, as in the max cover model (Church and Revelle 1974). Point-based models are the most widely used location models in the facility location literature. This approach would be most appropriate if CNG drivers demonstrate a preference to refuel close to home as opposed to a station more on their way from origin to destination.

A second class of models—flow-based location models– aim to serve demand consisting of paths on a network (Zeng et al. 2008). Flow-based models were developed in recognition of the fact that consumers tend to make certain kinds of purchases by stopping along their way on a trip between one location and another rather than by making a special purpose trip from home. These models typically begin with an origin-destination (O-D) trip matrix and shortest distance or travel time paths generated for each O-D pair. The pioneering flow-capturing model locates a given number of facilities with the objective of maximizing the number of trips that can be intercepted, without double-counting paths that can be captured by more than one facility (Hodgson 1990). The flow-refueling location model (FRLM) extends this by taking into account the driving range of vehicles and requiring one or more refueling stations to be adequately spaced along origin-destination paths to ensure that vehicles do not run out of fuel (Kuby and Lim 2005). The deviation flow-refueling location model (DFRLM) is an extension of the FRLM that incorporates drivers' willingness to deviate from their shortest paths (Kim and Kuby 2012). Some form of path-based methodology would be suitable if CNG drivers are shown to prefer a station along their way over one close to home.

2.2. Data and Methods

In this study, we interviewed 259 drivers of CNG vehicles at five CNG stations in Southern California using the same type of intercept survey as in Kitamura and Sperling's 1986 and 1987 studies. We then used GIS analysis to calculate: a) how far off the shortest path between their origin and destination did drivers travel in order to refuel, b) how far away from their home did they refuel, and c) which CNG station(s) was actually closest to their home or would have required the smallest deviation.

2.2.1 Survey

Students conducted the surveys in July and December of 2011 while drivers refueled their vehicles at five stations across the greater Los Angeles area, recording responses while the driver answered questions. We chose to study CNG drivers in the Los Angeles market because of the relatively large population of consumers driving single-fuel AFVs that can be quickly refueled. While many consumers drive flex-fuel vehicles, these vehicles can be filled with E85 or unleaded gasoline, making their refueling behavior unrepresentative of how consumers adapt to a sparse network of stations. Similar arguments can be made against studying gas-electric plug-in hybrids and biodiesel refueling. In addition, we chose not to study drivers of battery electric vehicles, whose choices will likely be influenced by the time it takes to recharge a battery. In our survey, consumers were primarily driving the Honda Civic GX, the main CNG-powered car produced by an original equipment manufacturer (OEM) at that time, although some drove converted vehicles or former fleet vehicles.

Four of the stations studied are operated by Clean Energy Fuels and one by Trillium. They primarily serve fleets that operate on CNG, but are open to consumer refueling as well (Figure 2.1). These stations were chosen because of their high usage by consumers (communicated by the companies) and to represent a variety of geographic situations and trip generators. Trillium operates the Anaheim station nearby three freeways, Disneyland, and Angel Stadium. Clean Energy's downtown station is next to the city's central business district (CBD). Their Santa Monica facility is located on arterial streets not directly accessible from freeway exits. Clean Energy also operates the Burbank and Santa Ana stations, both of which are near airports and along freeway commuting routes.

Figure 2.1. Locations of stations where CNG surveys were collected, as well as other CNG refueling stations with available public refueling.

Los Angeles is a large, congested, polycentric city. The vast majority (69%) of survey respondents reported that their primary reason for owning a CNG vehicle is unrestricted use of HOV lanes, as opposed to environmental reasons or the use of CNG as a domestic fuel. Driving long distances is not unusual in Southern California, and CNG's relatively low fuel cost compared to gasoline ($2.30-$2.90 per gallon of gasoline equivalent, or GGE) and free HOV access are both strong incentives to purchase CNG vehicles. Similar incentives may be introduced as mechanisms to boost fast-fueling AFV adoption in other geographic regions, making results from this surveyed population an important early bellwether of future refueling behaviors for other regions and some other types of AFVs. Along similar lines, in a study of future consumer hydrogen demand, Melendez and Milbrandt (2006) identified consumers who commute more than 20 minutes each way as an important attribute in identifying potential early adopters, based on literature sources as well as experts from government, industry, and academia.

The question of what drivers consider a "convenient" station location should be approached carefully, because the choices were limited by the nature of the existing AFV refueling infrastructure. Clean Energy Fuels and Trillium located these CNG refueling facilities at commercial fleet bases in partnership with the owner of the fleet. In the Los Angeles area, no CNG stations were available to study in heavily residential neighborhoods or long distances from freeways. We initially included a sixth station at a city bus depot in Pomona, but after two days only a handful of consumers had refueled there, and it was not cost-effective to continue. The Greater Los Angeles area, though, currently has one of the most mature publicly available CNG refueling infrastructures in the country and the largest population of CNG consumer drivers, making it one of the best places to conduct this research.

Survey questions focused on general socio-demographic information, vehicle ownership, reasons for owning an AFV and for choosing the station, and whether the driver felt that he or she had to detour to refuel. Most importantly for this study, the respondents detailed a series of stops completed on their trip immediately before and after the refueling station, including the type of stop (home, work, school, shopping, social/dining, or other), as well as their home location. Stop locations for each survey response were geocoded using either the cross-streets or exact locations provided by the respondent.

Because travel behavior (e.g., trip types, trip lengths, driver flexibility) is time-dependent, we stratified survey collection by time of day to ensure that 15- 20 surveys were collected for weekday morning (before 11 a. m.), mid-day (11 a.m. - 2 p.m.), and afternoon (after 2 p.m.) hours for each station. We elected the intercept survey methodology to gather more reliable information, as previous and next stops are fresher in the memory of respondents than if using a mail or telephone survey. The full survey instrument can be found in Appendix A

2.2.2 Deviations

Refueling convenience is a factor that drivers of traditional vehicles rarely have to worry about except in remote areas: gasoline and diesel stations are plentiful along well-travelled driving routes. One metric of convenience is *deviation*: that is, the time required to detour from the fastest path between two points in order to reach a refueling station.

Figure 2.2. Comparison of least travel-time direct path and refueling path, which forms the basis for deviation calculations.

We generated shortest paths between each driver's previous and next stops with and without the station as an intermediate stop based on least travel time (Figure 2.2). The focus on immediate stops before and after the station parallels Kitamura and Sperling's (1987) methodology, and does not focus on trip chains or tours, allowing for explicit focus on the deviation required to refuel. Travel times were estimated using arc lengths, speed limits, and global turn penalties, and calibrated by comparing route times against the GoogleMaps API. Using scripts created with ModelBuilder and Python to automate the calculations within ArcGIS 10's Network Analyst, we computed the deviation in minutes as the difference in the travel times of the two paths.

2.2.3 Closest Facility vs. Least Deviation Analysis

To address the degree to which station proximity to home influences refueling behavior, we derived the travel time between each respondent's home location and their closest CNG refueling facility using ArcGIS Network Analyst's Closest Facility tool (Figure 2.3). Only existing stations open to the public were considered as candidate sites, which were verified by viewing CNG refueling forums and websites, such as www.CNGprices.com.

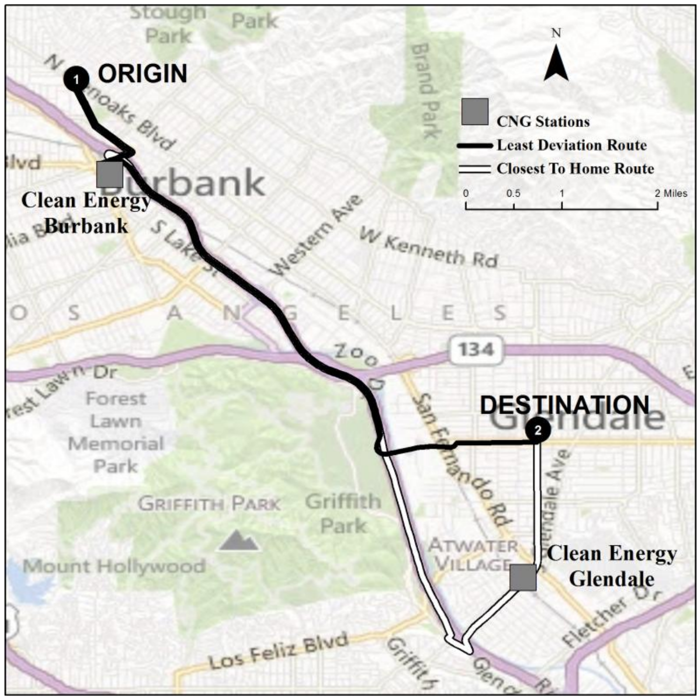

Figure 2.3. Example of a refueling route from origin at work (1) to destination at home (2) where a driver is faced with a choice between a station that requires the least deviation (Burbank) or is closest to home (Glendale).

If the closest station to home is not where the driver refueled, it implies that the driver chose a different station for reasons other than simple proximity to home. This analysis is therefore a useful diagnostic for whether point-based location models such as the *p*-median and max-cover models are appropriate for siting stations. Likewise, a test of validity for the application of flow-based facility location models would be to demonstrate that drivers refuel somewhere along a route between origin and destination, regardless of that facility's proximity to home. To analyze this behavior, we calculated the travel time for the two-step trips from each driver's previous stop to all candidate stations and then to each driver's next stop, using the same station list as for the closest facility analysis. We refer to the resulting shortest possible path to a refueling station between any given O-D pair as the *least-deviation route*. We then determined whether the driver actually selected this station, in similar fashion to the closest facility analysis (Figure 2.3).

Finally, we classified each refueling trip in a 2x2 matrix, based on whether or not they refueled at the closest station, and whether or not they refueled at the least-deviation station. As mentioned previously, a driver could conceivably select a station that is both closest to home and on their least deviation route, removing the need to make a choice between these two criteria of convenience. This situation is one that many patrons of conventional gasoline stations enjoy, given the ubiquity of such stations, and does not address the primary research question. Therefore, we isolated the two populations that, when faced with a choice, either a) selected a station on their least deviation route rather than the one closest to home or b) selected the station closest to home rather than the least-deviation station. Past investigation into this dichotomy is limited. Plummer, et al. (1998) surveyed households in St. Cloud, Minnesota, asking them to identify a set gasoline stations that they consider when refueling. They noted that while most people included the closest station to their home in their choice set, not all did, and that differing shopping patterns and journeys to work likely influenced choice of refueling station. Further, they found that commonly chosen stations lay on or near principal arterial routes, but they did not explicitly explore whether drivers minimized deviation. We hypothesized, then, that more drivers will refuel farther from home and on their least-deviation path as opposed to at a facility closest to home but requiring a larger deviation than necessary.

Next, we explored the subsample that chose a station that fit neither criteria to determine whether the station chosen was *almost* the closest to home or *almost* the one requiring the least deviation by rank or magnitude (e.g., less than five minutes more, or 2^{nd} closest station.). Given the uncertainties in actual travel time and the effects of congestion, accidents, road construction, and other unexpected incidents that impact network travel, which are not analyzed explicitly here, this analysis assesses whether the drivers in the "neither" category narrowly missed being in the closest to home or least-deviation categories. This methodology is then extended to other categories to provide a more robust categorization that can detect whether the closest-station or least-deviation choices made were marginal or not.

This paper is concerned primarily with the revealed preference of the station actually chosen by drivers. We did not explicitly model station choice from a choice set of all stations, as we do not know the drivers' familiarity with the entire CNG refueling infrastructure. Rather, we focused on the relative frequency of stations chosen when the station meets one of the criteria of interest to facility location models. Nevertheless, the survey did ask drivers to choose from several reasons why they refueled at the station, which we compared across the four station choice groups. We also compared socio-demographic characteristics across the four groups, and used t-tests to analyze differences in trip characteristics between the closest-to-home and least-deviation groups.

2.3. Results

CNG drivers exhibit a consistent willingness across stations to deviate from their shortest paths in order to refuel, with similar median deviation times at every station (Table 2.1). Given that CNG stations in Southern California were located at an assortment of industrial and public sector fleet bases as opposed to in consumer-oriented locations, the consistency across these five stations is striking. The deviation remains consistent across stations, despite the fact that trip lengths vary widely across the stations: Burbank's average trip length is 3.5 times longer than Santa Ana's, though their deviations were similar. Table 2.1 shows that at every station surveyed, less than half of the surveyed customers refueled at the station closest to home, while more than half used the station on their path of least deviation.

Table 2.1. Deviation, Closest Facility, and Least Deviation analysis results.

Station	Surveys Collected	Median Deviation (minutes)	% Closest to Home	% Least Deviation	Mean Trip Length (miles)
Burbank	51	5.2	30.6	66.0	42.9
Santa Ana	50	5.7	30.6	54.0	12.2
Santa Monica	52	6.5	46.0	67.3	18.6
Downtown	51	4.7	24.0	66.7	30.5
Anaheim	55	3.1	5.8	58.2	18.9
OVERALL	259	5.3	27.2	62.2	25.4

Regardless of geographical setting, this strong preference for lesser deviation as opposed to proximity to home in this early AFV refueling station infrastructure is evident in Table 2.1. Since these two classifications are not independent, however, we isolate the choice groups in order to compare the revealed preference of proximity to home versus minimized deviation. This is an important metric in assessing the use of point-based versus flow-based facility location models for placing early AFV refueling infrastructure.

2.3.1 Analysis of Station Chosen

Table 2.2 classifies the populations into the 2x2 matrix based on the closest-facility and least-deviation analyses, and labels the cells accordingly. Over 22% of the population, the "both" group of 59 drivers, had an easy decision: they could refuel at the station closest to home while simultaneously minimizing how much they had to go out of their way. When we isolate those drivers who chose one convenience criteria over the other (and not both or neither), the difference is dramatic. Based on the frequency of occurrence of refueling at either the closest station or the least-deviation station *but not at a station that satisfied both criteria*, CNG drivers selected the refueling station that requires the least amount of deviation by an order of magnitude (102:10) over their closest facility to home.

Table 2.2 Categorization of refueling station selection of all CNG drivers surveyed.

CATEGORIES	**Closest to Home**	**Not Closest to Home**
Least Deviation	"both" 59	"least deviation" **102**
Not Least Deviation	"closest" **10**	"neither" 88

We next examine whether drivers chose a station that was "almost" closest to home or the least deviation (Table 2.3). Of the ten drivers who chose a station closest to home rather than one that minimized deviation, eight refueled at the station with the 2^{nd} smallest deviation, i.e., 80% "almost" took the smallest deviation. Conversely, of the 102 drivers who chose their least-deviation station, only 36 of 102 (35.2%) refueled at a station that was 2^{nd} closest to home.

Table 2.3. Incorporation of marginal cases into the absolute 2x2 classification, by rank of stations.

RANK	Closest to Home	2nd Closest to Home	3rd Closest to Home	4th or More Closest	TOTALS
Least Deviation	59	36	15	51	161
2nd Least Deviation	8	13	3	13	37
3rd Least Deviation	2	4	7	8	21
4th or Greater Deviation	0	2	4	34	40
TOTALS	69	55	29	106	259

Figure 2.4 breaks down these same results in even more detail by plotting the travel time by which each station chosen exceeded one criteria or the other. In this graph, the 59 drivers in the "Both" group are shown at the origin at (0,0), while the 102 drivers in the least-deviation group are on the x-axis and the 10 drivers in the "closest to home" group are on the y-axis. All 10 of the drivers who chose the station closest to home deviated by less than 5 minutes more than necessary; whereas only 32 of the 102 who chose the least-deviation station refueled less than 5 minutes farther from home than necessary.

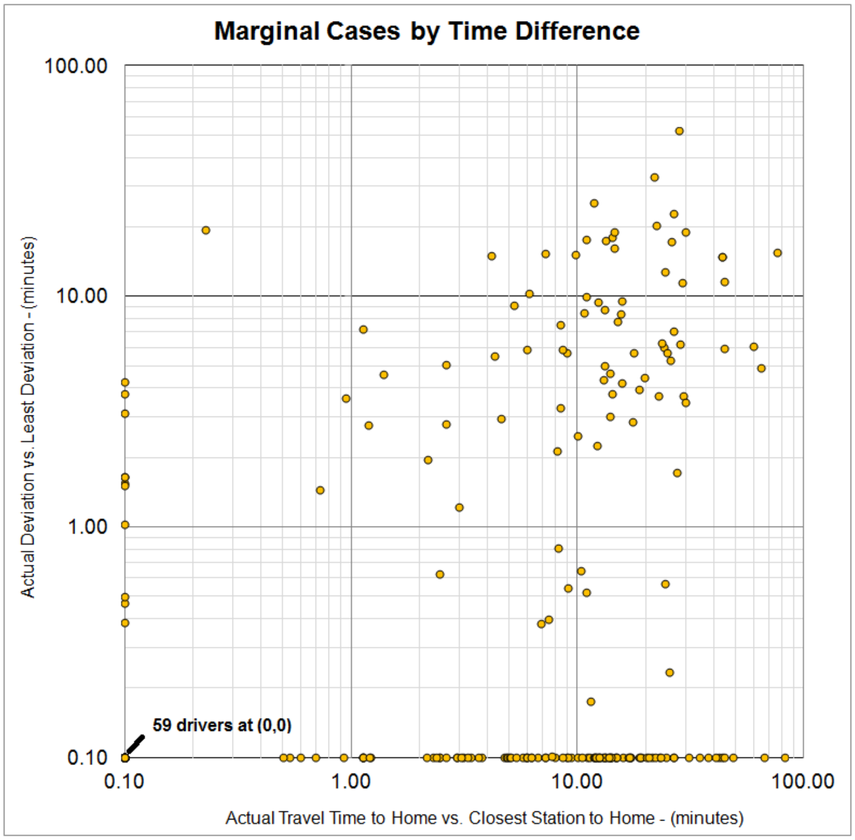

Figure 2.4. Scatter plot of difference (in minutes) between least deviation route and route traveled vs. difference (in minutes) of travel time from station to home and closest station to home.

While the points on the axes indicate a stronger revealed preference for minimizing deviation, there remain 88 drivers in the “neither” category in the interior of Figure 4. Of these, 32 refueled at a station that was between 1 and 10 minutes longer than their least deviation route, but 10 and 100 minutes away from their closest station to home. Only four refueled in the reverse manner. An additional five of the "neither" drivers were between 10 and 100 minutes further than their home's closest facility when refueling, but missed their least deviation refueling route by less than one minute. Only one driver refueled in the reverse manner. Finally, 17 drivers refueled at a station that was far from being optimal for either criteria (>10 minutes). In these cases, data uncertainty, sub-optimal decision making, unattractiveness of the bypassed stations and other factors such as safety, comfort, and familiarity with the network may have influenced these drivers' refueling behavior.

Finally, Figure 2.5 highlights the spatial relationship of the surveyed CNG drivers' home locations and the station at which they chose to refuel. In general, these "desire lines" (Berry, 1967) show that surveyed drivers did not refuel at the closest station to their home: only 27%, or 69 out of 259, did so. There was some regional variation in this behavior across the five surveyed stations, but at no station was the percentage of drivers refueling at their closest station to home greater than 45%. Also included in Figure 2.5 are the locations of other publicly available CNG stations that were in operation at the time of the study. Clearly, many CNG drivers could have filled up at any number of stations that would have been closer to their homes than the station they actually chose.

Figure 2.5. Desire lines graphic of CNG home locations and station at which driver refueled.

2.3.2 Comparison of the Four Groups

Descriptive statistics for the four groups from Table 2.2 are shown in Table 2.4. Trip lengths are substantially higher for the 88 drivers in the “neither” group than the 59 in the “both” group (21.68 vs. 6.75 miles), and their deviations are also largest. Perhaps the most dramatic difference among the groups is gender. Although the sample size in the “closest” group is quite small (10), they were 70% female. The other three groups were all less than 40% female, but this group also had the lowest percentage of both home-anchored and work-anchored trips. Many other characteristics (employment levels, age, refueling tank level) are similar across all groups. This is consistent with Sperling and Kitamura’s (1986) conclusion that “refueling concerns and attitudes … were not explained by socioeconomic (and to a lesser extent, demographic) descriptors nor by vehicle usage characteristics of drivers" (p. 22).

Table 2.4. Incorporation of marginal cases into the absolute 2x2 classification, by time difference between stations.

TIME	Closest to Home	<5 min. Closest to Home	5-10 min. Closest to Home	>10 min. Closest to Home	TOTALS
Least Deviation	59	32	19	51	161
<5 min. Least Deviation	10	11	7	22	50
5-10 min. Least Deviation	0	4	4	16	24
>10 min. Least Deviation	0	1	3	20	24
TOTALS	69	55	29	106	259

Turning to the primary reason for station selection (Table 2.5), we find that the majority of drivers in all groups, ranging from 60% to 77.6%, reported subjectively that they chose the station because of its "convenient location." This suggests that different individuals have different definitions and thresholds for convenience, in that drivers who selected a station neither closest to home nor with least deviation cited their station's location as "convenient" as frequently as those who actually achieved at least one of those optima.

Table 2.5. Primary Reason for Choosing Refueling Station.

Category	Brand loyalty	Convenient location	Low fuel price	Right-hand turn	Running out of fuel	No Answer	Total
Both	1.7%	77.6%	13.8%	0%	6.9%	0%	58
Least Deviation	1.0%	73.8%	9.7%	0%	15.5%	0%	103
Closest to Home	0%	60.0%	10.0%	0%	30.0%	0%	10
Neither	2.3%	73.9%	12.5%	1.1%	9.1%	1.1%	88
TOTAL	1.5%	74.1%	11.6%	0.4%	12.0%	0.4%	259

The closest-to-home group actually cited “convenient location” with the lowest frequency (60%) and “running out of fuel” with the highest frequency (30%). Refueling stops when running out of fuel may result from a premeditated choice or an opportunistic need, and may represent a tradeoff between visiting a convenient station and the immediate need for fuel regardless of convenience, a phenomenon discussed by Goodchild and Noronha (1987). One might suspect that those who refueled a station that was “neither” closest to home nor least deviation might have done so out of desperation, but in fact only 9.1% were running low on fuel. This group instead showed slightly higher brand loyalty and price preferences than those in the “closest to home” and “least deviation” choice groups. Overall, station selection appears to be overwhelmingly driven by some perception of convenience, with equal ancillary reasons of low prices and low tank levels.

2.3.3 Comparison of the Two Groups Faced with a Choice

We ran independent samples difference-of-means tests to compare trip characteristics of the “closest-to-home” and “least-deviation” groups (Table 2.6). Deviations by the least-deviation group were significantly smaller, unsurprising given the classification scheme, but an important validation of the refueling criteria. Much more surprising is that travel times and trip distances are *not* significantly different between the two choice groups, though the small sample size (n=10) of the closest to home group makes this finding somewhat tenuous. That the travel times and distances of refueling trips are not statistically significantly different is important because it eliminates an obvious explanation for the behavior, namely that those who care more about minimizing deviations are making significantly longer trip than those who choose to refuel closest to home. The implication here is that trip length *may not be* a significant factor in preferring stations on the way over stations near home. In fact, both groups had average trip lengths well above the 20-minute threshold proposed by Melendez and Milbrandt (2006) for identifying likely hydrogen vehicle early adopters.

Table 2.6. Difference of means results for choice groups. p_1: Equal variances assumed, p_2: Equal variances not assumed. *significant at $\alpha = .05$ level

Attribute	**Least Deviation (n=102)**		**Closest to Home (n=10)**			
	$\bar{x}_1$	σ_1	$\bar{x}_2$	σ_2	p_1	p_2
Deviation (minutes)	4.23	4.01	7.12	2.94	.029*	.014*
Travel Time (minutes)	36.73	62.18	28.08	11.36	.663	.227
Trip Distance (miles)	25.65	62.97	15.80	9.44	.623	.156

2.3.4 Subjective vs. Objective Detours

Lastly, we compare the subjective and objective definitions of “detour” of survey respondents as a robustness test to validate that groups of respondents are categorized correctly and statistically significant from one another. In the context of our study, a definition of detour can involve either a) the calculated least deviation from shortest path between origin and destination, or b) perceived detour, where the respondent was asked if he/she had to detour to refuel here—a subjective determination that could depend on many factors.

In the entire sample of 259 drivers, for those who stated subjectively in the survey that they detoured from their preferred route to reach the station at which they refueled, the calculated average deviation was 9.08 minutes, compared with 6.41 minutes for those who said they did not detour (p=.007). Thus, the calculated deviations are in line with the perceived deviations. There was an even larger difference (p<.001) in average calculated deviation between those who subjectively said they detoured within the least-deviation group (4.32 minutes) and the closest-to-home group (9.81). Finally, of the 102 drivers who refueled on their path of least deviation, 36 said they detoured to reach the station. Nearly twice that many, 66, said they did not.

2.4. Discussion

These results represent a glimpse into driving and refueling behavior of early AFV drivers, updating the work by Sperling and Kitamura (1986), Kitamura and Sperling (1987), and Plummer et al. (1998). Our 2x2 matrix shows a strong preference toward minimizing detours, and analysis of the marginal cases by facility rank and time magnitude reveals that considerably more drivers chose a station that was "almost" the least-deviation station than chose a station that was "almost" closest to home. The Trillium Anaheim station was the one most often visited even though it was not absolutely the closest to home or most on the way for the driver. It is surrounded on three sides by other nearby CNG stations, and it is located on a major arterial in plain view in a more commercial than industrial area, a potential explanation for these results. More generally, the group of drivers refueling here who fit neither model of convenience seem to have been navigating across a much wider area, which may simply inject more options and uncertainty into the travel times and refueling station choices, and could be explained by other factors than this dichotomy.

While the marginal cases add confidence to the main findings, caution must be exercised in extending these findings to other geographies. Factors such as traffic congestion, road construction, familiarity with certain areas, individual comfort levels, among others, could play a role in station selection, and these factors are not homogenous across all cities. While enthusiastic early adopters will tolerate more inconvenience when making their decision to purchase an AFV, convenience of the refueling infrastructure is an important factor—among others—for mainstream vehicle purchasers that must be addressed in order to improve AFV market share (Carley et al. 2013). Future research on these factors could yield further insights into drivers' reasons for refueling where they do and help increase adoption rates. Further analysis using logit-type choice models may reveal variables that lead drivers to choose a station closer to home versus one more along the way.

The consistency of deviations by drivers refueling at the downtown station compared to the other four is also noteworthy given Nicholas' (2010) finding that VKT were a good predictor of gasoline demand except for downtown gasoline stations. In our survey, the downtown CNG station performed quite typically of other stations with respect to deviation times, matching the overall sample results fairly closely. This may point to the difference between a CBD location in a mature gasoline station network, where there are usually several other stations outside the CBD that are also on the drivers' paths, compared with the same location in a sparse AFV station network, where the downtown station might be the only station on the way.

An explanation for these results could involve the nature of these CNG drivers' trips, which differ from those of gasoline-powered light duty vehicles, both nationally and locally. The 2009 National Highway Transportation Survey reports that 26.2% of all trips are work-anchored, though these trips do not necessarily include refueling. For a more direct comparison, CNG drivers reported that a far-higher 63% of their refueling trips were work-anchored, while a companion gasoline survey conducted at stations near the five CNG stations revealed conventional gasoline drivers refuel on the way to or from work 52.4% of the time. Furthermore, work-anchored trips are far more prevalent in this sample of CNG drivers than the 29% reported by Kitamura and Sperling's survey of diesel drivers in 1986. CNG drivers in this study also own more vehicles than their gasoline counterparts and frequently cited HOV lane access as the main reason for purchasing their AFV. These commuting drivers are exhibiting behaviors that are not representative of conventional vehicles in more mature infrastructures, but they are representative of suggested early adoption AFV policies that focus on multi-car households who use their CNG vehicle primarily for work-based trips of 20 miles or more, which also include additional benefits of HOV lane access, cheaper fuel, and tax credits (Melendez and Milbrandt 2008).

It is important to note that the networks of stations studied here were not planned using either a flow-based or point-based optimal location model. Nevertheless, drivers reacted to the ad hoc infrastructure in a fairly consistent manner in terms of favoring least-deviation refueling stops and a median deviation of less than 7 minutes at all stations. Placing CNG, hydrogen, or E85 facilities using flow-based models targeted at consumer refueling convenience for early AFV adopters could produce even more pronounced preference for minimizing detour than observed in Southern California CNG drivers using these commercially based stations.

Also unexplored in this study are the impacts of refueling station locations on nearby consumers' decision to *purchase* AFVs. Recent empirical research has provided insight into the types of consumers who are willing to purchase AFVs (Tal et al. 2013), but the role that proximity of infrastructure to drivers' home locations in deciding to purchase an AFV remains unclear. Visibility of infrastructure can have impacts on AFV adoption, as in the case of Argentina (Collantes and Melaina 2011), and could be a promising avenue of future research, particularly with respect to early market sales strategies aimed at boosting AFV adoption in targeted areas. The strategies for maximizing early market sales may not necessarily coincide with the results of this study, which analyzes how CNG drivers are utilizing an existing infrastructure. Figure 2.5 is inconclusive in this regard: drivers' home locations do not appear to be clustered around either the surveyed stations or other publicly available stations, and in addition it is not known whether these home locations are where the drivers lived when they purchased their CNG vehicles. Finally, the CNG refueling stations in this study are located in industrial or commercial areas, and these results are certainly representative of station locations at fleet bases, providing empirical data for decision-makers interested in these types of locations for public AFV refueling infrastructure.

2.5. Conclusion

For 59 drivers, or 22.8% of the surveyed population, the choice of station was an easy one: they could refuel both close to home and minimize deviation. When no CNG station exists that is both closest to home and most on their way, however, ten times as many drivers are observed to refuel at the station requiring the least deviation as opposed to the one closest to home. Within the closest-to-home group, the station chosen was “almost” the least-deviation station as well in 80% of the cases. In contrast, in the least-deviation group, the station chosen was “almost” closest to home in only about 1/3 of the cases and was far from being almost closest to home (not within 10 minutes) in half the cases. An additional 88 drivers, or 34% of the 259 total CNG drivers, chose a station that fit neither description, but more of these drivers were far closer to minimizing detour than to refueling at their closest facility to home. These results strongly suggest that more initial CNG drivers define convenience in terms of avoiding large detours rather than by proximity to home, though other factors may also impact their decisions.

Based on these conclusions, we suggest that the initial wave of AFV refueling stations should be focused along frequently traveled paths of drivers, such as home-work commute routes. Though placement of stations near residential areas will eventually become important, early infrastructure should focus on high-volume commuting routes, regardless of proximity to home locations, in order to serve likely early adopters of CNGVs or other fast-fueling AFVs, who use their vehicles for specific reasons. These findings have significant ramifications for early infrastructure planning of AFV refueling station locations, lending empirical evidence for the application of flow-based optimal location models as opposed to point-based models such as the *p*-median and max cover.

Given the small number of drivers (only 10) who opted for the station closest to home when no station satisfied both criteria, this study did not explore the factors influencing drivers to prefer stations close to home over stations on their way. Average deviation size differed significantly between the two groups, but more importantly, trip distances and travel time did *not*, meaning that those who chose to refuel at the station closest to their home do not appear to be doing so because they are making significantly shorter trips. The most promising lines of future inquiry are the gender difference (more females) and the size of the deviations, which were much larger for the group that opted for the station closest to home.

Additional research into the AFV purchasing decisions of consumers with respect to infrastructure placement is also necessary. This study focuses on how CNG drivers optimally utilize existing infrastructure, but the role that infrastructure location plays in the decision by a consumer to purchase a vehicle is a promising avenue of future study, the findings from which could then be operationalized in a location model that minimizes driver deviation and maximizes vehicle sales. The conclusions of this study need to be validated against drivers in different regions operating on different transportation infrastructures with stations located in more residential or retail areas. These conclusions are also not transferable to all alternative fuels or refueling infrastructures. AC/Level 2 electric vehicle charging stations should be determined by other criteria, given the long charging time. We also cannot extend these conclusions to alternative fuels with significant use of home recharging or home refueling, because that would be expected to even further reduce the need for public recharging or refueling close to home. Likewise, we do not yet know if these results translate to plug-in hybrid, flex-fuel (multi-fuel) or diesel vehicles that can easily fill up with gasoline or diesel when running low and no charging station or E85 or biodiesel station is available on the way or close to home. For installation of AFV refueling stations that do not commonly serve dual-fuel vehicles or refuel at home, such as hydrogen, CNG, and propane, these findings would be appropriate.

Chapter 3. AFV Refueling Stations and the Complexity of Freeway Interchanges: the Scale Dependency of Regional Highways on Local Street Networks

3.1. Introduction

With the emerging success of alternative fuel vehicle (AFV) manufacturing companies such as Tesla and the introduction of hydrogen vehicles to the consumer market in California in 2015, public interest in AFVs continues to grow. Though recharging infrastructure for electric vehicles (EVs) has proliferated in recent years, it remains sparse for fuels such as hydrogen, compressed natural gas (CNG), liquefied natural gas (LNG), and biofuels. This limited refueling infrastructure remains a crucial barrier to widespread adoption of these vehicles, which differ from EVs in that they refuel much more quickly and are generally not refueled at home. Initial placement of a public network of refueling stations for these AFVs is thus a more critical need that should be governed by a different set of location criteria than for EVs.

CNG and hydrogen are similar alternative fuels with respect to driving range (200-300 miles) and refueling speed (around 5 minutes). Initial evidence from surveys of CNG drivers conducted in Los Angeles indicates the appropriateness of deploying these types of AFV refueling stations along frequently traveled paths instead of focusing on residential areas (Kelley and Kuby 2013). In contrast, current development plans for hydrogen refueling stations in California suggest locating initial stations near where likely early adopters will live, followed by some stations that allow travel between clusters (Ogden and Nicholas 2011; Greene et al. 2008). While it is reasonable that early adopters would be more likely to purchase an AFV knowing there was a station near their home (Fayaz et al. 2012), widespread sustained success at a metropolitan scale could be limited by consumers' inability to drive along frequently traveled thoroughfares outside of these home-based cluster areas if there were no reliable network of stations along the way. Further, initial stations in centrally located, visible locations could expose a greater number of people from disparate areas of a region to AFV infrastructure and technology (Collantes and Melaina 2011).

To address the impact of passing traffic, some have incorporated roads with high traffic counts into their assessment of promising refueling station locations (Melendez and Milbrandt 2008; Plummer et al. 1998; Goodchild and Noronha 1987), but simply locating stations along busy roads cannot account for origins and destination of potential refueling trips. Continuous approaches have also been explored to provide station developers with minimum infrastructure needed along highway corridors (Sathaye and Kelley 2013), but this work provides density guidelines instead of exact sites. Flow-based facility location models do provide exact locations for stations, and they do use origin-destination traffic data, which accounts not just for volume but also direction of travel. This makes this classification of models applicable to metropolitan areas where limited initial refueling infrastructure will be built.

Hodgson (1990) and Berman et al. (1992) introduced the first flow-capturing models, which locate facilities such as banks or automated teller machines on an arc-node representation of a geographic network with the explicit goal of maximizing the amount of traffic passing by these facilities. Flow-capturing models have been considered for many applications outside of refueling station location, including billboard placement (Averbakh and Berman 1996; Hodgson and Berman 1997), vehicle inspection stations (Mirchandani et al. 1995), and locations for park-and-ride facilities (Horner and Groves 2007). Kuby and Lim (2005) specifically tailor this flow-based modeling logic to the problem of where to deploy initial AFV refueling infrastructure, incorporating the limited driving range of AFVs in the Flow Refueling Location Model (FRLM). This model allows paths to be traversable by potential AFV drivers by using a combination of refueling facilities instead of the single facility constraint in Hodgson's (1990) formulation. Since the FRLM's initial development, reformulations have improved the solution time of the model and helped to apply it to specific geographies (Capar et al. 2013; Kim and Kuby 2012; MirHassani and Ebrazzi 2012; Wang and Wang 2010; Zeng et al. 2008; Wang and Lin 2009).

Flow-based models identify network nodes at which to locate facilities, but the question of precisely where to acquire a parcel of land and build a station that will effectively capture passing traffic at a geographic representation of a road intersection remains a challenge. Digital representation of geographic data used by flow-based station location models is limited to relatively simple data structures due to the size and complexity of the solution methods. While that process does allow the model to produce a feasible solution, the omission of the local road network from regional representations of a transportation network, or aggregation of them to simpler features, creates uncertainty in the scalability of results between regional highway networks and local street networks. Typically, companies that use operations research models will pass the task of finding a suitable parcel to real-estate specialists, who will search within a radius of the optimal network nodes chosen. If not selected strategically, the final selected parcel may be substantially less convenient than indicated by the location model.

Each day, hundreds of thousands of vehicles pass through areas where major freeways intersect, making them likely optimal station sites for flow-based models such as the FRLM. It is impossible, though, to build a refueling station directly where limited-access highways intersect, requiring station developers to choose a location on the nearby local street network if that freeway interchange site is selected. Therefore, a driver's ability to exit a busy, limited-access highway, access a refueling station, and continue their trip on a freeway with a minimal amount of confusion or detour is a likely requirement for drivers to consider a station location near a freeway interchange as a viable option for refueling, and is currently unaccounted for in flow-based models for AFV station location. An example of this interrelationship between flow-based modeling results and the specific scale of street networks near freeway interchanges is demonstrated in Figure 3.1.

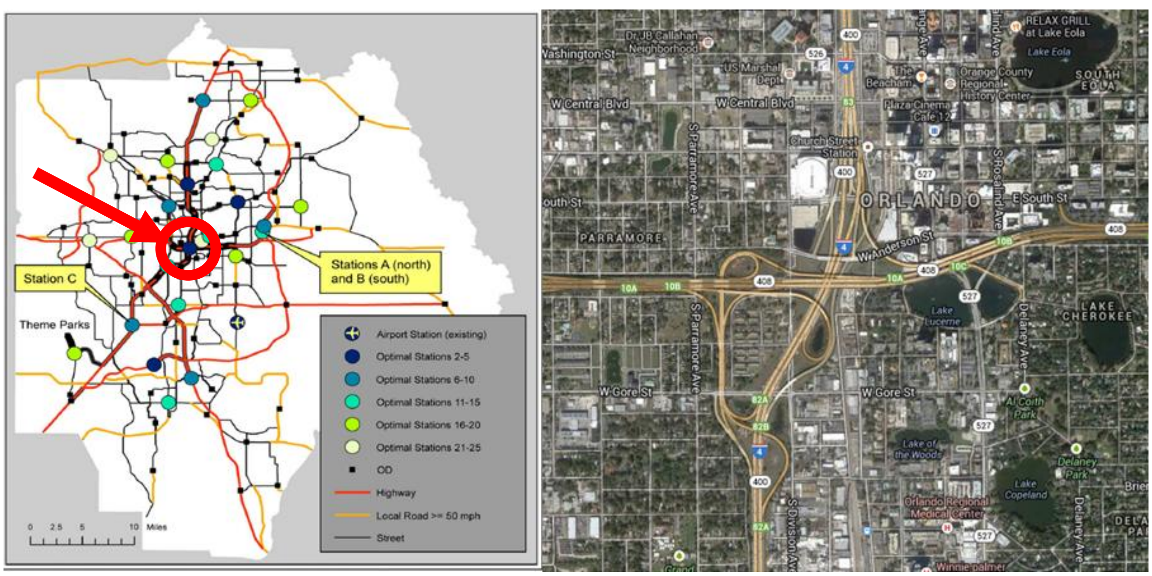

Figure 3.1. Optimal locations for hydrogen stations for FRLM in Florida (left), and the downtown station location area in Orlando, FL. Source: Kuby et al. 2009, Google Maps.

The left panel of Figure 3.1 is an example of results generated by the Flow Refueling Location Model (FRLM), which locates *p* facilities for the metropolitan Orlando, Florida area. The node in the road network that represents the intersection of Interstate 4 and State Highway 408 near downtown Orlando can capture the highest volume of passing traffic of any candidate site, making it an optimum station location for the Orlando region. The right panel of Figure 3.1 is a detailed view of the location that the FRLM recommends for hydrogen station construction, and it is unclear exactly where to place that station in such a way to facilitate refueling convenience for all passing traffic, which is what the FRLM implicitly assumes. Currently, flow-based station location models represent a freeway intersection node's interception of passing traffic as a binary variable, but its actual ability to capture passing traffic may be better represented as a proportion or fraction if station locations on the street network nearby are only convenient for a subset of travel paths through the interchange.

One way to measure this convenience is through analysis of deviations from a shortest path to reach a station. The initial flow-capturing models formulated by Hodgson (1990) and Berman et al. (1992) were structured as location problems, not location-allocation problems, since they did not explicitly account for where flow-based demand was served, and did not take deviations from a shortest path into account. Berman et al. (1995) first relaxed the constraint that customers must travel on a shortest path between an origin and destination to reach a facility, allowing deviations. Since then, deviations to reach a facility have been assessed by generating multiple paths aside from the shortest one between origin and destination (Li and Huang 2014; Zeng et al. 2008). This is incorporated into the Deviation Flow Refueling Location Model (DFRLM) for AFV stations, which uses pre-generated alternative routes between origins and destinations to produce an optimal solution, considering vehicle ranges and varying deviation tolerances (Kim and Kuby 2012). Yildiz et al. (2015) introduced a formulation of the DFRLM that does not rely on pre-generated routes, improving the solution time.

The magnitude of deviations in a road network is related to the relative positions of origins and destinations (Miyagawa 2010), but what consumers consider to be acceptable deviations on a road network is subject of recent study. Arslan et al. (2014) found that 2.5% of AFV drivers prefer to refuel on travel paths that were not the shortest travel path, and that deviation tolerance is higher when refueling networks are more sparse. They also note that drivers on longer trips do not consider deviations to reach refueling stations to be a significant factor, since the deviation travel time and distance is a small percentage of their overall trip length. Lines et al. (2008) finds evidence for this willingness to deviate, noting that early adopters stated that they would go a mile out of their way in order to access a hydrogen refueling station in Orlando, Florida. For travel time deviation, Kelley and Kuby (2013) find that AFV drivers tolerate up to about a six-minute deviation when accessing compressed natural gas (CNG) stations in Southern California before exhibiting a sharp decay. This deviation tolerance threshold will be used here to assess accessibility of potential station locations from limited access highways. If a driver can reach a station location that does not require them to deviate beyond six minutes from their shortest path travel time, and if this occurs for as many travel directions as possible through a freeway interchange, a location may be considered generally convenient for all drivers passing through these structures. Previous studies that compare travel paths involving different sets of major highways or freeways do not address the need to leave and return to limited access roads before continuing their trip, which is a key contribution of this paper.

Intersections of freeways are often topologically complex structures with a number of ramps, underpasses, overpasses, traffic signals, and one-way streets, all of which may act as impedances between limited access highways and station locations on surface streets, potentially limiting the willingness of drivers to access them. This indicates that analysis of the local, hierarchical, complex road network including and surrounding freeway interchanges is required for flow-based models to effectively provide recommendations for precise station locations, and is a previously unexplored topic in the AFV station location literature. More generally, this issue highlights the interrelationship between the effectiveness of locating refueling stations at the scale of a regional highway network and the scale of local road networks near a freeway interchange.

From this foundation, the research question of this paper is: what is the expected accessibility of potential AFV refueling station locations on local street networks near freeway interchanges? Specifically, can these sites be accessed with minimal deviation for all possible travel directions through complex freeway interchanges, and are there relationships between effective locations and interchange design type and local network characteristics that can be generalized across the study area, and potentially, other geographies? A new network GIS method is developed that can assess if a driver can leave a limited-access highway, reach a refueling station site, and continue on his or her trip in a convenient manner for all possible travel directions through a freeway interchange. The design of an interchange (three-, four-, and five-way interchange junctions), the relative prevalence of connector roads from entrances and exits, and distance from the center of the interchange are all tested against refueling accessibility measures for potential station sites within one mile of freeway interchanges. It is hypothesized that more complex, dense, interchange networks should present a greater volume of good candidate sites than those with less complexity. It is also hypothesized that good candidate sites are relatively close to a given interchange's center, but not necessarily adjacent to freeway entrances or exits, since those provide convenient access for only a subset of possible travel directions that drivers navigate through these structures. This focus on interchange network accessibility represents a key gap in the AFV station location literature that must be addressed given their frequent recommendation by flow-capturing facility location models.

The greater Los Angeles area includes a relatively high number of freeway interchanges compared to other metropolitan areas. Given the region's reliance on the automobile for personal transportation, these freeway interchanges carry high volumes of traffic through them each day, making them sites of interest to the flow-based modeling approach for AFV station location. These intersections feature some consistent designs (i.e., four-way cloverleaf, three-way T-junction), but each one's connectivity to the local road network may differ. Those offering a greater variety of connectivity options from freeway to local road and back may provide more promising locations for AFV infrastructure placement, but could also act as barriers to drivers unable to see the station and unwilling to navigate a complex local road network.

3.2. Data and Methods

Seventy-two freeway interchanges are located in the greater Los Angeles metropolitan area, and each was abstracted as a point feature in a GIS environment, representing the approximate central location of the freeway interchange structure. From this central point, a one-mile circular buffer was created in GIS to define the extent of the local road network of each freeway interchange, in which potential stations could be built. Adaptive buffers that account for non-uniform directionality from a central point have been applied in other studies, including those that account for pollution dispersion (Chakraborty and Armstrong 1997), accessibility (Miller 1999) or consumer preferences in delineation of service areas (Okabe and Kitamura 1996). While this study assumes a simple circular buffer away from the central interchange point instead of these alternate forms, this shape is applied because it is unknown if directional bias exists in the relationship between effective sites for refueling stations and interchange centers. Since only one station can be built within an interchange area during initial infrastructure deployment, and that station must necessarily be in close proximity to the interchange in order to capture all passing travel routes, this ensures that station developers will find effective sites in such locations.

3.2.1 Interchange Metrics and Candidate Nodes

Within each one-mile circular buffer, all nodes and arcs were used to compute metrics relative to general interchange complexity. To ensure topological consistency, all ends of arcs within the freeway interchange road network had to be coincident with a node located within the one-mile buffer, so arcs that crossed the boundary of the interchange buffer were not considered part of the one-mile network.

Candidate nodes were defined as intersections of either arterial or collector surface streets that were not topologically adjacent to freeway arcs. Nodes that represented underpasses or overpasses were excluded from the set of candidate nodes, and no additional candidate sites were generated along arcs between candidate nodes. Access arcs are those that facilitate access between surface streets and freeways, such as on-ramps, off-ramps, or frontage roads that connect freeways to the surface streets. Exit nodes are those near freeway entrances or exits, and defined as those candidate nodes that represent a direct intersection between access arcs and the local street network, and all other candidate nodes within a 0.1 mile radius. These are the types of locations where gasoline stations are commonly found along highways and freeways, and the impact of these locations' ability to serve all possible travel directions through an interchange is of interest to this study.

3.2.2 Freeway Traffic Capture Algorithm

This paper introduces a new method, named the Freeway Traffic Capture Algorithm (FTCA). The algorithm generates a score that assesses the relative effectiveness of each candidate node *k's* ability to serve as a viable proximate station location for the freeway interchange. It specifically measures if a street intersection can capture as many travel paths as possible that pass through the nearby freeway interchange with a user-defined deviation threshold. For each candidate node, the algorithm compares the shortest travel path through the interchange with no intermediary stops against the shortest travel path through the interchange that includes one refueling stop at the node in question. If the difference in travel time, also known as deviation, between the two routes is tolerably low, then the node is considered a viable station location for that particular travel direction.

For this study, the deviation tolerance threshold is considered to be six minutes, which is the point at which deviation frequency began to decay among the sampled population of 259 CNG drivers in Kelley and Kuby (2013). An illustration of an interchange, the aforementioned metrics, and an example of a comparison of travel routes is shown in Figure 3.2. In this case, point A is an artificial origin and point C is an artificial destination. Each of these points is along a limited access freeway. Point B is a candidate node on the local street network. If the shortest path, based on travel time, of a sequential route that travels through points A, B, and C is no more than six minutes greater than the shortest path travel time between only A and C, then location B is considered a viable refueling station location for freeway travelers moving from the west to the north through this interchange.

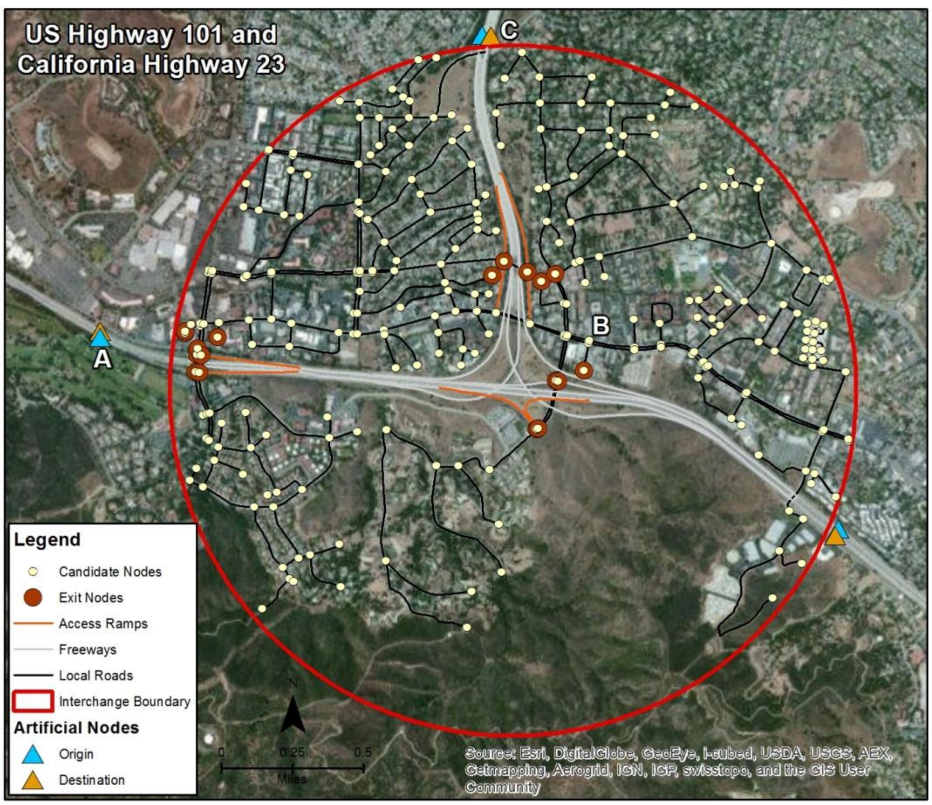

Figure 3.2. Example of a freeway interchange that illustrates a deviation from a shortest path along a freeway travel path to reach a station location.

To compute the shortest travel time paths for all interchanges and travel directions, sets of artificial origin and destination points were generated for each freeway interchange network along all limited access arcs both entering and leaving the local network (Figure 3.2). This allowed for the generation of shortest travel time paths through the interchange (Figure 3.3), using all possible combinations of origin-destination (*ij*) pairs, except same-pair routes, which were ignored for this analysis. Three-way interchanges required three origin and three destination points, creating 6 possible travel paths. Four-way interchanges required four origin and four destinations points, with a total of 12 travel paths (as shown in Figure 3.3) and five-way interchanges generated 20 travel paths.

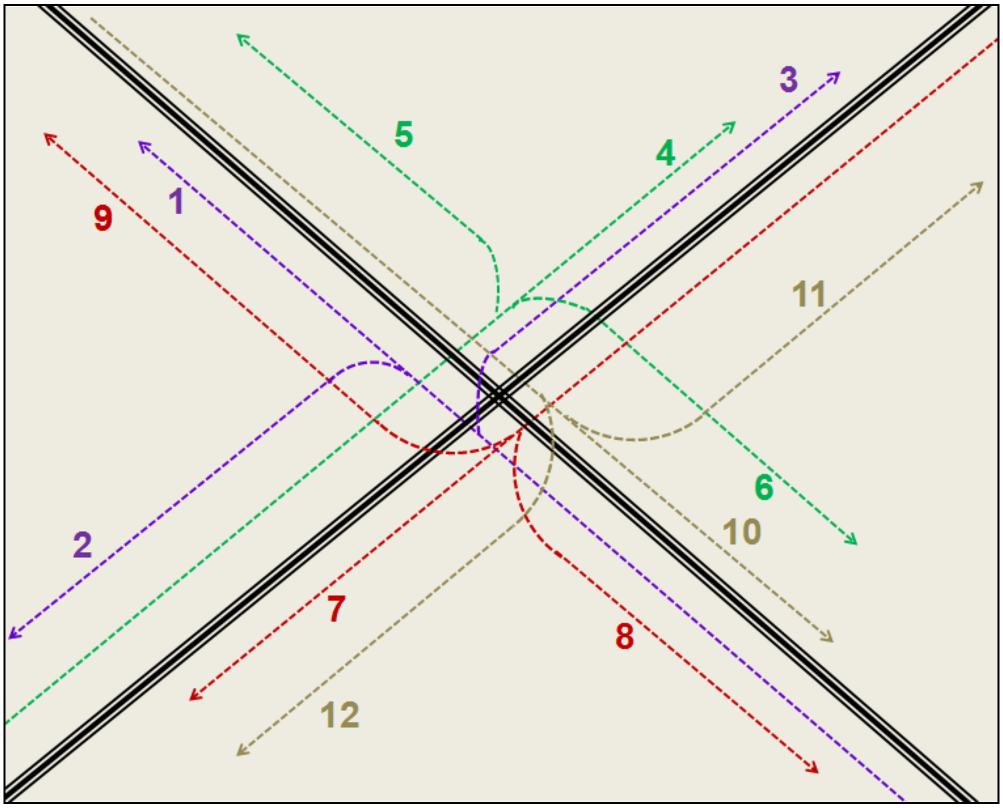

Figure 3.3. All possible shortest travel time paths (t_{ij}) for a four-way interchange.

Prior to running the algorithm, artificial origin and destinations were abstracted as point features using the Editor tool in ArcGIS 10.1, and were placed beyond the first exit or entrance external to the interchange neighborhood. This ensures that all travel paths can leave the limited access highway, reach any intersection of local roads within the one-mile interchange network, and continue along a freeway route to leave the vicinity. For each possible travel path through the interchange, the shortest path time (t_{ij}) and distance is recorded and stored, and then each candidate node (k) in the interchange network is entered as a new intermediary stop in the route. This new travel route (t_{ikj}) produces a separate shortest path travel time and distance, and if the difference between the travel time of t_{ikj} and t_{ij} is less than six minutes, the candidate node (k) for that shortest path through the interchange is given a score of 1 ($X_{pk} = 1$), otherwise, the route through the node receives a score of 0 ($X_{pk} = 0$). This process is repeated for *k* nodes in the interchange, and then for each shortest path route, until all candidate nodes are assessed for all travel directions. Finally, the Freeway Traffic Capture Algorithm score (A_k) is computed for each candidate node *k* in the network, formally defined as:

$$A_k = \frac{\sum_{i=1}^{p} X_{pk}}{P} \quad (1)$$

where:

A_k = algorithm score for candidate node *k* (continuous variable between 0 and 1)
X_{pk} = for path *p* through interchange, 1 if $t_{ikj} - t_{ij} \leq 6$, 0 otherwise
t_{ij} = shortest travel path (in minutes) from artificial origin *i* to destination *j*
t_{ikj} = shortest travel path (in minutes) from artificial origin *i* to candidate node *k* to destination *j*
p= index of travel path through the interchange
P = total number of travel paths through the interchange

The algorithm was constructed in the Python 2.7 programming language, and accessed the Network Analyst submodule of ArcPy. The average computation time for one travel direction for one interchange was 40 minutes, but varied depending on the number of candidate nodes in the buffer area. The road network dataset that contains arc distances, travel times, and turn penalties was generated in the ArcGIS 10.1 environment and reality-checked against results of popular web mapping APIs. The method introduced in this study could easily be extended to non-circular buffers in future work.

3.2.3 Traffic Flow

As constructed, the FTCA outlined in Section 2.2 inherently weights all possible travel directions through an interchange equally, but certain travel routes through interchanges carry more traffic than others. Uneven traffic flow is incorporated into the weighted FTCA using the following equation, which is a variation on Equation 1:

$$WA_k = \frac{\sum_{i=1}^{p}(0.5*f_p)\,X_{pk}}{\sum_{i=1}^{p}(0.5*f_p)} \tag{2}$$

where:

WA_k = weighted algorithm score (continuous variable between 0 and 1)
f_p = traffic freeway traffic flow volume along travel path p

Data on the traffic flow along the six, twelve, or twenty travel paths between the artificial origins and destinations through the interchanges generally do not exist. Available datasets typically include flow volumes between traffic analysis zones and traffic count data. The former employs predicted travel routes between zones to estimate traffic flow volumes, but not observed data. Annual average daily traffic (AADT) data from the California Highway Department data repository for the year 2013 do provide traffic counts (arc flows) at locations along limited access highways, which correspond to the approximate locations of the digitized artificial origin-destination point locations. To provide a rough estimate of the amount of traffic moving along the six, twelve, or twenty travel paths, the flow coefficient values (f) for each shortest travel path were derived as a sum of the origin point’s inbound traffic volume and outbound destination point’s traffic volume. This inherently double-counts traffic flow through the interchange since at least some of the traffic from the origin point moved to the destination point and was counted again, so flow volumes were halved to control for this. As in Equation 1, all traffic for the shortest travel path is considered to be captured by a candidate site *k* if the difference in travel times is less than the deviation threshold of six minutes. In (2), the sum of these traffic volumes are then divided by the total traffic volume observed in the AADT data for the interchange, providing a weighted and standardized value for traffic capture at each candidate site *k*.

3.2.4 Statistics and Topological Analysis

For each interchange, descriptive statistics were tabulated, including number of candidate nodes and exit nodes, number and length of arcs, and number, length, and percentage of arcs in the network classified as access arcs such as on-ramps, off-ramps, and frontage roads that connected ramps to surface streets. T-tests and ANOVA tests were first used to detect statistically significant differences between general interchange characteristics. Then, distributions of all unweighted and weighted FTCA scores and nodes' locations relative to interchange centers were generated. Next, statistical tests were conducted to detect differences in FTCA scores both within and across interchanges, focusing on factors such as interchange design, complexity, and distance from interchange center.

A general topological measure was applied to generate a formal mathematical metric of each network's complexity (Xie and Levinson 2007; Buckwalter 2001). The networks used in this analysis incorporate the complexities of freeway interchanges, and are represented in this study as non-planar graphs, which can be expressed as $G = (V,E)$, where V = the number of vertices (nodes) in the network, and E = the number of edges (arcs) in the network, except that nodes do not have to exist wherever edges intersect, such as at an overpass or underpass. From this basis, network topological metrics were expressed through graph theory measures of non-planar networks, including the Beta index, which provides a global complexity measure for the local street network (see Haggett and Chorley 1969). The ratio of arcs to nodes, known as either the Beta index or link-node ratio, will exhibit higher values with better connected and more complex networks. These types of network measures have been used to explore relationships between traffic volumes and network complexity (DeMontis 2005), but not to refueling station access.

3.3. Results

In total, 44,921 candidate nodes were identified and assessed for both unweighted and weighted interchange FTCA scores within a one-mile radius of the 72 freeway interchanges in greater Los Angeles, California. The number of candidate nodes ranged from 32 in a buffer zone network with a total road length of 12.5 miles (at the intersection of California Highways 133 and 241 in Orange County) to 1,131 candidate nodes and a total road length of 100.3 miles (at the intersection of Interstates 110 and 105 south of downtown Los Angeles). The median number of candidate nodes per interchange is 656, with an interquartile range between 462 and 826. General interchange statistics can be found in Appendix B.

3.3.1 Interchange Physical Characteristics

The average road length within the one-mile area around Los Angeles freeway interchanges is 58.3 miles, with higher values in interchanges with more travel directions. Accounting for all nodes and arcs, the mean Beta Index value for all interchanges is 1.17, ranging from 1.0 at the intersection of California Highways 133 and 241 to 1.39 at the intersection of California Highways 170, 134 and US Highway 101 in North Hollywood. Of the 72 interchanges in the study area, 38 are classified as four-way interchanges, such as the cloverleaf design, and 31 as three-way interchanges, such as the T-junction. There are also three five-way interchanges with the most complex networks in the sample, but given the limited sample size, statistical comparison of this interchange type to others is difficult. Isolating the three and four-way interchanges, then, there was observed variability in some of the key characteristics of freeway interchanges, based on these configuration classifications (Table 3.1).

Table 3.1. Statistical comparison of freeway interchanges: 3-way vs. 4-way. *significant at α=0.5 level, $^{+}$significant at α=0.1 level.

Factor	3-way (mean), n=31	4-way (mean), n=38	t-Statistic	*p* value
Total Nodes	726.21	1,109.84	-4.05	<0.01*
Total Arcs	839.45	1,295.82	-3.97	<0.01*
Candidate Nodes	529.84	695.82	-2.63	0.01*
β Index (all nodes)	1.15	1.18	-1.69	0.09+
Exit Nodes	35.25	66.45	-3.52	<0.01*
Total Access Arcs	91.19	176.05	-4.75	<0.01*
Pct Access Arcs	12.75	14.21	-0.73	0.47
Pct Access Arc Length	12.22	13.32	-0.67	0.50
Arc Length (mi)	46.98	66.56	-4.35	<0.01*
Access Arc Length (mi)	5.20	8.32	-4.85	<0.01*

Inbound AADT	547,571	874,591	-7.68	<0.01*

There are statistically significant differences observed in several metrics between interchange types. In the case of total nodes, total arcs, candidate nodes, exit nodes, total arc length, total access arcs, total access arc length, and inbound traffic per day, the four-way interchanges exhibited significantly higher values than three-way interchanges. Given the greater volume of infrastructure needed for a four-way interchange relative to a three-way, and their subsequent ability to move traffic, these differences are not surprising. The relative percentage of access arcs, both in count and in length, exhibits no significant difference between the two general freeway configurations. The Beta Index value is also significantly higher for four-way interchanges than three-way interchange (α=0.10). These results suggest that four-way interchanges are more complex structures than three-way interchanges, and they also offer significantly more candidate nodes.

3.3.2 Candidate Node FTCA Scores

Figure 3.4 provides examples of FTCA scores for all candidate nodes within one mile of two interchanges in greater Los Angeles. The left panel of Figure 3.4 is an interchange with many nodes capable of capturing all passing traffic, and the right panel is an interchange network without a single $A_k = 1.0$ location. There is a noticeable cluster of A_k=1.0 nodes near the center of the interchange network at the junction of US Highway 101 and California 110 near downtown Los Angeles, with a noticeable distance decay of A_k scores away from the center, and the first $A_k = 0.0$ node is not encountered until beyond 500m.

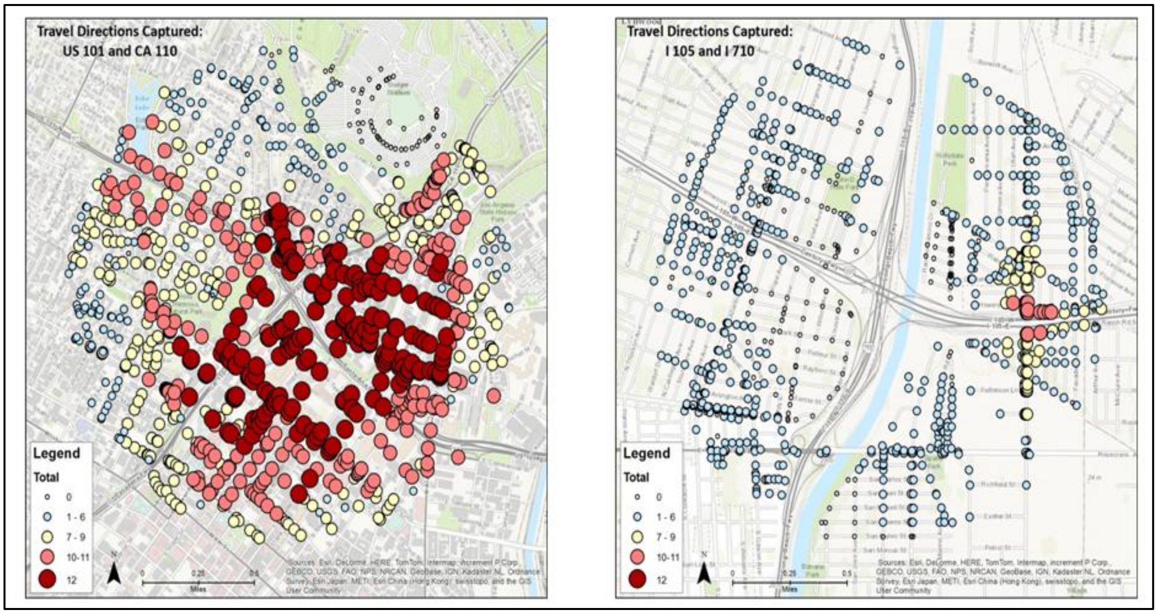

Figure 3.4. Examples of FTCA scores for two interchanges in greater Los Angeles.

The intersection of the Century Freeway (Interstate 105) and Harbor Freeway (Interstate 710) in Lynnwood has a small cluster of candidate nodes capable of capturing most, but not all, of passing traffic. These are concentrated around the Garfield Ave exit along the Century Freeway. The majority of the candidate nodes' A_k scores are less than 0.5, and are dispersed throughout the interchange neighborhood, including around freeway exits both west of and south of the interchange.

Across all interchanges and all nodes, the distribution of all sites' ability to capture passing traffic near greater Los Angeles's freeway interchanges is shown in Figure 3.5. In total, $A_k = 1.0$ for 6.7% of all candidate nodes, $A_k = 0.0$ for 18.4% or candidate nodes, and the other 74.9% of candidate nodes offer partial coverage. The weighted average FTCA score is 44.5% and the median is 41.7%. The mean unweighted FTCA score is 43.9%, with a median of 43.6%. More than half of the candidate nodes within three-way freeway interchanges had an A_k score of 0, but they did provide a greater percentage of A_k = 1.0 sites than four- or five-way interchanges. Using the weighted FTCA scores, only 35% of all candidate nodes could capture at least 60% of passing traffic, and of these, half feature WA_k scores between 0.6 and 0.8.

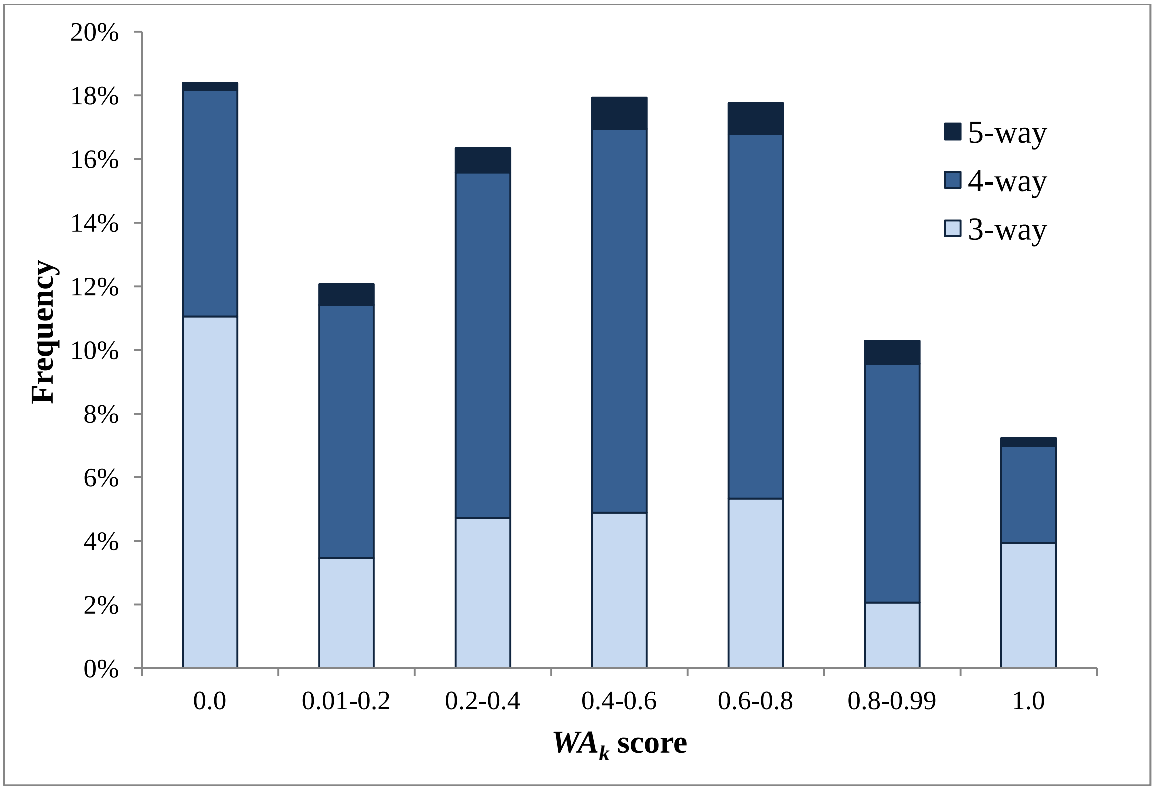

Figure 3.5. Distribution of WA_k scores, classified by general interchange type.

3.3.3 FTCA scores and Distances from Interchange Center

The relationship between candidate nodes' FTCA scores and distance from the interchange center is considered next. The number of total candidate nodes increase in expected fashion with each distance band away from the interchange center as a result of increasing area, but the distribution of A_k = 1.0 nodes does not follow this pattern (Figure 3.6).   The number of sites that can conveniently serve all possible travel directions reaches a maximum around 500m from the interchange center before exhibiting a decline around 1000m, then reaching a secondary maximum around 1300m. Nearly 20% of all candidate nodes from 200-500m have an A_k score of 1.0, but beyond 800m, they never account for greater than 10% of all candidate nodes for any distance band.

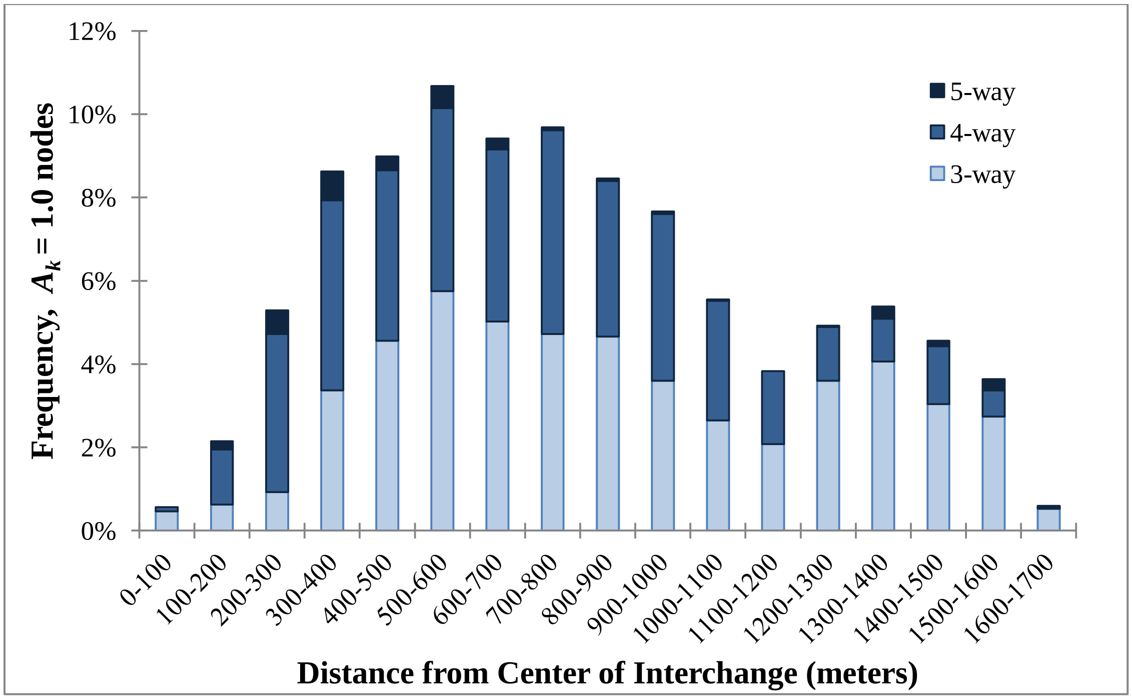

Figure 3.6. Relative frequency of nodes where A_k = 1.0, by distance.

The locations of A_k = 1.0 candidate nodes that are farther from the interchange center (beyond 1200m) are predominantly those within 3-way interchange neighborhoods. Those closer to the interchange (within 400m) are mostly those within 4-way interchanges, and A_k = 1.0 nodes for five-way interchanges reach their relative maximum between 200-600m. Candidate nodes where A_k = 1.0 are not uniformly distributed by 100m distance thresholds throughout interchanges (Table 3.2), weighting expected values by the area of each distance band (χ^2=2052, p<.001). This indicates that there is spatial variability in A_k = 1.0 sites' locations within interchange networks.

Table 3.2. Distribution of A_k = 1.0 nodes against distribution of all nodes and exit nodes.

Distance	All Nodes			Exit Nodes		
	A_k = 1.0	Total Nodes	% A_k=1.0	A_k = 1.0	All Exit Nodes	Relative % A_k=1.0
0-100m	17	237	7.17	16	36	94.12
100-200m	65	460	14.13	28	91	43.08
200-300m	160	750	21.33	84	175	52.50
300-400m	261	1189	21.95	105	251	40.23
400-500m	272	1416	19.21	101	214	37.13
500-600m	323	1947	16.59	78	225	24.15
600-700m	285	2271	12.55	72	215	25.26
700-800m	293	2539	11.54	91	225	31.06
800-900m	256	2932	8.73	51	191	19.92
900-1000m	232	3339	6.95	64	254	27.59
1000-1100m	168	3708	4.53	43	362	25.60
1100-1200m	116	3906	2.97	10	259	8.62
1200-1300m	149	4462	3.34	36	337	24.16
1300-1400m	163	4711	3.46	70	362	42.94
1400-1500m	138	5157	2.68	46	309	33.33
1500-1600m	110	5356	2.05	25	365	22.73
1600-1700m	18	541	3.33	3	42	16.67
Total	**3026**	**44921**	**6.74**	**923**	**3913**	**28.43**

The importance of candidate nodes located near freeway entrances or exits is also considered in Table 3.2. Exit nodes are the general locations where the local street network and freeway on- or off-ramps intersect, and are common locations for existing gasoline stations. The average A_k score of all candidate nodes within 0.1 mile of these highway exits is 72.7, but this value is not significantly higher than that of the entire population of candidate nodes (z=0.87, p=0.19). Nodes near freeway entrances and exits represent only 28% of all A_k = 1.0 nodes. Their relative prevalence within the set of all A_k = 1.0 nodes is highest close to the interchange center, accounting for 42% of those nodes with the ability to capture all passing traffic between 200-500m from the interchange. The secondary increase in A_k=1.0 nodes between 1300-1500m, visible in

Figure 6, is also partially explained by these sites, which are 39% of all A_k = 1.0 nodes at these distances away from the middle of the interchange.

Though it is difficult for locations far from the interchange center but near freeway entrances or exits to be convenient for *all* travel directions, they do perform well at capturing at least *some* passing traffic: only 1% of candidate nodes where A_k = 0.0 are near freeway exits. Some sites directly at freeway entrance and exit sites, but just beyond the one-mile interchange neighborhood boundary, were tested to ensure that additional promising candidate sites were not ignored, but deviations to reach these sites exceeded six minutes for travel directions that did not pass by these locations.

Isolating the factor of general interchange configuration, there was a statistically significant difference in mean A_k and WA_k scores at the candidate node level between three-and four-way interchanges (t=-21.98, p<0.01 and t=-25.98, p<0.01, respectively) and between three, four, and five-way interchanges (F=311.87, p<0.01 and F=409.73, p<0.01 respectively). Though the average FTCA scores of nodes in 3-way interchanges are significantly lower than those of their 4-way counterparts, these interchanges do have a greater percentage of candidate nodes with the ability to capture all travel directions (Table 3.3). There is also a statistically significant difference in distances between the center of the interchange and nodes where $A_{k\,=}$ 1.0 (F=70.15, p<0.01) between interchange configuration groups.

Table 3.3. Interchange configuration sub-types and FTCA metrics.

Group	**Candidate Nodes**	**Total**	**A_k score (mean)**	**WA_k score (mean)**	**A_k=1.0 (%)**	**A_k=0 (%)**	**Mean Distance A_k=1.0**
3-way	15,938	31	39.6	38.2	11.1%	31.2%	874
4-way	26,931	38	46.7	46.6	5.1%	11.8%	725

5-way	2052	3	52.6	52.0	5.3%	5.0%	648

3.3.4 Interchange-level FTCA Scores

Spatial variability of FTCA scores occur at the interchange level, as the general patterns found in the previous sections did not apply to all interchange networks. In the greater Los Angeles area, 50 interchanges had at least one candidate node that could capture all possible travel directions, but 22 lacked a single candidate site where $A_k = 1.0$. There are noticeable clusters of interchanges with both overall higher and lower connectivity, based on the median WA_k score (Figure 3.7). There are four interchanges in the downtown Los Angeles area where the median WA_k score is 0.6, and in all four cases, $A_k = 1.0$ for greater than 10% of all candidate sites. Turning to the key element of traffic capture, each of these interchanges in the downtown area carries greater than 750,000 vehicles per day. Some of these drivers travel from distant commuting locations, making them ideal candidates for nodes chosen by the flow-based modeling approach. Most of the higher traffic volume interchanges are along Interstates 5 and 405, and are in the central part of the metropolitan area, while the lighter volumes occur at the fringes of the study area.

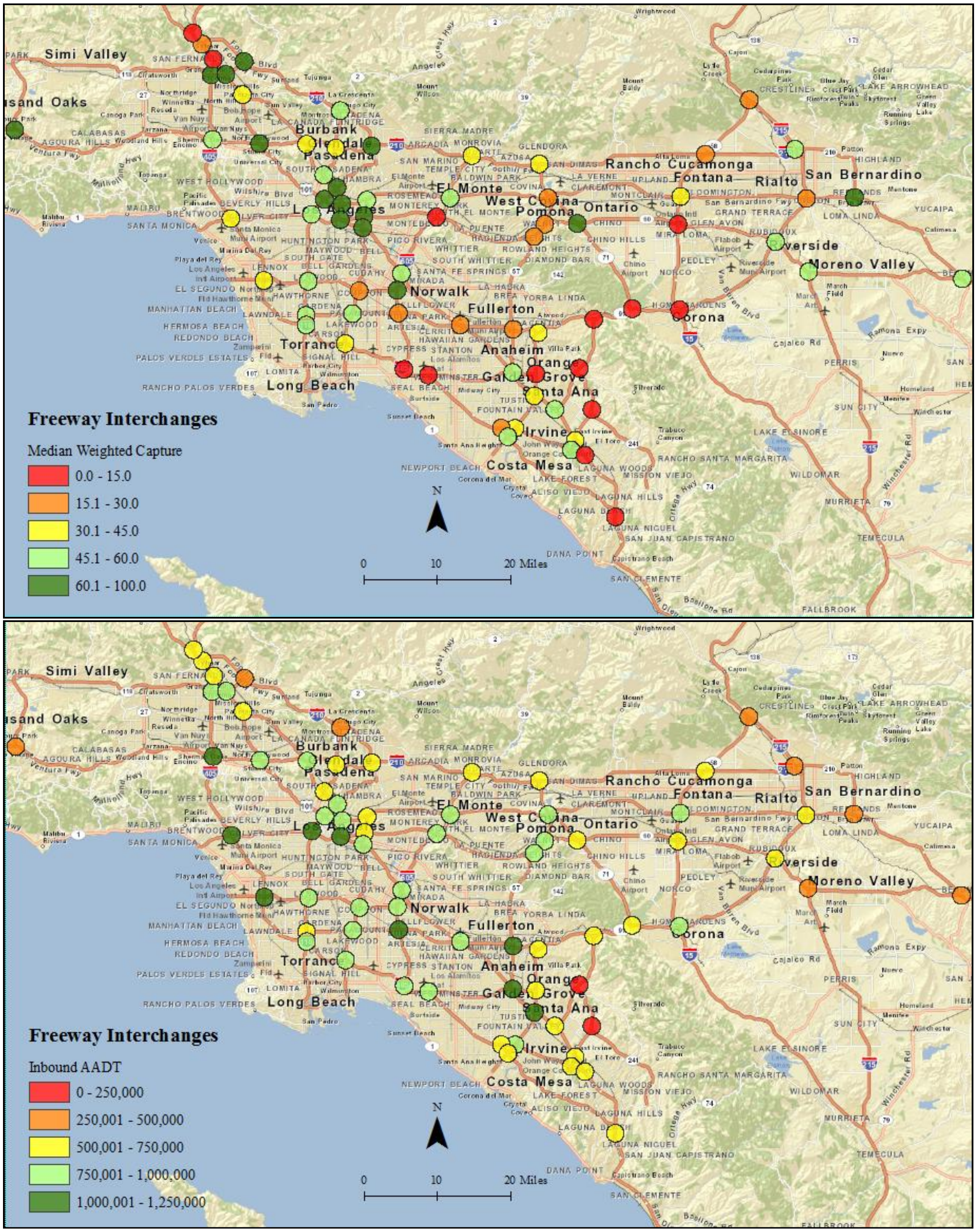

Figure 3.7. Los Angeles freeway interchanges, showing median WA_k scores per interchange and inbound AADT. Circles are sized to the 1-mile buffer area for each interchange.

Some of the interchanges with few sites capable of capturing passing traffic are coincident with some of the lower-traffic interchanges, but a number of interchanges that carry high traffic volumes offer relatively limited options for AFV refueling stations as well. For all junctions between Interstate 10 and Interstate 605 along the heavily-traveled Interstate 405 commuting corridor, there is not a single candidate node capable of capturing all refueling paths through an interchange, and each carries at least 750,000 vehicles per day. A similar situation exists along commuting corridors from the "Inland Empire" to both downtown Los Angeles and Orange County, which generally have very low traffic capture scores and more modest traffic flow volumes.

3.3.5 Differences in Interchange Characteristics

To determine which factors differ for interchanges that have at least one location capable of covering all refueling paths through an interchange, the interchanges were split into two categories: those that had at least one candidate node capable of covering all refueling routes and those that did not. Network complexity, measured by the Beta Index, or link-node ratio, is significantly lower for those without any candidate node where $A_k = 1.0$. These interchanges also have a higher percentage of access arcs such as on-ramps and off-ramps (Table 3.4). Road length and number of candidate nodes at or near freeway entrances or exits within the interchange networks did not significantly differ.

For each interchange, the overall relationship between FTCA score and distance from interchange center was converted to a scatterplot. Figure 3.8 provides examples of these scatterplots, which correspond to the interchanges shown on the maps in Figure 3.4.

A regression line was fitted to describe this relationship for each interchange, as shown in Figure 3.8. There is a relatively strong negative relationship between both unweighted and weighted FTCA score and distance from the center of the interchange for those interchanges with higher overall average traffic scores (Figure 3.8, left panel). The general slope of this relationship is significantly more negative for interchanges with at least one candidate node where A_k =1.0 (Table 3.4). Of the 50 interchanges with at least one node that captures all passing traffic, 78% had a negative relationship, compared to 43% of those without an A_k = 1.0 node.

Similarly, for interchanges without a site capable of capturing all passing traffic, nodes that could not capture any travel directions with a deviation of less than six minutes were significantly closer to the interchange than their counterparts with at least one node where A_k = 1.0.

Table 3.4. Interchange factor comparison for those that have at least one candidate node where A_k =1.0 and those that do not. *significant at α = 0.5 level.

Factor	Max A_k < 1.0 (n=22)	Max A_k = 1.0 (n=50)	t-statistic	*p*-value
β-index	1.13	1.18	-2.54	0.01*
Pct Access Arc	20.47	10.96	5.28	<0.01*
OLS Slope (Interchange Center vs. WA_k)	-0.004	-0.016	2.48	0.02*
Candidate Nodes	507	675	-2.52	0.01*
Exit Nodes	45	58	-1.23	0.11
Distance, interchange center to A_k = 0.0 (km)	1.06	1.17	-2.18	0.03*
Road Length (km)	84.86	97.85	-1.53	0.13

Many of the interchanges that lacked a single candidate site where A_k = 1.0 exhibit a generally positive relationship between FTCA score and distance from the interchange center, similar to the one shown in the left panel of Figure 3.8. Only one interchange with a positive relationship between A_k score and distance from interchange center had one or more A_k = 1.0 nodes. Freeway exits and entrances do seem to benefit the interchanges without any A_k=1.0 nodes. In 16 of these 22 interchanges, candidate nodes at or near freeway entrances or exits do have the maximum value possible in the interchange.

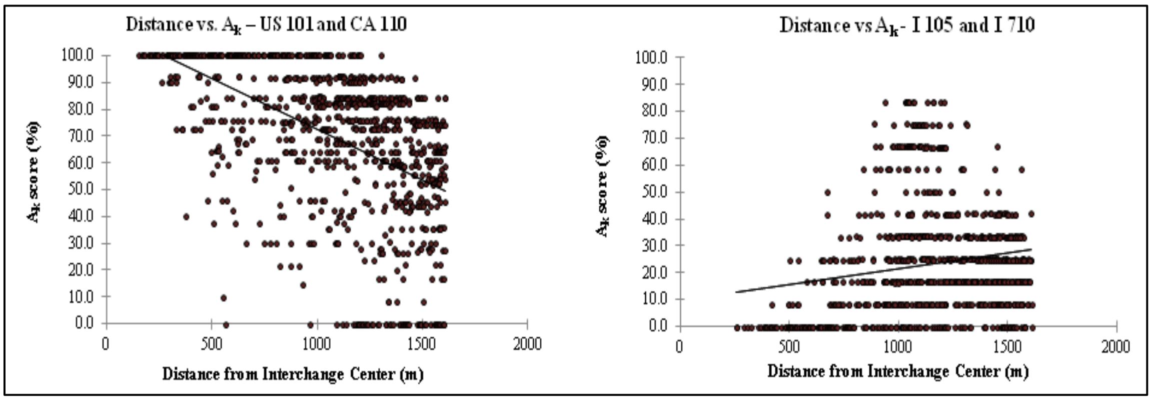

Figure 3.8. Examples of interchanges with relatively high WA_k scores (left) and low WA_k scores (right).

3.4. Sensitivity Analysis

One of the sources of uncertainty in the results provided by the FTCA lies in its reliance on the deviation tolerance threshold observed in Kelley and Kuby's (2013) survey data. While this six-minute deviation decay point provides a justifiable empirical metric for computation, this deviation tolerance may differ in other metropolitan areas. The deviation decay profile of gasoline drivers in Kuby et al.'s (2013) paper shows a rapid decrease in willingness to deviate beyond two minutes, indicating that as infrastructure matures, tolerance to deviate up to six minutes may deteriorate over time. Using a tolerance of two minutes would almost certainly reduce overall FTCA scores for the study area, and the amount of A_k = 1.0 candidate nodes found in the study. To account for the uncertainty in the deviation threshold metric, sensitivity analysis was conducted on the candidate nodes within the Interstate 10 and Interstate 405 neighborhood between downtown Los Angeles and Santa Monica, a key commuting thoroughfare that carries more than one million vehicles per day.

None of the 876 candidate nodes in the Interstate 10 and 405 network had an A_k score of 1.0 using the six-minute deviation threshold, of concern to station developers, given the high passing traffic volume. Increasing the deviation tolerance by 90 seconds did provide 38 nodes (4.3%) with an $A_k = 1.0$ score, and increased the mean A_k score for the local network from 0.40 to 0.67. The general relationship of A_k score and distance from the interchange center went from slightly positive to one that was more strongly negative, which is an indicator of interchanges with more promising refueling station locations. Conversely, setting the deviation threshold at 4.5 minutes reduced the mean A_k score from 0.40 to 0.14, and shifted the relationship between A_k score and distance from the interchange center to a more positive one, which is indicative of an interchange with limited effective refueling station locations. In this case, the maximum scores for A_k and WA_k were 0.75 and 0.73, respectively, using a deviation tolerance of 4.5 minutes. This is a reduction of nearly 0.10 from the six-minute threshold maximum values, or the equivalent of over 100,000 vehicles that can no longer conveniently access the station.

The deviation metric in the FTCA is a flexible parameter that could be modified for future use, which is important, given the variation in driver behavior and possible variation in deviation tolerance between geographic areas. For future application in other geographic areas, it could either be adjusted as such, or adjusted only for individual interchanges.

3.5. Discussion

The results indicate that four and five-way interchanges are more complex environments than three-way junctions, offering higher overall flow-capturing capability at local road intersections nearby. While the FTCA scores are helpful for identifying effective station sites on the local road network nearby for various interchange types, caution must be taken before deploying stations using this metric alone, as factors such as construction, freeway congestion, and accidents may deter drivers from relying on these stations for refueling. Drivers may choose to avoid or be drawn to these areas for reasons other than deviation convenience, including station amenities, perceptions of safety, and difficulty returning to the freeway after exiting and refueling. Local traffic was also not considered in this analysis, since virtually any trip anchored within the one-mile interchange network could access a station site within a six-minute deviation, but stations could serve as convenient locations drivers who work near interchanges, for example. Flow volumes of local traffic on arterial roads are generally far lower than those along freeways, which presumably serve far more disparate origins and destinations.

While the candidate nodes within one mile of three-way interchanges hold a significantly lower overall capability of capturing all passing traffic, they do offer a greater percentage of nodes that can capture all passing traffic than four- or five-way interchanges. T-junctions also provide more suitable locations farther from the center of the interchange compared to four- and five-way interchanges, which may help allay drivers' concerns about navigating a more complex environment closer to the freeway interchange. As a result of the percentage-based metric built into the algorithm, the stronger bimodal values in three-way interchanges are likely caused by the lower number of travel paths to cover relative to four- and five-way interchanges.

Additionally, the results of the FTCA analysis at freeway interchanges can be incorporated into flow-capturing models such as the FRLM when solving the models. The scores could help to fine-tune the results of the FRLM by focusing on freeway interchange nodes' ability to capture passing traffic, but it is important to note that the model can use one traffic capture value for each interchange location. In the cases where there are a number of candidate sites with equally high scores for the interchange network, additional steps would be required to determine a "best" site. GIS overlay analysis of land availability, zoning designation, and parcel ownership would be a likely further step before deciding exactly where to build a station, and the traffic capture of that specific location could then be incorporated into a flow-based regional station location model.

The weighting scheme that accounts for uneven traffic flow could also be modified to reflect a more accurate partition of how vehicles each day move through the interchange. Aggregation of inbound and outbound traffic then dividing by two only provides a relative estimate of the importance of varying traffic directions. A more accurate result of the weighted FTCA would also require data or a simulation method capable of partitioning flows from one origin to many destinations, but could provide better estimates of traffic capture for those locations unable to capture all passing traffic.

Finally, an understanding of land use and land availability must also be considered when choosing a station site near freeway interchanges. Land use around the 72 interchanges in this study is varied. Some of these are mainly in industrial areas where numerous parcels may be available on which to build a station. Others have shopping malls, universities, office parks, commercial areas or other major trip anchors within one mile of the center. In some cases, there are few greenfield locations around some of these interchanges, particularly the ones in more central parts of the city, and zoning and land values may make station development prohibitive in some cases where an $A_k = 1.0$ node exists.

3.6. Conclusion

The Freeway Traffic Capture Algorithm (FTCA) developed in this study enables analysts to compare accessibility of sites on nearby local street networks both within and across interchanges relative to the nearby freeway. Results from the algorithm can be used to explore the relative advantages and disadvantages of selecting locations to deploy limited AFV refueling infrastructure. By specifically accounting for travel time deviation that includes freeway access and local road networks, it directly addresses the crucial AFV adoption barrier of convenience and bridges the scale dependency of regional modeling results and local street networks. It also begins to provide options for exact station locations on local street networks around a freeway interchange. The methods introduced here should be usable by any retailer of fast-fueling alternative fuels if they are looking for convenient sites near freeway interchanges through which hundreds of thousands or even millions of drivers pass through daily.

Generally, the vast majority of candidate sites analyzed cannot perform as assumed by the networks used in common flow-based modeling approaches such as the FRLM. Less than 7% of all candidate sites within one mile of the 72 interchanges can capture all passing traffic, and 22 of these interchanges lack such a site. Those interchanges with locations capable of capturing all passing traffic were most commonly located 200-500m away from the center of interchanges along arterial roads, though there is variation across interchanges. Interchanges with a negative relationship between FTCA scores and distance from interchange center had a greater volume of effective station sites. Some of the interchanges along primary commuting routes had relatively low numbers of sites capable of capturing passing traffic, but the scores of those in the downtown area are relatively high. This is promising for drivers who may commute to the central business district in Los Angeles, but given the region's polycentricism, having dispersed well-connected interchanges is important to encouraging early adopters to refuel at these locations.

While it may be tempting to locate AFV refueling stations directly at freeway entrances or exits sites to mirror the existing locations of gasoline stations, results show that may not be an effective strategy for maximizing traffic capture for all drivers passing through interchanges in the initial stages of infrastructure development. Candidate sites near entrances and exits do a better job at ensuring at least some level of coverage than other sites, though, and are commonly the best locations in interchanges when an interchange lacks a node capable of capturing all passing traffic. These exit sites could play a more prominent role in station location as AFV refueling infrastructure expands in metropolitan areas and enough demand exists to sustain multiple stations within one mile of an interchange.

Given the relatively low performance of many sites near freeway interchange, it appears that ad hoc station site selection near busy freeway interchanges is unlikely to conveniently serve early adopters of AFVs. This must be considered before station locations can be effectively deployed at freeway interchanges. While travel time deviation reduction is an important factor for drivers when considering stations, future research must also focus on other considerations important to drivers who would potentially refuel at these locations, including perceptions of access difficulty, perceptions of safety, and fuel costs. Also unknowns is if drivers truly do access stations using shortest travel paths generated in the GIS environment that the FTCA assumes due to the complexity of interchange environments.

Depending on the fast-fueling alternative fuel being considered, existing gasoline fueling stations, or a similar type of facility, could be utilized as an AFV station site if they are coincident with promising FTCA scores. Other location types to consider for station placement near freeway interchanges could include arterial street intersections near major trip anchors such as malls, stadiums, universities, or office parks, provided these are coincident with high FTCA scores. From the standpoint of a station developer, existing fleet bases near freeway interchanges that have not yet converted to an alternative fuel could also be lucrative, if such sites can also effectively capture passing traffic from the interchange. These sites could serve both local and distant refueling demand in a metropolitan area in addition to the daily demands of a fleet based there. While refueling stations are the primary focus on the algorithm's construction, the FTCA could be extended to other uses. More generally, any type of facility that is accessed as a stop on the way between an origin and destination, at areas where high volumes of drivers pass through each day, and are expensive for service providers to build could employ the FTCA to improve the service performance of a site near a freeway interchange.

Chapter 4. Freeways, trip types, and choice sets: Observed AFV driving and refueling behavior at compressed natural gas (CNG) stations near freeway interchanges

4.1. Introduction

Some of the refueling station location literature for alternative fuel vehicles (AFVs) has focused on highway and freeway corridors as effective sites for initial infrastructure to boost AFV adoption. Limited-access freeways boast a huge number of passing vehicles within urban areas, and they also enable long-distance travel between cities. Incorporating the theoretical framework of the flow-based modeling approach first tailored to AFVs by Kuby and Lim (2005), recent studies have explored the deployment of refueling stations for AFVs along highway corridors, particularly for fast recharging stations for electric vehicles (Hwang et al. 2015; Honma and Toriumi 2014; Sathaye and Kelley 2013). Others recommend clustering stations first near where likely early adopters live (Brey et al. 2014; Ogden and Nicholas 2011), then extending refueling convenience to highway travelers. Nicholas (2010) notes that the intersections of residential arterial roads and freeway entrances and exits could be promising station locations.

Regardless of methodological framework for studies that incorporate highways, the aim has been to place stations to take advantage of the heavy nearby traffic volumes, but the explicit use of stations near multiple highways to advance AFV adoption within urban areas remains theoretical and unaddressed. Further, empirical data on interurban driver refueling behavior in these environments is sparse, and of high importance to effectively deploying limited AFV refueling infrastructure in these key locations.

The second paper in this dissertation (Kelley 2015) focused on the scale dependency between regional highway networks and local street networks near freeway interchanges. It developed a new method to assess the ability of the surrounding street network to capture passing traffic from the nearby freeway interchange. These locations are important because of their ability to serve the refueling demand of hundreds of thousands of vehicles passing through nearby freeway interchanges each day, an important consideration for initial AFV infrastructure where drivers generally do not refuel at home or work. This ability to capture passing traffic also forms the theoretical basis for the implementation of flow-based facility location models, which have a demonstrated applicability based on the behavior early AFV adopters (Kelley and Kuby 2013). Included in these models is an assumption that is either explicitly (Hwang et al. 2015) or implicitly made (Capar and Kuby 2013; MirHassani and Ebrazzi 2012; Lin et al. 2008) that drivers do not leave the highway network in order to reach a station. While deviations from a driver's shortest path have been incorporated into flow-based facility location models at the regional highway scale (Kim and Kuby 2012; Zeng et al. 2008), deviations required by the need to leave a freeway to reach a station are not generally considered. This is an important factor, since it was demonstrated in Kelley (2015) that only 7% of the nearly 45,000 candidate sites at which to build stations near freeway interchanges in greater Los Angeles, California are convenient refueling station locations for all possible travel paths through the region's 72 interchanges.

The freeway traffic capture algorithm (FTCA) does address this specific type of deviation when assessing viable candidate sites that can capture traffic from all possible freeway travel directions through the interchange, and can provide regional transportation planners with a general idea of how effective sites near freeway intersections are for initial station locations (Kelley 2015). Deterministic measurements alone, however, are likely insufficient to fully assess the viability of sites around highway interchanges, since perceptions of safety and comfort, infrastructure familiarity, fuel costs, range anxiety, congestion, and other factors that vary across individuals have been shown to affect AFV travel and refueling behavior (Carley et al. 2013; Caparello and Kurani 2012; Kurani et al. 2009). While convenience and deviation reduction is an important factor in choosing a refueling station, drivers are shown to consider other variables when selecting a station, such as station amenities and facility safety, but specific considerations differ across individuals (Wansink and van Ittersum 2004). Travel behavior is also quite variable at the individual level (Bohte and Maat 2009; Recker et al. 2001; Stopher 1992; Pas 1988). Therefore, before advocating a reliance on interchange-based stations and assessing their performance based on deviation reduction alone, it is important to collect and analyze activity-based data about early adopters and how they refuel at and perceive interchange-based stations.

Travel surveys are an important mechanism for studying driver behavior, and a few have been employed in the study of early AFV adopters. Most rich is the literature on electric vehicle driver behavior, and methods have ranged from diaries to GPS data loggers and focus groups to understand how drivers use their vehicles and refueling infrastructure (e.g., Tal et al. 2013; Kurani et al. 2008). Data focused on fast-fueling AFVs are less common, and largely centered on fleet use and effectiveness of government policy instruments to encourage fleet AFV adoption (Coria 2009; Johns et al. 2009; Yeh 2007; Flynn 2002). The results from Kelley and Kuby (2013) and Kuby and

Kelley (2013) offer initial insights into how compressed natural gas (CNG) drivers use a public refueling structure in greater Los Angeles, but did not tailor questions specifically to freeway stations. Nor did they ask drivers to list other stations at which they would consider refueling besides the station at which a survey is conducted. This "choice set" method, employed by Plummer et al. (1998), helps to determine general patterns of refueling behavior beyond the one observed refueling event.

In addition to gathering data on driver perceptions and attitudes about refueling stations near interchanges, the types of refueling trips taken by drivers are an important consideration. The nature of trips assumed by Kelley's (2015) FTCA involves the use of a freeway exit to access the station before returning to the freeway via a freeway entrance. If drivers are found to generally access refueling stations near freeway interchanges in this manner, termed doubly freeway-anchored, that could support the continued use of the existing FTCA to simulate and evaluate AFV driver refueling behavior in these environments. It is possible, however, that stations located near freeway interchanges are used primarily by drivers on trips that do not require freeway use and are accessed in different ways than the algorithm assumes. This could be a result of other nearby trip anchors, depending on the arrangement of residential or industrial areas in the station's vicinity. Understanding the distribution and variability in these trip types, both within and between stations, is crucial to effectively deploying stations near freeways and freeway interchanges. The distribution of observed refueling trips that are doubly freeway-anchored and those that are not is thus important, along with other factors of these refueling behavior types that significantly differ.

Given the complex nature of freeway areas, the potential variability in the ways that drivers refuel their vehicles at stations located near freeway interchanges, and the enormous throughput of these locations, this paper will seek to address the following research question: how do AFV drivers access refueling stations on local street networks near freeway interchanges that serve intra- and inter-urban travel? Specifically, what are the types of trips drivers take when accessing these stations, what factors do drivers consider to be important when accessing stations near busy freeway interchanges, and what role do stations near freeway interchanges play in drivers' choice sets when considering refueling stations across a regional network? These findings will augment the theoretical accessibility measures from previous studies while providing valuable insight on early AFV adopters' refueling behavior to station developers and regional transportation planners, while advancing location methods that focus on highways and freeways for infrastructure deployment.

While it is expected that there will be a mixture of trips both local and distant in nature observed by drivers accessing these stations, it is hypothesized that the majority of drivers will access these stations near freeways and freeway interchanges on doubly freeway-anchored trips that do not include any local trip anchors. It is also hypothesized that, if a driver is on a doubly freeway-anchored trip when accessing the station, the overall trip length is longer than those with at least one local anchor. It is also hypothesized that drivers who refuel in this manner consider other stations at freeway interchanges in their choice set, are less sensitive to congestion, and are more familiar with the regional refueling infrastructure.

4.2. Data and Methods

An intercept survey was conducted in August 2014 at four different CNG stations in the greater Los Angeles area. Three stations were located in close proximity to freeway interchanges on local streets nearby, which were the sites of interest to the FTCA (Kelley 2015). The individual stations were chosen because they represented differing arrangements of trip anchors nearby, but all three qualified as interchange stations. The Downtown and Irvine stations are operated by Clean Energy Fuels, and the Anaheim station by Trillium and the Southern California Gas Company. The Downtown station is 0.7 miles from the four-way interchange of California 110 and US Highway 101. The Anaheim station is 0.95 miles from a the five-way intersection of Interstate 5 and California Highways 55 and 22, and the Irvine station is 0.9 miles from Interstate 5 and California Highway 133, which is a four-way interchange.

A fourth set of surveys was collected in Fountain Valley at the Orange County Sanitation District along Interstate 405, located 2.3 miles from the three-way interchange of Interstate 405 and California Highway 7. These data were collected to provide a control group of a station easily accessible from one freeway, but not at an interchange. This station is near a middle-class residential area with direct access to and from HOV lanes along nearby Interstate 405. Data on perceptions of station characteristics at this location were statistically compared to the responses of the other stations within one mile of a freeway interchange. All station survey sites are shown in Figure 4.1.

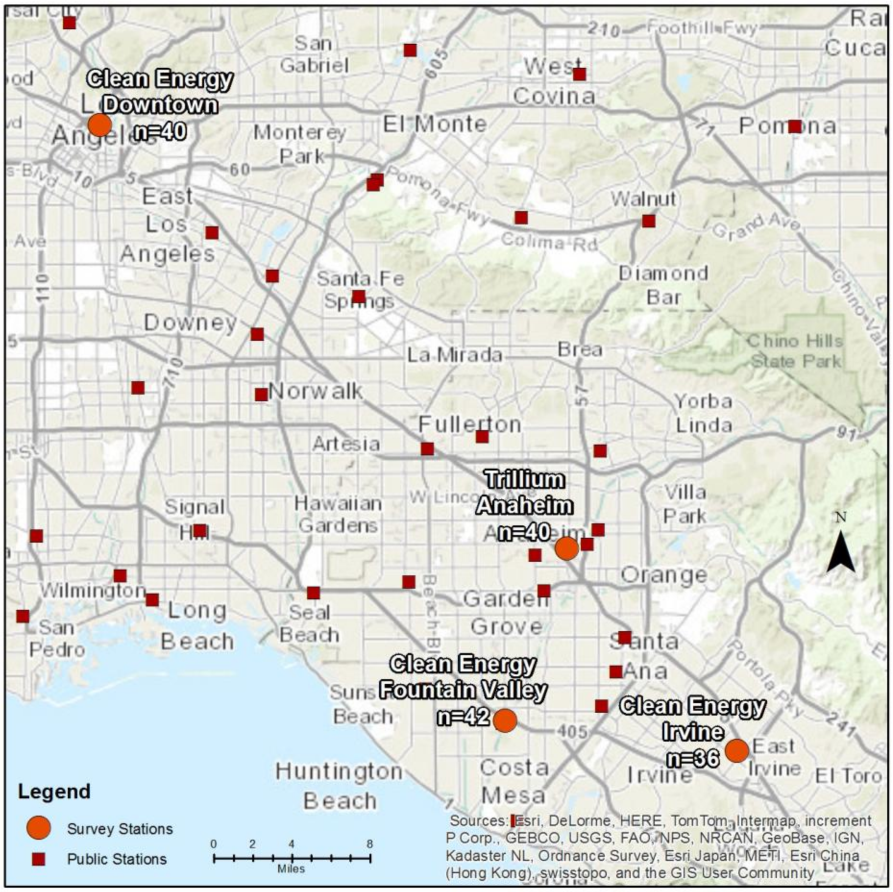

Figure 4.1. Stations at which intercept survey was conducted.

The station operators granted permission to conduct surveys of drivers while they refueled their CNG vehicles at these locations. None of the stations offer similar amenities to modern gasoline refueling stations, and three of them are part of larger civic or private complexes. The Irvine station is within the City of Irvine government facility, the Anaheim station is in the parking lot of Southern California Gas Company offices, and the Fountain Valley station is part of the Orange County Sanitation District's complex. In these three cases, a separate set of CNG fuel pumps exist behind secured gates at the complex for the company's own fleet based at that location. The pumps open to the public are outside the gates on the edges on the property. The Downtown station is a small, dedicated CNG refueling facility, with four pumps. All operate 24 hours per day, and there were no station attendants or company personnel regularly on-site during the intercept survey. Signage immediately surrounding the stations is sparse, and all but the Downtown station were not easy to locate upon entering the larger complex.

For the intercept survey, consumers and drivers of light-duty fleet vehicles who were not based at the station were interviewed, including vehicles for small businesses or government offices, since public use of interchange refueling stations would involve both types of users. More consumer drivers were surveyed than their fleet counterparts (76% against 24%), and many of these fleet drivers kept their CNG vehicles at their home location at the end of each day. In the cases where many vehicles from the same light-duty fleet stationed at a fleet base refueled at the station each day, only the first completed interview from any particular fleet was considered, so as not to over-represent any particular fleet's use of the CNG station.

Surveys were stratified by time of day to control for differing commuting patterns. The first set of questions gathered spatial data, asking drivers to report approximate stops before and after the refueling station, and approximate home locations or fleet base. If applicable, drivers were asked to provide freeway exits used to reach the station and freeway entrances that they planned to use to continue their trip. These responses provided the data necessary to assess the relative amount of doubly freeway-anchored refueling. Stated preference questions, based on a Likert scale of responses, assessed how drivers perceived the convenience of the station's location relative to the driver's origin and destination, its proximity to both the driver's home and work, its accessibility from the freeway, visibility from the freeway, safety of the facility, and whether congestion impacted the choice to refuel here. Drivers then stated how often they refueled at this station and how they found the station the first time they refueled here. Then, drivers were asked to indicate other CNG stations at which they generally refueled, or would consider as viable refueling sites. These were the stations that comprised the driver's choice set (e.g., Plummer et al. 1998). Open-ended responses and comments about the station or CNG vehicles in general were also recorded at the end of the survey. The full survey instrument can be found in Appendix C.

The driver's approximate stops immediately before and after refueling were recorded and stored in the ArcGIS 10.1 environment, along with the stated approximate home locations, following the methods of Sperling and Kitamura (1986) and Kelley and Kuby (2013). Spatial data for the CNG station locations, necessary to determine station locations in the choice set, were downloaded from the Alternative Fuels Data Center in the summer of 2014, to correspond with the stations available for public refueling at the time of the study. Travel paths both with and without refueling stops and network distances to trip anchors were calculated using Network Analyst. Refueling travel paths computed in Network Analyst were also compared against the freeway entrances and exits stated by drivers to see if drivers actually followed general shortest time travel paths when accessing station locations near interchanges.

Descriptive statistics were generated for the stated responses of CNG drivers regarding the perceptions of convenience, safety, accessibility and visibility of the station, and drivers' trip behavior and deviations. These values were then also statistically compared against the values from the control group at Fountain Valley. Choice sets of drivers were then analyzed to determine if stations at other interchanges appeared, and to explore other factors prevalent in choice sets, including the characteristics of frequently cited stations.

To compare the theoretical station access scores based on deviation reduction from the previous study against empirical data, drivers' travel routes were recreated using the reported previous and next stops and the freeway entrances and exits used, if any, and freeway-based routes were compared to those assumed to be convenient by the FTCA (Kelley 2015). This FTCA score is formally defined as:

$$A_k = \frac{\sum_{i=1}^{p} X_{pk}}{P} \qquad (1)$$

where:

A_k = algorithm score for candidate node k (continuous variable between 0 and 1)
X_{pk} = for path p through interchange, 1 if $t_{ikj} - t_{ij} \leq 6$, 0 otherwise
t_{ij} = shortest travel path (in minutes) from artificial origin i to destination j
t_{ikj} = shortest travel path (in minutes) from artificial origin i to candidate node k to destination j
p = index of travel path through the interchange
P = total number of travel paths through the interchange

From these findings, the relative presence of freeway-based travel when accessing refueling stations was determined, which is the behavior assumed by the FTCA. Scores from the weighted variation of that algorithm that incorporates uneven traffic flow through freeway interchanges were also considered.

Then, drivers were grouped into those that used a freeway immediately before and after refueling, and those that did not to assess the amount of doubly freeway-anchored refueling. Drivers who refuel in this manner were compared against those who behave otherwise, which could include drivers who did not use freeways at all to access the station, or those that did so on only one segment of their trip relative to the station.

This binary categorization of trip types is the dependent variable in a logistic regression model, specified to compare the characteristics of drivers on these double freeway-based refueling trips against those involving no freeway entrances or exits. Hypothesized variables including trip length, whether drivers consider other stations at freeway interchanges in their choice set, are less sensitive to congestion, and are familiar with the refueling infrastructure will refuel on these trips are entered as independent variables in the logistic regression model, in addition to other potential explanatory factors.

4.3. Results

In general, CNG drivers strongly agreed that the stations near freeway interchanges were conveniently on the way between their current origin and destination (Figure 4.2). Stated responses to a station's convenience relative to work were bimodal. Nearly half of all drivers who refueled at interchange stations either disagreed or strongly disagreed that the station was convenient to their home location. Despite the fact that many drivers said the station was not near home or near work, they did perceive the station to be conveniently on the way. Of the 93 drivers who either agreed or strongly agreed that the interchange station was conveniently on the way, nearly 20% disagreed or strongly disagreed that the station was convenient to *both* their home and work location.

It is interesting to note that many Irvine respondents strongly disagreed that the station was close to work, despite its proximity to nearby office parks and major employers.

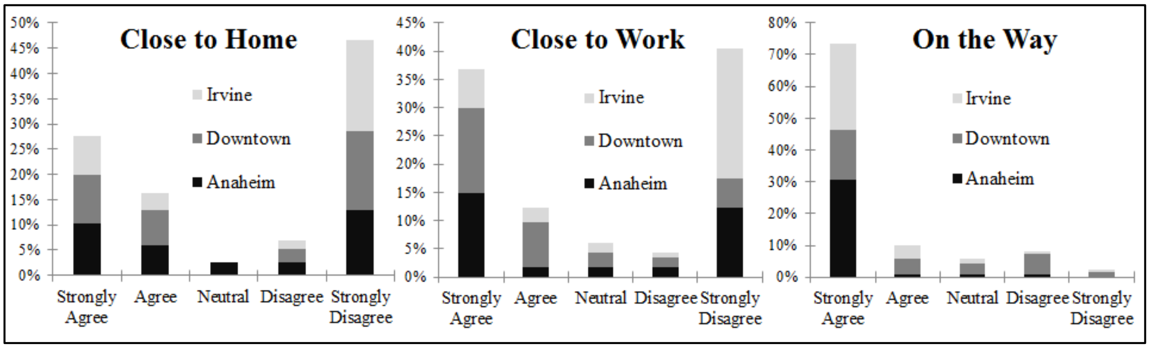

Figure 4.2. Stated response distribution to Likert scale questions for convenience questions, by interchange station.

Respondents generally considered all stations to be safe environments (Table 4.1), though some respondents did indicate in their open-ended comments that there were times of day when safety was a concern at both the Downtown and Anaheim stations. Drivers who refueled at freeway interchange stations also considered them significantly more convenient to their work location than the control group at Fountain Valley. Aside from this, no perception metric differed between the interchange stations and the Fountain Valley respondents. With relatively even distribution across stations, most drivers did not consider the stations to be visible from nearby freeways. Though the majority of drivers perceived the station to be conveniently on the way between their current origin and destination, the Downtown station was cited by the majority of those respondents who did not.

Table 4.1. Mean values of stated preference Likert scale questions, by station. 1 = strongly agree, 2 = agree, 3 = neutral, 4 = disagree, 5 = strongly disagree. *statistically significant difference of means from Fountain Valley control, (α=0.05).

Station	n	Close Home	Close Work	On the Way	Safety	Visible	Accessible
Anaheim	40	3.05	2.84	1.15	1.33	4.67	1.00
Downtown	40	3.23	2.22	2.18	1.63	4.70	2.00
Irvine	36	3.61	3.17	1.38	1.06	4.72	1.50
Fountain Valley (control)	42	3.14	3.85	1.38	1.33	4.49	1.26
All Interchange Stations	116	3.28	2.73*	1.68	1.35	4.70	1.50
Grand Total	158	3.25	2.75	1.6	1.34	4.64	1.50

The vast majority of trips were work-anchored, and refueling occurred along relatively long trips (Table 4.2). Drivers who refueled at interchange stations did so on trips averaging 26 miles in length, and deviated an average of 7.0 minutes from their shortest paths to reach an interchange station, which is slightly above that of the deviation threshold assumed by the FTCA. Home-anchored trips were significantly less prevalent at interchange stations than the Fountain Valley control group, though from Table 4.1, we see that drivers did not report a significantly different perception of convenience of the stations to their home locations. Trip lengths were significantly shorter for those drivers who refueled at interchange stations than those at Fountain Valley, but deviations and distances from home were not significantly different. At the three interchange stations, 87% of trips were work-anchored, compared to 57% that were home-anchored, and drivers indicated that they refueled at the surveyed stations 49% of the time. Fuel tank levels and frequency of refueling at the station did not significantly differ between interchange stations and Fountain Valley.

Table 4.2. Trip characteristics by station (% or mean value). *statistically significant difference of means from Fountain Valley control, (α=0.05).

Station	n	% Home Anchor	% Work Anchor	% Fuel Remaining	% Refuel Here	Trip Length (miles)	Miles from home	Mean Deviation (min)
Anaheim	40	67.5	85.0	28.8	62.5	26.3	13.4	8.6
Downtown	40	40.0	97.5	23.8	42.5	22.5	18.1	5.7
Irvine	36	63.9	77.8	18.1	38.9	29.6	16.8	7.8
Fountain Valley (control)	42	73.8	78.6	23.5	50.0	37.1	13.6	6.2
All Interchange Stations	116	56.9*	87.1	23.7	48.0	26.0*	16.1	7.9
Grand Total	158	61.4	84.8	23.7	48.7	29.0	15.4	7.0

Data from the Downtown station differed from the other interchange stations and the control group at Fountain Valley on a number of metrics. Drivers perceived the station to be more convenient to work, and all but one trip at the downtown station was work-anchored. This was the only station where less than half of trips were home-anchored. Compared to the other interchange stations and the Fountain Valley control group, refueling trips that included the Downtown station were shorter, occurred farther from home, and had higher rates of work-anchored trips. Though deviations to reach the Downtown station were shorter than other stations, drivers perceived it as less conveniently on the way between their current origins and destinations, and less accessible from the freeway, despite it being of similar distance to both freeway entrances and exits as the other three stations.

Another variable of interest was whether or not a driver's least-travel-time path between an origin and destination would otherwise pass through the freeway interchange near where the driver was interviewed while refueling. In Los Angeles, there is an expansive network of freeways that can provide multiple high-speed route options between any two locations in the metropolitan area, which can impact traveler behavior. That means that estimated deviations could be a result of both the amount of time needed to exit the freeway and return and the additional travel time accrued by taking an alternate freeway route between an origin and destination. Indeed, for the three interchange stations, deviations of drivers whose fastest path passed through the interchange near which the station was located averaged 4.9 minutes, compared to 11.8 minutes for those drivers that did not, which is a significant difference (t = -7.0, p<0.01). Including the results of the Fountain Valley station, these averages are 4.5 and 10.8 minutes, respectively, which is also statistically significant. Deviations to reach the station, then, are a function of both the local street network around the interchange *and* choices made by drivers who selected alternate routes along highway networks.

4.3.1 Choice Sets

Of the 93 CNG refueling stations operating and available for public refueling in Southern California during the study period, 49 appeared in the sample of drivers' choice sets, which included 265 total responses, meaning the average driver considered nearly two additional refueling sites in the region. Including three of the four sites at which surveys were conducted, 12 of the 93 available CNG stations were within one mile of a freeway interchange. While these stations represented only 13% of the total CNG stations in the region at the time, nearly 46% of drivers considered at least one of these stations in their choice sets outside of the one at which the survey was conducted (Table

4.3). This means that other interchange refueling stations are at least considered as viable refueling locations by nearly half of this population of early AFV adopters. Interchange stations represent 25% of all choices cited by drivers.

Nearly half of all drivers refueled at the station that was most conveniently on their way between their origin and destination, measured as the smallest deviation in additional minutes traveled (Table 4.3). In contrast, only 20% of drivers refueled closest to their home location. Despite there being a more efficient station for 50.6% of survey respondents, 83% of this subset of drivers either agreed or strongly agreed that the station was conveniently on the way between their origin and destination. In total, interchange stations were the most efficient refueling station at a significantly higher rate than the Fountain Valley control group. However, drivers at Fountain Valley did include the most efficient station in their choice set at a higher rate than those at interchange stations. There was no significant difference in the willingness to include another interchange stations in a driver's choice set, nor did Fountain Valley respondents refuel at the closest station to home at a significantly higher rate than interchange stations.

Table 4.3. Choice set characteristics of drivers, by station. *statistically significant difference of means from Fountain Valley control, (α=0.05).

Station	Choice Set Size (mean)	Station is Closest to Home (%)	Not Closest to Home but Closest to Home is in Set (%)	Most Efficient Station (%)	Not Most Efficient but in Set (%)	Interchange station in Set (%)
Anaheim	1.7	2.5	22.5	52.5	30.0	47.5
Downtown	1.6	37.5	35.0	67.5	17.5	25.0
Irvine	1.8	25.0	16.7	44.4	22.2	55.6
Fountain Valley (control)	1.8	16.7	31.0	38.1	38.1	54.8
All Interchange Stations	1.7	21.6	25.0	55.2*	23.3*	42.2
Grand Total	1.7	20.3	33.3	49.4	27.2	45.6

Interestingly, for 68% of Downtown respondents, that station *was* their most efficient choice but drivers tended not to perceive is as being as conveniently on the way compared to the other stations (Table 4.1). Downtown respondents did consider other interchange stations at a lower rate than respondents at the other three stations. With the exception of respondents at the Downtown station, less than half of drivers refueled at or considered the station closest to their home in their choice set. Distance from home to the closest station does seem to be a significant factor in a driver's willingness to consider refueling at that station: drivers who refueled at or considered the station nearest to their home had at least one station significantly closer to their home than those who did not consider that station (t = -2.12, p = 0.03), with mean values of 8.2 minutes and 9.6 minutes, respectively.

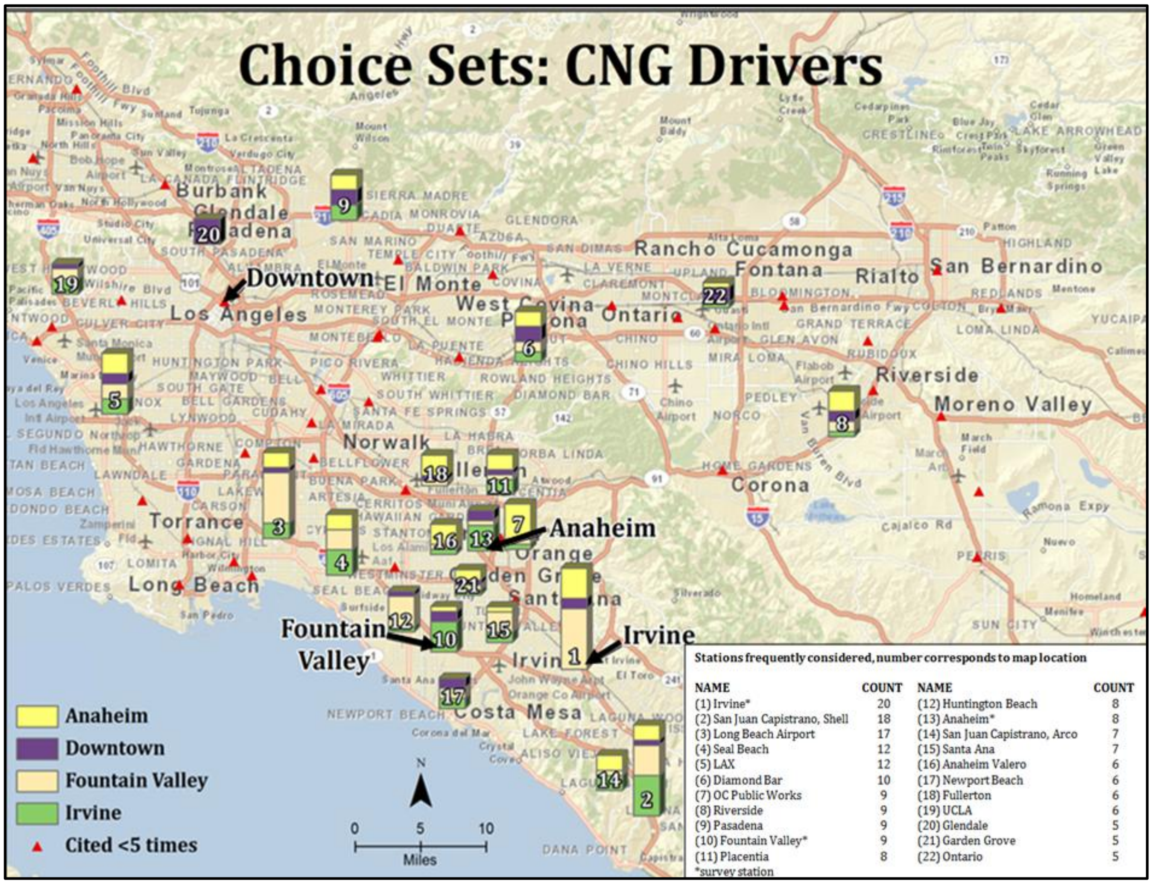

Figure 4.3. Distribution of stations often considered in CNG drivers' choice sets, showing both total citations and relative frequency by station at which survey was conducted.

The prominent stations in the aggregate choice set are those along major freeway commuting routes such as Interstates 405 and 5, but not always where major freeway interchanges intersect (Figure 4.3). The most frequently cited station was Irvine, notable since it is a station near an interchange, and could only be considered as part of the choice set for three of the survey sites. The stations in San Juan Capistrano and at the Long Beach Airport are also often noted, especially by drivers refueling at Fountain Valley and in Irvine, but were noted by at least one driver from both Downtown and Anaheim. The stations at Los Angeles International Airport (LAX) and in Diamond Bar are equally considered by drivers from all four stations.

Stations that appear at least five times in drivers' choice sets are significantly closer to major freeways than those that are not considered by at least five drivers (t = -2.17, p=0.03), and are located across the metropolitan area along major commuting routes. Socioeconomic similarity in frequently cited stations is also observed. The median income of the 138 unique block groups in which drivers live (or where their commercial fleet is based) is $32,444, 33% higher than the $24,366 median income of the Los Angeles metropolitan statistical area's block groups. The median income of the areas in which CNG stations are located is $22,619, lower than either statistic, but with the exceptions of the airport-based stations at LAX and Long Beach, the more frequently cited stations are in relatively wealthy areas. Seven of the ten most-cited stations are in areas where the median income exceeds $30,000, including the interchange stations of Irvine, Anaheim, and in San Juan Capistrano. In addition, the four interchange stations not considered at all are in areas where the median income level falls below $17,000. No driver explicitly stated that socioeconomic neighborhood status factored into the station choice, but the revealed behavior and choices of these early adopters indicates that it might.

4.3.2 Comparison to Freeway Traffic Capture Algorithm

Of the 23 stations cited at least five times by drivers as part of their choice set, five were located within one mile of a freeway interchange. Three interchange stations, including the Downtown station, were considered by fewer than five respondents, and four interchange stations were not considered at all. The interchange networks of those stations that were frequently considered were generally not well-suited to capturing all passing traffic, based on results from Kelley (2015), with weighted FTCA scores between 23.4 and 34.6, while the station locations themselves are at street intersections with scores ranging from 0.0 and 46.9. In contrast, those stations near freeway interchanges that were not considered had high overall theoretical connectivity between freeways and surface streets, with weighted FTCA percentages between 33.4 and 62.7, and stations at intersections with scores from 49.0 to 100.0. The sample size is limited, but these data suggest that theoretical accessibility from numerous travel directions through an interchange network may not be a prominent factor alone for drivers to consider refueling stations in their choice sets.

The FTCA developed in the previous study identified promising sites for fast-fueling AFV stations based on street intersections' ability to capture traffic from as many freeway travel directions as possible through the nearby freeway interchange. This algorithm is based entirely on a deviation metric, and does not consider the convenience and perceptions factors that were asked of survey respondents. To test the FTCA results, the locations of the three stations near interchanges were tested against their calculated scores from the previous study.

Excluding the Fountain Valley station, which is not located within a mile of a freeway interchange, 50 out of the 116 respondents who refueled in Irvine, Anaheim, and Downtown stated that their routes accessed the station by exiting a freeway, refueling, and continuing their trip out of the area via a freeway entrance. These trips, termed doubly freeway-anchored, are what the algorithm inherently assumes when assessing a driver's willingness to access a station or not at freeway interchanges. Using a combination of the freeway exits and entrances provided by drivers, previous stops, and next stops, travel routes were generated to see precisely which routes from the algorithm were observed in the survey. For the 50 drivers who refueled on doubly freeway-based refueling trips, the sample gathered from Anaheim exactly matched the expected exit/entrance combination that the FTCA indicated would involve a deviation of six minutes or less. Based on the deviation analysis in the FTCA, only five of the possible twelve possible interchange travel paths that required less than a six minute deviation were observed at the Downtown station. In contrast, seven unique travel routes were observed in Irvine, despite a score that indicated that only four could reach the station with a six minute deviation or less (Table 4.4).

Table 4.4. Comparison of theoretical refueling traffic capture passing through interchange and observed data from CNG refueling survey.

Interchange Station	FTCA, A_k (%)	Possible Directions Observed (%)	Doubly Freeway-Anchored (%)	Singly Freeway-Anchored (%)	Non-Freeway Trip (%)	Stops w/in 2 miles (%)
Downtown	100.0	37.5	20.0	50.0	30.0	45.0
Anaheim	35.0	35.0	60.0	27.5	12.5	22.5
Irvine	33.0	62.6	50.0	16.7	33.3	13.9

The Clean Energy Downtown CNG refueling station at Alhambra Ave and Alameda St is represented by at FTCA (A_k) score of 1.0, indicating that all freeway-based trips passing through the interchange of US Highway 101 and California Highway 110 should be able to reach the station and continue their trip with a deviation of six minutes or less, making it attractive to all drivers passing through the area on freeways in any direction. This doubly freeway-anchored refueling behavior is not representative of refueling trips involving the Downtown station: only 20% of respondents refueled at the station in this manner. Half of all drivers that refueled at this station indicated that their trip would require one freeway entrance or exit, and the remaining 30% of drivers stated the neither part of their trip involved a freeway, which included workers refueling their vehicles during the lunch hour. This station also has the highest percentage (45%) of trip anchors within two miles. Of the eight total refueling routes that involved both a freeway entrance and exit to refuel Downtown that encompassed five of the twelve travel routes through the interchange, and of the eight entrance-exit combinations stated by drivers, five routes matched the GIS shortest path route through the interchange.

The Clean Energy Irvine CNG refueling station, located at the City of Irvine government center at Oak Canyon Road and Valley Oak Drive, has a relatively low A_k score of 0.33, making it convenient from a deviation standpoint for only a few travel directions through the Interstate 5 and California Highway 133 interchange. Travel behavior by drivers using this station more closely represented the types of trips that the FTCA measured, as 50% of drivers that refueled at the Irvine station did so in a doubly freeway-anchored trip. Interestingly, 33% of trips were non-freeway refueling trips, despite only 14% of all trip anchors being within two miles of the station. This could be attributed to the relatively high speed limits of the nearby surface streets. Seven of the twelve possible travel routes through the interchange were observed by drivers, surpassing the theoretical A_k score of 0.33, though deviations for the subset of 18 drivers who used the freeway to both access and leave the station was 8.6 minutes, higher than the assumed six-minute deviation threshold.

The Trillium Station at the intersection of Gene Autry Road and State College Boulevard in Anaheim has an A_k score of 0.35, and these same seven travel directions that require a six minute deviation or less are the ones observed out of the possible 20 through the five-way interchange (nicknamed "The Orange Crush") where California Highways 22 and 57 intersect with Interstate 5. At this location, the A_k score is a good representation of drivers' willingness to access a refueling station near a freeway interchange. It is also the most reflective of the types of refueling trips assumed by FTCA, exhibiting the highest share of observed doubly freeway-anchored refueling trips and the fewest non-freeway trips. The seven observed travel routes through the interchange by drivers are convenient only for those travelling along Interstate 5 or California Highway 57. For the doubly freeway-anchored trips, 79.2% of drivers accessed the Anaheim station by the freeway entrance and exit at Gene Autry Lane, which features dedicated HOV lane entrances and exits.

For all drivers at these three stations, 74.6% of drivers stated that congestion on the freeways never deters them from refueling at any time of day. Even for the 13 drivers with freeway-based refueling trips but who chose different freeway entrances or exits than the calculated shortest path, only 2 stated that congestion avoidance was a motive for their detour. Congestion avoidance, therefore, does not seem to be a critical factor in station choice for these stations.

4.3.3 Refueling Trip Types

In total, 48% of drivers accessed stations on doubly freeway-anchored trips, while 15% reached the station completely on surface streets on relatively shorter trips. General characteristics of drivers who refuel on doubly, singly, or non-freeway based trips are shown in Table 4.5. There are notable differences in choice sets regarding stations both near home and at freeway interchanges, trip length, congestion avoidance, and perceived station convenience between the driver's current origin and destination across refueling trip types (Table 4.5). Willingness to include another station within close proximity of a freeway interchange increased among drivers on doubly freeway-anchored refueling trips, and only 31% of drivers on these trips refueled at or included the station closest to their home in their choice set, compared to 74% on completely local trips. More drivers who refueled on doubly freeway-anchored trips than singly freeway-anchored or non-freeway trips indicated that they avoided this station at certain times of day due to congestion, and more often stated that they first found this station using a web-based application on their cellular phones or tablets. Trip lengths were greater for drivers on completely doubly freeway-anchored refueling trips, but the stations were not noticeably farther from home. Nearly 90% of these drivers indicated that they either agreed or strongly agreed that they refueled here because it was conveniently on the way between their current origin and destination, compared to the 64% who did not use a freeway at all to access the station. Drivers with singly freeway-anchored trips were a hybrid between the two, with values always falling somewhere between the two extremes of station access types.

Table 4.5. Characteristics of CNG drivers who refueled based on freeway use category.

Trip Type	Total (%)	Closest to Home in Choice Set (%)	% Avoid Congestion	Distance from Home (min.)	% Int. Station in Set	Find Using App (%)	Trip Length (min.)	On the Way (%)
Non-freeway	15.3	74.1	18.2	22.8	37.0	22.7	7.2	63.6
Singly freeway-anchored	35.9	55.4	21.2	24.1	41.1	26.9	30.2	80.8
Doubly freeway-anchored	47.9	30.7	26.1	24.1	52.0	42.0	35.9	89.9
OVERALL MEAN	--	46.8	23.1	23.9	45.6	33.6	29.0	82.5

Drivers who accessed the station either completely or partially on surface streets were then grouped together to determine the significantly different factors between doubly freeway-anchored refueling and all others. With the noted variations in Table 4.5 in mind, a logistic regression model was specified, where the dependent variable is equal to one if a driver accessed a station using a freeway on both parts of their refueling trip and zero otherwise. The following logistic model examines the factors relevant to doubly freeway-anchored refueling behavior (Table 4.6).

Table 4.6. Logistic regression model, predictors for refueling trips doubly freeway-anchored against those that were not. *significant at α=0.05 level.

Coefficients	Estimate	Odds Ratio	Standard Error	z-score	*p* value
Intercept	-1.194	0.303	0.875	-1.365	0.173
Other interchange station in choice set?	0.167	1.182	0.392	0.427	0.670
Avoid congestion?	-0.623	0.533	0.467	-1.348	0.178
Is this station the closest to home?	-1.515	0.220	0.580	-2.610	0.009*
Total refueling trip length (miles)	0.035	1.036	0.010	3.396	<0.001*
Found station using app?	0.837	2.311	0.415	2.017	0.043*
Agrees that station is conveniently on the way	1.131	3.100	0.572	1.978	0.047*
Refuels here at least 60% of the time	-0.082	0.921	0.418	-0.197	0.844
Station distance from home location (miles)	-0.038	0.962	0.015	-2.498	0.013*

Total trip length is a positive and significant predictor of a drivers who exit a freeway, refuel, and immediately return to the freeway, as is whether or not a driver found the station using the CNG station application and if the driver either agreed or strongly agreed that the station was conveniently on the way. For each one-mile increase in trip length, the odds of refueling on a doubly freeway-anchored trip increased by 3%. Drivers who found the station using the CNG application for cellular phone were 131% more likely to access the station on doubly freeway-anchored trips. If a driver agreed or strongly agreed that the station was conveniently along the way between an origin and destination, there was a 210% increase in likelihood in refueling on a doubly freeway-anchored trip. Refueling at the station closest to home is a negative and significant variable, and decreased the odds of being on a doubly freeway-anchored trip by 78%, but interestingly, for each additional mile away from the driver's home, the odds of being on a doubly-freeway refueling trip decline by 3%. Variables that were hypothesized to have a significant influence on refueling on a doubly freeway-anchored trip but did not are: 1) the presence of another interchange station in the choice set, 2) indication of congestion avoidance at this station during certain times of day, and 3) frequent refueling at the station at which the survey was conducted.

4.4. Discussion

One notable difference between respondents at the three interchange stations and those at Fountain Valley is the perception that interchange stations are more convenient work locations. This may be an important consideration for station developers interested in placing stations along commuting routes or near office parks next to freeway interchanges, but this relationship may be related to the way in which drivers use their CNG vehicles and the land use around interchanges.

Many of these early adopters commute with these vehicles and are granted HOV lane access even if they are the sole occupant. This may provide easier access to interchange stations than they would otherwise have. If the HOV lane access privileges are modified in the future, drivers may consider interchange stations less convenient. Workplace convenience may also be related to the distribution of workplaces in the city and the distances to interchanges. While drivers were prompted to provide a home location, they were not asked to provide the same information about their place of work unless work was a noted trip anchor. It would be interesting to compare distance relationships between workplaces and both interchange stations and other stations away from interchanges such as Fountain Valley for all respondents.

The results of the trip distribution and choice set analyses suggest that CNG stations near limited-access highways do help facilitate travel in the greater Los Angeles area, and that drivers are willing to use them on longer trips that require freeway travel within the metropolitan area. That they are relatively prominent in drivers' choice sets may be related to their observed significantly higher efficiency along travel paths at the three interchange stations, but this result comes only from comparison to the Fountain Valley station.

The sample of drivers in this study who refueled at interchange stations may not be representative of eventual widespread use of AFVs and infrastructure elsewhere. In addition to the commuting behavior discussed above, they also may have chosen to refuel in the manner that they did simply because there were few other options, since refueling stations were constructed to serve commercial fleets, and drivers may simply have adapted to the existing infrastructure as best they could. Drivers in Los Angeles may be more conditioned to and accepting of freeway travel than others, and it would be interesting to see if this prevalence of doubly freeway-anchored refueling trips is encountered elsewhere.

While drivers who accessed the Anaheim station performed as expected by the FTCA, the other two stations near freeway interchanges did not. Only eight routes that accessed the Downtown station were doubly freeway-anchored, and there were three cases where a driver did not travel through the FTCA's assumed sequence of exits or entrances. In each case, the avoided location was the Alameda freeway off-ramp/on-ramp, which is a particularly congested area during commuting hours, yet no driver cited congestion as a deterrent when accessing the station. Interestingly, drivers avoided this area by using exits and entrances along Interstate 5 to reach the station, which was not within the one-mile buffer of the California 110 and US Highway 101 interchange in which the station lies. Similar behavior was observed in Irvine: five drivers chose to use the Interstate 405 freeway entrance or exit along Sand Canyon Road, which is not part of the freeway interchange network in which the Irvine station is located. Therefore, alternate delineations of interchange networks should be explored for its future application to incorporate these types of routes, since deviations assumed in the algorithm only incorporate deviations made *within the same* interchange network (Kelley 2015). The average deviation to reach these interchange stations was also seven minutes. This figure could perhaps be incorporated into future applications of the FTCA since the previous six minute threshold included data from stations that were not near freeway interchanges.

There are a number of uncertainties regarding the refueling station choice sets of this sample of early adopters. First, the term "congestion" often elicited a reaction from survey respondents outside the presence of heavy traffic volumes on the nearby freeways. Some respondents indicated that congestion *at the station* was a much larger factor in their refueling decision than congestion along the freeway, which was the focus of the survey question, and incorporating this factor would be of interest to future choice modeling. Light-duty vehicle owners frequently expressed frustration upon arriving at stations and seeing heavy-duty fleet vehicles such as buses and waste collection vehicles refueling, since those refueling events could last up to 15 minutes. In fact, some surveys were completed by drivers while they were waiting for their turn to refuel behind such a vehicle. All stations featured pumps that could fill at either 3000 or 3600 psi, but some vehicles could only refuel using one of those pressure levels, further limiting the amount of "open" pumps available to drivers upon arrival at the station. With the limited number of CNG stations available in the region, drivers either had to wait for other vehicles to refuel, or proceed to another station if enough fuel remained in the driver's tank. This suggests that certain stations were not mentioned in drivers' choice sets because they were notoriously occupied by one or more fleets with a number of heavy-duty vehicles during times of high refueling demand. This interaction between heavy-duty vehicles and light-duty vehicles sharing a limited number of pumps at a small refueling facility is an interesting factor in refueling choice and was not considered in this study.

Some respondents reported that that they were offered credit for fuel at Clean Energy's suite of stations when they purchased their vehicle as an incentive to do so. For these drivers, then, only Clean Energy stations may have occurred in their choice sets, not the entire set of 93 CNG stations. Another unexplained factor in the choice set analysis was station reliability. If a particular station garnered a reputation of being unreliable or not filling tanks to near capacity, it impacted drivers' willingness to consider it as part of their choice set. During the study period, some stations across the area had intermittent availability due to hardware failure, leaks, and other routine maintenance. With no attendant on-site, stations could potentially be unavailable for hours if an issue was encountered, causing drivers to avoid that location not just at the time of repair, but also jeopardizing its future consideration if the station frequently malfunctioned. Since some survey respondents were active in online CNG communities that facilitate sharing of station conditions each day, willingness to consider certain stations during the time period of the survey could have been influenced by some of these reports.

The survey did not ask drivers which stations they excluded from consideration and why, which could have provided insights into the types of facilities that early adopters systematically avoid, and might elicit some useful recommendations that would not emerge otherwise. Related to this, demographic and socioeconomic data about drivers were not collected in this study, but some of these factors could have impacted a respondent's willingness to consider other stations in relatively poorer or wealthier parts of the city. In addition to the uncertainties with the choice sets, these factors could also have impacted other metrics reported in the survey, such as willingness to use a web application, willingness to avoid congestion, or perceptions of safety.

4.5. Conclusion

This study contributes an initial understanding of how early adopters of AFVs specifically use refueling stations near busy freeway interchanges. These locations have the capability of capturing high volumes of passing traffic from the freeway interchange in addition to local traffic, and represent potential initial sites for AFV stations in other areas. Drivers considered interchange stations to be safe, accessible environments in which to refuel that were conveniently on the way for their current trip. In the case of CNG drivers in Los Angeles, drivers did not consider these metrics significantly differently than at a station along one freeway that is closer to a residential area and away from a freeway interchange. This means that station developers may not have to be concerned with building stations in complex interchange areas out of fear that drivers will avoid them.

The majority of drivers either agreed or strongly agreed that the station was conveniently on the way between their trip's origin and destination, even if for nearly 45% of drivers who refueled at interchange stations, there was a theoretically more efficient route available to them via another refueling station. Interchange stations were the most efficient station for drivers at a significantly higher rate than the Fountain Valley station, which is likely related the long distance, commuting-based nature of drivers' trips. Respondents also refueled at these stations despite their lack of visibility from nearby freeways. Nearly half considered other stations near freeway interchanges in their choice sets, which is noteworthy since these stations represent only 13% of the total CNG stations in the region. This is a similar rate at which drivers either refueled at or considered the station nearest to their home. Taken together, these results indicate that drivers do consider interchange station locations as viable options for refueling in this nascent AFV refueling infrastructure.

Stations that were common to drivers' choice sets were significantly closer to freeways and in relatively higher-income areas of the metropolitan area compared to those not considered at all. Drivers able to afford AFVs are likely wealthier than the average Los Angeles resident, and they may feel more comfortable in environments more similar to their home areas, which is a consideration that warrants future research for station deployment. Drivers clearly consider more than simply the convenience to a shortest path travel route when refueling at a station, and it would interesting to compare drivers' perceptions of safety, accessibility, congestion, and proximity to various trip anchors at these avoided locations to determine whether or not there are significant differences in these metrics between areas avoided and areas that are considered often in drivers' choice sets.

Nearly half of the respondents refueled by using a freeway exit, proceeding to the station, then leaving the area after entering a nearby freeway, without stopping at another trip anchor nearby, while only 15% of observed trips accessed the station without the use of a freeway. Drivers on longer trips, who agreed that the station was conveniently on the way for their current trip, and who found the station using a web-based application on their cellular phones were more likely to refuel at stations in this doubly freeway-anchored manner. These metrics provide station developers with an expected percentage of double freeway-anchored trips that will refuel at their station and the characteristics of drivers who are likely to exhibit this refuel behavior. If these findings are consistently found in other areas, it would mean that fuel companies can construct a station near a freeway interchange that can serve nearby residents and fleets while also ensuring that some customers will refuel at the station who are located in distant areas of the city.

Access to web applications, online forums, and online mapping tools enabled drivers to be more strategic about their station choices, and allow somewhat regular refueling at more than one station. Congestion avoidance did not seem to concern many survey respondents, and was also not significantly related to doubly freeway-anchored refueling. Even when traffic was perceptibly moving very slowly on the nearby freeways, drivers appeared indifferent to it because they either had HOV lane access or anecdotally indicated that those levels of congestion a normal part of living in the region.

HOV lane access, then, could be explored as an incentive to entice more drivers to consider station locations near freeway interchanges, provided there is convenient access to the local street network.

This observed variation in trip distribution for station use for interurban travel could also be incorporated into future multi-objective station location models that consider the aims of both flow-capturing and point-covering models when deploying highway-based AFV refueling stations to help increase AFV adoption within metropolitan areas. As the public refueling infrastructure continues to grow for AFVs, perceptions relative to convenience, accessibility, and safety may evolve, and drivers may alter their use and perceptions of freeway-based stations. These factors will be important to consider and monitor for urban areas interested in deploying their own infrastructure for fast-fueling AFVs.

Combined with the metrics from the FTCA, this survey of drivers who refuel at stations near freeway interchanges can be advanced in two future research directions. One would be to construct a spatial decision support system that combines deviation reduction metrics and freeway station refueling behavior data with spatial analysis and geovisualization. This would allow decision-makers to explore alternate scenarios that would result from different station locations both within one freeway interchange and across freeway interchanges in a metropolitan area or region. Another future research objective would be the creation of a typology of freeway interchanges that assess deviation reduction, driver behavior, and station perception. This would require data on types of interchange environments that drivers avoid and would also require driver behavior and perception data of these stations in other geographic areas, but could be a useful tool when assessing freeway traffic capture.

Chapter 5. Conclusion

5.1 Review

There is general agreement that the lack of a convenient refueling infrastructure is the most crucial barrier before widespread adoption of AFVs will occur (Melendez 2006), but there is not a consensus in the station location literature about how to operationalize convenience in order to recommend effective station locations. If the goal is to locate stations conveniently for customers, and if the definition of convenience is near where early adopters will likely live, then each station can only serve a small number of people who live within a few miles, numbered in the ten thousands. Whereas if the definition of convenience is to serve travel routes that customers from across the metropolitan area traverse each day, then each station can serve hundreds of thousands of people. With the latter from of convenience in mind, this dissertation research informs the critical investment decision of where to place initial AFV refueling stations within metropolitan areas or larger regions. The findings most relevant to refueling station deployment for fast-fueling AFVs are:

1) Early adopters of CNG vehicles refuel on the way between origins and destinations ten times more often than they refuel near their home, when there is no station that satisfies both criteria. This means that a strategy that primarily considers drivers' trips across a metropolitan area, and not only the home

locations of early adopters, is a more appropriate representation of demand for early refueling infrastructure.

2) Freeway interchanges, through which the highest volumes of traffic move in a metropolitan area each day, can be appropriate locations to place refueling stations that are on the way for any given driver's origin or destination. Stations cannot actually be built at the intersection of limited access highways. Therefore, suitable sites on nearby street networks must be chosen. An ad hoc process of locating stations on these street networks near the interchange, however, is unlikely to succeed. The Freeway Traffic Capture Algorithm (FTCA), a new network GIS method developed for this purpose, systematically assesses each site on the local street network's ability to capture all traffic passing through the interchange in a convenient manner, using deviation from a driver's shortest path as the metric by which to assess a candidate site's suitability.

3) The most effective locations for stations near interchanges are relatively close to the interchange center, and not necessarily immediately adjacent to freeway entrances or exits. In the case of Los Angeles freeway interchanges, surrounding street networks with lower relative amounts of on-ramps, off-ramps and frontage roads and are generally more complex are *more* likely to contain at least one location capable of capturing all passing traffic somewhere within a one mile radius of the interchange center.

4) This sample of early AFV adopters generally perceived stations near freeway interchanges to be safe, accessible environments that were conveniently on the way for their current trips. Importantly, drivers did not consider these metrics in a significantly different manner compared to a station along one freeway that was closer to a residential area and away from a freeway interchange. This may help allay the anxiety that station developers will feel in building a station in an area that they feel that drivers will likely avoid.

5) Nearly half of all drivers who chose to refuel at these stations exited a freeway, refueled, and immediately returned to the freeway, with no other trip anchor nearby. Using logistic regression, significant factors that are found to increase the likelihood of refueling on these doubly freeway-anchored trips are: longer trips, finding the station using an application, and agreement that the station was conveniently on the way between the driver's current origin and destination. Stations that are cited multiple times in drivers' choice sets of stations are significantly closer to freeways than those not cited, and are in relatively wealthy parts of the metropolitan area compared to those not cited.

Collectively, these findings indicate that stations in heavily traveled nodes of the metropolitan highway network can play a crucial and effective role in the nascent stages of AFV development in other cities, particularly if located in a manner that incorporates the observed scale interdependency between regional highways and local surface streets near freeway interchanges. The results of this study are likely not transferable to Level 2

(240V) public charging infrastructure for EVs, but would be applicable to locating battery switching and direct current EV fast-charging infrastructure near interchanges. The drivers of natural gas vehicles considered in this analysis in Southern California do represent an analog population of early adopters of all other fast-fueling vehicles. Before assuming that results are immediately transferable to the development of a hydrogen or biofuel refueling infrastructure, though, the role of fleets and the natural gas vehicle refueling infrastructure in Southern California must be considered, and represents an important decision point for other regions.

5.2 The Roles of Consumers and Fleets

The interaction of fleet and consumer AFV drivers should be explicitly considered in future research, for vehicle purchasing policy, station construction, and station usage for all fast-fueling alternative fuels. The majority of the survey respondents in this study owned private vehicles sold on the consumer market, but this is not representative of total CNG vehicle use in the region. The CNG refueling stations that were the survey sites for this research were built to encourage one major local fleet to switch from gasoline to CNG as a transportation fuel. Conversations with employees of the companies who own and operate these stations indicated that fleet vehicles are responsible for the vast majority of their fuel sales in Southern California and are therefore the major market of interest at present, while the consumer market is only considered additional marginal income. This impacts the way in which drivers perceive the station network, particularly regarding shared station usage, though this may not necessarily be the case for hydrogen vehicles during their initial use.

Hydrogen fuel cell vehicles are widely considered to be a successor to gasoline vehicles in the consumer market, and their role as a fleet vehicle is unknown. They have only become available for lease by consumers within the past few months. What is also unknown is the role that initial stations built near interchanges would serve as infrastructure for fast-fueling AFVs such as hydrogen fuel cell vehicles, particularly if the strategy is aimed at boosting consumer adoption. If left completely to the private sector, it is not difficult to imagine that a mature AFV refueling infrastructure will eventually resemble that of gasoline stations if hydrogen vehicle sales match that of conventional vehicles. As more stations are built and conveniently placed along commuting routes that connect residential areas to other areas of a city, drivers may shift their refueling behavior to these stations closer to their homes and away from the stations near freeway interchanges. Additional stations may also be built near freeway interchanges beyond the initial ones that can capture all travel directions. With enough demand, station developers may elect to simply place stations at multiple freeway entrances and exits for most or all travel directions through one interchange, replacing the one sited using the logical framework of the FTCA.

The eventual implication is that stations involved in the crucial initial investment that enabled widespread AFV adoption may experience an eventual decline in station usage, which could dissuade investors from these locations. For natural gas vehicles, this may not be a concern, as the presence of an anchor fleet that operates with CNG or LNG near a freeway interchange ensures consistent usage of that station, even if lower percentages of the volume of passing traffic leave nearby freeways to refuel near interchanges over time. Strategies that ensure longer-term viability of stations are a critical avenue of future research and it is recommended that part of this strategy involves explicit definition of the roles of both fleet and consumer AFVs in the regional transportation plan.

5.3 Policy Recommendations and Strategies

In the United States' current political climate, many recommendations that involve the expenditure of public funds can be difficult to advance, which includes investment in transportation infrastructure. To alleviate these concerns and reduce the potential public investment in AFV refueling infrastructure, it is suggested that natural gas station deployment should identify relatively large existing fleet bases that have not yet converted to alternative fuels within one mile of interchange centers, provided they are located on the local street network at locations that also have high FTCA scores. In addition to the daily refueling demands of the fleet anchored there, such locations would be able to capture both fleet and consumer AFV traffic passing through the nearby freeway interchange while simultaneously serving as a convenient station for nearby residents or employees. Additional smaller fleets in the area that would not have the necessary capital to invest in an AFV station at their own base could also make use of this station as well.

An alternative strategy to locating and building stations at fleet bases would be to identify automobile dealerships within one mile of freeway interchanges. This could decouple consumers' reliance on fleets to adopt alternative fuels before they can have an infrastructure available to them, and potentially alleviate some of the frustrations encountered at stations shared by heavy-duty fleet vehicles and light-duty vehicles. Examples of these locations in Los Angeles are the Toyota and BMW dealerships at the

US Highway 101 and California Highway 134 interchange in North Hollywood, and the Honda dealership at the intersection of Interstate 10 and California Highway 110 in downtown Los Angeles. Similar sites can be found at freeway interchanges in other cities.

Should high FTCA scores be found to be coincident with dealerships, that means that stations nearby could capture passing traffic on the freeway in the same manner as the aforementioned fleet strategy. Then, placing stations at or near dealerships would allow automobile manufacturers to offer AFVs on the market to both consumers and fleets without having to invest in refueling infrastructure on their own property. Partnerships with station developers could generate lucrative agreements for both parties, while new or used AFVs sold by the dealership could be driven by potential buyers in a setting free of range anxiety. Employees at the dealership and customers alike could occasionally refuel the vehicles at the station as part of a test drive, providing familiarity and comfort with a new vehicle and refueling technology. Since AFV stations currently lack attendants, providing drivers with this training could reduce consumer anxiety when the decision to purchase the vehicle is made. In contrast to the fleet-based strategy, which is currently the more attractive option for CNG station developers, the dealership-based alternative could have a substantial positive impact on consumer adoption while also servicing nearby vehicle fleets of other alternative fuels.

This strategy could also address another outstanding need in the AFV literature, which is an analysis of the relationship between the proximity of refueling infrastructure to one's home or daily activity locations and an individual's decision to purchase an AFV. That decision likely includes both the location and distribution of stations and the location and distribution of travel and trip anchors across an urban area, but is not well understood. The combination of an automobile vehicle dealership and a refueling station along a frequently traveled route may increase the likelihood of a potential buyer to consider an AFV for personal transportation, and could be a subject of future inquiry.

While HOV lane access was an important incentive for Los Angeles-based commuters to consider a transition to CNG vehicles, this may not be the case for potential early adopters in other markets that do not have as many people who participate in long distance commutes. Cities similar to Los Angeles can pursue these same types of incentives to encourage adoption of AFVs, but stronger tax incentives for vehicle purchasers, exemption from congestion pricing, and fuel subsidies may be more effective for cities with more dense built environments and fewer freeways compared to Los Angeles.

5.4 Methodological Considerations

Results from Chapter 4 demonstrate that refueling stations near interchanges served a mixture of drivers' trip types, which carries major implications for the existing facility location models that make assumptions—either explicit or implicit—about how drivers access stations. Further, Chapter 2 proves that early adopters of AFVs refuel at stations on the way far more frequently than those near home given the initial refueling infrastructure available to them, and results from Chapter 4 demonstrate that drivers who access these stations as a stop along a freeway trip consider them to be conveniently on the way for their current trip. However, there were some drivers in both studies that refueled on relatively shorter trips, or on there-and-back refueling trips from either home or work. Clearly, there is some non-zero percentage of drivers who refuel at stations in ways that are assumed by both point-based and tour-based approaches, even if it is not the majority.

To incorporate this mixture of trip types, the FTCA could also be extended to applications more suited to point-based coverage models. One example would be to structure an alternative formulation that assesses the ability for drivers to travel on there-and-back trips to a station near an interchange from home or work locations. Trip convenience could be assessed from nearby trip anchors within some acceptable travel time threshold from all possible travel directions involving the freeway interchange.

Another avenue of future research relevant to station location modeling is how best to incorporate the coefficients produced from the FTCA into flow-based models. The simplest method would be to apply the fraction or percentage of traffic that could theoretically be captured by the best available site within an interchange to the interchange's overall ability to capture passing traffic in the model. It is also possible that instead of applying a single fraction or percentage that represents the best overall site in an interchange based on all travel directions, the FTCA could return only the travel directions through an interchange that are relevant to paths being assessed between traffic analysis zones, or other trip origins and destinations. That approach may be of particular interest to the arc-based formulation of the model.

Combined with the metrics from the FTCA, a spatial decision support system could be developed that would combines deviation reduction metrics and freeway station perception and refueling behavior data with spatial analysis and geovisualization. This would allow decision-makers to explore alternate scenarios that would result from deciding to build stations at certain locations both within one freeway interchange and across freeway interchanges in a metropolitan area or region. The ability to assess trade-offs from a certain arrangement of stations would be a powerful tool and would also allow the inclusion of local knowledge into station deployment.

Another future research objective would be the creation of a typology of freeway interchanges that assesses both deviation reduction and station usage and perception. Combining the metrics of the interchanges studied in Chapter 3 with the behavioral and perception data from Chapter 4 provides a foundation from which to build such a typology. Effective locations are both a product of the street network around the interchange and a person's willingness to consider that environment. To strengthen such a study, data should next be gathered on the types of interchange environments that drivers avoid. This would also be aided by driver behavior and perception data of these stations in other geographic areas such as cities in Europe or Asia, but could be a useful tool when recommending the viability of station sites at highway and freeway interchanges for areas looking to deploy an initial wave of AFV refueling stations.

5.5 Future Considerations

The role of AFVs and personal automobility in regional plans will likely be a matter of some debate in the coming years, and that discussion could be impacted by emerging technologies. The transition from gasoline to any alternative fuel may provide immediate economic and environmental benefits, but does nothing to discourage the impact that automobiles have on urban form, which is a subject of interest to the field of urban planning and community development. The relationship between the negative impacts of urban sprawl and the proliferation of personal automobiles is well-established in the transportation planning literature. Recommendations from this field typically focus on the restructuring of urban design and urban transportation systems, often attempting to shift people to alternative modes of transportation aside from the personal automobile. Therefore, policy recommendations that advocate simply shifting the personal vehicle fleet in a metropolitan area from one fuel to one or more different fuels may not be seen as a satisfactory solution by some urban planners. Policies that integrate AFVs and refueling infrastructure in tandem with changes in urban design may more aggressively reduce the environmental and equity concerns that have been demonstrated to occur as a result of current transportation systems.

Finally, autonomous vehicles are beginning to emerge as a viable technology and could begin operating on roadways in the United States within the coming decade. There are a number of uncertainties about how this technology will proceed and its impact on transportation, or how successful it will ultimately be, but it does warrant notice for the deployment of AFVs within urban areas. Autonomous vehicles could be readily be produced as AFVs, but the change in driving patterns brought about by autonomous vehicles is not yet well understood, regardless of the fuel they consume. Autonomous vehicle owners could potentially be less sensitive to congestion, deviation time, and overall trip length since they can use their time in transit to work on other tasks besides driving. That ability may make owners indifferent to long commutes between their homes and places of employment and less likely to take mass transportation, which could possibly contribute to the continuation of urban sprawl. One consideration that has been suggested for autonomous vehicles is that they be owned by neighborhoods or groups of people. If ownership of these vehicles is shared between many households, that could mean that driving and refueling behaviors found by individual vehicle owners in this study may not necessarily apply to autonomous vehicle driving and refueling patterns, making them more similar to the refueling patterns of fleet vehicles such as buses or taxis.

AFVs are an emerging and promising technology, and are likely to play a substantial role in urban transportation in the coming decades, but the precise manner in which the vehicles and stations will be deployed is a process that is only beginning. In California, clusters of hydrogen stations near likely adopters are currently under construction, but the overall results from this analysis indicate that stations near busy freeway interchanges can play an important role in infrastructure deployment. Ultimately, regional planning authorities should incorporate the local driving and refueling characteristics in the process of choosing where to locate initial stations, and avoid the ad hoc station deployment methods that have occurred to date.

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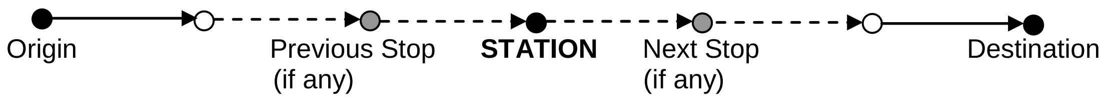
APPENDIX A

CONSUMER CNG REFUELING SURVEY
DATA COLLECTED JULY-DECEMBER 2011

1. Before you begin refueling, please check how much fuel was in your tank when you stopped. *Circle one of the below, whichever is closest.*

⅞ ¾ ⅝ ½ ⅜ ¼ ⅛ "at or below empty (or reserve light is on)"

2. The following section is about the trip you are on right now. Please fill in the table below with this diagram of a one-way trip in mind:



Note: The difference between a "stop" and your "origin" or "destination" is that stops are shorter and secondary, while your origin or destination activity (depending on whether you are going or returning) defines the primary purpose of your trip. If you are making no other stops on this entire trip before returning to your origin, then your final destination is the same as the origin. Please be as exact as possible about locations by providing the exact name (e.g.,_______ School, ______ Mall and nearest intersection (e.g., ______ & _______ Sts) in ______ city/state.

	ADDRESS OR LOCATION (PLEASE BE AS SPECIFIC AS POSSIBLE)	LOCATION TYPE					
		Home	Work	School	Shopping	Social/Dining	Other
ORIGIN/ START OF TRIP							
PREVIOUS STOP (IF ANY)							
THIS STATION							
NEXT STOP (IF ANY)							
FINAL DESTINATION							

3. If the trip above did not include your home, please give us the approximate cross streets where you live so we can estimate how far from home you are refueling your vehicle.

Cross Streets ____

City_________________

4. Please rank the top 3 reasons that you selected this station today.

Please write "1" next to the most important reason, "2" next to the second most important reason, and "3" next to the third most important reason.

___ Brand loyalty
___ Convenient location
___ Convenience store
___ Low fuel price
___ Other reason - Please specify ______________________
___ Use of credit cards
___ Right-hand turn
___ Running out of fuel

5. Did you detour from your preferred route to your final destination to visit this station?
□ Yes □No

6. Did you make a right turn or left turn to enter this station? □ Right □Left

7. How frequently do you refuel at this particular station? ________% of the time

8. What type of vehicle are you refueling today? *Please check the box to the RIGHT of your vehicle:*

Gasoline		Diesel		Hybrid		Plug-in Hybrid	
CNG-Orig. Equip. Mfr		CNG-After Mkt		LNG		Propane	
Flex-Fuel (E85)		Biodiesel					

9. Who owns the vehicle you are refueling today?
□Me □Another household member
□My employer □Someone else - Please specify______________________________

10. Do you, or other members of your household, own any other vehicles, and if so what kinds?
Please write the number of other vehicles after each type of vehicle owned:

Gasoline		Diesel		Hybrid		Plug-in Hybrid	
CNG-Orig. Equip. Mfr		CNG-After Mkt.		LNG		Propane	
Flex-Fuel (E85)		Biodiesel		Hydrogen		All-Electric	

11. How many total people live in your household? ______

12. How many of those people are drivers? ______

13. What is your age? ______

14. Are you: □Male □Female

15. What was the last grade of school you completed?
□Grade school □Some high school □High school graduate
□Some college □College degree □Graduate degree

16. Are you employed?
☐ Yes ☐No

THE NEXT TWO QUESTIONS ARE FOR CNG DRIVERS ONLY
17. Do you have the capability to refuel your vehicle at your home? ☐ Yes ☐No

18. Please rank the top 3 reasons that you own a CNG vehicle. *Please write "1" next to the most important reason, "2" next to the 2nd most important reason, and "3" next to the 3rd most important reason.*
___ Use of HOV lane
___ Environmental concerns
___ Lower fuel price
___ CNG is a domestic, not imported, fuel
___ Lower maintenance costs
___ Other reason - Please specify ______________________

APPENDIX B

ALL SOUTHERN CALIFORNIA INTERCHANGE METRICS

Name	Cand. Nodes	WA_k (avg.)	A_k (avg.)	Inbound AADT	β	Access Arcs (%)	A_k 1.0	A_k 0.0	Type
CA133 CA241	32	0.0	0.0	119,600	1.00	38.7	0	0	3 way
CA91 CA241	568	6.8	4.9	539,800	1.05	19.6	0	461	3 way
I10 CA110	1,007	53.8	54.2	1,122,000	1.22	13.1	0	14	4 way
I110 I405	487	46.7	46.3	960,000	1.16	16.9	0	34	4 way
I15 CA60	176	11.9	11.4	708,000	1.08	27.6	0	120	4 way
I405 CA133	321	47.4	52.4	543,300	1.21	17.3	0	37	3 way
I10 I15	182	42.7	42.5	913,000	1.08	26.9	0	28	4 way
I5 CA133	656	34.6	36.0	536,500	1.13	16.1	0	113	4 way
I10 I215	416	31.9	31.6	722,000	1.10	18.8	0	143	4 way
I15 CA210	151	29.5	29.3	565,000	1.03	25.7	0	12	4 way
I405 I10	876	39.8	39.7	1,063,000	1.30	9.8	0	57	4 way
I405 I105	713	32.9	30.3	1,008,000	1.14	21.3	0	21	4 way
I5 CA14	109	9.7	11.0	624,000	1.12	57.9	0	43	3 way
I5 CA57 CA22	811	54.4	54.9	1,249,100	1.11	24.1	0	12	5 way
I710 I405	667	37.7	36.6	909,000	1.23	15.9	0	89	4 way
CA91 CA71	254	7.5	6.7	575,000	1.05	14.0	0	213	3 way
I10 CA57 CA71	416	24.1	25.3	836,500	1.09	24.1	0	64	5 way
I105 I710	914	23.1	23.1	899,000	1.22	15.4	0	166	4 way
I15 CA91	493	17.4	16.6	812,000	1.09	16.0	0	166	4 way
I215 CA210	514	40.3	41.5	350,000	1.21	6.4	0	61	4 way
I405 I605	614	14.2	14.3	804,100	1.21	15.2	0	342	3 way
I605 CA91	786	25.4	25.5	1,059,500	1.12	9.6	0	150	4 way
I5 I210	297	19.9	22.6	597,000	1.16	15.0	1	137	3 way
I5 I405 south	540	17.7	18.1	622,500	1.14	8.1	3	326	3 way
I5 CA134	415	43.2	43.5	887,000	1.29	11.6	4	33	4 way
I405 CA55	798	35.4	35.5	951,900	1.17	16.7	5	138	4 way
CA91 CA57	840	31.4	31.2	1,006,000	1.09	15.8	7	178	4 way
I10 I605	493	47.3	47.4	810,000	1.12	15.8	8	74	4 way

I210 I605	456	35.0	36.6	659,000	1.14	13.0	12	100	3 way
I5 CA73	737	23.4	22.2	568,400	1.10	1.7	13	400	3 way
I405 US101	489	51.1	51.0	1,056,000	1.28	12.7	14	21	4 way
CA60 CA71	602	59.5	60.5	603,000	1.13	12.0	15	6	4 way
CA261 CA241	197	13.3	13.6	127,400	1.04	9.3	16	145	3 way
I5 I405 north	276	23.5	25.4	543,000	1.27	1.1	16	142	3 way
I15 I215	130	35.7	38.0	322,000	1.06	14.0	16	50	3 way
I110 I105	1,131	55.9	55.9	986,000	1.23	17.1	19	12	4 way
I110 CA91	805	49.1	50.0	627,000	1.15	17.2	20	77	3 way
I5 I605	833	45.0	44.9	981,000	1.21	10.7	20	100	4 way
I605 CA60	466	26.8	26.7	953,000	1.10	15.6	20	205	4 way
I405 CA22	568	19.1	20.8	772,500	1.16	4.5	31	301	3 way
CA55 CA73	683	48.4	52.1	724,600	1.15	15.4	32	23	4 way
I5 CA55	935	44.6	44.8	1,236,000	1.15	10.3	32	130	4 way
I5 CA91	872	33.4	33.7	921,100	1.12	14.6	34	191	4 way
CA2 CA134	487	40.8	40.5	695,000	1.21	16.3	35	117	3 way
CA57 CA60	869	27.3	27.4	790,000	1.11	7.4	35	289	4 way
I710 CA60	773	60.0	60.5	744,000	1.25	14.1	44	51	4 way
CA55 CA22	1,061	23.5	24.4	653,400	1.13	6.1	49	561	3 way
I5 CA118	656	61.5	60.7	805,000	1.26	13.9	51	9	4 way
I215 CA91 CA60	778	57.4	57.3	654,000	1.20	9.8	52	55	4 way
I210 CA2	554	46.2	46.7	399,500	1.23	0.9	60	127	3 way
I405 CA118	671	63.2	62.8	806,000	1.32	11.1	61	9	4 way
I710 CA91	1,071	50.8	50.6	872,050	1.26	12.1	63	110	4 way
US101 CA23	274	52.3	52.4	470,000	1.24	9.4	64	67	3 way
I5 CA170	483	49.0	52.7	596,500	1.21	5.6	66	23	3 way
I215 CA60	464	46.3	46.9	444,000	1.13	8.3	72	139	3 way
I10 CA210	303	62.7	64.5	412,000	1.18	15.5	79	32	3 way

I405 CA73	942	32.5	33.6	687,000	1.20	6.1	81	247	3 way
CA91 CA55	661	37.2	37.7	732,000	1.10	11.1	83	247	3 way
I210 CA118	386	55.5	55.2	364,000	1.18	10.7	86	73	3 way
I5 CA110	764	57.0	58.0	804,000	1.19	15.3	87	115	4 way
I5 I710	815	70.6	70.5	884,000	1.32	6.9	87	22	4 way
I5 CA2	860	57.0	59.7	746,500	1.18	11.9	91	44	4 way
CA210 CA57	762	42.5	43.7	581,000	1.09	7.8	97	173	3 way
I5 I10 CA60	825	63.7	64.1	1,125,000	1.18	14.7	108	27	5 way
I605 I105	921	60.0	62.0	789,000	1.17	15.1	123	41	3 way
CA170 CA134	621	65.3	65.9	910,500	1.39	5.4	125	10	4 way
I10 CA60	482	50.2	50.6	260,000	1.27	5.1	131	109	3 way
I5 CA261	1,111	47.2	54.7	640,700	1.11	7.0	148	108	3 way
I10 I710	828	46.3	46.9	560,000	1.15	11.4	159	182	3 way
I5 I10	934	68.9	68.8	952,000	1.21	11.3	210	24	4 way
US101 CA110	1,034	69.9	70.0	937,000	1.19	14.1	216	64	4 way
I210 CA134	802	72.1	73.6	646,000	1.19	11.7	346	31	3 way

APPENDIX C

CNG FREEWAY INTERCHANGE REFUELING SURVEY:
DATA COLLECTED AUGUST 2014

Station ________________________ Date___/___/_14_ Time ________

☐ Personal Vehicle ☐Fleet Vehicle Survey Number ________

(1) Can you refill this CNG vehicle at home (personal) or base (fleet)?
☐ Yes ☐No

(2) (Personal Vehicle only)
Do you or other members of your household own any other vehicles?
☐ Yes ☐No

If so, what are they? Please write the number of vehicles next to the vehicle type:

Gasoline		Diesel		Hybrid		Plug-in Hybrid		Flex-Fuel (E85)		Hydrogen	
CNG – Orig. Equp.		CNG – After Mkt.		LNG		Propane		Biodiesel		All-Electric	

(3) What are your approximate home cross-streets?
__________________and____________________ In which city? __________________

(4) Where was your last stop immediately before this refueling stop?
__________________and____________________ In which city? __________________

(4a) What type of activity was this?

☐ Home ☐Work ☐ Shopping ☐Social/Dining ☐ School ☐Other

(5) Where is your next stop immediately after this refueling stop?
__________________and____________________ In which city? __________________

(5a) What type of activity was this?

☐ Home ☐Work ☐ Shopping ☐Social/Dining ☐ School ☐Other

(6) What was your fuel tank level when you arrived at this station (before refueling)?

☐ Fuel Light on ☐1/8 tank ☐ 1/4 tank ☐3/8 tank ☐ 1/2 tank ☐> 1/2tank

(7) Which exit/ramp did you take when leaving a freeway to access this station?
____

___Did not exit a freeway on this trip

(8) Which entrance/ramp will you take when to access a freeway after refueling?

____

___Will not re-enter a freeway on this trip

Convenience Questions

(9) I refueled at this CNG refueling station because it is convenient to my home location.

Strongly Agree (1)	Agree (2)	Neutral (3)	Disagree (4)	Strongly Disagree (5)	Not Applicable

(10) I refueled at this CNG refueling station because it is convenient to my place of work.

Strongly Agree (1)	Agree (2)	Neutral (3)	Disagree (4)	Strongly Disagree (5)	Not Applicable

(11) I refueled at this CNG refueling station because it is conveniently on the way between my origin and destination.

Strongly Agree (1)	Agree (2)	Neutral (3)	Disagree (4)	Strongly Disagree (5)	Not Applicable

(12) This CNG station is a safe, comfortable environment in which to refuel.

Strongly Agree (1)	Agree (2)	Neutral (3)	Disagree (4)	Strongly Disagree (5)	Not Applicable

(13) This CNG station is easily visible from the freeway.

Strongly Agree (1)	Agree (2)	Neutral (3)	Disagree (4)	Strongly Disagree (5)	Not Applicable

(14) It is easy to access this CNG station from the freeway.

Strongly Agree (1)	Agree (2)	Neutral (3)	Disagree (4)	Strongly Disagree (5)	Not Applicable

(15) Low fuel price was an important factor in me refueling at this station.

Strongly Agree (1)	Agree (2)	Neutral (3)	Disagree (4)	Strongly Disagree (5)	Not Applicable

(16) Does congestion on the nearby freeway make you avoid this station at certain times of day?

□ Yes □No If yes, what times of day would you avoid this station?

____

(17) How did you find out about this refueling station? Check all that apply.

□ Road signs □Passing by here on a past trip □ Internet Search □Internet community group (such as cngchat.com) □Advertising □Word of mouth □ GPS □Other :

(18) How often do you refuel here?

□ rarely (0-20%) □occasionally (20-40%) □ relatively often (40-60%) □ frequently (60-80%) □ most of the time (80%+)

(18a) If less than 40%, at which station do you primarily refuel?

(19) What other CNG stations do you refuel at, or would you consider refueling at?

(20) Other general comments about this station.