COMPARISON OF IDEALIZED AND REAL-WORLD CITY STATION SITING MODELS FOR HYDROGEN DISTRIBUTION

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1. INTRODUCTION

The development of a hydrogen refueling infrastructure is a challenging proposition, especially in the transition where the number of hydrogen vehicles is low. These challenges include the high cost of producing and delivering hydrogen at a small scale to meet a limited demand and providing enough refueling stations and distributing them widely for consumers to feel comfortable about purchasing a fuel cell vehicle. The often-cited chicken-and-egg problem focuses on the early markets for fuel cell vehicles and the development of an early hydrogen refueling infrastructure. At very low market penetration of hydrogen vehicles (<5% of total vehicles), providing stations throughout a region to ensure adequate consumer convenience can be costly. These early stations will have significantly fewer customers and will sell much less fuel than typical gasoline stations. As a result, it will be difficult for these stations to benefit from the economies of scale that can be achieved with hydrogen infrastructure technologies. One of the key challenges for developing a hydrogen infrastructure is supplying hydrogen to small and growing markets at a reasonable cost.

Researchers at UC Davis have been developing a suite of systems models to analyze and better understand the design, economics, costs and benefits and consumer convenience of hydrogen production, delivery and refueling infrastructure. One key area that we have been focusing upon is the important issue of customer refueling convenience at low market penetration. This work continues to build upon previous models used to determine optimal station siting within specific urban areas in California[1-4].

In addition to the detailed city level model, we are developing high-level regional models that attempt to quantify the cost and environmental impacts of hydrogen infrastructure. In order to simplify these models, an alternative approach is taken with respect to determining the distribution and layout of refueling stations and the hydrogen delivery networks (trucks and pipelines) that supply them. "Idealized city" models are used to describe hydrogen delivery systems in relatively dense (i.e. urban/metropolitan) areas in terms of a few easily specified parameters and have been used to develop hydrogen delivery costs for many US cities[5-8]. The idealized city model (ICM) is useful because it provides a quick and easy way to estimate delivery requirements of a range of city sizes. The goal of this study is to compare these two approaches in order to verify and improve the ICM.

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2. MODELS AND METHODS

2.1 Objective and Technical Approach

The objective of this analysis is to integrate UC Davis infrastructure models that span a range of scale and complexity in order to better understand the development and cost of hydrogen infrastructure. To do so, we have compared and integrated consumer convenience based refueling station siting models with ICM. This serves to validate and improve upon the ICM, which represents hydrogen delivery in urban areas. The approach that we use is to apply each of these refueling station infrastructure models ("real-world" vs "idealized") to four urban areas in California, Sacramento, San Diego, Bay Area and Los Angeles, and to compare the results.
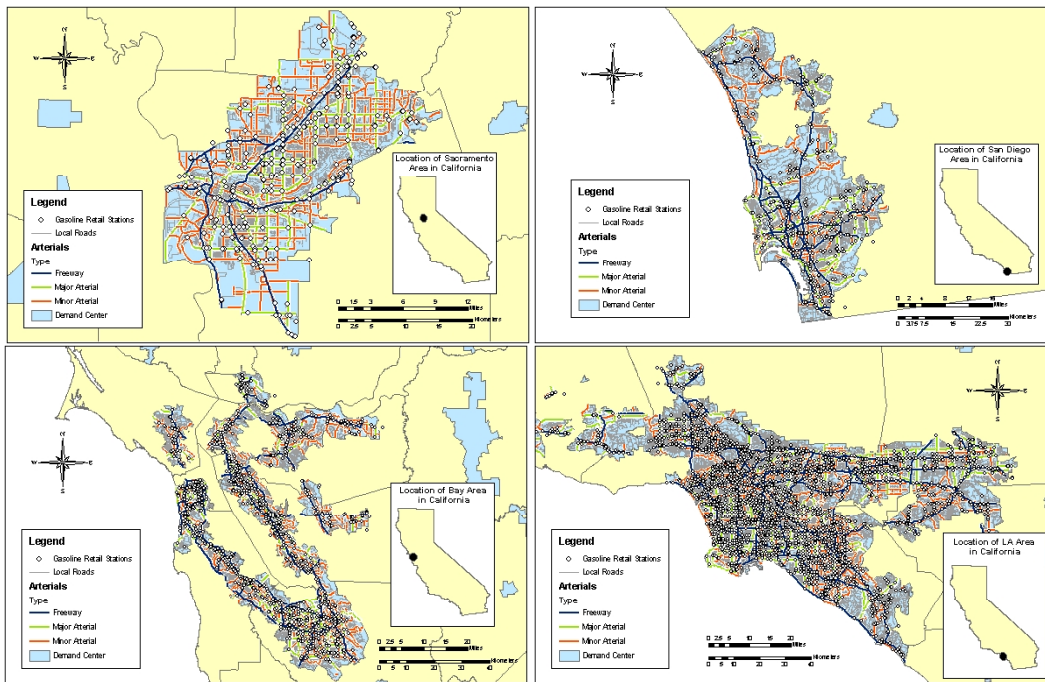
2.2 Identifying Demand Clusters

Figure 1   Maps showing the dense urban areas (demand centers) considered, street networks and gasoline stations for (a) Sacramento (b) San Diego (c) Bay Area (d) Los Angeles.

Traditional city boundaries are not used for the analysis of the "real" cities. Instead, a GIS method developed by UC Davis researchers, previously described in other publications [8, 9], was used to identify high-density urban clusters that could support a hydrogen refueling infrastructure. These clusters were determined by converting spatial distribution of population density into potential hydrogen demand density based upon assumptions about hydrogen vehicle ownership and fuel economy. These areas were aggregated into contiguous clusters, which define the cities or demand centers. Because of the

nature of large consolidated urban areas in the Bay Area and Southern California, these "cities" tend to encompass many smaller cities and municipalities (see Figure 1). For the purposes of comparison with the ICM, the area for each of these cities is determined and a radius is calculated for an ideal circular city of equivalent area. Additional geographic data was necessary for the analysis of these urban areas, including locations of existing gasoline stations, traffic results and road networks.

2.3 Consumer Convenience Based Siting Models

The deployment of hydrogen refueling stations will have a critical impact on the level of service and convenience for owners of hydrogen vehicles and will also influence the choice of vehicle purchases for potential customers. Thus, it is critically important to optimize the layout of stations at low market penetration to maximize consumer utility, stimulate future demand growth, and reduce station redundancy and costs.

The station siting methods employed here have been described in more detail in previous publications by Nicholas et al. ([1-4]). The goal of this GIS-based station-siting model (HySS1) is to efficiently site a reduced network of hydrogen refueling stations in existing gasoline station locations. To do so, potential stations are considered by calculating the driving time from every census tract to the station. Potential customers are assigned to the nearest station possible and the station that yields the lowest overall travel time is chosen. This process is repeated until the desired number of stations is reached to build up a network of refueling stations.

This methodology yields very detailed results about likely travel times associated with specific layouts of hydrogen refueling stations and station locations that could potentially be used for siting actual stations. However, it is also data intensive – requiring detailed city information including data about traffic and street networks and gasoline station locations – and computation intensive – requiring lengthy runs (on the order of days) on a PC to site many stations in large cities. For each city, the models determined the order of preference for any number of stations within the city up to approximately 50% of stations.

2.4 Idealized City Models

Contrasted with the previous method, the ICM uses simplifying assumptions to design a layout of refueling stations and determine delivery distances. The development and application of the ICM has been documented in previous publications ([7, 8, 10]). ICM is a Microsoft Excel®-based model of hydrogen delivery systems in urban areas. Using readily-available aggregated geographic data about these urban areas (including population, population density, and land area), simplifying assumptions are made in order to develop estimates of delivery system layout for a specified delivery mode. The results of ICM provide a functional relationship between the city size, the number of refueling stations in a city and the length of pipeline and truck-based hydrogen

delivery modes, which have a large influence on delivery costs. The advantage of using ICM is that it allows for a quick estimate of the relative magnitude of costs for different delivery modes without requiring the significant data inputs (existing station locations, traffic flow data, street networks and population distribution, etc.) that are needed for a GIS based analysis. However, real cities may not necessarily match the idealized description, and the goal of this analysis is to understand how and when the model can be applied properly.

The "idealized city" is a circular city with a homogenously distributed population and hydrogen demand, rectilinear paths to approximate the street and pipeline network, and lengths that are normalized in terms of the city radius. The assumption of uniform population and hydrogen demand leads a uniformly distributed network of hydrogen refueling stations. The ICM can be upgraded to include grid-based station siting, which can be used to approximate the density of major arterial streets in a city where stations would be located.

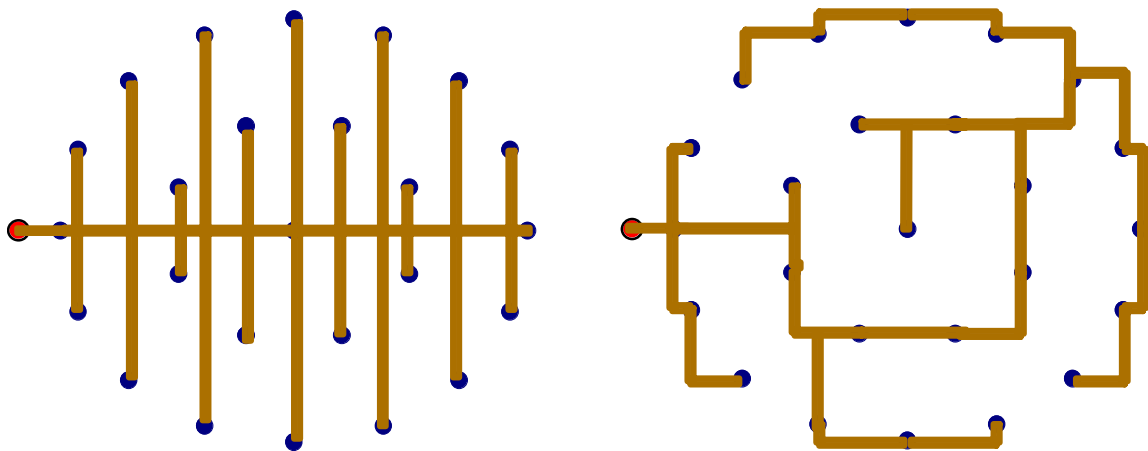## 2.5   Laying Out A Hydrogen Delivery Infrastructure

Figure 2   Representative truck and pipeline network paths from hydrogen depot for ICM.

Figure 2 shows a schematic representation of how truck routes and pipelines are laid out in ICM and the GIS-based real city models. Delivery is modeled as transport of hydrogen from a hydrogen depot (i.e. hydrogen production facility or city-gate shipment node) to a dispersed group of refueling stations. The model user specifies the number of refueling stations for each city or demand cluster. The specific characteristics of each type of delivery mode are described in the next sections.

2.5.1 Pipelines

One of the important goals for determining the layout of the pipeline network is to minimize the total length of pipelines that span the refueling stations spread across the city. To do so, an optimization technique known as the *minimal spanning tree* (MST) algorithm is used to choose from among possible pipeline network configurations to find the one that yields the shortest pipeline network. A distance matrix that describes the shortest potential right-of-way distance between each station and all other stations and from the hydrogen depot to all stations is generated by GIS for each of the four real cities and by the ICM for the idealized city. An algorithm then chooses the shortest complete network among all the potential network segments. This model uses length as the only determinant of cost, whereas more sophisticated models for laying pipelines may have additional factors, such as spatially determined land values, that will also influence costs.

2.5.2 Trucks

One of the key assumptions in calculating driving distances for truck delivery is that each truck will travel from the hydrogen depot to only one station before returning back to the depot. To calculate truck delivery distances, a similar distance matrix, which describes truck travel route distances between the hydrogen depot and each of the refueling stations must be generated in GIS or the ICM. Once this matrix is generated, it is a relatively straightforward task of calculating truck driving distances based upon which stations need hydrogen resupply and when. The comparisons shown in this paper assume that all stations are of equal size so that trucks are driven with equal frequency to all stations.

2.6 Metrics for Comparison

For hydrogen delivery, the most important factors affecting the levelized delivery cost ($/kg) are [6]:

- Scale (or hydrogen flow rate into the city). Scale is important for liquid hydrogen delivery systems, because liquefiers have strong scale economies. For pipeline systems, the pipeline capital cost contribution is strongly scale dependent. For compressed gas truck delivery there are mild scale economies in compression.
- Number of stations. This determines the spatial extent of the infrastructure and is particularly important for pipeline delivery costs. (since pipeline distances and costs will not scale linearly with the number of stations).
- Distance (this is particularly important for compressed gas trucks and for pipeline delivery, and less so for liquid hydrogen delivery).

In this study, *distance* is the main factor that will vary between the ideal and real model results because the total hydrogen flow and the number of stations are kept the same for each model. Thus, as a first approximation, we concentrate on comparing the key distances that affect distribution cost. If the ideal and real city

models estimate about the same travel distance for trucks or the same pipeline length, we would say that they are in good agreement, and would predict similar hydrogen distribution infrastructure costs. The goal is to improve ICM so that it allows us to quickly estimate infrastructure costs without having to use a complex, data and computationally intensive full GIS model. As mentioned previously, distances are normalized to units of city radius to allow for appropriate comparison between real and idealized cities.

3.   RESULTS AND DISCUSSION

The results of the analysis for the two station-siting methods gives us the relationship between the number of stations within the city and the normalized length of the distribution system (i.e. truck driving distances and pipeline network length). Table 1 shows the individual parameters for the four California cities in the analysis.

Table 1.   City parameters for the demand clusters

	Sacramento	San Diego	Bay Area	Los Angeles
Area (km^2)	887.8	1746.1	2936.1	4359.8
City Radius (km)	16.8	23.6	30.6	37.3
Arterial Road Length (km)	563.6	1188.9	3030.2	5391.3
Arterial Road Length (radius)	33.5	50.4	99.1	144.7
Arterial Road Density (km/km^2)	0.6	0.68	1.03	1.24
Arterial Road Density (r/r^2)	10.7	16.1	31.6	46.1
Grid Spacing	10.0%	6.7%	3.3%	2.2%
Gasoline Stations	304	632	1246	3355
Gas Station Density (/km^2)	0.34	0.36	0.42	0.77

3.1   Trucks

Figure 3 shows the results of the truck analysis for Sacramento. The figure shows the total driving distance, in units of city radii, needed to supply different numbers of stations. Four different potential hydrogen depots located at the city gate were chosen to illustrate the differences that might arise from their placement. From Figure 1, it is clear that Sacramento is elongated like an ellipse rather than circular. Four depots were chosen at different points along the city gate and the two at the top and bottom of the city tend to have longer truck travel distances while those along the middle of the city have shorter truck distances. All the distances tend to increase linearly with the number of stations that are supplied with hydrogen and the slopes of the lines indicate the average truck distance for each hydrogen depot. The ICM, which assumes a circular city (shown as the solid line), matches fairly well to the real truck analysis differing between 1 and 24% depending upon which depot is chosen. Assuming that the depot location would be chosen to minimize truck travel decreases the difference to between 1 and 12%.
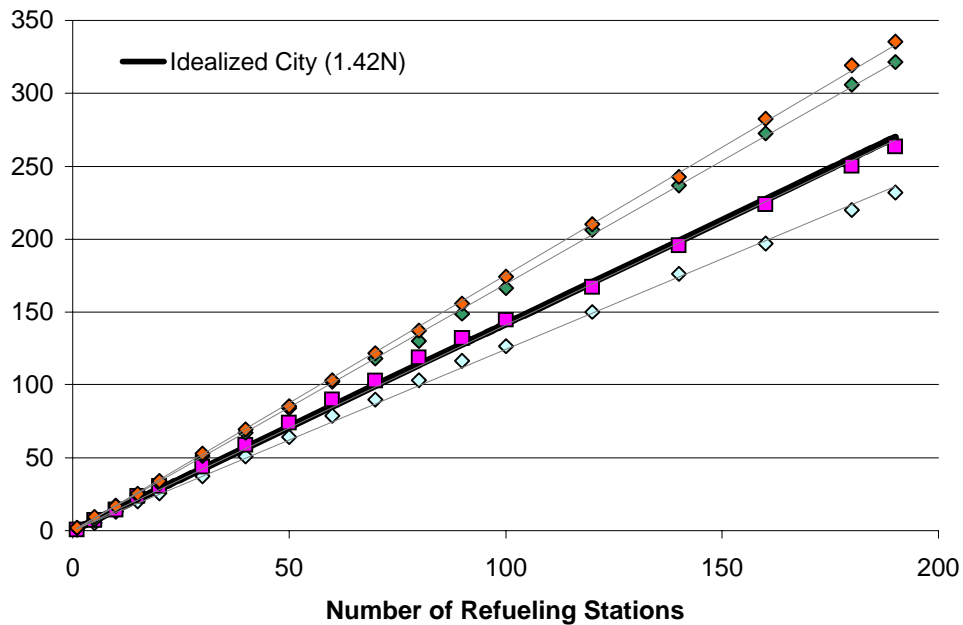
Figure 3   Truck travel distances along arterials for Sacramento from the H_2 production site at the city edge to a network of H_2 refueling stations. The four symbols represent different locations for the H_2 production site. The results from the ICM are shown as a black line.
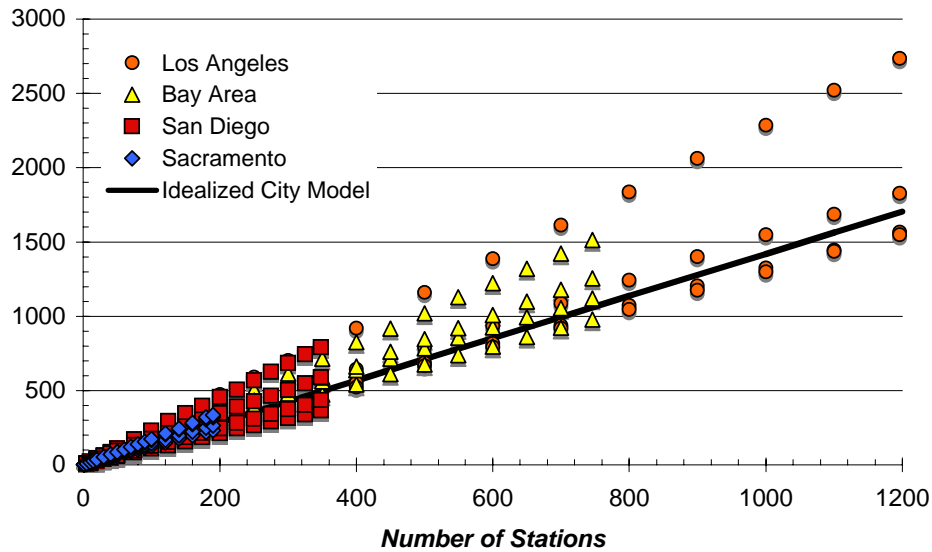

Figure 4   Truck travel distances as a function of number of refueling stations for four potential H_2 depots in each of the California cities and comparison with idealized city results.

Figure 4 shows the truck travel distances for each of the California cities as a function of the number of refueling stations within the cities. Regardless of the size and shape of the cities, each city shows a similar trend and spread of truck travel distances. Generally, the ICM more closely approximates the better-located

hydrogen depots (i.e. those with lower truck distances, up to 15% deviation) while the deviation from the most poorly located depot can be quite significant (over 50%).

3.2   Pipelines

Figure 5 shows the pipeline length as a function of the number of stations in Sacramento. Because the model assumes that the station locations are spread out to maximize consumer convenience at any number of stations throughout the city, the addition of new refueling stations initially results in large increases in pipeline distance, while later station additions result in lower additional pipeline lengths. Unlike the case with the truck delivery, the location of the hydrogen depot does not appear to affect the distances associated with hydrogen delivery.
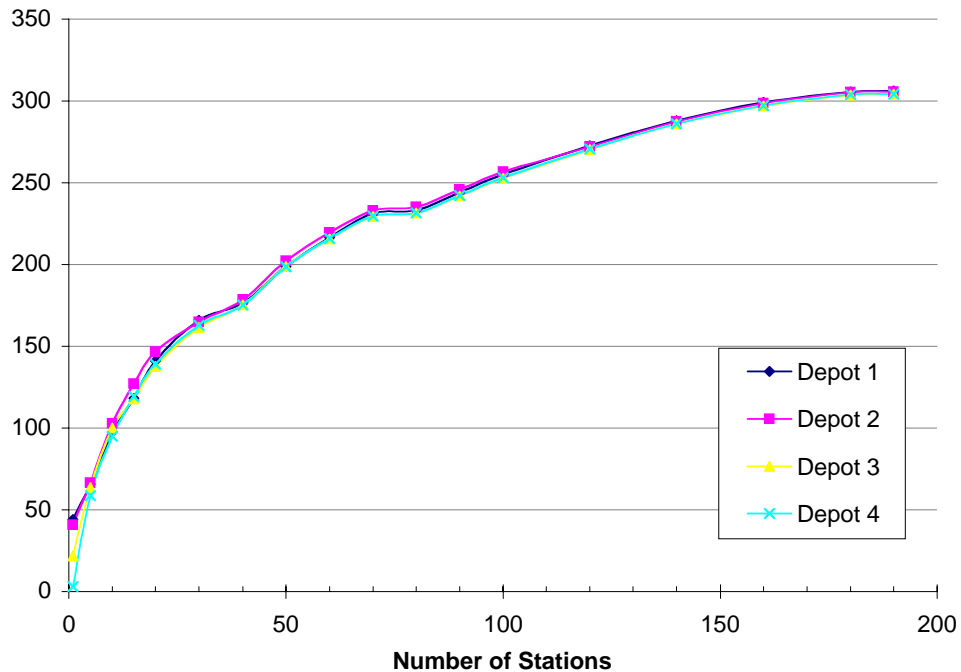

Figure 5   Comparison of pipeline distances according to the Sacramento GIS station-siting model, when the hydrogen production plant (depot) is placed in four different locations around the edge of the city.

Figure 6 shows the normalized results for Sacramento (i.e. lengths are in units of city radii) and the results are compared to the grid-based ICM pipeline results. As seen in Table 1, the grid spacing for Sacramento, which is calculated from the density of major arterials and highways within the city, is 10%. The ICM pipeline results for the 10% grid have excellent agreement with the Sacramento pipeline results. This is the grid spacing that is predicted (shown in Table 1) when comparing the length of the arterial road network in the city with an idealized circular grid.   Results for other grid sizes are also shown in the figure. The use of smaller grid sizes (4% and 1%) or no grid constraint (no grid) will lead to an overestimation of the pipeline lengths associated with the same

number of refueling stations because stations are located "further apart" along the grid network.
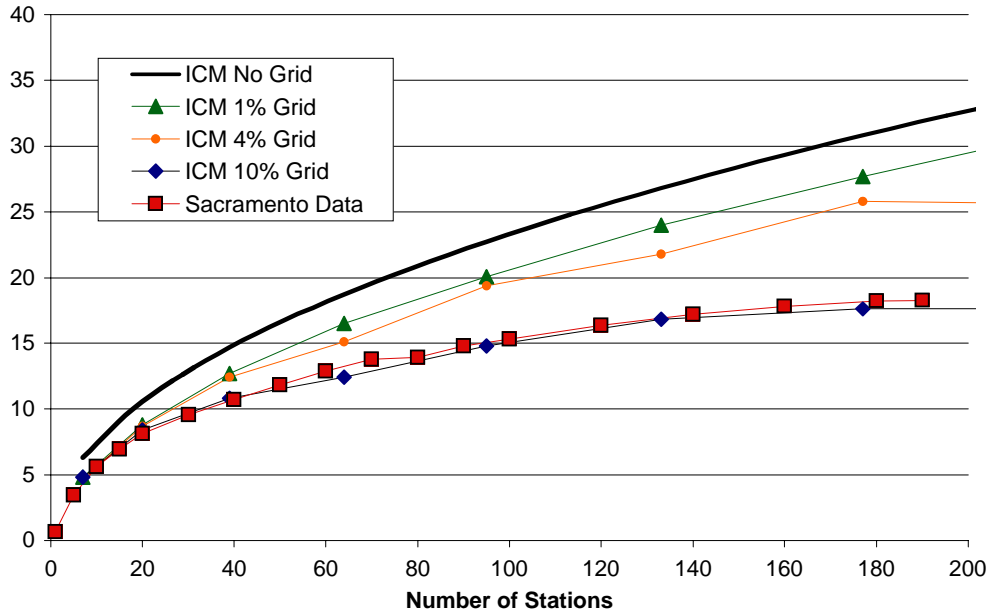

Figure 6   Pipeline distribution system length according to the ICM unconstrained and constrained to a rectangular grid with spacing = 1%, 4% or 10% of the city size. Estimated pipeline length is also shown for Sacramento data.
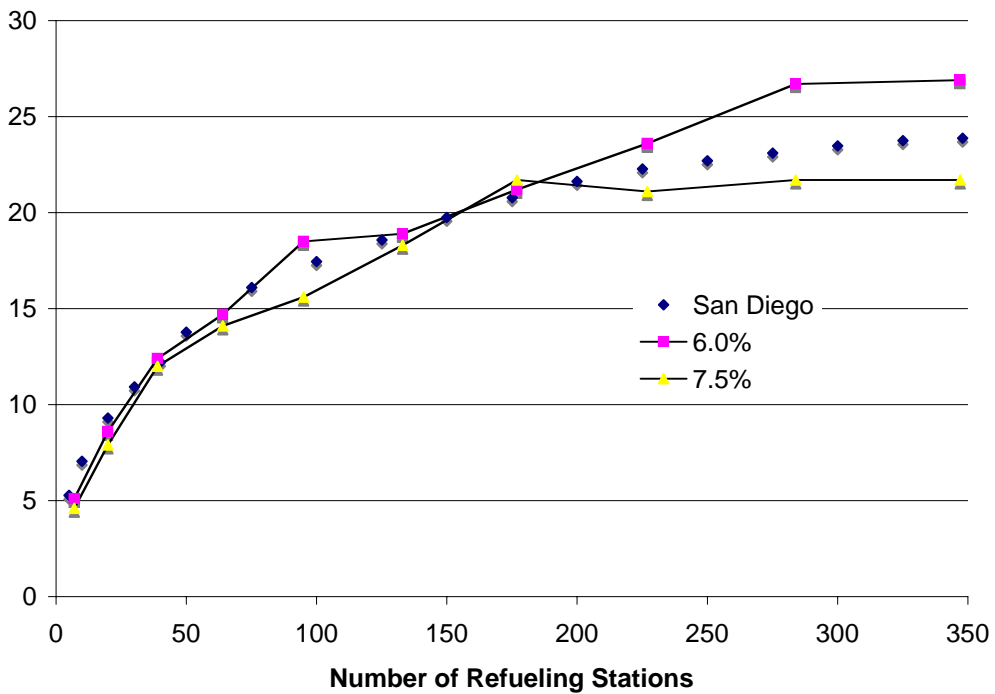

Figure 7   Pipeline comparison for ICM and San Diego (6.7% grid spacing).
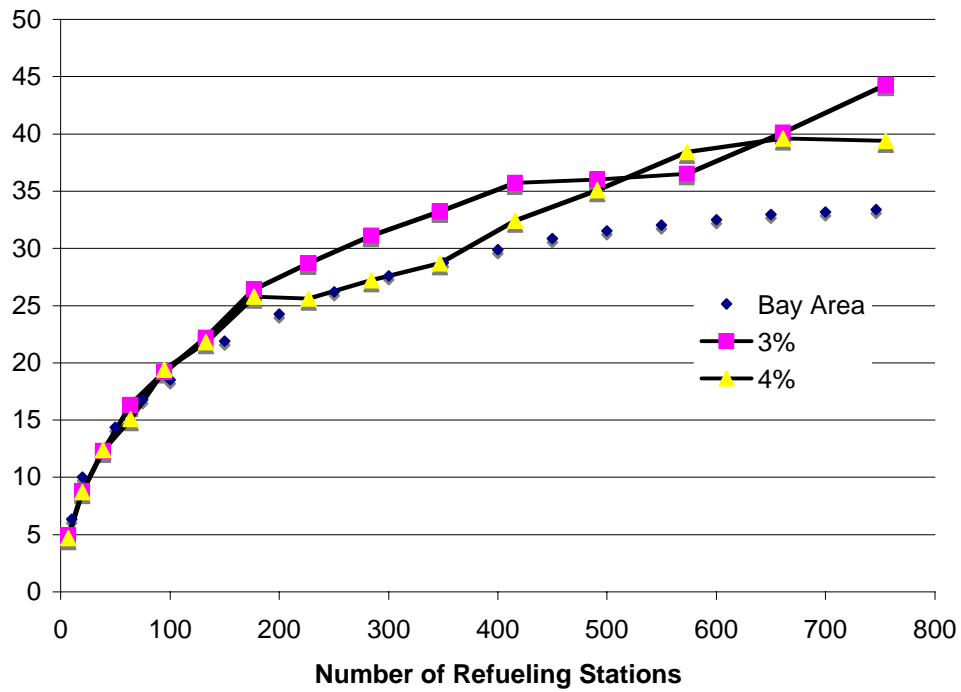
Figure 8   Pipeline comparison for ICM and the Bay Area (3.3% grid spacing).
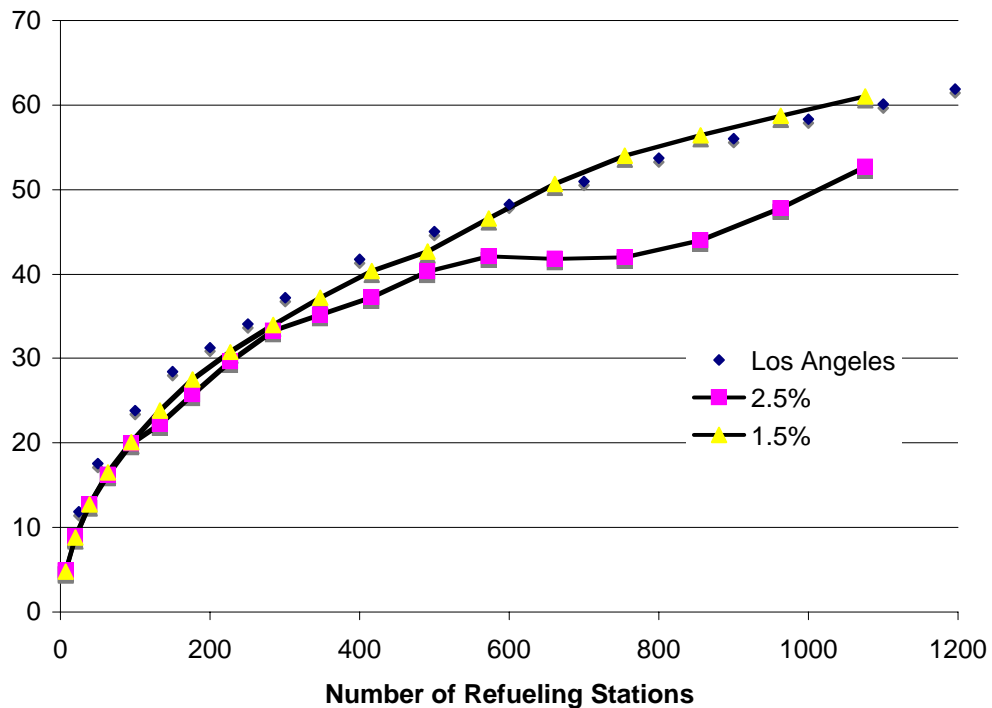

Figure 9   Pipeline comparison for ICM and Los Angeles (2.2% grid spacing).

Figures 6-9 show the pipeline comparison between the ICM's grid based pipeline network length and the GIS-based optimized pipeline network for

Sacramento, San Diego, the Bay Area and Los Angeles. In the last three cases, the ICM was not run for the exact grid spacing that was calculated for each city, so two different curves representing the closest idealized grid spacings were plotted on the figure for comparison.

Because the exact idealized grid spacing pipeline lengths weren't calculated for San Diego, the Bay Area and Los Angeles, the deviation between the real-city data and the ICM cannot be calculated. However, in looking at the figures qualitatively, it is clear that the deviation is smallest at low numbers of stations and starts to become more significant as the number of stations increases, and it varies by city. The deviation appears largest for the Bay Area, which makes sense since it is the city that differs most from the assumptions of the ICM. However, even in this case, the largest differences are likely to be on the order of 20-30%, which may be acceptable for rough calculations of pipeline and delivery costs, given all of the other uncertainties. Other cities appear to have maximum deviations of less than 20%. Figures 10 and 11 are maps of the pipeline network layout as determined by the minimal spanning tree algorithm.
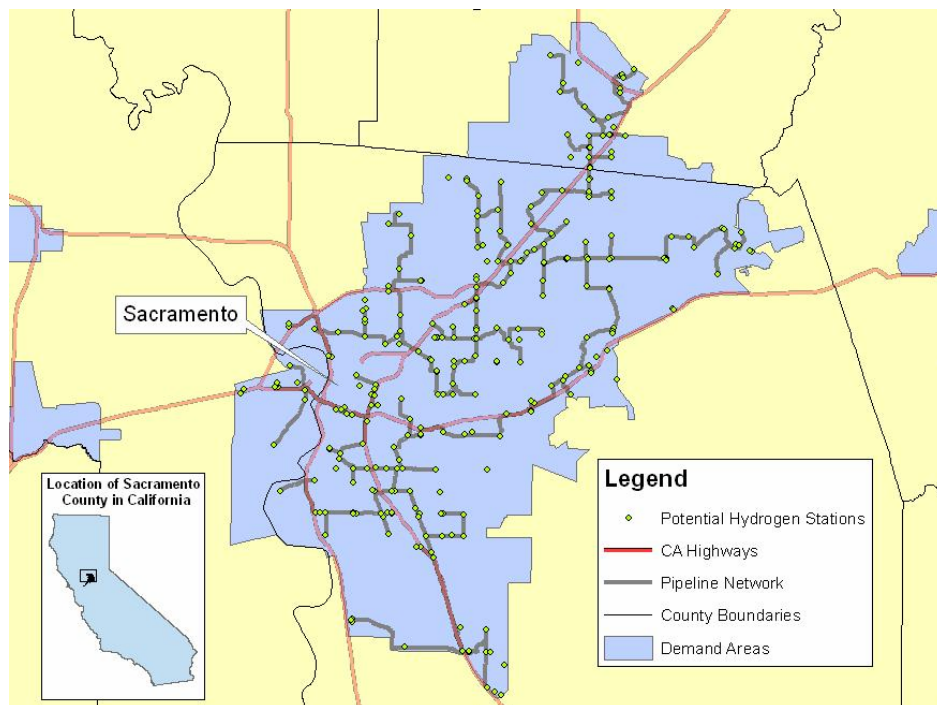

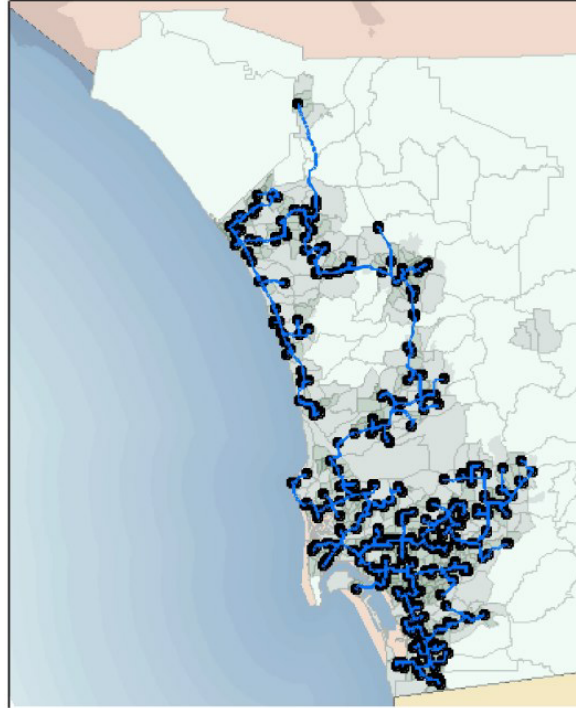Figure 10   Shortest path pipeline network for Sacramento

Figure 11   Shortest path pipeline network for San Diego

There appears to be good agreement between the results of the GIS based station siting model and ICM based station siting for both pipelines and trucks. In order for the pipelines ICM to be useful, it is necessary to know the grid spacing for the city of interest. For this analysis, the grid spacing for a city was calculated by summing up the length of arterial roads and comparing this with an idealized circular grid. Because we were running the detailed GIS analysis, this grid spacing calculation was easily done with the data we had available. In practice, the calculation of grid spacing for the ICM could limit its usefulness because of the lack of data. However, in the future, we will look at the correlation of other parameters (such as population density or gas station density) to grid spacing to make the ICM easier to use.

4.   CONCLUSIONS

The idealized city model appears to adequately describe the distribution systems for the four "real" cities in California: Sacramento, San Diego, the Bay Area, and Los Angeles. Hydrogen station siting based upon consumer convenience and idealized city models lead to similar distances (and consequently costs) for truck distribution and pipeline network to a series of refueling stations. This verification and improvement of idealized city models allows for quick estimates of the costs associated with hydrogen distribution from central hydrogen production facilities to a network of refueling stations. Characterizing a city of interest to do detailed GIS based station siting can be data intensive and requires information about traffic flows, population density and distribution, city size, and gasoline station locations. By characterizing a city in terms of a reduced set of

parameters, including city area, population, and street density (i.e. grid spacing), the idealized city model can provide good estimates for hydrogen delivery infrastructure.

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Dr. Christopher Yang is a Research Engineer at the Institute of Transportation Studies at the University of California, Davis and co-director for the "Infrastructure Modeling" Track within the Hydrogen Pathways program. His primary research focus is on modeling of hydrogen production and distribution infrastructure in order to understand how a hydrogen economy might evolve over

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