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Hydrogen Station Siting and Refueling Analysis Using Geographic Information Systems:
A Case Study of Sacramento County

By

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B.S. (University of Puget Sound) 1997

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CHAPTER 1. INTRODUCTION

Growing energy security and environmental concerns in the transportation sector have prompted policy makers to explore hydrogen as an alternative to petroleum. One of the major obstacles to the deployment of an alternative fuel vehicle is the distribution of the fuel itself. In the case of hydrogen, the infrastructure for refueling cars is almost non-existent. The question of which comes first, the fuel stations or the vehicles, has been likened to the “chicken and egg” allegory¹. Manufacturers are unwilling to build vehicles when fuel is not available, and fuel providers are unwilling to build fuel stations when there are no vehicles.

To address the chicken and egg issue, several strategies have been suggested. For convenience, I divide the strategies into three broad categories: Macro-level, meso-level, and micro-level. The sufficient number of stations is referred to as macro level. Relating individual sites to their placement in a network is referred to as meso-level. Individual site evaluation is micro-level. All three levels are important and must be considered when siting hydrogen stations.

The aim of this thesis is to employ meso-level analysis in order to make a macro-level estimation. Meso-level analysis is used to generate a reasonable network of station sites, and this network is compared to the existing network of stations. By comparing networks of varying number to the existing network, generalizations about the sufficient number of stations are made. Although the focus of this thesis is meso-level siting, all three levels should be considered.

One strategy to overcome the chicken and egg problem has been to make macro-level estimations of the sufficient number of stations necessary to support a hydrogen fuel cell car fleet². These studies include estimations based on retrospective analyses of non-gasoline experiences in the U.S.³ and New Zealand,⁴ estimations based on aggregate coverage rules,⁵ and estimations based on stated preference survey research.⁶ These estimates are useful, but only to quantify the investment necessary for a hydrogen infrastructure.

Another strategy has been to look at the best placement for conventional gasoline⁷ and alternative fuel stations individually.⁸ There has been little work in the academic arena, however, on relating macro-level station number estimations to micro-level placement of those stations based on consumer refueling behavior.

The field of operations research, however, provides methods for meso-level analysis of refueling stations. Some of the work has been aimed at connecting metropolitan regions,⁹ and some of the work has been aimed at capturing market share within a metropolitan region.¹⁰ Building on previous research, this thesis presents methods of relating the number of stations to station placement on a regional scale, using a geographic information system and incorporating operations research methods. The methods explored in this report are most applicable when examining station networks within a metropolitan region rather than between metropolitan regions. This work promises to quantify more accurately the number of stations needed in an area, based on the unique geography of a region.

CHAPTER 2. LITERATURE REVIEW

2.1 Micro-Level Siting Considerations

The placement of individual stations has been an issue for the petroleum industry since the first station opened for business in 1907.¹¹ The network has evolved over time, and market forces have shaped its development. Until recently, potential sites have been evaluated solely on the micro-level siting techniques described in this section. A review of the history of station siting and of the factors considered in siting decisions provides a foundation for building a refueling network using meso-level siting techniques.

2.1.1 Siting History

The sites for the first “gasoline stations” were actually existing kerosene outlets, and the outlets were usually hardware stores, grocery stores, drug stores etc. Gasoline appeared in these outlets around the turn of the century with the introduction of the automobile.¹² The siting of these stores was not necessarily centered around the convenience of the motorist, and selling gasoline was a sideline business.¹³ The gasoline was most commonly kept in a barrel behind the store, and the gasoline was dispensed by pouring it into the tank of a vehicle. This method was slow and inefficient, causing many motorists to maintain fueling facilities at home, being supplied with gasoline by tank wagon.¹⁴

Refueling from a barrel proved hazardous, but pumps introduced around 1910 enabled tanks to be stored underground. Pumps reduced the risk, and increased the number of potential sites for gasoline stations. Soon pumps located on the curb sprang up

to service the gasoline demand. This method of dispensing was an improvement over pouring the gasoline in the tank at a hardware store, but soon the popularity of the automobile overwhelmed the capacity of the curbside outlets, and long lines along the streets created a traffic hazard.

An alternative to these curbside pumps was obtaining gasoline directly from the bulk plant.¹⁵ The gasoline was significantly cheaper since two middlemen, the tank wagon operator and the curbside pump operator, were excluded from the supply chain. Soon operators of bulk plants began installing separate fueling facilities on the premises and these outlets may be considered by some to be the first drive in service stations.¹⁶ Drive in service stations gained in popularity through the 1920s, even though curbside refueling continued to be important as well. By 1927, there were 125,000 drive in stations, 52,000 garage stations, 140,000 curbside stations.¹⁷

In the years following WWI, there was a recognition that traffic was an important factor in station siting, and many retailers sited their outlets near busy intersections. These outlets tended to be in built up areas of the city. The lots were small, usually 60 feet by 60 feet.¹⁸ Curbside refueling was also important. Soon, the volume on roads increased, speed increased, roads were widened, and expressways began to be built making some high traffic sites infeasible for station siting. The link between traffic and gasoline sales had to be reconsidered.¹⁹ New access roads and changes in zoning law created new opportunities for station development, sometimes leaving older stations “high and dry”.²⁰

After WWII, few rules guided site selection for retail stations, and according to one source, automobile traffic was not a large factor in site selection. Little money was

invested by the oil companies on researching site selection. Due to the increase in investment capital, many retailers, including oil companies, rushed to establish themselves in new markets. This resulted in indiscriminate purchasing of urban retail sites, often resulting in unwise siting.²¹ With the advent of the interstate highway system in 1956, freeway interchanges became hotbeds of automobile oriented retailing including service stations, motels, and restaurants.²²

2.1.2 Gasoline Station Siting Attractors

Gasoline station siting is unique in that by the very nature of the product, the clientele is highly mobile. There are several explanations as to why a customer may patronize a station. One explanation is that the customer is just passing by a station and decides to buy gasoline and perhaps other daily items based on the route he or she took irrespective of the location of the gasoline station. Another explanation might be that a customer likes the attributes of the station or the price of the gasoline, and makes a special trip to patronize a station. Alternatively, a customer may be shopping at a retailer nearby, and the station is affiliated with the retailer, such as is the case with a warehouse store. Most likely a station choice is dependent on a mix of the decision factors. Three factors are particularly important in siting decisions: traffic, local population, and position on the street.

Traffic

As was recognized early in gasoline marketing, traffic passing by a station is an important consideration in station siting - the more traffic, the more potential customers

for the station. Freeway interchanges and the intersections of major arterials have thus become popular locations for stations. But while traffic is important in determining the location of a site, at times too much traffic, especially fast traffic, can be detrimental to patronage. The ideal site has large volumes of slow moving traffic with good ingress and egress.²³

Local Population

One way to estimate the potential sales of a gasoline outlet has been to assess the population surrounding the station (See Table 1). This appears to be true in many cases,

Distance	Percentage of Respondents
1 block	8.8
2-3 blocks	21.0
one-quarter mile	19.0
one-half mile	13.1
three-fourths mile	6.1
one mile	9.0
more than one and one quarter miles	23.0
Total	100

TABLE 1. Distance of most frequently used station from motorist's home.²⁴

but where there is a large transient population, the local population may not predict potential sales. This effect may be cancelled out somewhat since some of the local population may become transient gasoline purchasers somewhere else, and vice versa.²⁵

In the 1960s, to quantify the proportion of customers drawn from the immediate neighborhood, a rough rule of thumb of one-half to thirds of patrons was used.²⁶ This estimate should be adapted to the specific location being considered, but in general, there is a link between home and station.

Trip time from work	Trip time from home (min)					Total
	0-5	6-10	11-20	21-30	>30	
0-5	238 (18.7)	53 (4.2)	92 (7.2)	52 (4.1)	33 (2.6)	468 (36.8)
6-10	95 (7.5)	51 (4.0)	37 (2.9)	11 (.9)	10 (.9)	204 (16.0)
11-20	103 (8.1)	33 (2.6)	72 (5.7)	25 (2.0)	14 (1.1)	247 (19.4)
21-30	55 (4.3)	17 (1.3)	24 (1.9)	50 (3.9)	8 (.6)	154 (12.1)
>30	54 (4.2)	16 (1.3)	28 (2.2)	9 (.7)	93 (7.3)	200 (15.7)
Total	545 (42.8)	170 (13.4)	253 (19.9)	147 (11.5)	158 (12.4)	1273 (100.0)

() = Percent of grand total

TABLE 2. Refueling location relative to the home and work locations.²⁷

More recent studies seem to indicate similar information. In a paper by Kitamura and Sperling,²⁸ the relationship between a gasoline station location and the customer's trip origin or destination was explored. They surveyed 1521 drivers at 8 service station locations in the San Francisco Bay area and the Sacramento region. The sites were chosen to represent a cross section of station types and land use settings. They found that home was the most common origin or destination for those refueling, accounting for 74.8 percent of trips.

The time from the station to the origin or destination also shows some interesting relationships. Most people prefer to refuel five minutes from their origin or destination; these trips accounted for 71.9 percent of refueling trips. Drivers also show a strong tendency to refuel at the beginning of a journey. The work by Kitamura and Sperling indicates that consumers prefer to refuel near their home, and to a lesser extent, their

work (See Table 2). They suggest that a large amount of refueling occurs along the commute route.

Position on Street

Beyond traffic considerations and local population, the position on the street contributes to a station's success. Corners have been recommended locations for gasoline stations since the early days of gasoline stations. Ingress and egress is often easier, and there is the potential to capture traffic from two streets. Station visibility is also generally better on a street corner than for stations along a road (inside sites).²⁹

The determination of which street corner is the best is related to predominant traffic patterns along the streets in question. According to one source, "The most preferred location (for a service station) is a corner; and since more people will stop for gasoline and other services when they are returning from (rather than going to) work, the best corner is that on the far side of the street which is the normal direction used by people returning home".³⁰ Other advantages include high visibility due to the additional street width, and ingress and egress is easier for far side corner sites on streets with heavy traffic.³¹

2.1.3 Micro-Level Siting Barriers

Although micro-level hydrogen station siting barriers are not specifically addressed by the model presented later in this report, this section on barriers is included as background to the reader. Implementation of any station arrangement suggested by the model may not be possible if zoning and community attitudes do not favor hydrogen. Important issues include public perceptions of hydrogen, NIMBYism and zoning, factors determining community attitudes, and historical resistance to gasoline station siting.

Micro-level siting for hydrogen has thus far been limited to industrial areas, presumably to avoid any conflict with zoning and public safety concerns. If hydrogen were to become a competitor to gasoline, stations would have to be strategically placed to insure optimal access, especially at the start of its introduction. However, the public is not familiar with hydrogen, and there may be resistance to siting stations next to homes and businesses, exactly where they are most needed. It is uncertain whether there will be a public outcry against this new “untested” type of station.

Public Perception of Hydrogen

Hydrogen is perhaps best known for causing the Hindenburg disaster. The airship, Hindenburg, was filled with hydrogen and it exploded over Lakehurst New York on May 6, 1937.³² Hydrogen was blamed for the accident, but years later, the true cause of the accident was discovered. The metallic paint on the skin of the airship was extremely flammable, and this skin caught fire before the hydrogen. The spectacle of the Hindenburg disaster influenced public perception about hydrogen thereafter, even though the hydrogen was not the main contributor to the explosion at Lakehurst.

The public may also incorrectly associate hydrogen with the hydrogen bomb.³³ The hydrogen bomb is the most powerful weapon in the world, but the power of the hydrogen bomb is attributable to a fusion reaction, not a chemical reaction, such as happens in normal conditions. Many people know only that hydrogen is related to a weapon, and don't know why. Both the Hindenburg and the hydrogen bomb could potentially give hydrogen a bad public image.

In fact, gasoline is just as volatile, if not more volatile, than hydrogen. For example the lower explosive limit of gasoline is 1.4%, meaning that gasoline will combust at a mixture of 98.6% air and 1.4% gasoline vapor. Hydrogen's lower explosive limit is 4%.³⁴ Gasoline is not safe, we are merely accustomed to using it.

NIMBYism and Zoning

Hydrogen's reputation may cause public resistance to hydrogen stations being sited next to homes and businesses. Public resistance such as this has been dubbed NIMBYism or Not In My Back Yard-ism. NIMBYism usually refers to opposition to a large project that local residents do not want such as: interstate highways, dams, prisons, nuclear power plants, or casinos. However, NIMBY attitudes can also apply to smaller scale projects such as a hydrogen station. NIMBYism often arises when zoning ordinances fail to prevent the siting of objectionable projects near residential areas.

The concept of zoning emerged nearly a century ago as a way of preventing the siting of potentially noxious land uses near residential areas. The credit for the first comprehensive zoning law in the United States goes to New York City for its 1916 ordinance that grouped the entire city into one zone or another.³⁵ Although the zoning

was supported by many groups, it was most strongly supported by those who wanted to preserve the value of their land by keeping out undesirable land uses such as industry or apartments.³⁶ This point is articulated in a quote from 1920: “So long as undesirable properties could encroach upon an area in which good residences and good income bearing properties were already established, there would be no stability or trust in real estate as an investment”.³⁷

The official rationale, that developed a bit later, differed a little bit from the reasoning in New York. The officials justified widespread zoning with the following objectives:

- 1) To segregate inconsistent land uses
- 2) To prevent congestion
- 3) To provide for the economical provision of public services.³⁸

However, real estate values (and itinerant economic and class segregation) seem to have been the main driver in developing zoning law.

As of now, the siting of hydrogen facilities is governed by the National Fire Protection Association 50A standard.³⁹ This standard is designed to regulate large scale hydrogen transfer stations, and is not well suited to reflect the realities of urban or suburban siting. The cautiousness of this standard is indicative of the way hydrogen is viewed by the public and officials. Even though this standard is overly restrictive and is likely to change, opposition groups may use this standard as evidence that hydrogen is indeed not safe for consumers.

Until hydrogen codes stabilize, zoning variances will likely have to be granted to allow hydrogen station siting. A variance is needed when a development does not

comply with the land use zoning category for the site in question.⁴⁰ The variance procedure usually mandates that the neighbors in the immediate vicinity be informed of the land use change. These meetings are often the breeding ground for opposition to the land use, and objections in these meetings must be heard.

One of the universal factors that influence NIMBYism is geographical proximity.⁴¹ Simply stated, those who live closer to the planned development are more concerned about it. Those living or working 2-6 blocks away are more or less indifferent for small scale projects such as a gasoline station. Paradoxically, consumers prefer that their refueling stations are close to their residences. Resolving this inconsistency will enable more efficient siting of stations.

Factors Determining Community Attitudes

If hydrogen stations are to be sited in convenient locations, community attitudes must change. The first factor determining community attitudes towards a proposed business is the “quality” of the clientele of that business. If the clientele of the proposed business are seen by community members as social undesirables, they will not be welcome in the community.⁴² In the case of hydrogen stations this factor may actually play a positive role. Those people who drive hydrogen powered cars could be seen as environmentally responsible, or at least forward thinking, and as such, they should be welcomed.

The facility characteristics, including type, size, operating procedures, reputation of the sponsoring agency, and appearance, all affect how the community perceives a proposed development. Hydrogen stations fare well on most of these criteria. The

facility type can be seen different ways. On the one hand, fueling stations of any sort are seen as a quasi-industrial operation, and anecdotal evidence suggests that residential groups oppose this kind of development.⁴³ On the other hand, if the hydrogen station serves local residents, this will be seen as a positive.

Hydrogen stations are not large, so size will not be much of an issue. Operating procedures of a hydrogen station could be seen a problem if the public is not given assurances that the station will be run safely. Community groups are concerned with adequate supervision and proper staffing, and attention to this detail can tip the scales on acceptance of a project. One challenge for hydrogen stations is the appearance of the large above ground tanks that store the hydrogen. Many stations today have unsightly above ground tanks. This is due in part to the fact that burying the tanks is technically difficult and expensive.

The reputation of the sponsoring agency is also important. Spokespeople can enhance the reputation of the proposed facility. This may be hydrogen's best asset. Hydrogen is politically attractive due to its environmental and energy security benefits. Even though the community may be apprehensive about the unknown, support from influential politicians may speed the acceptance of hydrogen vehicles and stations.

The attitude of the community is also formed by familiarity with the kind of project in question. In the case of hydrogen, there is little familiarity with the characteristics of the gas or a station that dispenses it. Many of the characteristics of hydrogen are similar to that of compressed natural gas (CNG), yet natural gas is viewed by the public as safe simply because they are familiar with using it in the home. There

are some concerns with the siting of CNG stations, but on the whole there is little alarm by local groups typical of a NIMBY reaction.

Historical Resistance to Gasoline Station Siting

The public has been sensitive to the placement of gasoline stations since they started showing up in great numbers in the 1920s.⁴⁴ Even as early as 1915, beatification campaigns were initiated to improve the public image of gasoline stations.⁴⁵ Appearance was not the only issue that impeded the siting of gasoline stations. People complained about fire hazards, odor and noise. These influences “tended to retard the spread of new stations, since most cities and large towns either required building permits or the passage of special ordinances before construction could be undertaken.”⁴⁶ An example of an early attempt at regulation can be seen by the Chicago Parks Department in which they prohibited station siting along boulevards, and in certain residential districts.⁴⁷

It appears as though there is currently a movement to review the siting policies of hydrogen stations, but this issue is mentioned here to underscore that these problems have been tackled before, and history may provide a guide to success in the future. According to one source: “Gas stations were often permitted only in industrial districts until the automobile became common. For an extended period during the 1920s and 1930s, the pendulum swung in the other direction and stations were constructed in restricted business districts, and in residential areas where they rapidly gained a reputation as a nuisance.”⁴⁸

History may also repeat itself on the view of hydrogen stations as fire hazards. In the early days of gasoline retailing, gasoline stations were seen as unique fire hazards. In

1939, a board of zoning appeals in Hempstead, N.Y. argued that "...a gasoline service station necessarily involves the storage and use of gasoline and oil, which are so highly inflammable and explosive that they increase the danger of fire no matter how carefully planned are the governmental regulations."⁴⁹ Since then, the positions of planners have become less severe. Although there is a risk of fire, planners have since realized that this risk is not an extraordinary one if building codes are followed.⁵⁰ Hydrogen appears to be under the same scrutiny as gasoline once was, relegating hydrogen stations to industrial areas. The possible NIMBY reaction to stations is likely to subside with a safe operation record.

Public image is also important for early hydrogen stations. Early gasoline stations branded with the name of a major oil company were sometimes seen as "show places" that would set the standards for other unbranded stations that may be selling their products.⁵¹ This fact is important in that hydrogen stations may also become showplaces for the oil companies or agencies that build them. This recognition that there will be public scrutiny on the first stations is important if hydrogen stations are to become accepted by the public.

2.1.4 Examining NIMBYism at the Neighborhood Level – A Case Study

Since hydrogen stations do not exist in any great number, there are no case studies of NIMBYism regarding hydrogen station siting. However, a study in New Zealand by Tom Fookes examines NIMBYism as it relates to regular gasoline stations. The station chosen for the study went through a neighborhood review process just as many projects do in the United States. Hydrogen stations, if publicly funded, would go through a

formal review process under the National Environmental Policy Act (NEPA) and, in California, the California Environmental Quality Act (CEQA). As part of the process in New Zealand, local residents were given the chance to voice objections and concerns to the potential siting of a gasoline station situated near a neighborhood. The research was conducted five years after the construction of a gasoline station and compared the original objections to the views of the same people after five years of operation. His conclusions were as follows:

- 1) Some adverse effects were present, but turned out to be minor.
- 2) Some positive amenity such as increased lighting and security resulted from the developments.
- 3) The range of issues raised was similar to those raised in NIMBYism on a regional scale.
- 4) The closer the resident to the development, the more likely he/she is to voice concern.
- 5) “Factory style activity”⁵² was seen as a detriment to residential character.
- 6) Reactions were “knee-jerk” and attributable to fear of the unknown.
- 7) Efforts to address people’s concerns in the beginning were subsequently seen as positive by the residents.

Perhaps the most important points we can glean from his conclusions are that the community can act hastily, but that working with the community to address their concerns is seen as positive.

2.1.5 Zoning's Systematic Effect on Hydrogen Stations

By regulating the types of land uses that are allowed in certain areas, the character of those areas can be systematically affected over time. For example, the 1916 zoning law in New York⁵³ was passed in part because residents of affluent residential neighborhoods wanted to preserve the character of their streets. In essence they said “No Stores In My Back Yard”. This idea seems to have pervaded subsequent zoning law passed throughout the United States. Consequently, large tracts of land are zoned for housing with little or no land zoned for commercial. This contributes to the need to drive to the store and reduces the option to walk. Although this may not have been an intended consequence of zoning, the systematic effect it had on housing and the people living in that housing is undeniable.

Looking at hydrogen station siting, one option is to continue with restrictive zoning, so that stations are only sited in industrial areas. The systematic effect this would have on hydrogen's acceptance as a fuel would be detrimental, and could possibly cause hydrogen to fail as an alternative fuel. In a study conducted at UC Davis, some CNG car drivers felt unsafe when going to industrial areas to refuel. Some female drivers would not refuel at night for this reason.⁵⁴ Applied to the population as a whole, these problems would be magnified, and hydrogen might be negatively associated with unattractive and inconvenient industrial areas.

Making the initial decision to purchase an alternative fuel vehicle is also linked to the visibility of stations, more so than the comprehensiveness of a refueling infrastructure. In a study done on CNG users in New Zealand, the effect station siting had on the vehicle purchase decision was investigated.⁵⁵ CNG was introduced on a wide scale in New

Zealand in about 1980. The network was spotty at first, but continued to grow until about 1988. In the early stage, those who knew of or regularly saw a CNG station next to their home or business were more likely to buy a CNG vehicle than those who had no such exposure. The proximity of a station to one's home was found to affect the purchase decision more than the density of stations in the region surrounding the homes. The implications for hydrogen as a fuel is clear: Hydrogen will be less preferred if zoning restricts stations to industrial areas or out of the way places. The stations must be visible in order for hydrogen to succeed.

2.2 Meso-Level Siting

Meso-level siting, as the name implies, is broader in scope than micro-level siting. The demand on a particular station is affected by the locations of other stations around it. In this way, stations can be evaluated as part of a greater refueling network. There are several different ways to determine the interaction between station locations and customers. The concept of meso-level analysis is encompassed by location-allocation theory.

2.2.1 Early Location Theory

Some of the earliest work on location theory was developed by Alfred Weber who formulated a method for industrial location in 1909.⁵⁶ The optimal location for an industry took into account the locations of raw materials and potential markets. The goal of this model was to minimize the total cost of transporting raw materials and finished goods. The method used was geometric in nature and not suitable for solving multi-location problems.

2.2.2 P-Median Problem

Efforts were made to extend Webber's work to multi-location problems, but despite efforts, no real progress was made. Other graphical methods were developed in the interim for modeling retail environments, most notably Reilly's "law of retail gravitation."⁵⁷ This theory is based on the assumption that the interaction between a retail location and the customer is defined by Newton's law of gravity.

In the early 1960's, several efforts to extend Weber's work to multiple facilities were successful, spawning the solution to the general facility problem.⁵⁸ The solution to the multi-facility problem is generally called the p-median location-allocation model. The extension of this concept to physical networks of roads, pipes, power lines etc.⁵⁹ enabled more realistic representations of the physical world.

The p-median problem model is a relatively simple idea in the retail context. Consumers are assumed to patronize the closest store to their home. The consumers are assumed to be at fixed locations and the goal is to optimize the retail locations such that the aggregate distance to the consumer is minimized. The number of locations (p number of facilities) can be specified, and given that number of locations, the optimal arrangement of those stations can be derived.

2.2.3 Variations of the P-Median Problem

There have been many variations of the p-median problem, all having the aim of more accurately representing reality. However, different approaches are needed to answer different questions.

One such variation is the market share model (CIM) designed to optimize retail locations.⁶⁰ The name "competition ignoring model" signifies that the service being provided by a firm is distinct enough that when additional outlets are located competition from other firms can be ignored.

The model postulates that consumers patronize the closest retail location from their home based on straight-line distance in continuous space. The decision not to use the road network in optimization was based on ease of use, and the recognition that road

networks may be subject to change and therefore unreliable for modeling future demand. Accessibility is assumed to decrease with distance, and contour lines are delineated around a location to indicate the decreasing levels of accessibility. For example, a 70 percent contour line represents accessibility 70 percent of optimal. The model is designed to optimize new sites given the locations of existing retailers.

Another model proposed is the market share model (MSM).⁶¹ This model assumes that demand is inelastic with distance, meaning customers are assumed to patronize the closest facility regardless of how far the customer is from the facility. This model also uses continuous space, and market areas are delineated by Thiessen polygons.⁶² A Thiessen polygon is a polygon around a facility that defines the area closer to that facility than any other facility.⁶³

One of the criticisms of the p-median model is that in optimizing the entire system, there is the potential for individual access to vary widely.⁶⁴ For example, a farmer far from civilization would likely have little effect on the optimal placement of facilities, and may have to travel a long distance to the closest facility. In some cases this may not be the desired outcome of the model. Emergency service facilities such as fire stations are such an example where the standard p-median model was not deemed appropriate. To address situations such as these, several possibilities have been suggested. One idea is to set an absolute limit on the distance of a consumer to a facility. Another idea is to minimize the variability of the distance of the consumer to the facility. A third idea is to minimize the maximum distance of any individual to a facility.⁶⁵

Two of the most popular models using the p-median idea are the set covering model and the maximum covering location model. The set covering model, used for

emergency services, determines the minimum number of facilities required to place individuals within a defined distance from a facility.⁶⁶ The maximum covering model assumes that consumers have a limit on how far they will travel to a certain facility. The model restricts the number of facilities to be sited and maximizes the number of customers that are within a critical distance.⁶⁷

2.2.4 Flow Capture Allocation

Another method of allocating customers to a facility is flow capture. This method of allocation assumes that consumers patronize a facility as a result of passing by that facility on the way to another location. Indeed this may be an appropriate model to site gasoline stations. In the micro-level analysis section, traffic flow was identified as a good indicator of where to site stations.⁶⁸ However, local population is also a factor in deciding the best locations, and due to data availability, the analysis presented later in this report is based on local population.

The relationship between demand and both traffic flow and local population was investigated by Goodchild and Noronha.⁶⁹ The authors note that because gasoline is one of the commodities most subject to impulse buying, a flow capturing model may be appropriate to predict demand. In this model, customers choose a route regardless of whether he or she plans to refuel along the way. This model is compared to a model that predicts demand based on the characteristics of the local population and the distance of the population to a station.

Since detailed origin destination data were not available, the authors used traffic counts on major arterials as a surrogate for actual route data. The number of cars along a

link was aggregated to the midpoint of the road segment and multiplied by the link length to represent an opportunity to refuel proportional to the length. The author then used the p-median method of identifying optimal sites. The solution using the traffic was termed the “traffic solution.” For the “residential solution”, the data were aggregated by census tract, and optimal locations were again chosen by the p-median method using continuous space rather than confining travel to roads.

Regressions were run on actual gasoline volume data from London, Ontario. For the residential solution, six variables were found to have roughly equal explanatory power for predicting volume: Adults aged 20-69, total population, households, census family households, families, and total income. For the traffic solution, the ten year forecast (1991 forecast) proved the best predictor of gasoline volume. P-median solutions were found for both the 1991 forecast, and adults aged 20-69.

The objective of the optimization was to identify the best 20 out of 33 sites. Both methods achieved similar results and 15 of the 20 optimal locations were the same. The authors postulated that the results were similar because the residents, to a large degree determined the amount of traffic in an area. The evidence suggests that the local population adequately predicts station volume.

Another flow capture model proposed by Berman, Larson, and Fouska⁷⁰ optimizes locations based on route choice. Rather than use traffic counts as a proxy for route choice,⁷¹ this model measures the number of customers passing by a point, based on a path determined by another purpose; passing by a location such as a gasoline station is merely coincidental. The points considered in this model are nodes on the transportation network. The model then optimizes a number of locations to maximize the number of

people passing by facilities. The validity of this model was not tested using actual data, however this model may be appropriate for facilities such as gasoline stations. One weakness of this model is that detailed origin-destination data must be available to implement the model.

2.3 Macro-Level Siting

Station siting at the most aggregate level is simply a process of defining the number of stations necessary in a region. These estimates are useful in meso-level analyses since they can provide a useful starting point to analyze the distribution of stations. This estimation is also important to quantify the amount of investment necessary to initiate a hydrogen refueling infrastructure. This measure is ultimately a subjective one since some customers may accept the inconvenience of only a few stations, and others require more stations to feel comfortable purchasing and driving a hydrogen fueled vehicle.

The fact that customer acceptance depends on the number of stations and their convenience leads to a dilemma. Fuel providers will not build stations if there are no vehicles to use them, and vehicle manufacturers will not build vehicles if there are no places at which to refuel them. The situation has been likened to the chicken and egg allegory: which comes first, the fuel stations or the vehicles to use them?⁷²

This search for the minimum number of alternative fuel stations was explored through retrospective looks at experiences with diesel cars in the United States, and with compressed natural gas (CNG) cars in New Zealand. Sperling and Kurani looked at diesel networks in California which grew from 9 percent of stations in 1976 to 25 percent of stations in 1984.⁷³ As no comprehensive data were available, the number of stations was not an exact count, but rather an estimate based on several sources of data. A survey of diesel drivers was conducted in 1986 to investigate how fuel availability affected their decision to buy a diesel car. The survey found that fuel availability was not *the* major concern when buying a diesel car. Other considerations such as fuel economy and

maintenance were the most important in the initial purchase decision. However, it must be noted that when diesel fuel was promoted as an alternative fuel in 1976, 9 percent of stations already carried diesel. Based on this information, the authors surmised that ten to fifteen percent of stations would be required to remove fuel availability as a major obstacle to the deployment of an alternative fuel.

In a later paper, Kurani examined the CNG network in New Zealand, which may provide a clearer picture of the introduction of an alternative fuel.⁷⁴ New Zealand had recently discovered large reserves of natural gas offshore, and due to the energy crisis in the early 1980s, started a program to promote its use. The case of CNG more closely approximates the possible development of a hydrogen refueling network than does the diesel case. First, CNG is a gaseous fuel like hydrogen, and the range of CNG cars is similar to that of current fuel cell vehicles. Also, the CNG network started from a level of zero percent of stations in 1979, and climbed to fourteen percent of stations by 1987. The author conducted a survey of CNG customers similar to that given to diesel vehicle drivers in California and found that at about ten percent of stations, drivers no longer viewed fuel availability as a major problem. This percentage was reconciled with the earlier estimates of fifteen percent in the diesel case based on the fact that there were more overall stations selling normal gasoline than previously thought. This points to an inherent weakness of the percentage of stations approach. Accurate data on the number of stations are necessary to set and evaluate the minimum level of stations.

Another study, by Greene,⁷⁵ investigated the role that fuel availability plays in the purchase price of a bi-fuel or dedicated alternative fuel vehicle. Additionally he looked at the willingness to pay for availability as a function of price per gallon of fuel. The

results are based upon two separate surveys conducted in November and December 1996 by CARAVAN® Opinion Research Corporation under contract from the National Renewable Energy Laboratory. The results are consistent with previous studies which indicate that the critical range of stations lies between zero and 20% of existing stations. The study states that, all else being equal, consumers are relatively unconcerned about availability when stations reach a level of 20% or more. David Greene's study is particularly useful in that he estimates the share of the market for alternative fuel given different percentages of availability. He estimates that "with a \$0.10/gallon price advantage, a 20% market share is obtained at less than 25% availability. Given a \$0.25/gallon price advantage, it takes less than 5% availability to attain a 20% market share. At 20% availability, an 80% market share is reached".⁷⁶

An approach based on metropolitan land area is explored by Melaina.⁷⁷ The method based on metropolitan land area assumes a maximum distance that any driver in a metropolitan area must travel to reach a station. A standard coverage area for a station is defined based on this maximum distance (3 miles for a developed network). The total metropolitan area in the United States is defined by the U.S. Department of Transportation (DOT).⁷⁸ This land area divided by the standard coverage area gives the total number of stations required for a refueling network.

A second approach put forth by Melaina is based on arterial roads.⁷⁹ The U.S. DOT classifies roads by the intensity of their use. Melaina suggests that an estimate of hydrogen stations can be approximated by siting hydrogen stations along the most used arterials at appropriate intervals (10 to 20 miles). Melaina favors this approach to the percentage of stations approach or his own metropolitan land area approach, because

heavily used arterials are concentrated in major metropolitan areas, reflecting the variation in needs for different metropolitan regions.

Melaina compares the three methods to predict station numbers in the U.S. at 17,700 with the percentage of stations approach, 4500 with the metropolitan land area approach, and 9200 with the arterial roads approach.⁸⁰ Using 10 percent of stations as suggested in the CNG study instead of the 15 percent used by Melaina yields 11,800 stations. These approaches provide a starting point for analysis, but deal with consumer refueling behavior only in the abstract. The arterial roads approach touches upon the issue by recognizing that most refueling is done along major arterials, but says nothing about the individual placement of stations. Although the arterial roads approach may correctly estimate the demand for fuel, it may overestimate the number of stations needed to supply that fuel. For example, a large station with greater economies of scale could accommodate most of a downtown area, whereas two stations in the same area may provide double coverage at greater facility cost and higher fuel cost.

CHAPTER 3. METHODS

The research outlined above provides clues as to how to overcome the chicken and egg problem. However, the ultimate form of a network in a metropolitan region is only vaguely suggested. A factor that customers appear to care about in refueling is the time from the origin or destination of their trip to a refueling location. This assumption is supported by the retail siting strategies that use local population as a metric for the viability of a site, and by origin and destination studies discussed in the literature review.⁸¹ Traffic, according to one study, is largely coincident with population.⁸²

A GIS can help synthesize various sources of information in order to make informed assessments of possible station sites. Additionally, a GIS can more accurately describe the relationship between origin or destination data and station location by calculating the driving time to the station. The variable to be minimized in this model (Hydrogen Station Siting Model 1 or HySS1) is region-wide average driving time to the nearest station from home or work. The model is similar to the p-median problem formulated by S.L. Hakimi.⁸³ Commuter home and work locations were determined using the Sacramento Area Council of Governments (SACOG) origin and destination data. Additionally, home locations were determined from census data.

3.1 Study Area and Data Used

The area studied is Sacramento County. This region was chosen owing to the ease of data verification and access to accurate gasoline station counts⁸⁴ and relevant GIS information. A more realistic scenario would be to study the metropolitan region as a

whole. However, Sacramento County has many of the elements of an entire metropolitan region, including a large central business district, several freeways, and varying population densities.

The effectiveness of a hydrogen network is evaluated by measuring the driving time to the nearest station from the origin or destination during the 6:30AM - 7:30AM rush hour⁸⁵ and from census data of people aged 18-65.⁸⁶ The 6:30-7:30 time period was used because the majority of trips during this time are assumed to be commute trips with the origins being homes and the destinations being places of work. Even though people do not usually refuel at this time in the morning, using this time period helps establish where the commuters live and work. Refueling could occur at any time of day. The census population of people aged 18-65 was used to establish where people of driving age reside, whether or not they commute.

One important reason that the origin-destination data for commuters and census data are being used is the lack of more detailed information on the origins and destinations of fuel cell vehicles commuters. Data are being developed to identify these important inputs, but they are not yet available. Using the model, the rush hour numbers or census counts need only be replaced by the number of potential fuel cell vehicle commuters, and the model run again. As an example of how fuel cell car owners might be identified, a scaling factor based on average household income could be applied to origin data. Those origins with high income might have a higher percentage of fuel cell car ownership, and the number of trips from those origins could be scaled proportionally. The census data could be scaled in the same way.

When evaluating population or rush hour traffic, the data are grouped by traffic analysis zone (TAZ). TAZs are natural choices because these zones have been identified by Sacramento area traffic modelers as areas having roughly homogenous travel characteristics. Origin-destination volumes are also available for this analysis unit. As noted above, if the potential market can be identified within a TAZ, those numbers could be input instead of the numbers generated for general traffic.

Population data of 18-65 year olds from the census were also evaluated using TAZs. The original analysis unit for the census data used was 2000 census block groups. These data were made to conform to the boundaries of traffic analysis zones by first converting them to densities of persons per square kilometer. These the zones were then partitioned into one quarter kilometer grid cells using spatial analyst in ArcView 3.3 for a total of 16 grid cells per square kilometer. The TAZ boundaries were then overlaid on the grid cells. The sum of the grid cell densities within each TAZ was then divided by 16 (the number of grid cells in a square kilometer) to obtain the population within each TAZ.

Two street networks were used to interpret the scenarios in this analysis. One street network was developed by Sacramento area traffic modelers for their SACMET travel model.⁸⁷ The other network is called StreetMap® and is commercially available from Environmental Systems Research Institute (ESRI).⁸⁸ The SACMET network is a simplified version of the actual road network, and the speeds along roads were calculated for free flow conditions. It must be noted that the travel times calculated on the SACMET network are consistently lower than those in everyday congestion. Additionally, the street network is simplified meaning that the network does not include minor streets or the intersections with those streets. Consequently, the driving times may

in some cases be over or under-estimated depending on how the actual route is represented in the computer generated path. The StreetMap® network is more detailed, and speeds along roads are slightly slower. However, because this network is more detailed, it is more computationally intensive and time consuming to work with. Consequently, most scenarios were only run with the SACMET network.

Many factors may influence the form of a hydrogen refueling network, and an even greater number of scenarios accounting for those factors. Rather than trying to test for all scenarios, the analysis in this report presents a scenario which mirrors a reduced gasoline network. This is done so that redundancies in the gasoline network can be identified, and to allow comparisons to be made easily to the existing gasoline network. Some of the scenarios not tested are home refueling and workplace refueling. Home refueling refers to refueling done at the vehicle owner's house, and workplace refueling refers to refueling done at the owner's workplace. While the model has the flexibility to incorporate such scenarios, there is no clear indication as to whether home or workplace refueling will become the dominant paradigm for hydrogen vehicles. Additionally, precise data on where hydrogen vehicle owners may live and work are not available, making such analyses of little value.

3.2 Model Description

The first step in the model is to reduce the number of station possibilities using the k-means clustering technique. This reduces the computing time to run the scenarios. The second step is to let the model select a subset of the potential sites based on the minimization of average driving time. A flow chart of the process can be seen in Figure 1.

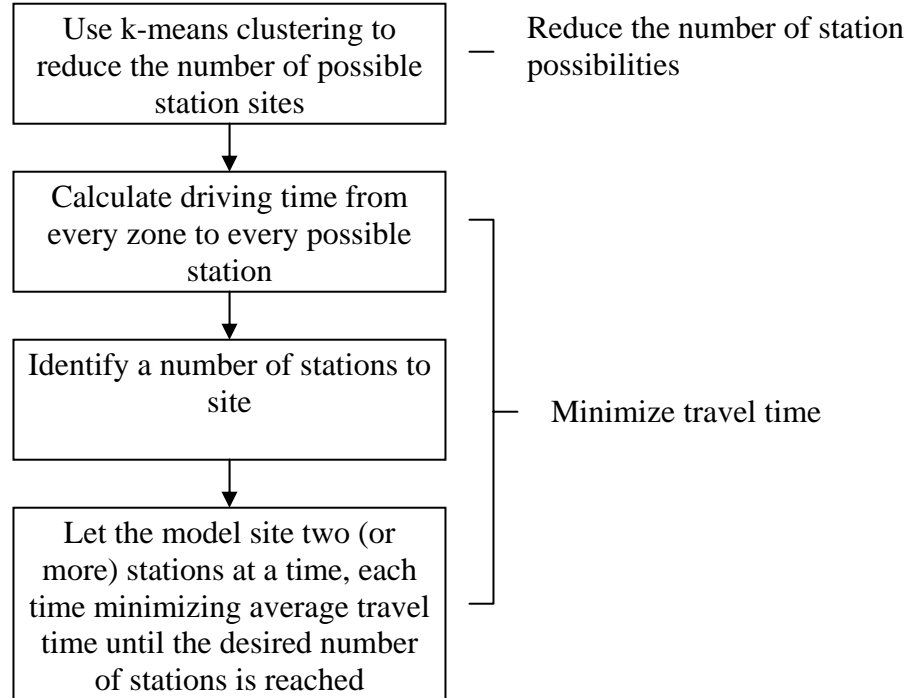


FIGURE 1. Hydrogen station siting flow chart.

3.2.1 Model Assumptions

The scenarios tested mirror the use of the current gasoline network and are based on the following assumptions:

- People prefer to refuel near home or near work.
- The distribution of hydrogen infrastructure is correlated to the existing gasoline infrastructure.
- People will refuel at public fuel stations much as they do today.

These assumptions can be changed relatively easily to allow different scenarios to be tested. For example, if a person were able refuel at home, then the model would use only

workplace destination data to site stations since he or she would no longer need to refuel near home.

3.2.2 Reducing the Number of Possible Station Sites

The limitation on the number of possible sites is a function of computer speed. The more possible sites, the longer it takes the model to test all the siting combinations. By reducing the number of sites using the k-means cluster technique, data sets with larger geographic distribution can be attempted. In our case, 319 stations and 701 zones was a small enough data set that we could try both options. Each approach yielded similar results. For larger data sets, such as an entire metropolitan region, the process described below is a method that can be employed to reduce the number of possible station choices.

Various data sources were examined in order to get a wide geographic distribution of stations. Existing gasoline stations proved to provide the best guide to identifying possible sites. In essence, the possible sites should approximate the extent of the gasoline network, and the hydrogen station sites are the best subset of those possible sites. It is important to remember that selected sites can move several blocks in any direction without drastically affecting the outcome of subsequent calculations. Furthermore, existing stations may not be available to sell hydrogen due to zoning restrictions, and zoning restrictions may force a hydrogen station to be sited at a location near the suggested site.

K-means clustering is similar to the p-median problem discussed earlier in that the objective is to minimize the sum of the distance to each of the k centers.⁸⁹ K-means clustering is computed using continuous space instead of using the road networks to

define distances and times. The K-means clustering technique is an appropriate first step in reducing the number of potential sites since little resolution in the data is lost. For example, if there were a solitary station far from other stations, the station would most likely represent a cluster of one. Many stations very close together would represent another cluster. In this way, a good geographic distribution is maintained for the station network. The k-means clustering was performed with the SPSS statistics package⁹⁰ using the latitude and longitude of the existing gasoline stations.

3.2.3 Evaluating Station Choices

After the possible station sites are chosen, a subset reflecting the desired size of the network must be selected. As discussed earlier, there are other factors that influence a person's refueling location, but proximity to one's origin or destination appears to be a strong indicator for this choice (see Tables 1 and 2). Therefore, the measure that is used to evaluate station siting is the travel time from a person's origin or destination to the hydrogen station. The origin information for the number of commuter trips was obtained through the SACMET travel model and the origin data for the number of individuals at home locations (regardless of whether they were commuters) were taken from census population data. Destination data were taken exclusively from the SACMET travel model. As mentioned earlier, there is a distinction between the data taken from the SACMET travel model, and the data taken from the census. The data taken from the SACMET travel model represent the origin of commute trips and as such are only a proxy for actual commuter residences. The data taken from the census represents the home locations of everyone aged 18-65 regardless of whether they commute or have a car.

Even though people usually refuel on the way to somewhere, evaluating station sites with this criterion is data and computationally intensive and is left for future analyses. Although the model does not capture refueling that occurs along a travel route, it does reflect a situation where a driver would have to spend no more than double the time from his or her home or work to a station to refuel. In other words, if a station were five minutes away from home or work, then the driver would have to spend no more than ten minutes extra to go to a station on the way to or from work.

Some simplifying assumptions are made because the travel model captures only aggregate data. For example, all the people leaving a zone in the morning are all assigned to the nearest station. Another simplification of the model is that all the people in a traffic analysis zone (TAZ) are assumed to start or end their journey at the approximate center of a TAZ.

The travel time along streets from every TAZ to every possible station site is calculated using a GIS network analysis program⁹¹ and a street network. For example, if there were 319 potential station sites, then for each TAZ, there would be a corresponding travel time to each of the 319 stations. From this list, the model can calculate the average travel time to the closest group of stations by cycling through each group. This process is similar in concept to the p-center and p-median problems in operations research.⁹² The program to run the model was written in C++.⁹³ If the model were trying to find the best three stations out of 319, it would identify a group of stations to be tested, say stations 1, 2, and 3, then calculate the closest station for each of the 701 TAZs. Some TAZs would be assigned station 1, some TAZs station 2, and some TAZs station 3. Seven hundred and one travel times for the individual TAZs are multiplied by the number of trips to or

from that TAZ, then summed for a region wide “travel time * trips”. This “travel time * trips” is then divided by the number of total trips for the region to get an average travel time per trip in the region given stations 1, 2, and 3. Figure 2 shows this process graphically. The model then goes on to test the next unique combination of stations such

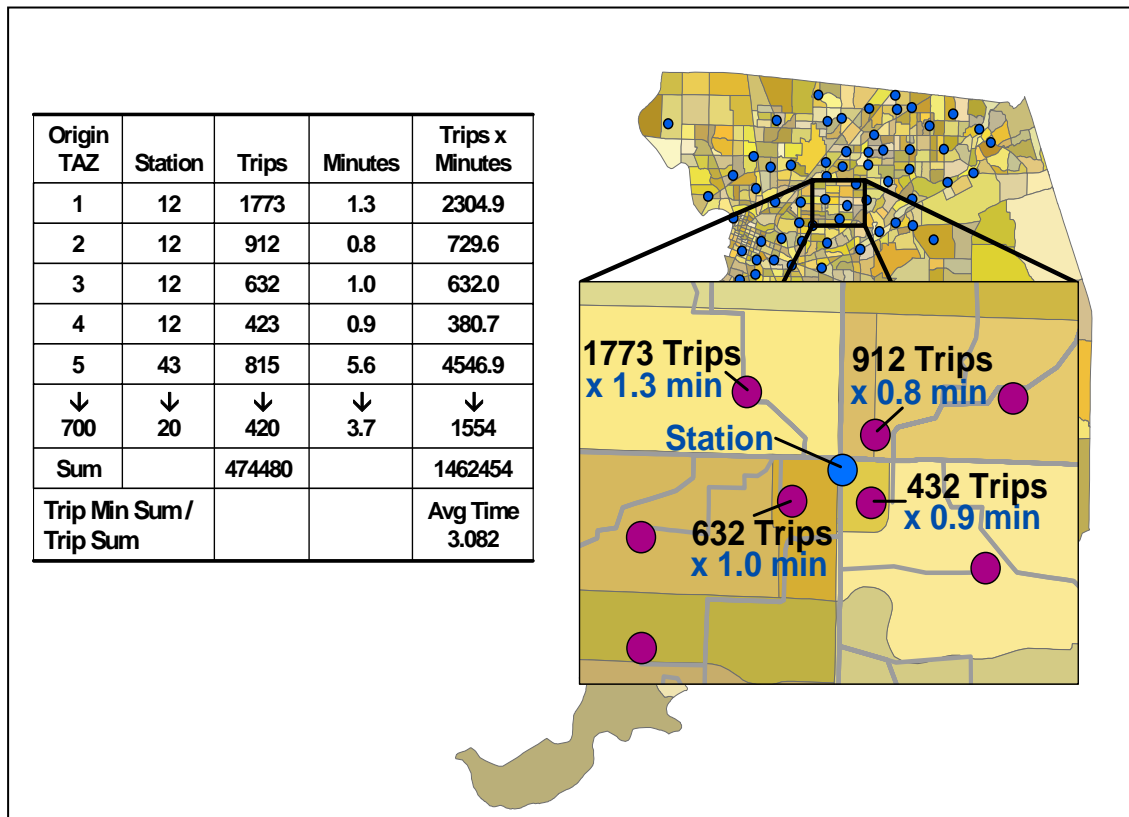


FIGURE 2. Map showing the assignment of trips from a TAZ centroid to the nearest station. The corresponding table showing the process of calculating average travel time for a station scenario. The gray lines represent the shortest path from the TAZ to the station.

as 1, 2, and 4, and compares the average travel time for that group of stations with the previous group. The function to be minimized is shown in Figure 3. The resulting group of stations with the lowest average travel time for the region would be selected from 319 possible stations for a total of 5,359,519 three-station combinations.

$$\begin{aligned} & \min \sum_{ij} t_{ij} D_{ij} X_j \\ & \text{s.t. } \sum_j D_{ij} X_j = TD_i \\ & \sum_j X_j = N \\ & X_j = \text{binary variable} \end{aligned}$$

where

i = Origin TAZ
 j = Destination station
 t_{ij} = Time cost between TAZ zone i and station zone j
 D_{ij} = Number of trips from TAZ i to station zone j
 X_j = Build or don't build at station zone j
 TD_i = Total trips from zone i
 N = Number of stations to site

FIGURE 3. Function to be minimized. The sum of the trips from TAZ i to station D is minimized. X indicates whether a site is selected based on whether it helps minimize the total travel time for the region.

In order to speed up the process of site selection, we chose to let the model site two stations at a time. When the best two-station combination was found, the model would regard those stations as given and find the next two stations that minimized the travel time. The model repeated this process until the given number of sites was selected. A potential drawback to siting stations in this manner is that the sites selected depend on the size of the group being sited. Siting two stations and then two more for a total of four will give one a different site selection than selecting a group of four simultaneously. However, the average travel time to a station for each method is very similar. If one wanted to select 30% of 319 existing stations simultaneously, it would take $3 \cdot 10^{81}$ years using this enumerative model. Selecting by two takes a few hours, and gives comparable results.

The average number of minutes per trip can be used to determine the sufficient number of stations in an area as an alternative to using the percent of stations or arterial roads approach. Using driving time gives a more detailed look at the sufficient number of stations and relates the number of stations to the unique geography of a region. Unless people in different regions are willing to drive longer on average to get to a station, average driving time should be constant across regions. For example, more densely populated regions may require fewer stations per driver to provide the same average driving time to a station as more stations in a sparsely populated region. This may also indicate a threshold of population or traffic density that determines whether a hydrogen infrastructure is cost-effective in a region. For example, if a small number of stations resulted in a low average trip time and served a large number of trips, hydrogen may be more feasible due to increasing economies of scale.

CHAPTER 4. MODEL APPLICATION

Applying this model to an area such as Sacramento County gives some insight into effective siting strategies and the effect the number of stations has on average driving time. The model was run with up to thirty percent of existing stations, or 96 of Sacramento County's 319 stations.⁹⁴ To find the minimum average driving time for this number of stations, stations were sited two at a time up to 96.

Twelve scenarios are tested. The scenarios tested are: 1 station, 2 stations, 4 stations, 8 stations, 16 stations, 32 stations, 64 stations, 96 stations, and 319 stations (the existing gasoline network). Additionally, a scenario in which two stations are placed in areas not recommended by the model is tried, as well as two scenarios where stations are placed along a possible hydrogen pipeline.

In addition to analyzing Sacramento County, a scenario analyzing stations along the highways in the six county Sacramento region was completed. This analysis helps characterize the behavior of the model in large metropolitan regions, and its applicability for interregional analyses.

4.1 Results

The effect on driving time to stations was measured for each scenario by the methods described earlier. The results are shown in Figure 4 and reflect the model output selecting from the 319 existing stations. The best fit for the line follows a power function, whose equations are shown in Figures 6-8. The average driving time from home to a station is shown using origin data for both number of people and number of commute

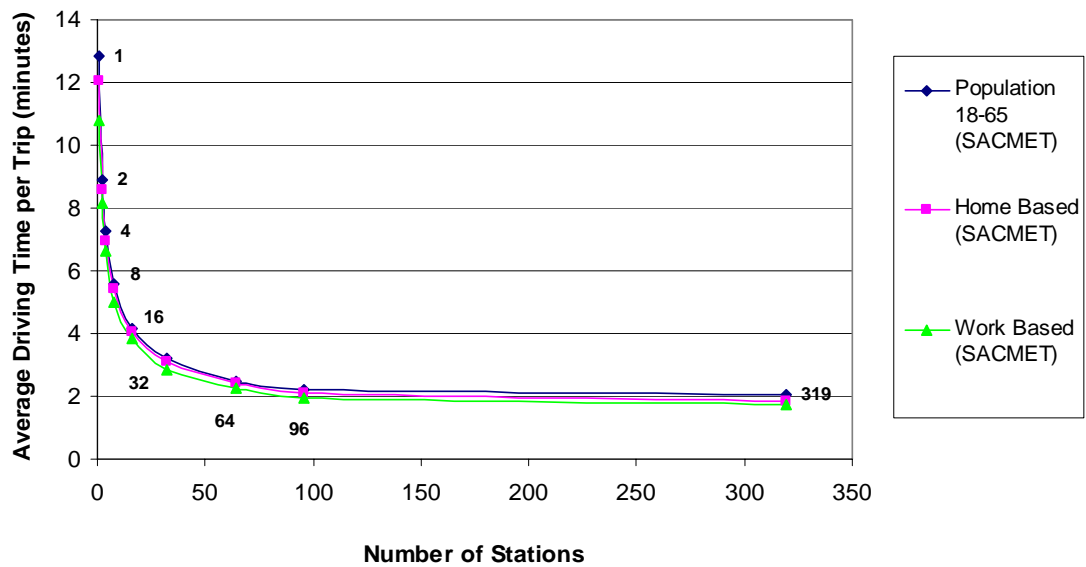


FIGURE 4. Relationship between station number and average driving time using the SACMET⁹⁵ road network. Average travel time to the nearest station was minimized for three different population groups. The home based and work based scenarios represent commute hour origins and destinations. The inputs do not make a large difference in average travel time.

trips. The average driving time from work to a station is also shown. The generally lower average travel time to a station from rush hour destinations serves to illustrate that the destinations, presumably employment centers, have better access to high-capacity, high-speed roads than do the origins of rush hour trips. These employment centers are presumably more clustered as well so that a station near several employment centers may be able to provide low travel times to a large number of people. The higher average travel times calculated from census data could be attributed to the fact that commuters, on average, live closer to faster roads than do those who do not commute or own a car. Another factor may be that some trip origins during the commute hour may in fact be employment centers and not places of residence and assumed in this analysis. For reasons discussed before, average travel times from employment centers are lower. However, each data set shows a similar relationship for the average time versus the

number of stations. Improvement in average travel time is relatively large for the first few stations with the improvement decreasing as more stations are added.

To test the characteristics of the SACMET road network, the home-to-station and work-to-station scenarios were also run using the StreetMap® road network. The results are shown in Figures 4-8. We can see that the average travel times are consistently higher when the StreetMap® road network is used. The estimates are most divergent

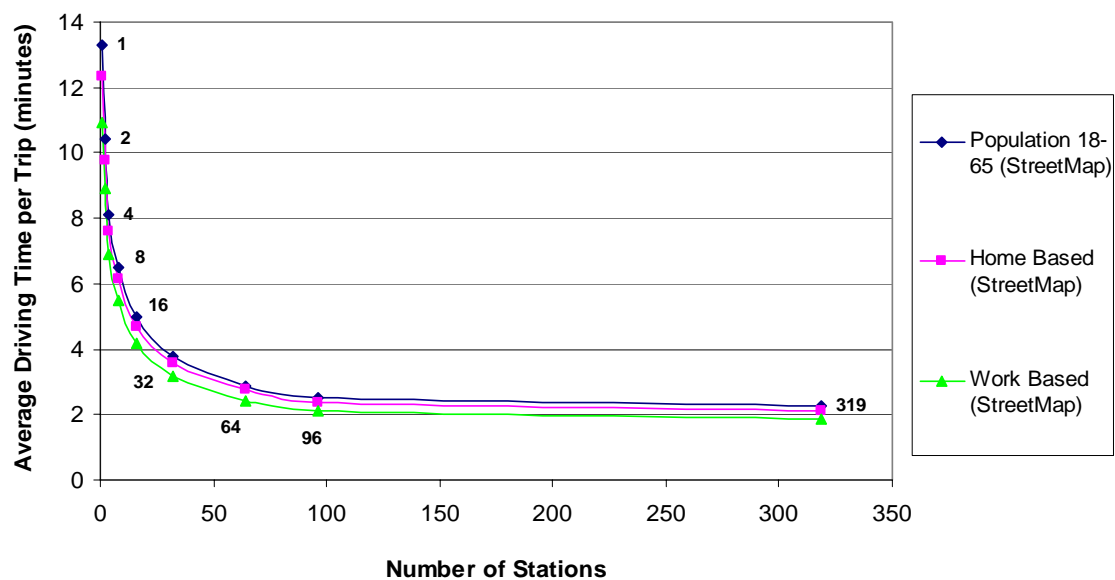


FIGURE 5. Relationship between station number and average driving time using the StreetMap⁹⁶ road network. Average travel time to the nearest station was minimized for three different population groups. The home based and work based scenarios represent commute hour origins and destinations. The results using StreetMap show a similar relationship to the results using SACMET.

using the population data. The maximum divergence occurs at 16 stations where the StreetMap® estimate is 20% higher than the average travel time estimate using the SACMET network. However, the estimates for the average travel time using the StreetMap® network are on average 14.2% higher than using the SACMET network. Consequently the 20% divergence is only 5.8% off the average for the series. Although the travel times are on average higher using the StreetMap® network, the general

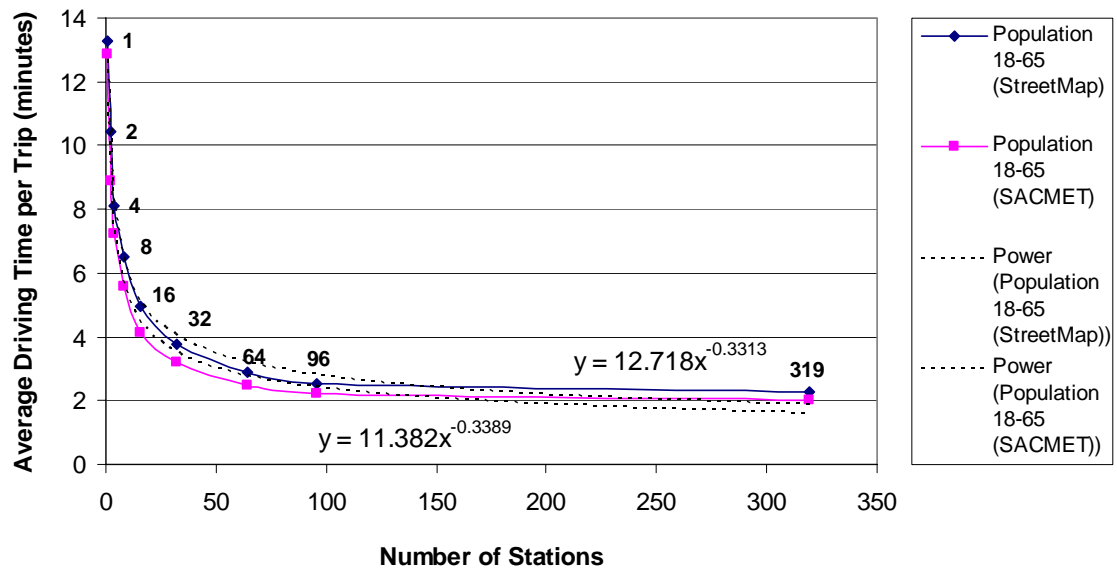


FIGURE 6. Comparison of the average travel times using the same population inputs, but different road networks. The StreetMap® road network results in generally higher average travel times.

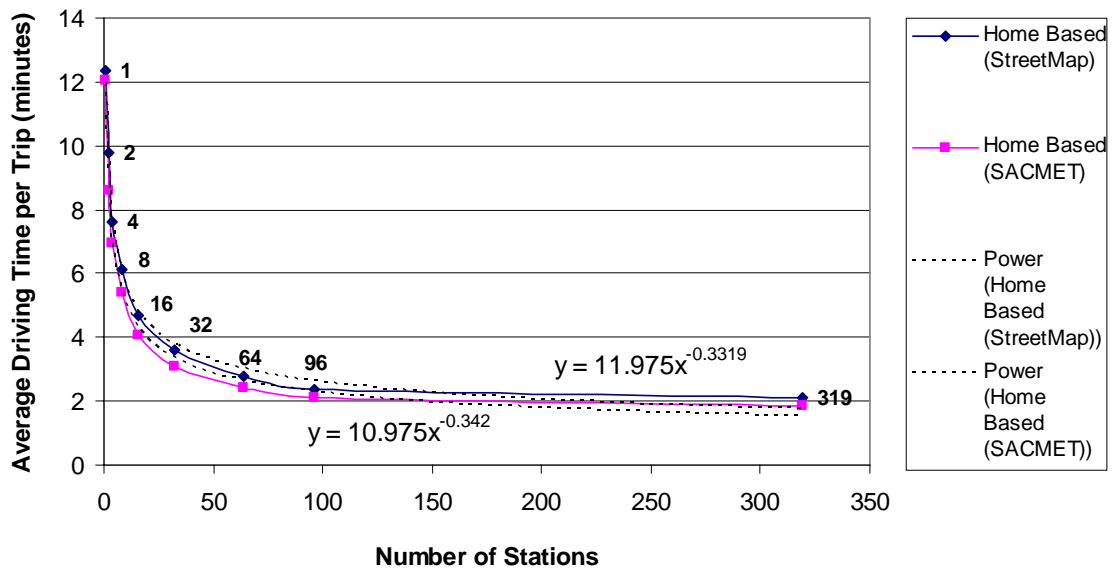


FIGURE 7. Comparison of the average travel times for home based commuters using the different road networks. The majority of trip origins during the 6:30 to 7:30 AM rush hour are assumed to be home locations. The StreetMap® road network results in generally higher average travel times.

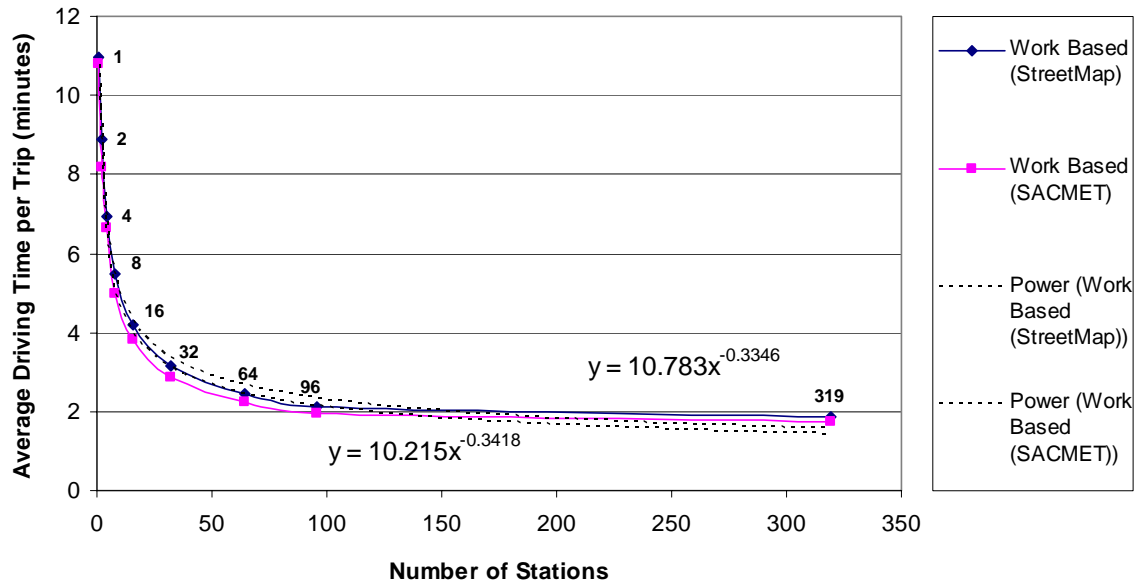


FIGURE 8. Comparison of the average travel times for work based commuters using the different road networks. The majority of trip destinations during the 6:30 to 7:30 AM rush hour are assumed to be home locations. The StreetMap® road network results in generally higher average travel times.

relationship between the average time to a station and the number of stations is similar, and the best fit for the line is still a power function. For the purposes of this report, neither road network is superior since the objective is to compare the scenarios to the existing network. Since the SACMET road network enables faster calculation, this network is preferred.

The variability of the data was also checked. Using the commute hour origins (home based trips), the time variability in time to the nearest station using the SACMET network was tested. The results are shown in a boxplot in Figure 9. The boxplot represents individual commuters' travel times to the nearest station. For those zones that have few commuters there are correspondingly few data points. As evidenced by Figure 9, for lower numbers of stations, the variability in travel time to the nearest station is high for individual commuters even though the average for all commuters is comparatively

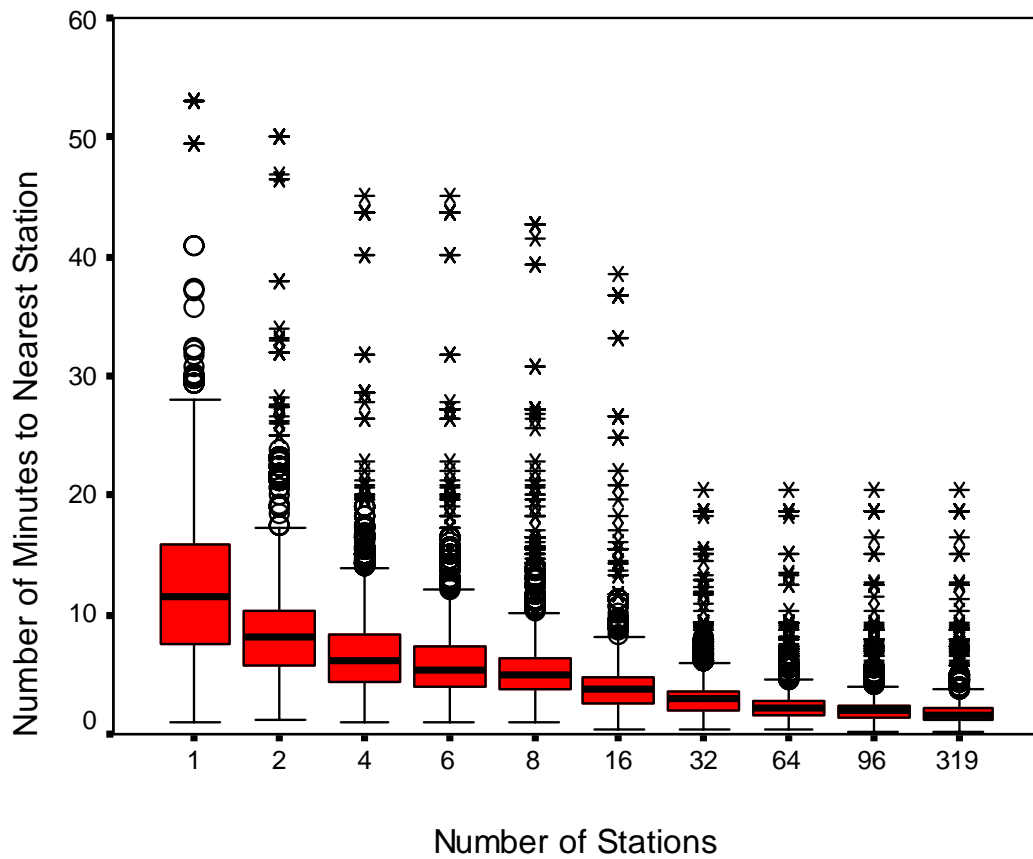


FIGURE 9. Boxplot showing the median and quartile values. The black bar represents the median value for the number of minutes to a station. The red area below the median value represents one quarter of the commuters (quartile). The area defined by the boundary of the red below to the solid line represents another quartile. The area above the median value is defined similarly to the bottom half. The values represented by circles and stars are outliers.

low. For example, if the region had only one station, some commuters would have to travel for over fifty minutes to get to a station even though the average time to the station is twelve minutes and 2 seconds. However, this sort of variability may be normal for any gasoline network. The boxplot for the existing 319 stations indicates that some commuters travel must travel over twenty minutes to the nearest gas station. These areas are likely rural, but this finding provides insight into the applicability of the model for gasoline stations. Whereas some services such as fire protection or ambulance services

should not display as much variability in the time from facility to “customer”, it appears as though some variability is acceptable in a refueling infrastructure. It is unsurprising to find similarities between the refueling networks selected by the model and the existing gasoline infrastructure, since the model selects a subset of the existing stations. However, at a level of 10-20% of existing stations, the variability in the travel time to the nearest station appears similar to that of the existing infrastructure. The apparent similarity in the variability suggests that the current gasoline infrastructure is redundant since fewer stations produces travel times similar to the existing network.

4.2 Validation

Another way to explore the characteristics of the resulting networks was to compare the ratio of gallons pumped in the existing gasoline network to the ratio of trips or population allocated to a certain station. Assuming that the model perfectly predicted consumer behavior, the percentage of gallons pumped from the stations surrounding a chosen station should equal the percentage of total demand allocated to that station from the surrounding communities. The approximate monthly gallons for each existing gasoline station was estimated by the market research company MPSI.⁹⁷ This comparison provides a means of validating the model.

The six station case was used to perform the comparisons between demand allocated to a station and the gallons pumped in the area around the stations. The stations closest to the station chosen by the model were identified, and the gallons from those surrounding stations were aggregated to the station chosen by the model. The aggregated gallons at a station were represented as the percent of total gallons pumped in

Sacramento County. Since there were six stations in the scenario tested, each station would get about 17 percent of the demand if the demand were evenly distributed. Similarly, 17 percent of the demand would be allocated to each station if the demand were evenly distributed.

However, we can see in Figure 10 that demand and gasoline are not evenly distributed. The percentage of rush hour trips allocated to each station is indicated by the

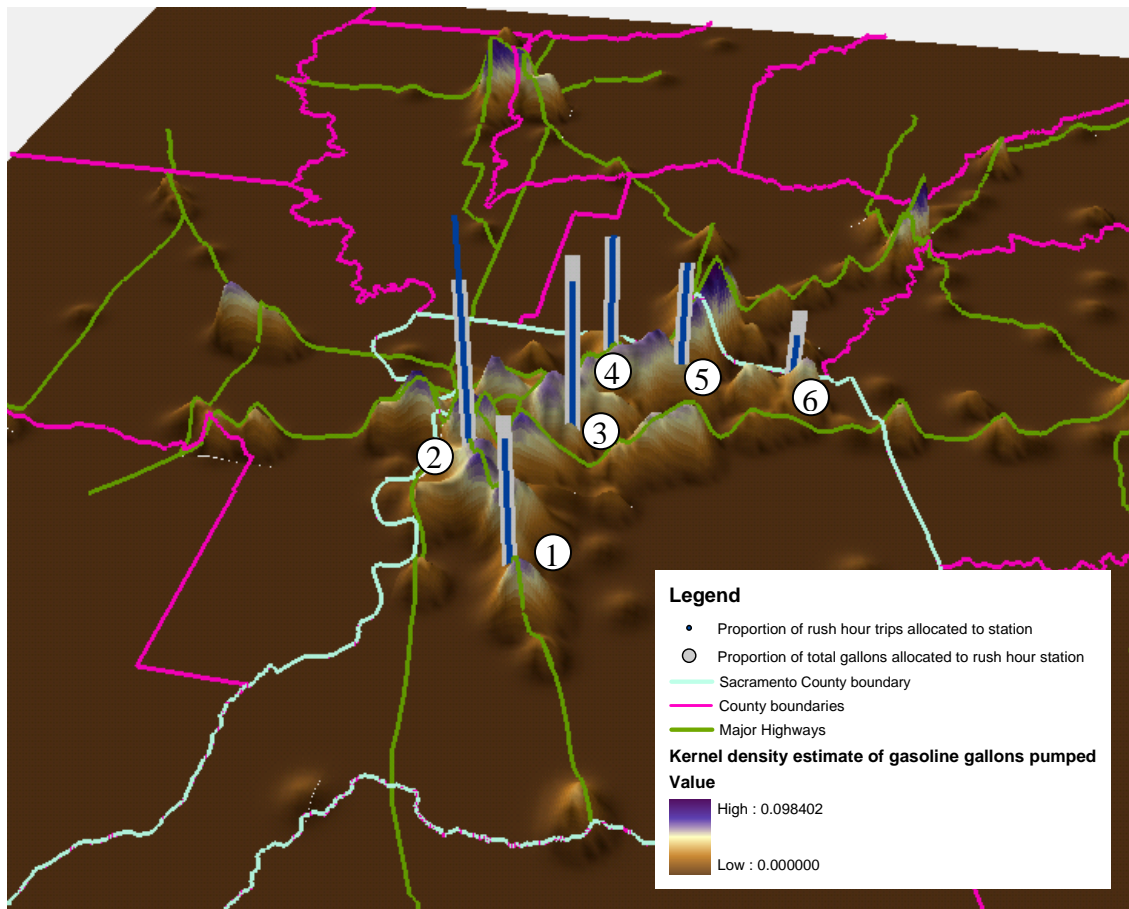


FIGURE 10. Comparison of the proportion of rush hour trips allocated to each station versus the proportion of gasoline pumped in same regions. There is a greater proportion of trips in the downtown area at station 2 (blue line) compared to the proportion of gasoline gallons (gray line) pumped in the same area. This could be due to the fact that gasoline stations serve markets other than commuters. The “mountains” in the picture are kernel density estimates and are proportional to gasoline gallons pumped. They are for visualization only.

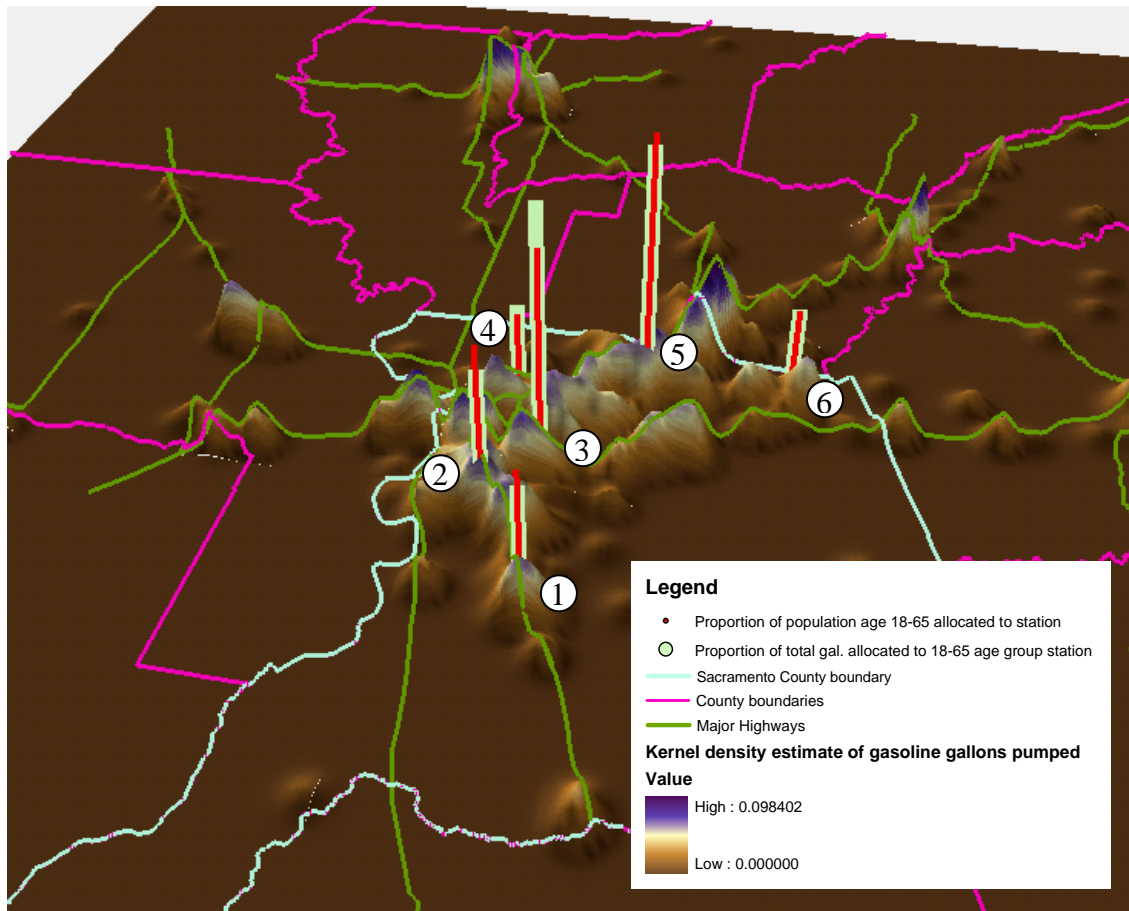


FIGURE 11. Comparison of the proportion of census population aged 18-65 allocated to each station versus the proportion of gasoline pumped in same regions. There is a lesser proportion of trips allocated to station 3 in downtown area compared to the proportion of gasoline gallons (light green lines) pumped in the same area. This could be due to the fact that some people refuel near work. More analysis is needed to support this conclusion. The “mountains” in the picture are kernel density estimates and are proportional to gasoline gallons pumped. They are for visualization of the existing infrastructure only.

dark colored bars in Figure 10. The heights of the bars are proportional to the demand allocated to a station. The features resembling mountains are actually kernel density estimates of gasoline gallons and were created using the Crimestat II® point pattern analysis package.⁹⁸ The kernel density estimates displayed are simply for visualization of the distribution and intensity of gasoline sales, and not for detailed analysis.

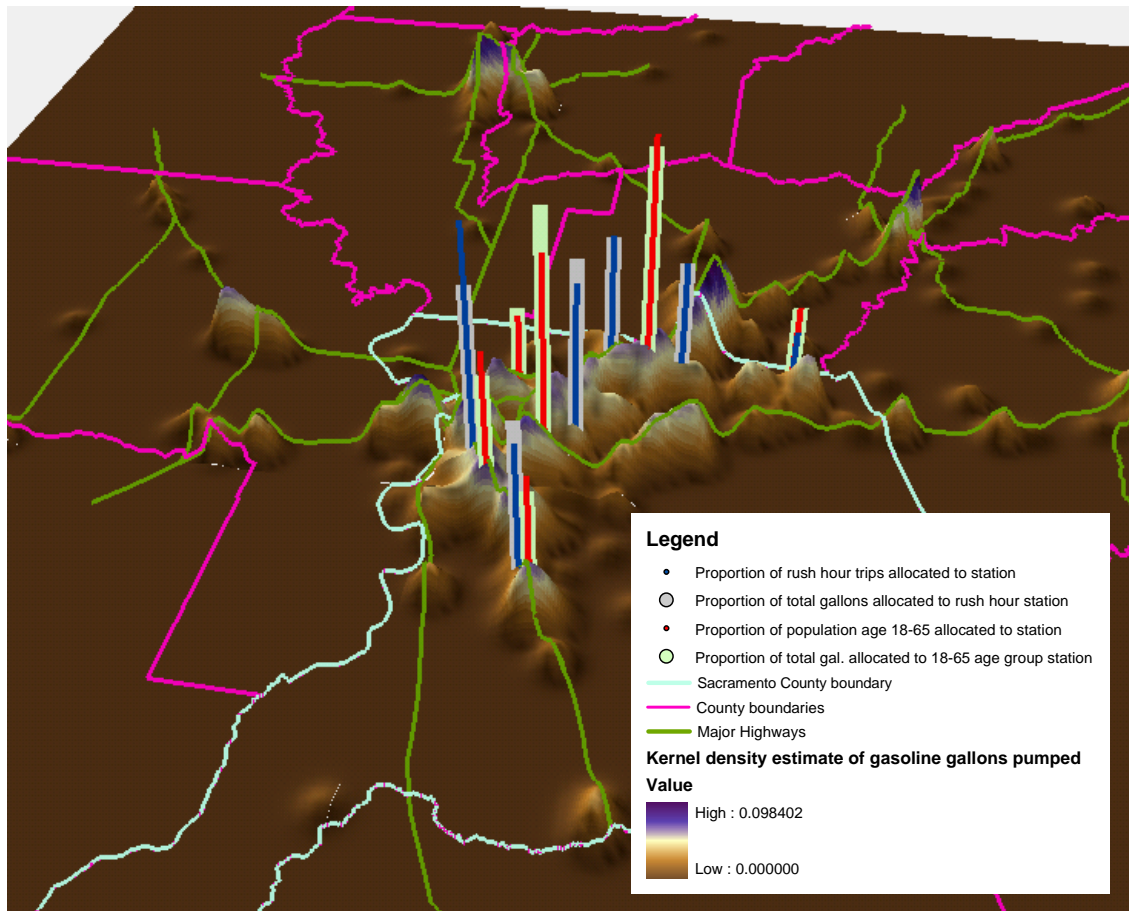


FIGURE 12. Comparison of the locations of stations sited using different input criteria. The six stations selected for each scenario are in different locations because the distribution of population/trips is different. The “mountains” in the picture are kernel density estimates and are proportional to gasoline gallons pumped. They are for visualization only.

The uneven distribution of demand, indicated by the different heights of the bars in Figure 10, is expected from the model since minimizing average travel time tends to favor the location of stations near populations that would otherwise have to drive a long distance to get to a station. In this way, a relatively small population can influence the model if it is far from other centers of demand. If we compare the percentage of trips allocated to a station to the percentage of gallons pumped, we can see that there is general agreement. However, since gasoline stations don't exclusively serve the commute market, we would not expect the percentages to match exactly. The downtown area

shows the greatest difference in the trips allocated to a station versus the gallons pumped in the area. Perhaps this indicates that many people start a trip downtown during the morning rush hour even though the origins are not the places of residence.

Using the census data of the residences of 18-65 year olds, a different representation of demand is revealed (Figure 11). The model chooses different stations to minimize the average travel time for the region. We can see that the greatest allocation of population to a station does not occur downtown, but rather northeast of downtown at station 5 in Figure 11. The greatest allocation of gasoline, however, was attributed to the station closest to downtown. This result may indicate that some refueling occurs downtown even though the downtown station is not the closest to a patron's residence. However, more investigation is needed to verify this conclusion. Locations chosen using both criteria are shown on the same map in Figure 12.

4.3 Scenario Testing

There are 319 gasoline stations in Sacramento County. Thirty two stations (Figure 13) corresponds to Kurani's assessment of 10% as sufficient to reasonably serve the CNG vehicle market in New Zealand. One can see that at the 10% level in Sacramento County, the average driving time to a station is about three minutes and five seconds when the SACMET road network is used. In a worst case scenario, this would be an average diversion of no more than six minutes and ten seconds from the commute route. The worst case scenario is calculated by assuming that a proposed station is in exactly the opposite direction as the commute route, and that refueling would require going to the station, returning home and continuing on to work. With the existing

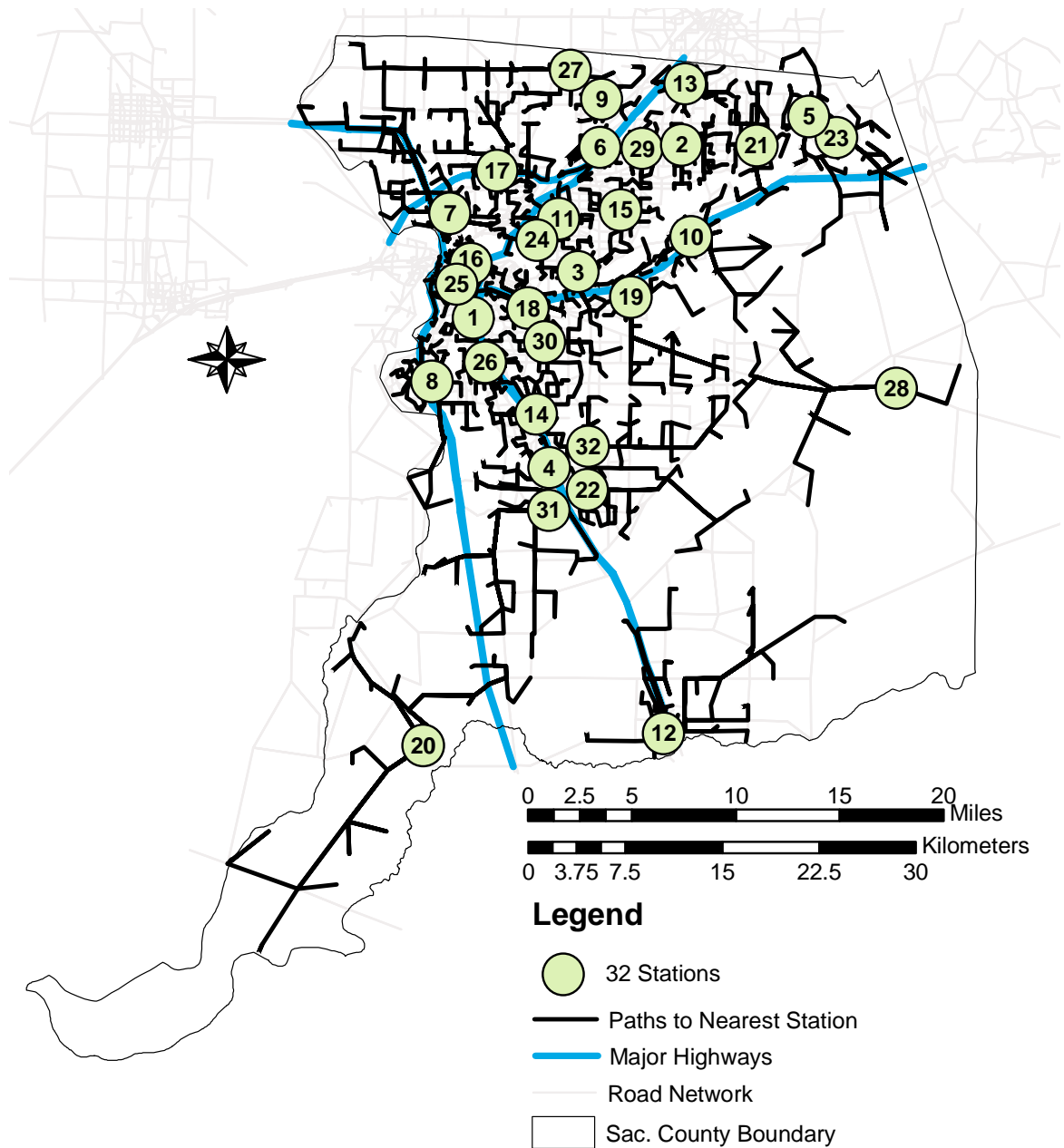


FIGURE 13. Analysis of a thirty two station network. Thirty two stations is ten percent of existing stations in Sacramento County. The numbers represent the order in which the model assigned the stations. Most initial stations are sited along freeways. It should be noted that locations are dependent on the size of the groups being sited.

network of stations, commuters traveling from home now accept one minute fifty seconds to a station (Figure 4), or a worst case scenario of three minutes forty seconds, if route choice is considered. At a level of 96 stations, or roughly 30% of existing stations, the

average one-way travel time increases approximately 16 seconds from that of existing stations, which increases the worst case scenario by 32 seconds. Even at a level of 5% of existing stations, one way average driving time from home to a station is only about four minutes.

If the population of persons aged 18-65 is used, then the average time to a station is currently two minutes and two seconds. At 30% of stations, the average time to a station is two minutes and fourteen seconds for a difference of twelve seconds. At 5% of existing stations the average time to a station is four minutes nine seconds.

To test the hypothesis that station placement does make a dramatic difference and to test the sensitivity of the model, two stations were poorly placed (Figure 14). They were not located in a remote area of the county; rather they were placed in relatively populated areas away from high traffic arterials. One was placed a mile north of the central business district, and the other was placed two miles east of the central business district between Interstate 80 and US 50. The data used for the analyses were rush hour commuter origins. The consequence of requiring everyone to drive on slower streets to get to a station was a noticeable increase in average driving time, as shown in Figure 15. This does not suggest that stations should not be sited within neighborhoods; however, it does indicate that neighborhood placements should be considered carefully. Only if a large number of people live in an area with poor freeway access should an initial station be sited in a neighborhood far from a freeway. This is in fact the case in parts of Sacramento, and the model chose a neighborhood site as one of the initial sites. However, most of the first sites were along freeways.

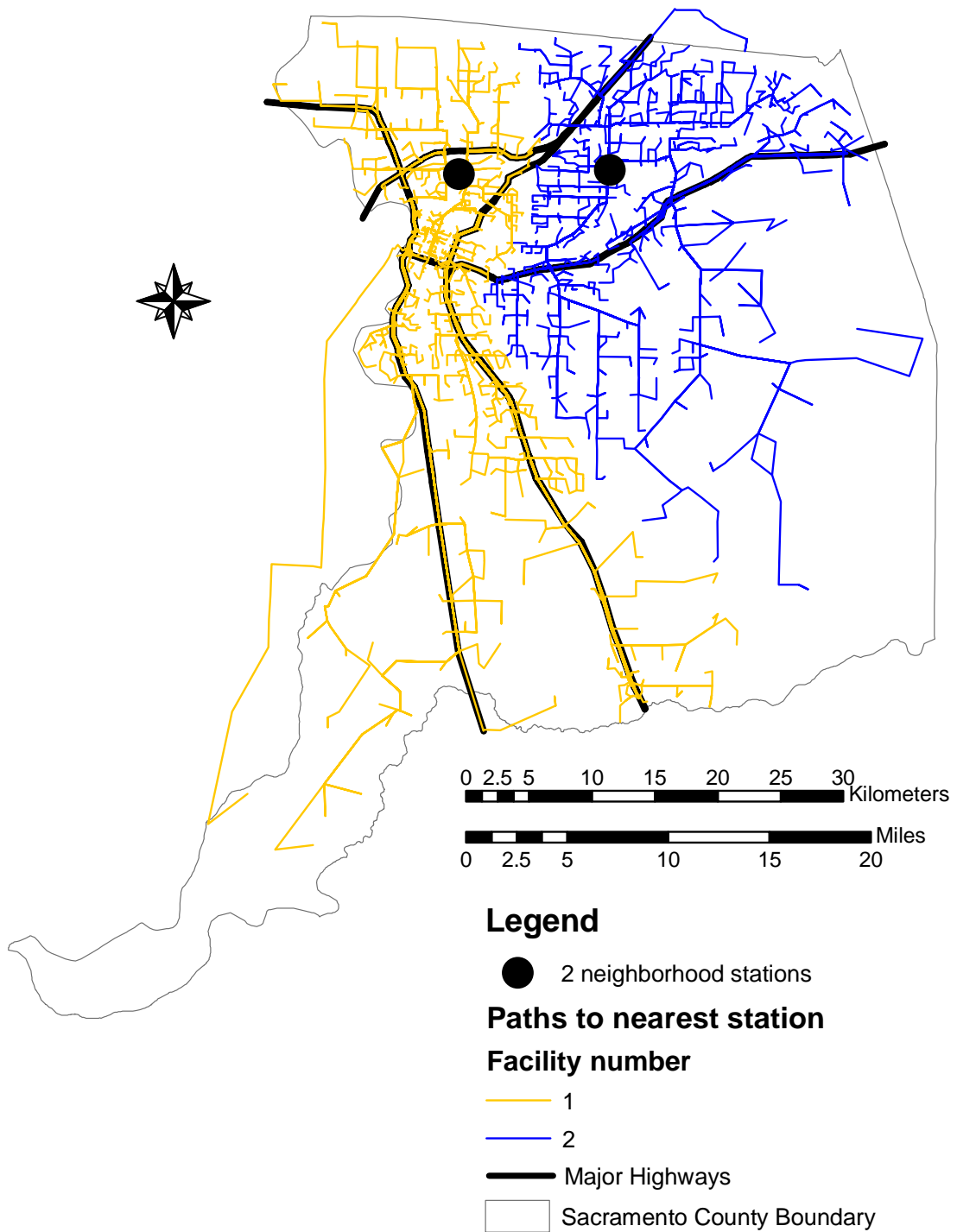


FIGURE 14. Two stations placed in neighborhoods far from freeways. Requiring all of commuters to travel on slower roads increases the average travel time. Each line represents the path from a TAZ to the nearest hydrogen station.

The next scenario tested was the pipeline strategy. Building on the assumption that stations in close proximity to freeways would be the best placement for high volume stations, a pipeline was assumed to be constructed along either Highway 50 or Interstate 80. By examining driving time in Figure 15, we can see that Highway 50 would be a better choice of the two freeways, assuming that construction costs were roughly equal.

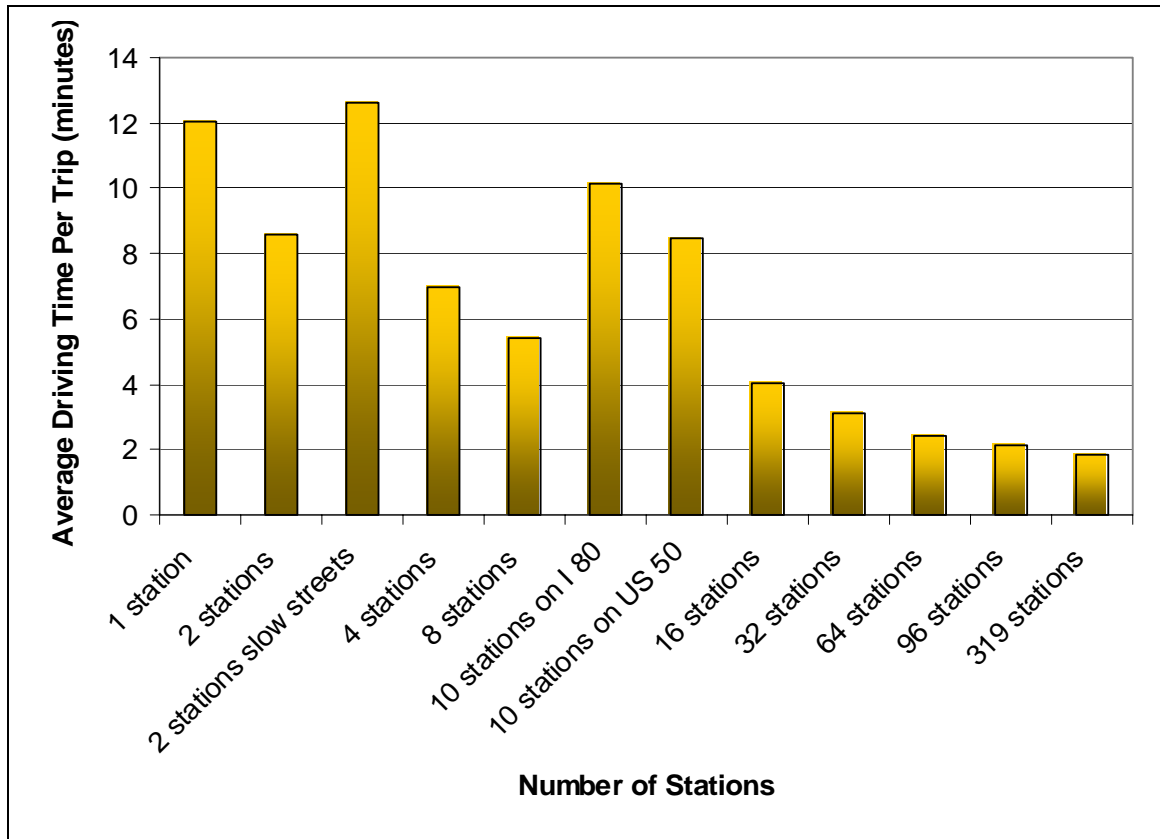


FIGURE 15. Average travel time for all scenarios tested.

Figure 15 also serves to highlight that two well-placed stations can serve the public just as well or better than ten sited solely because of a pipeline. Pipelines should be considered, but the overall network should be well distributed.

In order to facilitate travel between metropolitan regions, some have suggested locating hydrogen stations at regular intervals along major freeways. The model

suggested in this report would be most applicable in this context to site stations that would be used by both intraregional and interregional traffic. In California, an interval of twenty miles along selected freeways has been posited by the group Energy Independence Now in their “Hydrogen Highway” document.⁹⁹ The model was applied to the corridors identified in the document to evaluate the effect station placement had on average travel time. It must be noted that this map was released to promote discussion, and does not constitute a plan.

The hypothetical map released by the state of California includes only two stations in Sacramento County, with two more resting near the county line. However, in the six county Sacramento region, there are 11 regularly spaced stations. The most realistic scenario, therefore, was to evaluate the entire six county region. Three scenarios were tested and run on the SACMET road network. The first scenario was based off the “Hydrogen Highway” map released by Energy Independence Now. These stations were spaced approximately every 20 miles along the selected freeways unless a station was already present. The hydrogen highway freeways are indicated by the thicker lines in Figure 16.

The average time to a station is about 13 minutes for the regularly spaced stations (Figure 17). Using the same highways and the same number of stations, the model was applied to minimize average travel time to a station. This resulted in about a ten and a half minute average travel time. The station locations can be seen in Figure 16, and the time comparison can be seen in Figure 17. The last scenario tried was one in which all major freeway locations were included in the analysis. The freeways included are shown in Figure 16, but for map clarity, the station locations are not shown. Including a greater

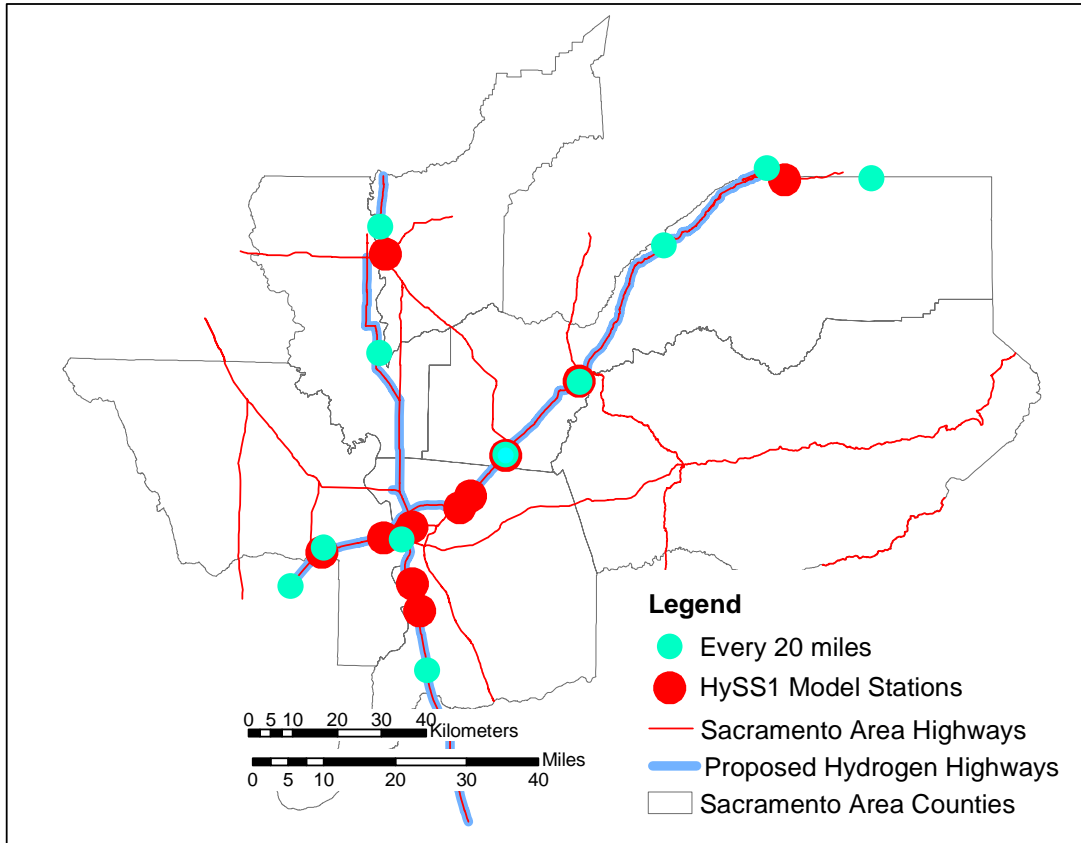


FIGURE 16. Application of the model along selected freeways in the Sacramento Region. For clarity, the eleven stations along all Sacramento area highways (red lines) are not pictured here.

distribution of potential sites results in an eight minute average travel time to the nearest station.

The three highway scenarios highlight a few important issues. First, interregional and intraregional networks have different functions. Some stations in an interregional network may see little traffic, but are nonetheless necessary to enable travel along a corridor. However, stations that serve local traffic are less constrained in location by vehicle range than those stations along an interregional corridor. Customers making daily trips are likely concerned more with the convenience of using a station rather than whether it is physically possible to make a journey. If the model is to be applied to a

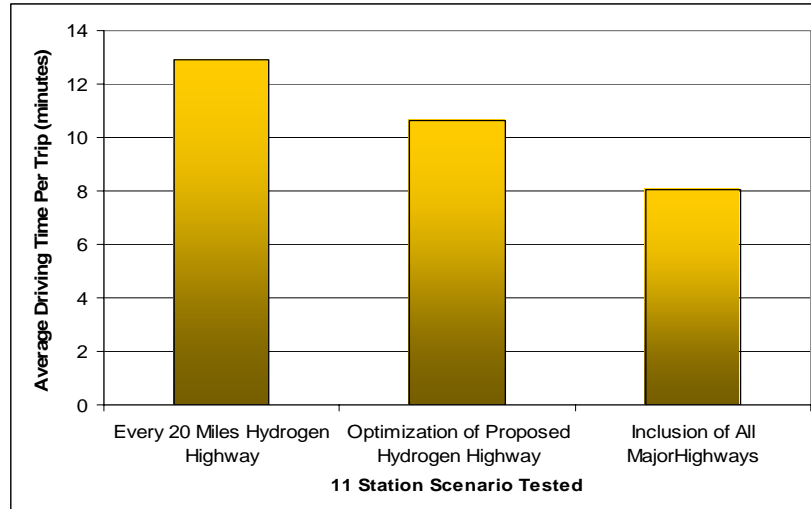


FIGURE 17. Graph showing the average travel time for hydrogen highway scenarios. Each scenario represents the average travel time to the nearest of eleven stations. Each scenario has a different distribution of stations.

hydrogen highway, maximum distances between stations must be established for the hydrogen highway. When the model was applied to the designated hydrogen highways in the Sacramento region, an interval of 40 miles separated hydrogen stations in two cases. This may or may not be acceptable for drivers on a hydrogen highway. If a 40 mile interval were not acceptable, a constraint could be introduced into the model to force stations to be no more than, say, 30 miles from the next station on the highway.

The second issue raised is that metropolitan regions may have to augment hydrogen highway stations with stations on other freeways to have an effective hydrogen highway network for local travel. Restricting the 11 stations to the designated corridors resulted in a ten and a half minute travel time. Expanding the distribution of possibilities to include stations along all major freeways resulted in an average travel time of about eight minutes, a significant improvement.

CHAPTER 6. CONCLUSION

A network of hydrogen fuel stations needs to be put in place in concert with the commercialization of hydrogen vehicles. Various studies have analyzed how many stations are needed, but not where they could or should be sited. Geographic Information Systems (GIS) provide a way to synthesize siting criteria to make intelligent siting decisions and evaluate the placement of hypothetical stations in a network. The method used in this report can be applied in any region that has GIS data.

The model performed well in the Sacramento County example, and gives a clearer picture of how the number of stations relates to geographical location. Significant improvements in driving time were achieved as initial hydrogen stations were added to the network, with driving time improvements diminishing as more stations were included.

However, the application of the model should be viewed in context with both micro-level and macro-level siting. Additionally, alternate meso-level siting models should be considered when viewing the results. The model applied here draws upon other studies that suggest a relationship between home or work to a station, but is not tested against alternative siting models.

The exact placement of stations is not specifically addressed in the model and will be affected by micro-level siting considerations. Traffic speeds and volumes along specific roads should be factored into the siting of an actual station. The siting results from this model should be interpreted as suggestions and not absolutes. Furthermore, micro-level siting barriers are not incorporated into the model. The resistance to siting

hydrogen stations next to homes and businesses will play a role in the ultimate form of the refueling network.

The most important task to overcome siting barriers will be to educate the public about hydrogen. This should be a nationwide effort to debunk the myths about hydrogen, and provide facts as to its dangers and potential. This will hopefully preempt many of the objections that citizens have. Efforts at education should focus around the adjacent homes and businesses. Even though the public may be vaguely aware of hydrogen through a mass education campaign, the importance of the facts becomes greater the closer the resident is to the site. This education will have the power to assuage homeowners and businesses regarding property values.

Another important issue that must be resolved is the zoning code. The code should be changed in municipalities where stations will be sited. Having special variances issued for each station would likely be infeasible. Changing the zoning code to apply to all appropriately zoned parcels may also give confidence to those who think they have been singled out for having something dangerous near their home or business. Just as zoning has the power to systematically discourage hydrogen, favorable zoning can encourage hydrogen.

In addition to framing the results with respect to micro-level siting concerns, looking at the results as they relate to macro-level siting is informative. The estimates for the sufficient number of stations ranged from 10% to 50% of existing stations. The results from the model help interpret these estimates. At a level of 10% of stations, the network is not equal in terms of average travel time to the existing network. At a level of 50% of stations however, the model suggests the network is more than adequate.

The results from the model not only inform previous estimates of the necessary number of stations, but conversely suggest a sufficient number of stations. The model seems to agree with Greene's conclusion that the critical range of station availability is in the 0% to 20% range. Even at relatively low levels such as 5% the average travel time to a station may be acceptable. For relative parity with the convenience of the existing gasoline network, the model results suggest that for a metropolitan region similar in geography and density to Sacramento County, a level of 30% of stations is sufficient.

The scenarios tested with the various inputs and road networks such as SACMET and Streetmap® serve to highlight some important aspects of this model. Most importantly, the scenarios help to show the variability of the results. Different inputs result in different average travel time curves and therefore it is difficult to state with certainty the average travel time to a station. However, the relationship between the existing network of stations to some fraction of that network holds relatively constant across all scenarios.

The results, however, need not be tied to a percentage of stations. Perhaps a constant average time to a station is a more appropriate metric, since some areas, particularly rural ones, may not have the degree of redundancy found in an urban or suburban refueling network. In rural areas, the percentage of stations necessary to provide convenience similar to the existing network is likely higher than in Sacramento County, but the average time to a station may be similar to that in Sacramento County.

In addition to providing interpretation of macro-level station estimates, the model results can reasonably support some other conclusions. Freeway stations, with a few exceptions, are the most effective initial stations, with neighborhood stations rising in

importance later. Siting many stations along a pipeline does not necessarily provide the utility of a few well-placed stations.

Examining the hydrogen highway scenarios highlight some weaknesses of the model and the need to establish absolute limits for the distances between stations. Other models that incorporate flow capturing could be incorporated to aid in the interregional analyses. Additionally, the results suggest that for intraregional refueling networks, careful consideration must be given to stations sites not along the designated hydrogen highways in order to design an effective intraregional refueling network.

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APPENDIX A

Average Travel Time Results Using the SACMET Network

<i>Population 18-65</i>		<i>Home Based Commuters</i>		<i>Work Based Commuters</i>	
Number of Stations	Average Travel Time to Nearest Station (min)	Number of Stations	Average Travel Time to Nearest Station (min)	Number of Stations	Average Travel Time to Nearest Station (min)
1	12.85	1	12.03	1	10.81
2	8.9	2	8.57	2	8.16
4	7.25	4	6.95	4	6.65
6	6.2	6	6.05	6	5.68
8	5.59	8	5.42	8	4.99
10	5.09	10	4.95	10	4.56
12	4.66	12	4.58	12	4.27
14	4.36	14	4.28	14	4.02
16	4.15	16	4.06	16	3.82
18	3.96	18	3.87	18	3.65
20	3.82	20	3.72	20	3.49
22	3.69	22	3.58	22	3.34
24	3.56	24	3.45	24	3.22
26	3.44	26	3.34	26	3.1
28	3.35	28	3.25	28	3.01
30	3.27	30	3.17	30	2.93
32	3.2	32	3.09	32	2.86
34	3.13	34	3.02	34	2.8
36	3.06	36	2.96	36	2.74
38	3	38	2.91	38	2.7
40	2.95	40	2.85	40	2.65
42	2.9	42	2.8	42	2.61
44	2.85	44	2.75	44	2.56
46	2.81	46	2.7	46	2.52
48	2.76	48	2.66	48	2.49
50	2.72	50	2.62	50	2.45
52	2.68	52	2.58	52	2.42
54	2.64	54	2.55	54	2.39
56	2.61	56	2.52	56	2.36
58	2.58	58	2.49	58	2.33
60	2.54	60	2.46	60	2.3
62	2.51	62	2.43	62	2.27
64	2.49	64	2.41	64	2.25
66	2.46	66	2.38	66	2.22
68	2.44	68	2.36	68	2.2
70	2.41	70	2.34	70	2.18
72	2.39	72	2.32	72	2.16
74	2.38	74	2.29	74	2.14
76	2.36	76	2.27	76	2.12

78	2.34	78	2.26	78	2.1
80	2.33	80	2.24	80	2.09
82	2.31	82	2.22	82	2.07
84	2.3	84	2.21	84	2.06
86	2.29	86	2.19	86	2.04
88	2.27	88	2.18	88	2.03
90	2.26	90	2.17	90	2.01
92	2.25	92	2.15	92	2
94	2.24	94	2.14	94	1.99
96	2.23	96	2.13	96	1.97
319	2.04	319	1.86	319	1.73

APPENDIX B

Average Travel Time Results Using the StreetMap Network

<i>Population 18-65</i>		<i>Home Based Commuters</i>		<i>Work Based Commuters</i>	
Number of Stations	Average Travel Time to Nearest Station (min)	Number of Stations	Average Travel Time to Nearest Station (min)	Number of Stations	Average Travel Time to Nearest Station (min)
1	13.27	1	12.36	1	10.95
2	10.42	2	9.78	2	8.9
4	8.11	4	7.6	4	6.92
6	7.26	6	6.79	6	6.1
8	6.51	8	6.15	8	5.5
10	5.96	10	5.61	10	5.03
12	5.53	12	5.26	12	4.73
14	5.23	14	4.95	14	4.44
16	4.98	16	4.69	16	4.19
18	4.76	18	4.48	18	4.01
20	4.57	20	4.32	20	3.84
22	4.4	22	4.17	22	3.69
24	4.24	24	4.03	24	3.57
26	4.1	26	3.91	26	3.45
28	3.97	28	3.79	28	3.35
30	3.86	30	3.69	30	3.26
32	3.77	32	3.59	32	3.17
34	3.68	34	3.5	34	3.1
36	3.59	36	3.42	36	3.03
38	3.52	38	3.35	38	2.97
40	3.44	40	3.28	40	2.9
42	3.38	42	3.22	42	2.85
44	3.31	44	3.17	44	2.79
46	3.26	46	3.12	46	2.75
48	3.2	48	3.06	48	2.71
50	3.15	50	3.02	50	2.67
52	3.1	52	2.97	52	2.64
54	3.05	54	2.93	54	2.6
56	3.01	56	2.89	56	2.57
58	2.97	58	2.85	58	2.53
60	2.93	60	2.82	60	2.5
62	2.9	62	2.79	62	2.47
64	2.87	64	2.76	64	2.44
66	2.84	66	2.73	66	2.42
68	2.82	68	2.7	68	2.39
70	2.79	70	2.67	70	2.37
72	2.76	72	2.64	72	2.34
74	2.74	74	2.61	74	2.32
76	2.71	76	2.59	76	2.3

78	2.69	78	2.56	78	2.28
80	2.67	80	2.54	80	2.26
82	2.65	82	2.52	82	2.24
84	2.63	84	2.5	84	2.22
86	2.61	86	2.48	86	2.21
88	2.6	88	2.46	88	2.19
90	2.58	90	2.44	90	2.17
92	2.56	92	2.42	92	2.16
94	2.55	94	2.4	94	2.14
96	2.54	96	2.39	96	2.13
319	2.29	319	2.09	319	1.86