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Detailed Analysis of Urban Station Siting for California Hydrogen Highway Network

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Detailed Analysis of Urban Station Siting for the California Hydrogen Highway Network

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ABSTRACT

As a follow-up analysis to two station siting analyses completed by the authors for the California Hydrogen Highway Network, this report takes a closer look at the regional differences between the four main metropolitan areas in California: Greater Los Angeles, the San Francisco Bay Area, the Sacramento Metropolitan Area, and the San Diego Metropolitan Area. The purpose of this analysis is twofold: to generate a general model to assess hydrogen needs in different regions, and to apply the model to compare its results with the California Hydrogen Highways report. In the Hydrogen Highways report, the number of stations needed was determined by the percentage of the population in each region. In the analysis that follows, average driving time to the nearest station (convenience metric) is used to determine the number of stations necessary for each region. By using convenience to determine the share of stations, regions that are less dense will be served as well as those regions with high density. In our analysis, we examine varying average driving times to the nearest station. The results suggest that the percentage of stations needed to meet a convenience target differs among regions depending on density. For example, a four minute average travel time in Sacramento requires 7.2 percent of stations, whereas only 3.3 percent is required in Los Angeles. The prediction equation developed predicts station needs depending on population density, and a desired level of convenience, and, noting the caveats explained in the paper, can be applied to any region.

INTRODUCTION

The California Hydrogen Highways Report[1,2]presents a vision for the deployment of a hydrogen refueling infrastructure throughout the state of California. The plan is to proceed in two phases. In the first phase, 50 stations will be distributed among the four main metropolitan areas in California: Greater Los Angeles, the San Francisco Bay Area, the Sacramento Metropolitan Area, and the San Diego Metropolitan Area. In the second phase, 250 total stations will be deployed throughout the state, including stations that connect the regions together. The method used to divide the stations among the regions was an educated guess and was based loosely on population.

Using the Hydrogen Highways report as a starting point, this paper will take an in depth look at the regional differences that could affect the deployment of a hydrogen refueling network. Whereas the number of stations for each region in the Hydrogen Highways report was determined based on population, this paper will explore an alternative method based upon customer convenience measured in terms of the average travel time to one's nearest station. By examining regions of differing density, we generate rules of thumb that can be used to examine the refueling network needs of other regions without running travel time calculations.

Intuitively, we can see that density affects how many stations are needed to service a population. If everyone in a region lived in a one square mile area, then one station might be sufficient to serve that area. Conversely, if the same number of people were more dispersed, more stations would be needed to prevent customers from having to drive long distances to a station. In the same way, denser metropolitan areas may need fewer stations than regions where the population is more dispersed.

Understanding this tradeoff is crucial to the design of a network for hydrogen, or any alternative fuel. Customers expect a certain level of service, and if a minimum level of station coverage is not achieved, then few customers will want to use a hydrogen vehicle. If this threshold cannot be achieved because it is prohibitively expensive, then a hydrogen infrastructure would be postponed until it was economically feasible. It follows that denser regions can more easily meet any threshold since a small number of stations can serve a large number of people. By comparing different regions we can begin to draw conclusions and general rules for required station coverage.

BACKGROUND

The sufficient number of refueling stations to satisfy an initial market for alternative fuel vehicles has been investigated in a number of studies[3,4,5,6,7,8,9]. The estimates range from 10% of existing gasoline stations to 30% of gasoline stations. Two of the studies[7,8] further break down the sufficient number of stations into urban and rural needs.

Few of these studies however have focused on the difference in needs among urban regions[9]. The needs are connected primarily to the percentage of existing stations. While this method is convenient, it is not always consistent. For example, the number of stations in the U.S. in 1970 was 222,000 [10] while the number of registered cars and light trucks was 103.5 million [11] meaning there were approximately 466 cars per station. By 2002 the number of stations had declined to 170,018 [12] while the number of cars and light trucks had increased to 220.9 million[11] or approximately 1300 vehicles per station.

By looking at the trends in auto ownership, and number of stations we can see that basing an estimate of the number of stations needed on a percentage of stations represents a snapshot in time. For example, 10% of stations in 1993 represents 20,741 stations [13] while 10% of stations in 2002 represents 17,002 stations[12]. Compared to these national statistics, the number of stations in California show and even more marked decline[12]. Clearly we can see that percentage of stations calculations are dependent upon the time period they are made.

Another problem with the percentage of stations calculations is that they do not account for regional differences. A small investment per capita may provide adequate convenience (measured in travel time to the nearest station) in one region, because of its density, whereas a comparatively large investment per capita would be required in less dense regions.

METHODS

Representing the number of stations necessary in terms of a percentage of existing gasoline stations is a convenient way to convey information. However, this statistic can not be used uniformly to predict stations needs from region to region. For example, 10% of stations in the Los Angeles region would provide a different level of convenience than 10% of stations in the Sacramento region. Instead, the average travel time to the nearest station will be used to compare the needs of different regions. This method is based on the assumption that people from different regions have the same tolerance for driving time to the nearest station. This means that people from the urban L.A. region are just as satisfied driving four minutes to a station as people from the urban Sacramento area. Using this metric, the relationship between population density, number of stations and convenience can be studied.

Study Area Definition

The areas studied are the metropolitan regions of Los Angeles, San Francisco, Sacramento, and San Diego. These regions are defined by their respective planning organizations: Southern California Association of Governments (SCAG), Association of Bay Area Governments (ABAG), Sacramento Area Council of Governments (SACOG), and San Diego Association of Governments (SANDAG). For the purposes of clarity, the abbreviations of LA, SF, SD, and Sac will be used to refer to these study areas even though these abbreviations denote only the main city in the region.

In some cases these regions are defined by county boundaries, and in some regions boundaries do not follow county boundaries. Due to the arbitrary nature of the political boundaries drawn, only the central urban area within these regions was analyzed. The central urban area within each regions was calculated using a method developed by Nils Johnson[14]. This method identifies the boundaries of contiguous high population density areas such as in LA, SF, SD, and Sac.

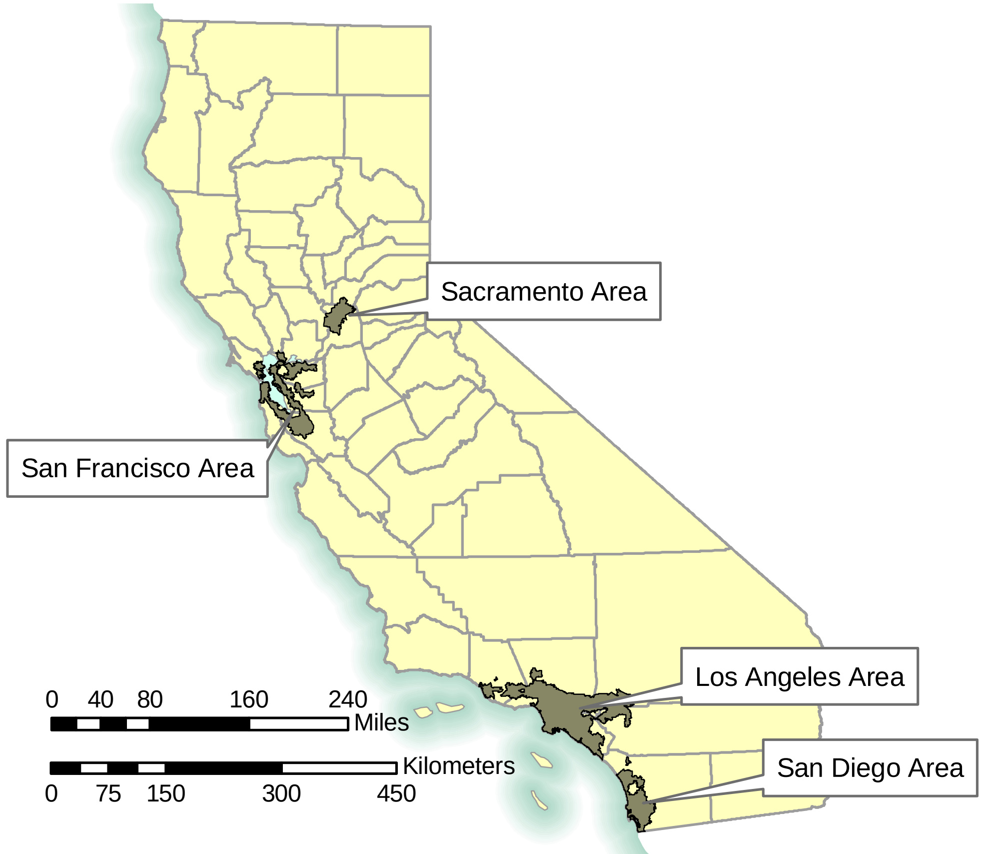

FIGURE 1 Map showing the four study regions. These regions are the central population centers within each of the metropolitan regions.

Zone Boundaries and Zone Size

The zones used to divide population in this analysis were urban census tracts. Census tracts vary in land area but each tract represents about 4,000 people with similar living conditions. The urban census tracts were identified as those census tracts whose center lay within the central urban area.

In the first phase of analysis, the year 2000 census tract population was used to approximate customer locations. Many alternative metrics can be used including number of households, driving age population, or number of vehicles per household, but since population is the most easily obtainable, initial analyses will be grounded in this metric.

An issue with choosing the right zone boundaries is the size of the zones. If the size of the zone is too big, the center of the zone is not well suited to approximate customer locations. If the zones are too small, then the computing time becomes unmanageable. To explore the effect of zone size on the results, a sensitivity analysis was performed on the Sacramento region. For this region, three zone definitions were applied, and the impact on travel time was calculated.

Station Locations

This analysis uses existing gasoline stations as possible locations for hydrogen stations. The model is not so precise that hydrogen stations need to be co-located with the gasoline stations chosen. Gasoline stations are merely placeholders that represent a likely refueling area.

Hydrogen stations can be located in the surrounding area without affecting the calculations significantly.

The list of stations used comes from the California Energy Commission (CEC)[15]. It is a list of all gasoline stations as of 2002 with a total of 20,939 stations, 9,397 of which are retail stations. The number of stations in California in 2002 according to the National Petroleum News was 9,730[12], a difference of 3.6%. From comparison with other more accurate lists from MPSI[16] that break station counts down by county, some counties had an under count, and some had an over count. Despite these irregularities, the list from the CEC is the only one that is provides station locations for all California, and hence was used for all calculations.

Road Network

Driving time between a census tract and a station was calculated using the StreetMap road network from Environmental Systems Research Institute (ESRI)[17]. This road network is a consistent nationwide road network and provides driving time results that are comparable from region to region. It should be noted that this network approximates speed, and does not take congestion into account. Therefore the driving time results should be interpreted as approximate, and possibly shorter than actual.

Model Description

The model used is described in detail in another paper[6], but a brief overview will be given here. The scenarios that we are testing mirror the use of the current gasoline network and have the following assumptions:

- People prefer to refuel near home.
- The distribution of existing gasoline infrastructure is correlated to the future hydrogen infrastructure.
- People will refuel at public fuel stations as opposed to home refueling.

In order to find the best placement of stations, the model minimizes the average travel time to the nearest station for a region. This is called a p-median problem in operations research[18,19]. The p-median problem model is a relatively simple idea in the retail context. Consumers are assumed to patronize the closest station to their home. Home based refueling was chosen for this analysis since the correlation between home and refueling is stronger than for any other location[20]. The consumers are assumed to be at fixed locations and the goal is to optimize the retail locations such that the aggregate time for all consumers 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. The travel time to the nearest station is weighted by the number of people associated with a route from a zone to a station. This can be seen visually in Figure 2.

Origin TAZ	Station	Trips	Minutes	Trips x Minutes
1	12	1773	1.3	2304.9
2	12	912	0.8	729.6
3	12	632	1.0	632.0
4	12	423	0.9	380.7
5	43	815	5.6	4546.9
↓ 700	↓ 20	↓ 420	↓ 3.7	↓ 1554
Sum		474480		1462454
Trip Min Sum / Trip Sum				Avg Time 3.082

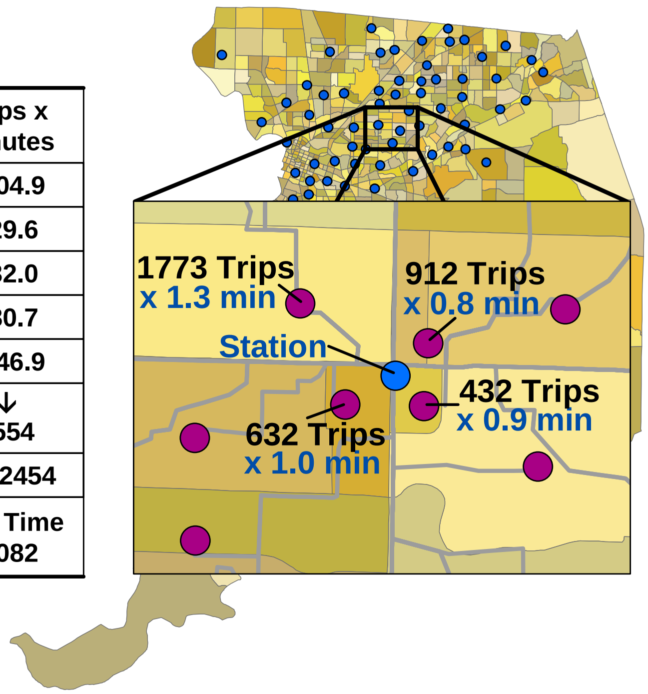

FIGURE 2 Map showing the assignment of trips from a Zone to the nearest station, and the corresponding table showing the process of calculating average travel time for a station scenario (Reproduced with permission from author[6]).

The locations of the consumers' homes are approximated by the center of a census tract. As stated before, census tracts are based on population, not size. Smaller dense tracts approximate a consumer's location more accurately than a larger tract. Accordingly travel times may be more accurate in areas with denser census tracts. This effect will be investigated further in the results section.

RESULTS

As expected, each region analyzed is distinctive. A summary of relevant statistics for each region is shown in Table 1. We will later compare the results of this analysis to that in the California Hydrogen Highways report.

	Population in Urban Center	Urban Area (sq mi)	Urban Density (people / sq. mi)	Urban Density (people / sq. km)	Avg. Tract Size (mi)	Avg. Tract Size (km)	Number of Urban Stations	Number of People Per Station	Avg. Minutes to Closest Station
L.A.	14,340,402	2,645	5,421	2,093	0.9	2.33	3,355	4,274	1.60
S.F.	5,474,575	1,111	4,927	1,903	0.96	2.48	1,246	4,394	1.72
SD	2,538,862	606	4,189	1,618	1.1	2.84	572	4,439	2.20
Sac	1,247,224	331	3,768	1,454	1.21	3.12	304	4,103	2.24

TABLE 1 Regional refueling profiles.

Some interesting trends emerge from Table 1. The average travel time to the nearest station decreases as the urban density increases. The number of people per station, however, does not seem to show any trend.

Effect of Zone Size on the Results

One possibility that could potentially invalidate the travel time calculations is the size of the zones. The zones become smaller as the population density increases(Table 1), and it is possible that the difference in travel time is related wholly to the size of the zones being studied. To account for this possibility, the Sacramento Region was analyzed using various zone sizes. Three zones sizes were tried: Tracts, Traffic Analysis Zones (TAZ), and ¼ Traffic Analysis Zones. Traffic analysis zones are zones identified by Sacramento Area traffic modelers[21] that have similar traffic behavior. A summary of all the zone characteristics is in Table 2.

Region	SAC			SD	SF	LA
Zone Boundaries	Tracts	TAZ	1/4 TAZ	Tracts	Tracts	Tracts
Number of Zones	274	610	2440	553	1162	2936
Avg size (square mi)	1.21	0.56	0.14	1.10	.96	.90
Avg size (square km)	3.12	1.43	0.36	2.84	2.48	2.33
Avg time to nearest station	2.24	2.09	1.99	2.20	1.72	1.60

TABLE 2 Zone characteristics for the Sacramento region. All zone categories represent the same region size.

TAZs represent roughly a doubling of the number tract zones and the ¼ TAZs represent a nine-fold increase in zones. Using these boundaries we can calculate the average travel time to the nearest station.

Clearly, increasing the zone resolution has an effect on travel time, but the effect is not great. The differences in the results generally increase as the number of stations sited grows. The difference is greatest when calculating the average travel time to the nearest station using the full gasoline network. The time computed using tracts was 2.24 minutes, whereas the time using ¼ TAZs was 1.99 minutes. We should keep this difference in mind as we interpret the results from the other regions, but the differing resolution has little effect on the results for zones on the scale of tract size or less. The area of the curve we are most interested in is from 0% up to about 15% of stations. At 15% of stations, the results between tracts and ¼ TAZs in the Sacramento area differ by only 0.1 minutes or 6 seconds.

Model Application

The scenario testing produced some interesting results. When we increase the number of stations from 0% we see the average driving time rapidly drop after the initial stations are added to the network (see Figure 3). For example, the average travel time in the Los Angeles region to one station, two stations and three stations is 25, 21, and 18 minutes respectively. The difference after adding the second station is four minutes, but the difference after adding the third station is only three minutes. This decreasing difference is repeated as more stations are added.

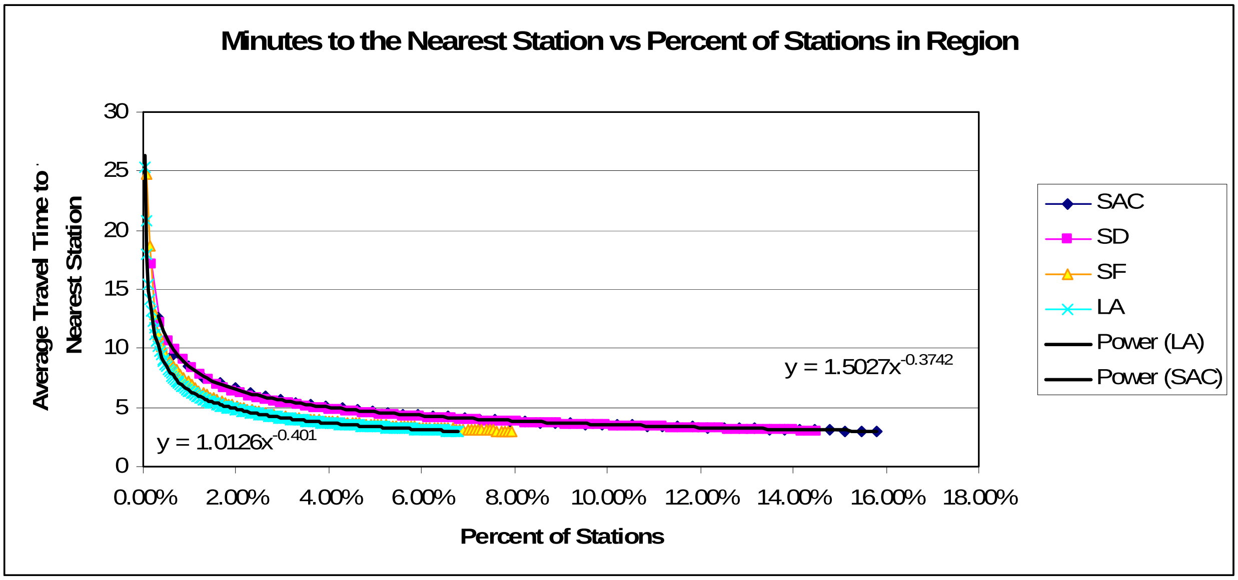

FIGURE 3 Relationship between average driving time to the nearest station and percentage of stations. To highlight the region that will be analyzed, the scenarios for each region stop when they reach 3 minutes.

The relationship between travel time and percentage of stations shown in the above graph can be seen numerically in Table 3. The absolute numbers are shown in Table 4. Notice that the percentage of stations required to meet a travel time target is different for each region.

	LA	SF	SD	SAC
3 Minutes	6.8%	7.9%	14.5%	15.8%
4 Minutes	3.2%	3.5%	6.8%	7.2%
5 Minutes	1.8%	2.1%	3.7%	4.3%
6 Minutes	1.2%	1.4%	2.3%	2.6%
7 Minutes	0.8%	1.0%	1.6%	1.6%

TABLE 3 Relationship between average driving time to the nearest station and the percentage of stations in each region necessary to achieve that driving time.

	LA	SF	SD	SAC	Total
3 Minutes	228	99	83	48	327
4 Minutes	109	44	39	22	153
5 Minutes	61	26	21	13	87
6 Minutes	39	17	13	8	56
7 Minutes	26	13	9	5	39

TABLE 4 Relationship between average driving time to the nearest station and the number of stations in each region necessary to achieve that driving time.

The results shown in these tables show some interesting characteristics of travel time calculations. When viewed in conjunction with table 1 we can see that that the LA region requires fewer stations as a function of land area than Sacramento. The density of the region seems to reduce the number of stations per mile. In LA for example, there is on average one station every 3.4 miles in the 3 minute case if all the stations were distributed uniformly across the land area. The Sacramento region requires a station every 2.6 miles to meet the same criteria. Stations are not placed this way in this model, but the statistic is illustrative. This effect could be due to a few factors. The main reason is probably because the distribution of population is different in the two areas. In the Los Angeles region, people are more clustered than in the Sacramento region. There are areas of high density that reduce the average travel time significantly when stations are placed near them. Since the population centers are not as intense in the Sacramento area, one station does not have as pronounced an effect. Another factor that might contribute to lower travel time for a lower percentage of stations in the L.A. case is that there are many more high speed roadways that reduce travel time. A smaller effect may be due to the zone size (See Table 2).

We can visualize the differences between a high density area such as in L.A. and a lower density area such as Sacramento, in a boxplot. This type of plot breaks down the individual travel times from each zone that make up the averages. In Figure 4, L.A. and Sacramento are compared at the levels of three, four, five, six, and seven minutes.

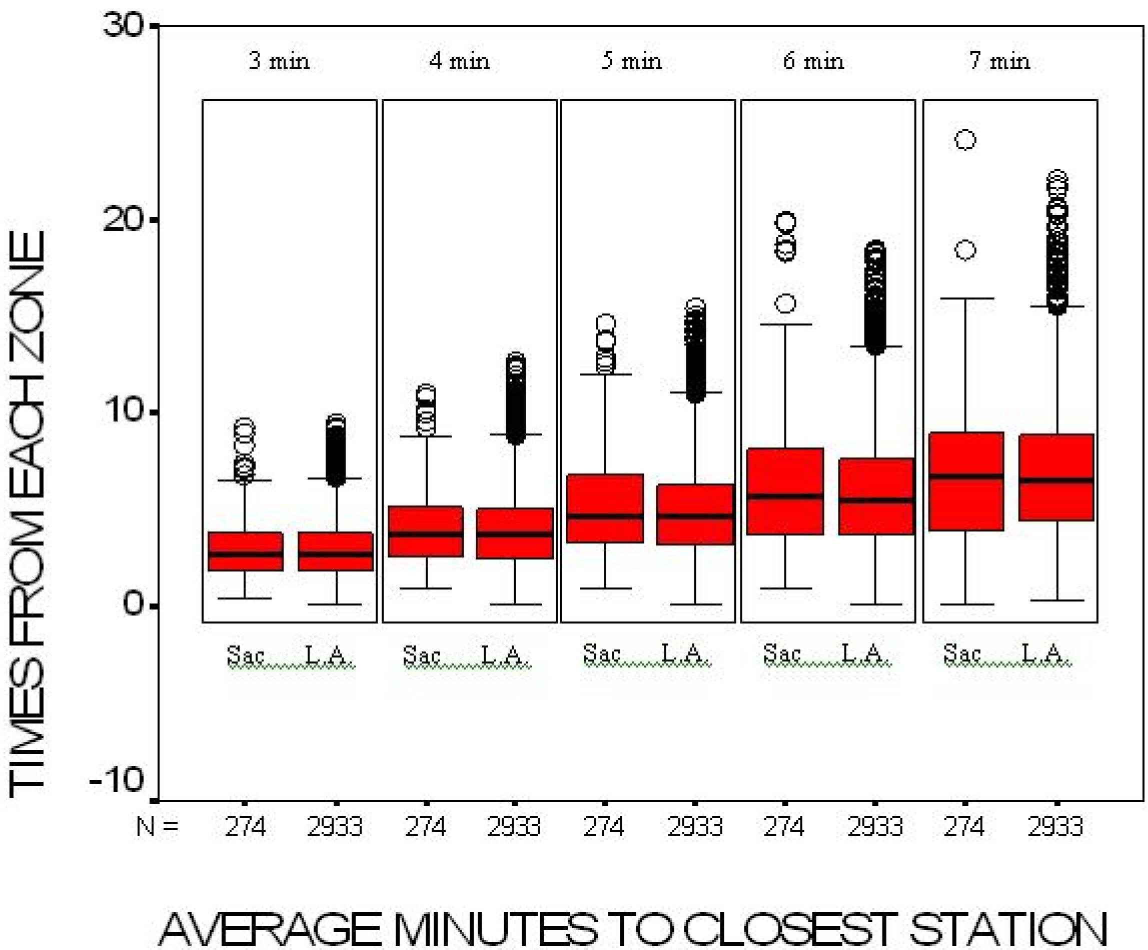

FIGURE 4 L.A. and Sac scenario zone times compared in a boxplot. The black line is the median. The red areas above and below the line are quartiles. The bounded areas above and below the red areas represent quartiles. The other marks are outliers.

Figure 4 shows that, upon closer inspection, the L.A. and Sacramento areas look similar when viewed as boxplots. Even though there is a greater density of stations per square mile in Sacramento, there seems to be better access in the Los Angeles region. However, there are many more outlier zones in the Los Angeles region. This is not surprising since there are many more zones overall, but it does appear that there are more zones that are not as well served as in the Sacramento Area.

One can see by Table 3 that the percentage of stations needed to achieve a certain driving time increases as the population decreases (Regions are ordered by population with the largest first). The percentage of stations is also tied to the population density. Even though the LA region is twice as populous as the SF region, the requirements are similar. Conversely, the Sac region with the lowest population and the lowest density requires a higher percentage of stations to meet a driving time target. The fluctuation in the percentage of stations required cannot be wholly explained by population or population density, however, population density does seem to correlate in part the percentage of stations needed to achieve a certain driving time (Figure 5).

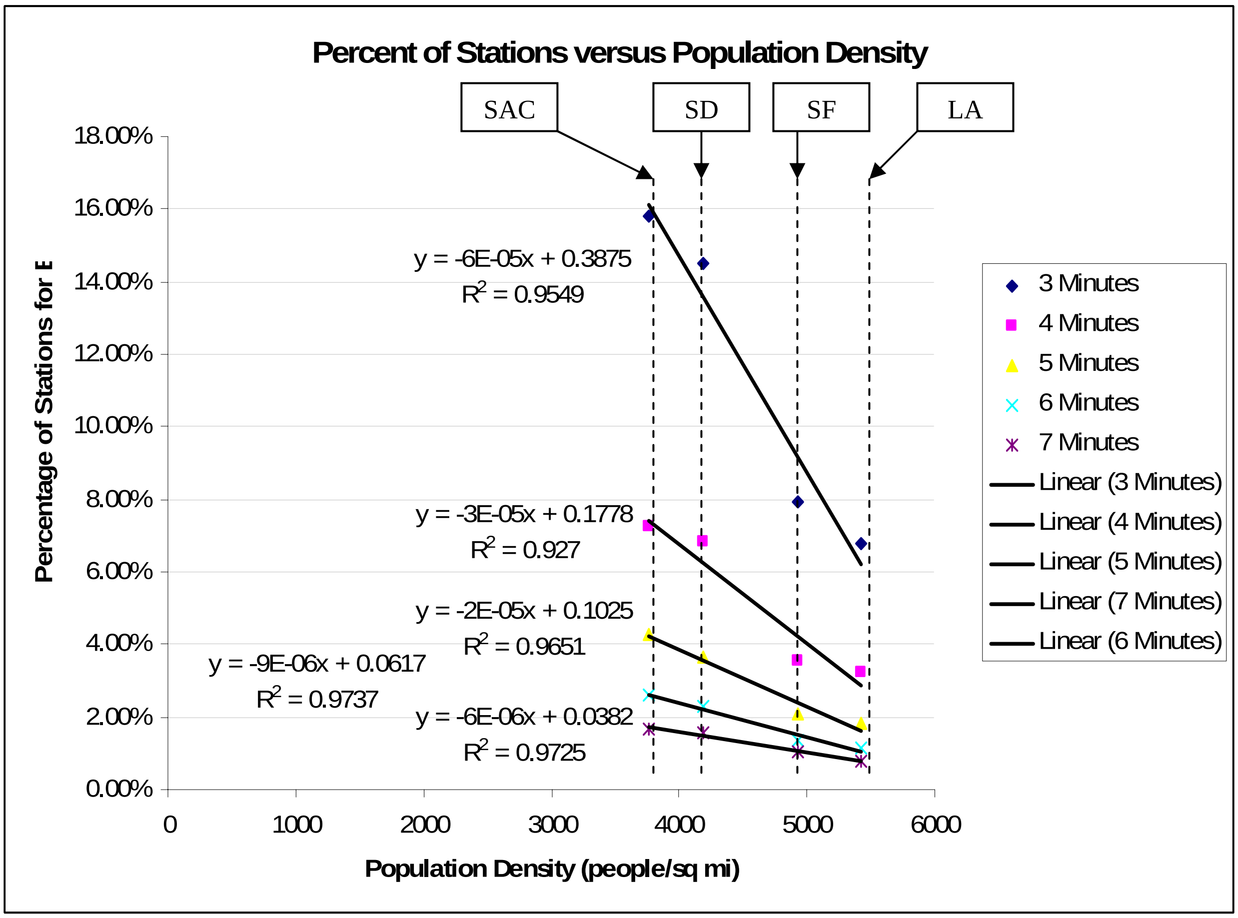

FIGURE 5 Relationship between the percentage of stations in each region needed to achieve a travel time target, and the density of that region.

Using the equations in the above graph, one can compute the number of stations necessary to achieve a travel time target based on the density in a central metropolitan region. For example, knowing the population density of Seattle enables the rough calculation of the percentage of stations necessary to achieve a three, four, five, six, or seven minute travel time target. A more general equation using any density, and any travel time target is as follows:

$$z = \frac{2.8578y^{-2.6230} - 0.08444y^{-2.4262}}{-1653}x + 0.08444y^{-2.4262} - \frac{2.8578y^{-2.6230} - 0.08444y^{-2.4262}}{-1653} * 5421$$

where

z = Percentage of Stations

y = Travel Time Target

x = Density (Persons per square mi)

$3 < y < 7$

$3500 < x < 5500$

For metric, replace -1653 with - 639 and 5421 with 2093

FIGURE 6 General equation for the percentage of stations in each region as a function of travel time and the population density of a region. This represents only a best fit for the data, and the results should be interpreted along with information in Table 1 and Fig. 4.

The equation in Figure 6 represents the best fit for the data in the California case. However, if population distribution patterns do not follow those of the dense areas in California, the general equation above may not fit the data in those regions. The above equation can be represented in three dimensions as well (Figure 7).

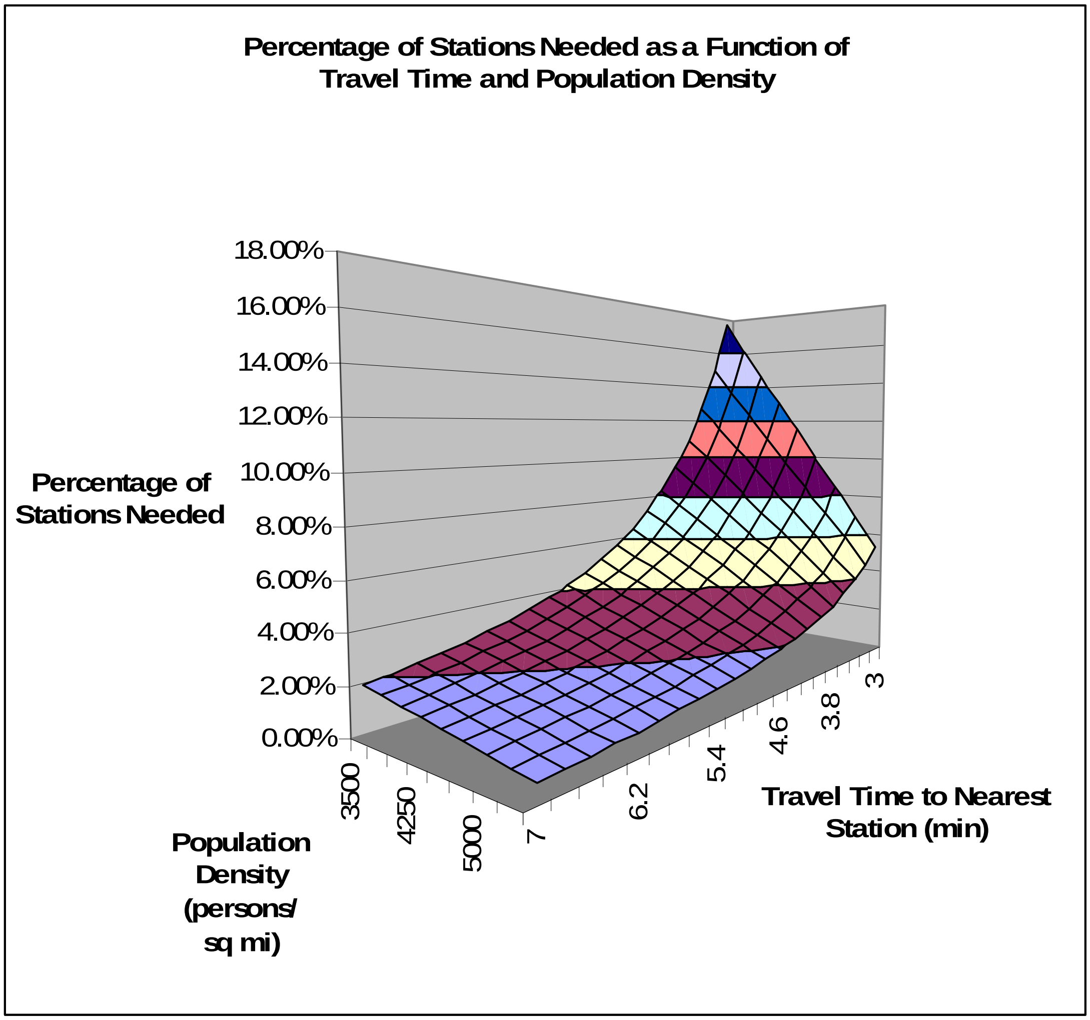

FIGURE 7 Three dimensional graph showing the relationship between the percentage of stations in each region needed to achieve a travel time target, and the density of that region.

In the three dimensional view, we can see how to approximate the percentage of stations needed in a region depending on the density of that region. We need to interpret these results carefully though. As stated earlier, the percentage of stations is not a completely reliable metric and there are some inconsistencies between the regions. Looking at the number of people per station in Table 1, we see that there are more people per station in San Diego than in all other regions. This may explain why the data points for the estimate of percentage of stations needed to achieve a travel time target lie above the line (Figure 5) since a higher percentage of stations would logically be needed if there are not very many stations to begin with. However, this reasoning does not hold for the San Francisco region. There are more people per station in San Francisco than in Los Angeles, yet a smaller percentage of stations is needed in SF to meet a travel time target. Another possibility is that the relationship between percentage of stations and population density is not linear as shown in Figure 5. Whatever the general relationship, there are geographic factors, such as intense population clusters, unique to each region that will make the actual convenience vary from any general rule.

One way to control for the varying number of stations in each region is to assume that each region should require 1 station for every 4300 people. Then the percentage of stations needed in an area match the predicted number of stations. For example, San Diego "should" have 590 stations. If we take 14% of 590 (3 minutes as calculated in Figure 5), then we come up with exactly how many stations the model predicts are needed for this travel time, 83 stations (Table 4). In this way we can predict the number of stations independent of the existing number of stations. However, this does not work for the San Francisco region, and so this method requires further investigation.

Looking at the Hydrogen Highways example of 50 stations throughout the state in the first phase, and 250 stations in the second phase (233 for the regions when the 17 stations between regions are taken into account), we can see an alternative method for distributing the stations based on maintaining a constant travel time. The hydrogen highways report allocated half of the stations to the Los Angeles region and divided the rest among the regions based on population. We can compare these results to those that base the division of stations based on equal travel time for all regions. The results are shown in Table 5.

	LA	SF	SD	SAC	Total Stations	Average Travel Time
Travel Time Method Phase 1	25	12	8	5	50	7.1
H2 Report Phase 1	25	15	6	4	50	--
Travel Time Method Phase 2	117	48	43	25	233	3.9
H2 Report Phase 2	117	71	29	16	233	--

TABLE 5 Comparison between the number of stations in the Hydrogen Highways report and the number of stations calculated using average travel time.

The results using the travel time method are similar in some respects to the results from the methods used in the Hydrogen Highways report. In particular, the number of stations in the Los Angeles region match up well. This is somewhat surprising since allocating half of the available stations to the Los Angeles region was an educated guess by the authors in recognition of the fact that there likely was a correlation with density. In reality, the Los Angeles region accounts for 60% of the population among the regions.

The second half of the stations in the Hydrogen Highways report were allocated based on population. It is in the SF, SD, and SAC regions that we can see some differences in the results. The San Francisco region requires many fewer stations than in the hydrogen highways report, and the less dense areas of San Diego and Sacramento require more.

CONCLUSION

As demonstrated in the above analysis, there is significant regional variation in refueling infrastructure. When deciding how many stations are needed in an area, using the percentage of stations alone may not be a reliable metric. Population density appears to be correlated to the percentage of stations needed in an area. Even though generalizations can be made using population density, a region's specific road network, station distribution, and population distribution make each region's station requirements vary from this generalization. Additionally, percentage of stations comparisons are only valid if the average number of people per station among regions is relatively constant. In our analysis, the average people per station was about 4300 people. If the average number of people per station differs from this level, the recommendations for the percentage of stations required in a region may no longer be valid. Additionally, this model is most appropriate for home based refueling. Work based refueling would likely result in a lower percentage of stations needed to achieve a travel time target[22].

When the model was applied to the Hydrogen Highways example, constant travel time was used to determine how best to allocate limited resources to achieve equality in consumer convenience. Even though results in this analysis and the Hydrogen Highways report were similar in some cases, using travel time as a metric to assess consumer convenience suggests that denser regions with clustered population require fewer stations to provide convenience similar to less dense regions.

Based on this report, the Los Angeles and San Francisco regions require fewer stations per capita, possibly due to the dense clustering of people. However, the small size of Sacramento and San Diego enables the urban areas of these regions to be served by relatively few stations even though a higher investment per capita is required. The appropriateness of average travel time as a metric for convenience is as yet untested, but this metric does provide a way to examine the needs of regions that differ in geography and population distribution.

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REFERENCES

1 Tiax. 2005. *Volume Ii: Consultant Report, Blueprint Plan for the Ca H2 Net*. Accessed 7/15 2005. Available from http://www.hydrogenhighway.ca.gov/plan/reports/volume2_050505.pdf.

2 Cal EPA. 2005. *Volume I: Summary of Findings and Recommendations for the Ca H2 Net*. Accessed 7/15/05 2005. Available from http://www.hydrogenhighway.ca.gov/plan/reports/volume1_050505.pdf.

3 Sperling, Daniel and Kenneth S Kurani. 1987. Refueling and the Vehicle Purchase Decision: The Diesel Car Case. In *International Congress and Exposition, SAE Technical Paper Series*:6. Detroit Michigan: Society of Automotive Engineers.

4 Kurani, Kenneth S., Thomas Turrentine, and Daniel Sperling. 1996. Testing Electric Vehicle Demand in 'Hybrid Households' Using a Reflexive Survey. *Transportation Research Part D: Transport and Environment* 1, no. 2: 131-150.

5 Greene, David. 1998. Survey Evidence on the Importance of Fuel Availability to the Choice of Alternative Fuels and Vehicles. *Energy Studies Review* 8, no. 3: 215-231.

6 Nicholas, Michael, Susan Handy, and Daniel Sperling. 2004. Using Geographic Information Systems to Evaluate Siting and Networks of Hydrogen Stations. *Transportation Research Record*, no. 1880: 126-134.

7 Nicholas, Michael and Nils Johnson. 2005. Rural Needs for Hydrogen Station Coverage. In *NHA Annual Hydrogen Conference*. Washington D.C.

8 Synnovate Motoresearch. 2003. Consumers Weigh in on the Hydrogen Transition. In *9th Biennial Conference on Transportation and Energy*. Asilomar, Pacific Grove, CA.

9 Melaina, Marc. 2003. Initiating Hydrogen Infrastructrues: Preliminary Analysis of Sufficient Number of Hydrogen Stations in the Us. *International Journal of Hydrogen Energy* 28, no. 7: 743-745.

10 Anonymous. 1972. Npn Fact Book. *National Petroleum News*.

11 Oak Ridge National Labs. 2002. *Transportation Energy Data Book*. Edited by Stacy C. Davis and Susan W. Diegel: Oak Ridge National Labs.

12 Anonymous. 2005. Annual Station Count Slowly Regains Lost Numbers. *National Petroleum News* 97, no. 5: 2.

13 Lindberg, Greg. 1993. No Surprises; Retail Outlet Count Down in Most States. *National Petroleum News* 85, no. 4: 1.

14 Johnson, Nils, Christopher Yang, Jason Ni, Joshua Johnson, and Zhenhong Lin. 2005. Optimal Design of a Fossil Fuel-Based Hydrogen Infrastructure with Carbon Capture and Sequestration: Case Study in Ohio. In *National Hydrogen Association Annual Hydrogen Conference*. Washington, D.C.

15 California Energy Commission. 2002. *California Retail Service (Gas) Stations, Fleet Fueling Facilities and Private Storage Tank Sites*. Accessed July 14 2003. Available from http://www.energy.ca.gov/gasoline/gasoline_stations/index.html.

16 Market Planning Solutions International. 2003. *Sacramento Valley 2003 Study*. Accessed March 20 2004. Available from http://www.mpsisys.com.

17 Environmental Systems Research Institute. Arcview, Redlands, CA.

18 Hakimi, S. L. 1964. Optimum Locations of Switching Centers and the Absolute Centers and Medians of a Graph. *Operations Research* 12, no. 3: 450-459.

19 Hakimi, S. L. 1965. Optimum Distribution of Switching Centers in a Communication Network and Some Related Graph Theoretic Problems. *Operations Research* 13, no. 3: 462-475.

20 Kitamura, Ryuchi. and Dan Sperling. 1987. Refueling Behavior of Automobile Drivers. *Transportation Research* 21A, no. No. 3: 235-245.

21 Sacramento Area Council of Governments. Sacmet Travel Model,1415 L Street, Suite 300 Sacramento, CA 95814.

22 Nicholas, Michael. 2004. Hydrogen Station Siting and Refueling Analysis Using Geographic Information Systems: A Case Study of Sacramento County. Masters Thesis, University of California Davis.