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Technical and Economic Assessment of Regional Hydrogen Transition Strategies

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TECHNICAL AND ECONOMIC ASSESSMENT OF REGIONAL HYDROGEN TRANSITION STRATEGIES

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Report to the United States Department of Energy
Hydrogen, Fuel Cells and Infrastructure Technologies Program
National Renewable Energy Laboratory
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TECHNICAL AND ECONOMIC ASSESSMENT OF REGIONAL HYDROGEN TRANSITION STRATEGIES

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In this final report, we present results from research conducted under NREL contract number XCM-4-44000-01, from December 2005 - November 2006. The overall goal of this project is to better understand regional infrastructure development strategies for widespread implementation of hydrogen as an energy carrier.

I. INTRODUCTION

I.1. Motivation for Study

Hydrogen offers potential advantages as a future energy carrier, with respect to reduced emissions of greenhouse gases and air pollutants, and enhanced energy supply security. However, the current lack of an extensive hydrogen (H_2) infrastructure is often cited as a serious barrier to the introduction of H_2 as an energy carrier, and to the commercialization of technologies such as H_2 vehicles. Because H_2 can be made at a wide range of scales (from household to large city) and from a variety of primary sources (fossil, renewable and nuclear), there are many possible pathways for producing and distributing H_2 to users. One of the key challenges is developing a viable transition strategy toward widespread use of hydrogen, supplying hydrogen to growing markets at the lowest cost.

I.2. Background

UC Davis' previous research has developed a suite of hydrogen system models. This work has been partly supported by NREL, and has been substantially leveraged by the ongoing Hydrogen Pathways program and other hydrogen-related activities at UC Davis.[1]

UC Davis's hydrogen models are characterized by:

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[1] The Hydrogen Pathways Program is a four-year multi-disciplinary research program, begun in 2003, funded by a consortium funded by 20 industry and government sponsors to examine the implications of hydrogen for future transportation. The P.I. is co-director of this program. This gives us access to ready industry feedback and comments on our research. We also have interactions with the California Fuel Cell Partnership (UC Davis is a member) and the California H2 Highway Network (where P.I. Joan Ogden served on the Advisory Panel).

1) **High level of geographic detail, enabling a regional case study approach**
We capture the site-specific nature of H_2 infrastructure design problem by use of Geographic Information System (GIS) data as a basis for understanding the spatial relationships between hydrogen demand and supply and existing infrastructure.

    - UCD models incorporate high spatial resolution GIS-based census data (available at the block level) to estimate hydrogen demand spatially.
    - GIS-based city or interstate traffic flow data are used for station placement and sizing.
    - We utilize detailed GIS information about existing infrastructure to locate hydrogen infrastructure (natural gas system; electricity system; location of existing gasoline stations; location of existing pipelines that could be used as rights of way)

    In previous work, we have analyzed a variety of H2 systems from city scale to regional scale with these methods.

2) **Simplified "idealized city" models to describe hydrogen delivery systems in urban areas** in terms of a few easily specified parameters such as city size, population density, market penetration. This work has contributed to the H2A delivery team effort.

3) Use of **spatial optimization methods to find low cost system spatial layouts** for hydrogen production and delivery systems.

4) Use of **dynamic programming and other optimization methods to find low cost transition paths** over time.

5) **Combination of engineering economic models with geographic/spatial analysis, allowing us to analyze costs a range of different regional demand and supply scenarios**. We estimate costs for hydrogen production, delivery and refueling (variables include: selection of a wide range of alternative hydrogen supply pathways; city size; city population density; urban versus rural; various levels of market penetration; hydrogen system component performance and cost assumptions; vehicle type, performance and cost)

I.3. Objective of Study

In FY'05, UC Davis researchers worked with NREL analysts to integrate the our existing infrastructure models with other DOE-supported hydrogen models, so as to answer specific questions related to the development of hydrogen infrastructure development. .

In FY'06, we continued this collaboration and extended it. Our research contributes to NREL's mission to understand how the development of hydrogen infrastructure might proceed, and complements other ongoing projects supported by NREL and the U.S. DOE to study hydrogen transitions, including:

- HyDS
- H2 Infrastructure for Commercialization Introduction;
- H2A Production, Forecourt and Delivery Teams
- Electrolysis scenario options analysis.court and Delivery models
- Hydrogen Transition Analysis Team;

A goal of the proposed studies develop "rules of thumb", as a means to more efficiently study infrastructure development in succeeding years.

II. TECHNICAL APPROACH

Task 1. Case Studies of Hydrogen Delivery System Design and Cost: A Comparison of Detailed GIS Models and Idealized City Models

In recent years, several researchers have developed simplified EXCEL-based models of hydrogen delivery systems within urban areas, to estimate the costs of distributing hydrogen by truck or pipeline (Mintz, Ringer, Molburg, Ogden 2005; Melaina 2005, Ogden et al. 2004). These idealized models utilize aggregated geographic data about cities (population, population density) and simplifying assumptions about city geometry, distribution of population, and hydrogen refueling station siting and sizing to develop estimates of delivery system layout and costs. The advantage of simplified models is that they allow a quick estimate of the cost of hydrogen delivery infrastructure. However, real cities do not necessarily match the idealized description, and today's gasoline refueling stations are located based on factors other than the distribution of population.

An alternative approach is to examine infrastructure design for particular cities, using GIS tools with a high level of spatial detail. As part of the UC Davis Hydrogen Pathways program, we have developed detailed GIS based models for optimal refueling station siting and sizing in real cities, based on traffic flow data, population data at the block level, and estimates customer convenience measures (such as travel time to stations) (Nicholas MS Thesis 2005). Our GIS models give a much more accurate estimate of infrastructure design and costs for particular cities, than idealized models. However, detailed GIS models are considerably more complex and time consuming to run.

In this task, we continue work begun in our earlier NREL-supported research to compare the results for hydrogen delivery system design and cost from existing simplified models to those from a highly detailed geographic information system (GIS) model developed at UC Davis. The goal is to compare and validate the simplified models, and further improve them with insights from the GIS models.

We use our detailed GIS models to size and site refueling stations in various cities, and estimate the design and cost of urban delivery and refueling systems to serve these stations. These estimates are then compared to the results of simplified city models that use much less detailed input information. The design of infrastructure depends on the city size and population density, so we compare results for several cities encompassing a range of sizes and densities. We also consider alternative market penetration scenarios.

We address the following questions: How well do the idealized models match more detailed GIS models? Do they tend to over estimate or underestimate infrastructure costs? The goal is to understand the differences between the simple idealized models, and more complete GIS models, and to improve idealized city models to allow more accurate, quick comparison of hydrogen delivery options based on a few input variables.

The improved simple models (informed by the results of detailed GIS studies) should be useful in future analytic work where a rapid estimate of hydrogen delivery costs is needed.

Technical Approach

Subtask 1.1 – GIS Analysis of City Station and Distribution Systems

- Collect geographically relevant data for a number of representative cities including census, road network, and refueling station data
- Perform a station siting analysis that will determine the optimal location of different numbers of refueling stations for each urban area
- Calculate the pipeline and truck delivery distance as a function of the number of stations in the stations networks based upon real city distances and rights of way

Subtask 1.2 – Idealized City Model (ICM) Analysis of Station and Distribution Systems

- Run the idealized city model given specific parameters for the representative cities chosen in Subtask 1.1
- Determine pipeline and truck delivery distance as a function of number of stations in the city network

Subtask 1.3 – Comparison of GIS Analysis to ICM Results to Improve ICM

- Compare the delivery distance (total pipeline network length or truck driving distance) vs. the number of stations for each of the models
- Determine differences between GIS and ICM-based approach to delivery
- Develop grid-based ICM for pipeline delivery distances
- Link grid spacing for ICM to readily obtainable city parameters
- Develop functional formulae which will allow easy calculations (in a spreadsheet) of hydrogen delivery distances for trucks and pipelines in cities and urban areas that have not been analyzed using detailed GIS methods

Task 2. Coordination with NREL Analysts

In this task, the UC Davis research group worked with NREL, the DOE Transition Analysis program, the H2A Delivery team, and the FreedomCAR Delivery Tech team to share insights about transition strategies for hydrogen vehicles. The P.I. Joan Ogden, Dr. Christopher Yang, and other UC Davis researchers held briefings in March 2006 and April 2006, and attended the USDOE Hydrogen Transition Analysis group meetings in January 2006 and August 2006, where they presented a paper on case studies in Southern California.

RESULTS

Task 1. Case Studies Of Hydrogen Delivery System Design And Cost: Validation And Improvement Of The "Idealized City" Models Developed At UC Davis To Represent Hydrogen Delivery In Urban Areas.

Researchers at UC Davis have developed simplified EXCEL-based models of hydrogen delivery systems within urban areas, to estimate the costs of distributing hydrogen by truck or pipeline. These "idealized city" models utilize aggregated geographic data about cities (population, population density) and simplifying assumptions about city geometry, distribution of population, and hydrogen refueling station siting and sizing to develop estimates of delivery system layout and costs, for a specified market penetration of hydrogen vehicles. The advantage of simplified models is that they allow a quick estimate of the cost of hydrogen delivery infrastructure. However, real cities do not necessarily match the idealized description (Yang and Ogden 2006).

An alternative approach is to study urban hydrogen infrastructure design using geographic information system (GIS) tools with a much higher level of spatial detail for specific cities or urban areas. As part of the UC Davis Hydrogen Pathways program, we have developed detailed ARCVIEW based models for optimal refueling station siting and sizing in real cities, based on traffic flow data, population data at the block level, and estimated customer convenience measures (such as travel time to stations) (Nicholas 2005). Our GIS models can provide a much more accurate estimate of infrastructure design and costs for particular cities, than idealized models. However, detailed GIS models are considerably more data-intensive, complex and time consuming to run.

Here we present comparisons of the results for hydrogen delivery system design and cost from our idealized city models (which run quickly in EXCEL and require relatively simple, aggregated geographic data) to those from a highly detailed geographic information system (GIS) ARCGIS-based model developed at UC Davis. The goal is to compare and validate the idealized models for hydrogen delivery in cities, and further improve them with insights from the GIS models. This work is a continuation and extension of work begun in FY'05.

The goal of this task is to compare results from our detailed GIS models for hydrogen infrastructure design (Nicholas et al. 2004, Nicholas 2005) with those from the UC Davis idealized city model, ICM, (Yang and Ogden 2006).

The approaches taken in each type of station-siting and delivery layout models (idealized versus GIS) are discussed below.

Hydrogen Station Siting in Urban Areas

In the idealized city model (ICM), we make the following assumptions:

- A "generic" idealized city is used. Distances are given in terms of the city radius.
- The city is circular in shape

- The city population and population density for US cities are found from census data.
- The population distribution is homogeneous (population density is constant)
- The total number of hydrogen stations is a specified input parameter.
- Stations are situated to minimize the distance between the population and stations.

Given the assumption of homogenous population distribution, an even distribution of stations throughout the city maximizes consumer convenience. This assumption leads to a conservative estimate for distribution distances because stations are spread as far apart from one another as possible.

By contrast, in our detailed GIS model for real cities, we make the following assumptions:

- Specific cities are chosen as case studies. (Our first set of cities/urban areas are loacated in California (Sacramento, San Diego, San Francisco Bay Area and Los Angeles). In subsequent work, we intend to look at other cities outside of California of various sizes and population densities)
- The population distribution is specified from census block data
- Hydrogen stations can be sited at existing gasoline station sites.
- The total number of hydrogen stations is a specified input parameter.
- Average travel time along the road network from home to the nearest hydrogen station is taken as a measure of customer convenience.
- Hydrogen stations are chosen (from among gasoline station sites) to maximize consumer convenience (minimize *average* consumer travel time) from home
- Optimize station location by picking amongst existing gasoline stations

This approach requires road network, population distribution and gasoline station spatial data, as well as significant computation time. However, this method provides a means of determining the costs and visualization for an actual infrastructure layout.

Identifying Demand Clusters

Traditional city boundaries were not used for the analysis of the “real” cities. Instead, a GIS-based method developed by UC Davis researchers, was used to identify high-density urban clusters that could support a hydrogen refueling infrastructure (Johnson et al. 2005). These clusters were determined by converting the 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.

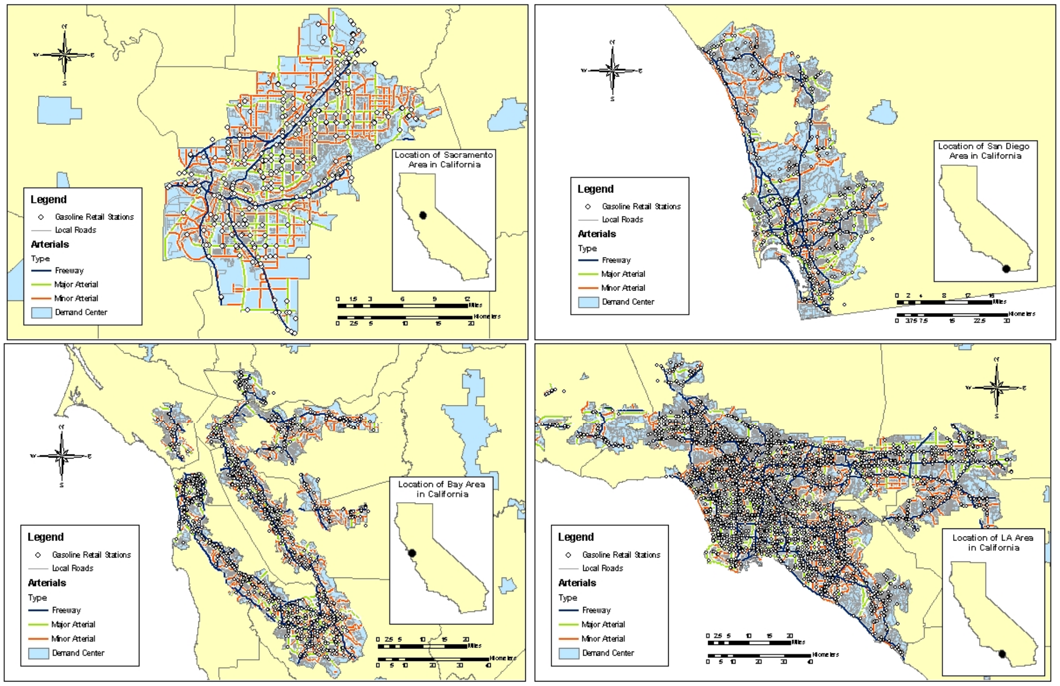


Figure 1 Maps showing the dense urban areas (demand centers) considered, street networks and gasoline stations for (a) Sacramento (b) San Diego (c) Bay Area (d) Los Angeles.

Hydrogen Infrastructure Layout – Pipelines and Trucks

For each model type, stations are sited independent of hydrogen infrastructure delivery considerations. Only after stations are sited are the delivery distances and costs of delivery determined. 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. These hydrogen depots are assumed to be located at the city gate. 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.

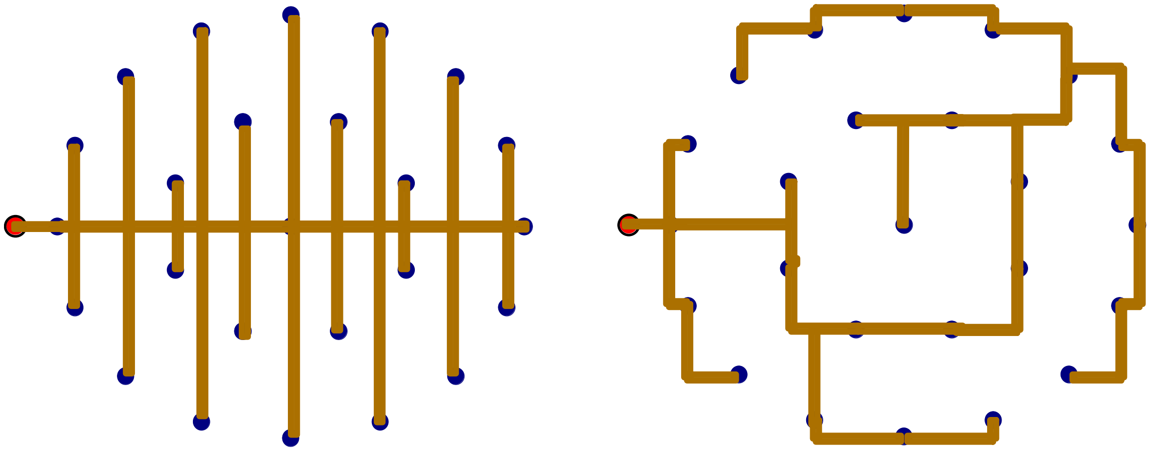


Figure 2 Representative truck and pipeline network paths from hydrogen depot for ICM.

Pipelines

The major goal 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. For the pipeline infrastructure layout, we assumed the following:

- Hydrogen Stations are connected in a network by pipelines, following rights of way
- Hydrogen production is at city gate (edge of city)
- We use arterial roads as pipeline rights-of-way for real-world case studies
- For the idealized city model, pipelines follow a rectilinear grid (to approximate major road network).
- In both models, a minimal spanning tree (MST) algorithm is used to layout shortest pipeline network.
- This model uses length as the only determinant of cost, whereas more sophisticated models for laying pipelines could have additional factors, such as spatially determined land values, that will also influence costs.

Truck Delivery

As a basis for comparison, we considered the distance traveled by trucks between the hydrogen production site and the network of hydrogen stations. To model truck delivery in real and idealized cities, we made the following assumptions:

- Each truck delivers its entire load to one station and then returns to a central production plant.
- Hydrogen production takes place at the edge of the city. (For the real-world city, several different production locations were tried at different points around the periphery of the city.)

- Truck travel distances were measured using GIS tools along the arterial road network for real-world case studies
- Distances were calculated along a hypothetical rectilinear idealized road network for idealized city case studies
- The comparisons in this report assume that all stations are of equal size so that trucks are driven with equal frequency to all stations.

Hydrogen Infrastructure Comparison

The analysis for the two station-siting methods yields a functional relationship between the number of stations within the city and the normalized length of the distribution system –truck driving distances and pipeline network length. Table 1 shows the individual parameters for the four California city demand clusters in the analysis that the ICM uses to calculate delivery distances.

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

Metrics for Comparison Between Ideal City and Real City Results

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

- **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. (For fewer stations, a less extensive pipeline network is required).

- **Delivery distance.** (This is related to the physical size of the city (expressed as a characteristic length such as the city radius, and is particularly important for compressed gas trucks and for pipeline delivery, and less so for liquid hydrogen delivery).

In our comparison, since the total hydrogen flow and the number of stations are kept the same for the real and ideal models, ***distance*** is the main factor that could vary between the ideal and real model results. Thus, as a first approximation, we concentrate on comparing the key distances that affect distribution cost that the two models predict. If the ideal and real city models estimate about the same travel distance for trucks or the same pipeline length, we say that they are in good agreement, and would predict hydrogen distribution infrastructure costs. The goal is to find a good idealized city model that will allow us to quickly estimate infrastructure costs without having to use a much more complex, full GIS model.

Trucks

For the idealized city model of truck delivery, the station layout and the theoretical truck routes (along a rectilinear road system) are shown in Figure 4. (The distance (D_{trucks}) can be calculated in terms of the city radius (R_{city}) and the number of stations ($N_{stations}$).) This is plotted in Figure 5. The total truck travel distance (one way from the hydrogen production plant to all of the stations) is given by the following equation:

$$D_{trucks} = 1.42 \cdot N_{stations} \cdot R_{city}$$

(Total truck travel distance is the total distance traveled to make N trips from the central plant to each of the N stations.)

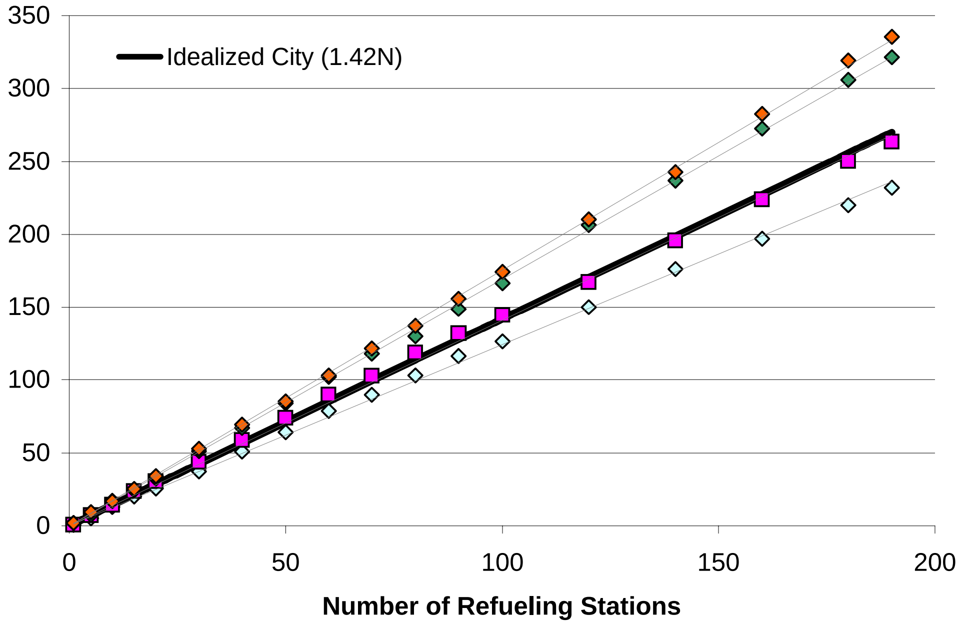


Figure 3 Truck travel distances along arterials for Sacramento from the H_2 production site at the city edge to a network of H_2 refueling stations. The four symbols represent different locations for the H_2 production site. The results from the ICM are shown as a black line.

Figure 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 the map of Sacramento, it is clear that the city is elongated somewhat 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%.

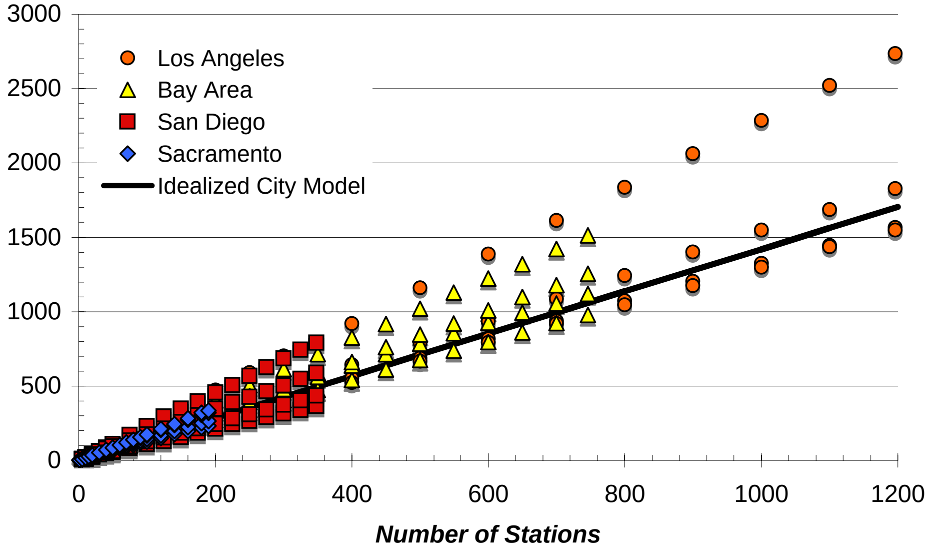


Figure 4 Truck travel distances as a function of number of refueling stations for four potential H_2 depots in each of the California cities and comparison with idealized city results.

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%).

Pipelines

Figure 5 shows the model results for 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.

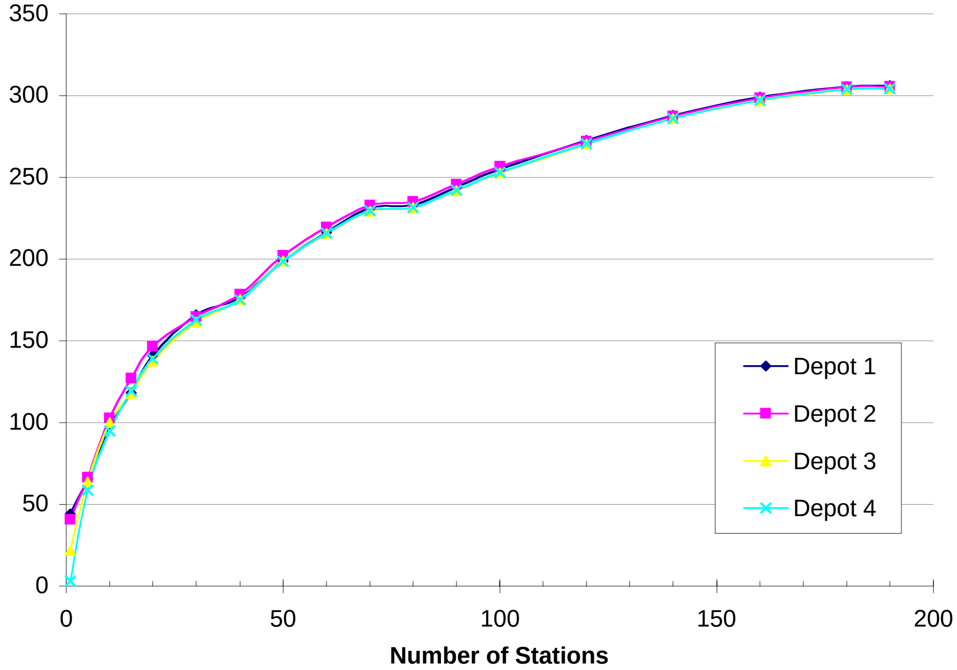


Figure 5 Comparison of pipeline distances according to the Sacramento GIS station-siting model, when the hydrogen production plant (depot) is placed in four different locations around the edge of the city.

Figure 6 shows GIS-based model prediction of pipeline length for the four California cities. The figure also shows the pipeline distance comparison of the ICM prediction with the GIS based city analysis. The length of the idealized city model pipeline grows approximately as the square root of the number of stations in the city. The graph shows that at low fraction of stations within a city, the ICM is able to predict pipeline length, but that as the fraction of stations in the city grows larger, the pipeline length for the real city analysis does not grow as quickly.

Modifying the pipeline result of the idealized city model to better match real city data

As the unconstrained idealized city model places stations thoughout a city, the spacing between stations becomes smaller, which leads to an ever-increasing total pipeline network length. However, in real cities, gasoline refueling stations are located along a limited network of major arterial and collector roads. Once widespread coverage is established throughout a city, additional stations serve to 'fill in' the gaps between existing stations. Thus, as more stations are added, the length of the pipeline increases up to a point, but beyond a certain point, stations are added along main roads already served by a pipeline. Thus, the pipeline length does not increase significantly beyond this point. This is evident in Figure 7. In going from 100 to 200 stations, the idealized model predicts that the Sacramento pipeline length grows by about 50%, roughly as the square root of the number of stations. The real city data shows pipeline length growing by only about 20%.

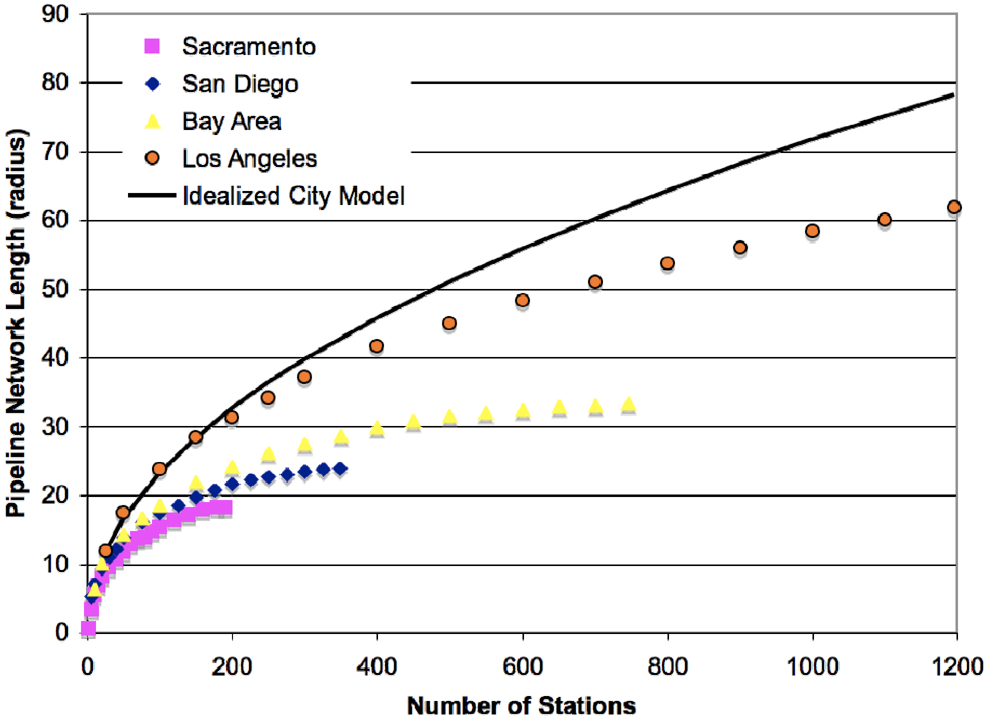


Figure 6 Idealized city model pipeline length vs GIS based analysis of pipeline length for four California cities

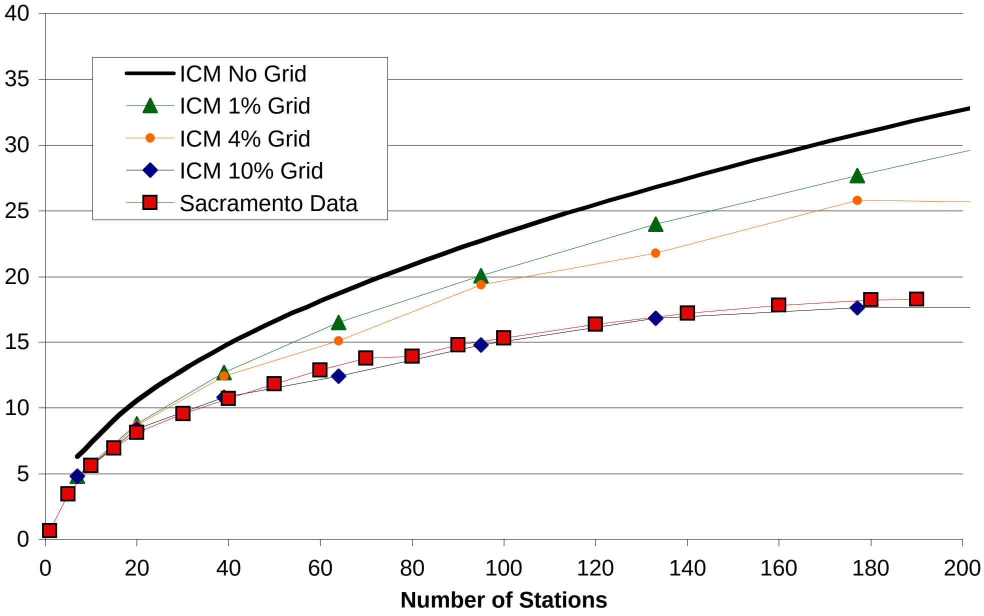


Figure 7 Pipeline distribution system length according to the ICM unconstrained and constrained to a rectangular grid with spacing = 1%, 4% or 10% of the city size. Estimated pipeline length is also shown for Sacramento data.

To better match the layout of refueling stations in real cities, we constrained the idealized city pipeline network to lie along nodes of a fixed rectangular grid of hypothetical “major roads”. We assumed that these major roads are evenly spaced across the city. The spacing between major roads is some fraction of the city extent (extent = distance from one side of the city to the other ~ city diameter). Specifying the grid spacing for a circular city will directly correspond to a certain length of these major roads and a specified number of grid nodes (i.e. intersections). Alternatively, knowing the total length of these major roads within a city can also yield the grid spacing.

Figure 7 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.

The dense area of Sacramento that was studied has approximately 1400 km of arterials, which corresponds to 85 city radii. This length of major roads within a circular city corresponds to a grid spacing of 11%. As seen in Figure 7, an idealized city grid spacing of 10% yields a very similar total pipeline network length to the one studied in Sacramento.

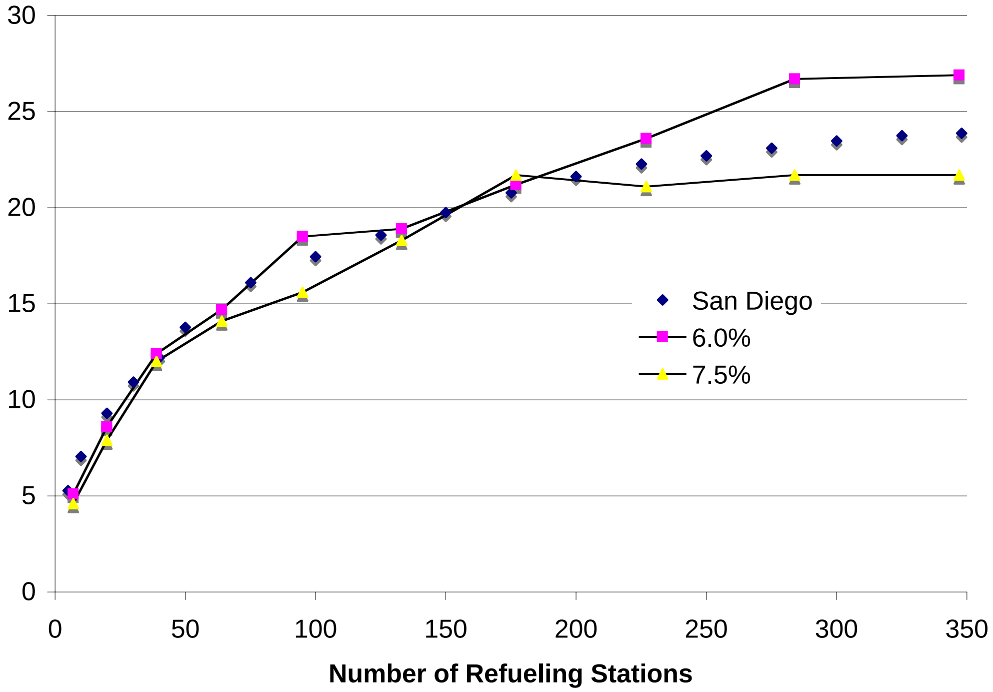


Figure 8 Pipeline comparison for ICM and San Diego (6.7% grid spacing).

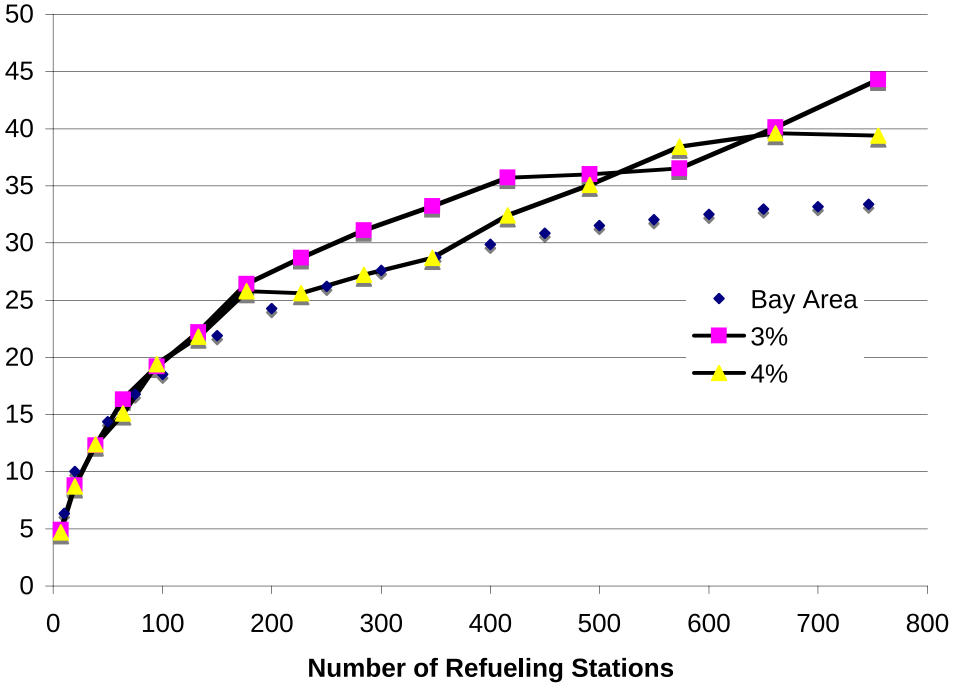


Figure 9 Pipeline comparison for ICM and the Bay Area (3.3% grid spacing).

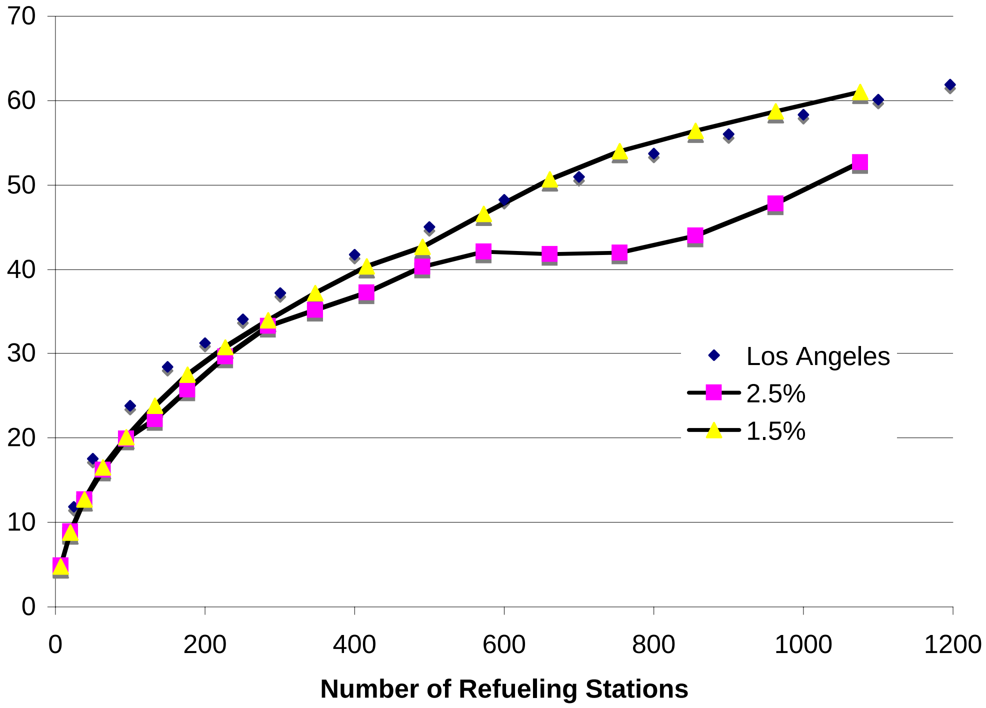


Figure 10 Pipeline comparison for ICM and Los Angeles (2.2% grid spacing).

Figures 7-10 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 bracketing the 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.

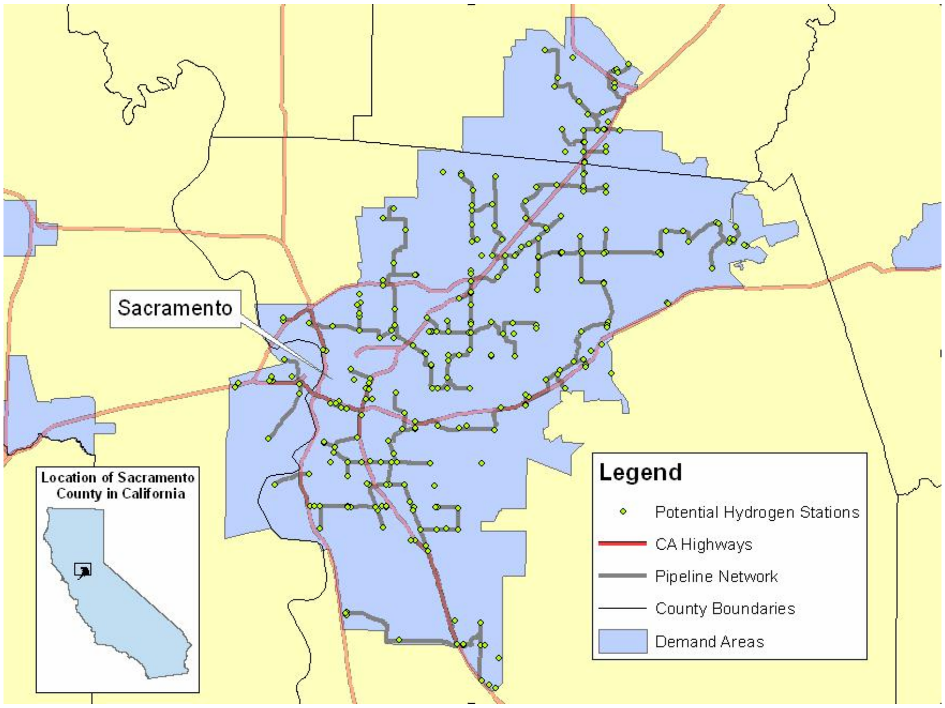


Figure 11 Shortest path pipeline network for Sacramento

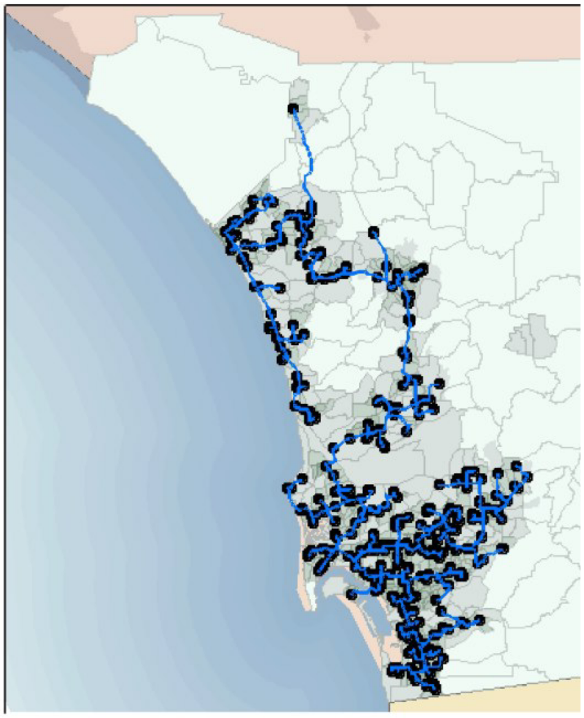


Figure 12 Shortest path pipeline network for San Diego

There appears to be good agreement between the results of the GIS based station siting model and ICM based station siting model 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.

Task 2. Coordination with NREL Analysts

In this task, the UC Davis hydrogen research group worked with the DOE Transition Analysis program, the H2A Delivery team, and the FreedomCAR Delivery Tech team to develop insights about transition strategies for hydrogen vehicles. Dr. Joan Ogden, Dr. Christopher Yang, and other UC Davis researchers held briefings for USDOE and NREL analysts in March 2006, April 2006, and June 2006, and attended the USDOE Hydrogen Transition Analysis group meetings in January 2006 and August 2006, where Joan Ogden presented a paper on UC Davis case studies in Southern California.

The UC Davis team met several times with analysts from NREL and USDOE to coordinate hydrogen analysis efforts, and present our results.

January 10, 2006, Washington, DC. Joan Ogden attended the USDOE Hydrogen Transition Analysis Team meeting.

March 16, 2006: Long Beach, CA. Following the National Hydrogen Association meeting, a team UC Davis researchers met with the Hydrogen Transition Analysis team lead by Dr. Sig Gronich of USDOE, including Margaret Mann (NREL), Keith Parks (NREL), Corey Welch (NREL), Brian James (DTI). We presented our results on hydrogen transition studies from the H2 Pathways program. The meeting agenda is given below.

- Introductions and review agenda
- Presentations by UCD Team
    - Overview of UCD H2 transition modeling (Joan Ogden)
    - Station siting analysis for CA H2 Highway. Review of recent work on station siting and sizing (Mike Nicholas)
    - Review of GIS datasets for California used in UCD infrastructure studies (population, roads, traffic flows, gasoline stations) (Mike Nicholas)
    - Analysis of near-term H2 station costs (Joan Ogden)
    - Getting to 1% H2 in Southern California study (Marshall Miller)
    - H2 from waste biomass in CA (Nathan Parker)
    - Hydrogen Infrastructure Transitions (HIT) model (David Zhenhong Lin)
    - Verifying Ideal Models for H2 Delivery with Real City Data (Chris Yang)

    - H2/electricity study with CEC Advanced Energy Pathway project (Chris Yang)
- Presentations by DOE team
- Discussion of how UC Davis might interface with DOE Transition studies and next steps

April 18, 2006, Davis. CA. UC Davis researchers held an all-day infrastructure modeling workshop with members of the DOE FreedomCAR Delivery Tech Team and the H2A Delivery Team, led by Mark Paster. Researchers from Nexant and Argonne National Laboratory also attended. We discussed possibilities for incorporating some of UC Davis's infrastructure models into the next version of H2A delivery model.

June 28, 2006, Davis, CA UC Davis Researchers hosted NREL analysts Cory Welch and Keith Wipke for a 1-day working meeting. NREL researchers presented their latest hydrogen transition studies, and the UC Davis team presented results from the UC Davis H2 Pathways program. We discussed possibilities for future research collaborations.

August 10, 2006. **Washington, DC.** Joan Ogden attended the USDOE Hydrogen Transition Analysis Team meeting and made a presentation on UC Davis's work on "Geographically-Based Infrastructure Analysis for California"

September 28, 2006. Hydrogen Pathways Workshop, Davis, CA. Dr. Sigmund Gronich of the USDOE gave a keynote talk at the UC Davis Hydrogen Pathways workshop on US Transition strategies.

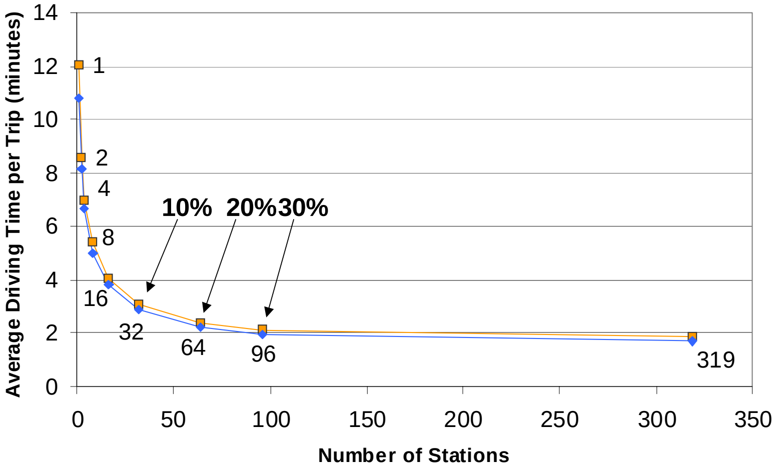
Options for Early Refueling Infrastructure in Southern California

UC Davis researchers have employed a variety of GIS-based methods to study scenarios for H2 station deployment. In preparation for the August 10, 2006 Transition Analysis meeting, USDOE analysts asked UC Davis to study various options for early infrastructure development in Southern California. Here we present results from several studies relevant to a H2 transition in California

We examined key questions related to siting hydrogen refueling stations
- How many H2 refueling stations would be needed for consumer convenience?
- Where should they be located?
- How does this with vary with average travel time and city characteristics?

Figure 13 shows results from a study that considered early H2 infrastructure rollout in Sacramento.
- H2 Stations were sited to minimize the average travel time to the nearest station for all commuters

- We used the existing gasoline network as a baseline for comparison to hydrogen station networks
- Utilized census and traffic data to identify customer locations



Relationship Between Number of Stations and Average Travel Time – H2 offered 10-30% of existing gasoline stations might provide adequate convenience

Figure 13

In Figure 13 we illustrate the relationship between the number of stations and the average travel time for consumers from home to the station. Hydrogen station locations are selected from among all 319 gasoline stations in the city. The selection is done to minimize the overall travel time for all vehicles, based on real traffic data from Sacramento. Once 10-30% of gasoline stations offer hydrogen, the average travel time doesn't decrease much. This suggests that hydrogen need not be available in every gasoline station to offer consumer convenience similar to gasoline today (Nicholas 2004).

In later work, we studied how the required fraction of stations offering hydrogen varied for different cities (Nicholas and Ogden 2005).The fraction of H2 stations required for a particular average travel time is lower for denser cities (see Figure 14).

Building on these studies, we examined how the average travel time varied for a particular scenario of placing the first 200 stations in Southern California. The stations were sited as follows:

We started with existing and planned H2 stations (17 sites) plus 23 CNG fleet sites for a total of 40 stations, about 1% of the total number of stations in the LA area. We then added more CNG fleet station sites (an additional 20 sites), municipal agencies with

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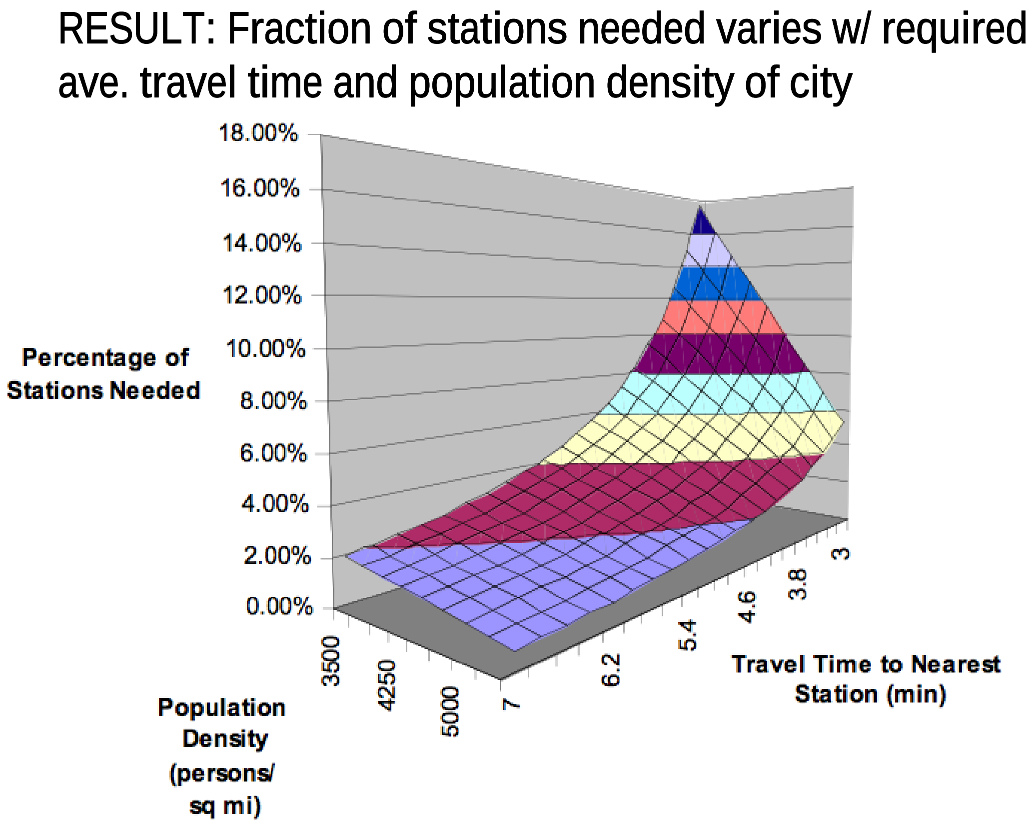
RESULT: Fraction of stations needed varies w/ required ave. travel time and population density of city

Figure 14

fleets (another 40 stations) and finally, optimally selected gasoline retail stations sites (another 100 stations.) Figures 15 a-d show the buildup of stations. In Figure 15e, the average travel time is estimated based on actual LA traffic and census data. For this scenario, the average travel time drops to less than 5 minutes, with only 200 stations (about 5% of the total number of gasoline stations in LA today.)

In another study, we sited stations to maximize the number of customers within 3 minutes of the stations. Scenarios with 10, 20, 50, 100 and 165 stations are illustrated in Figure 16. With only 100 stations, it is possible to place stations so that 45% of the population lives within 3 minutes of a station.

In future work, we plan to evaluate the costs for infrastructure deployment strategies in Southern California.

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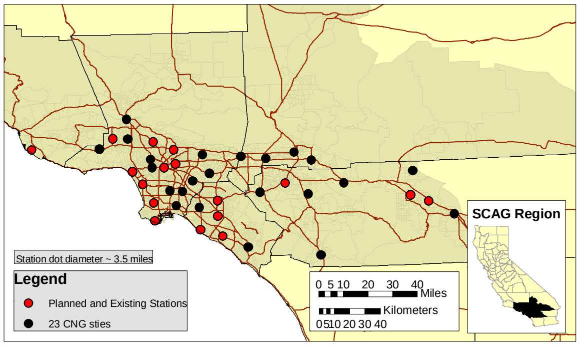
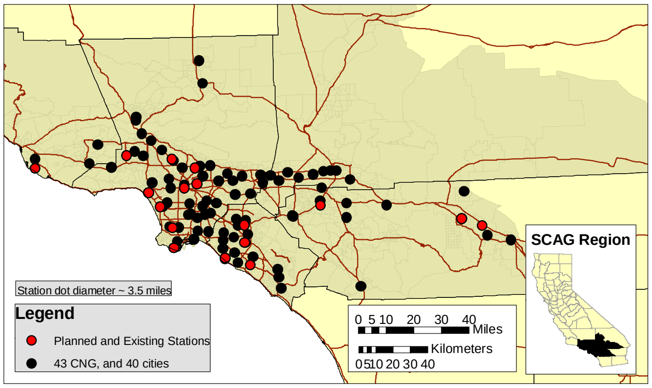
Figure 15

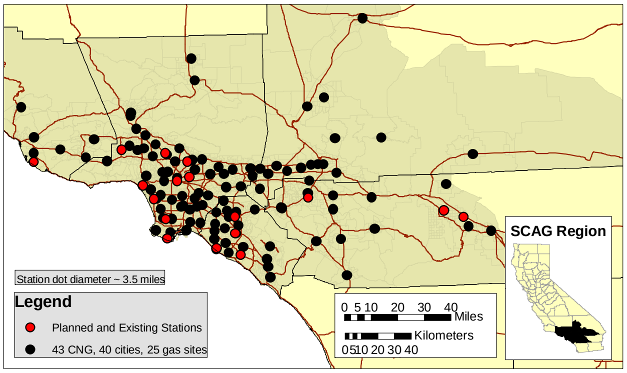
1% of stations in LA (40 stations total):
17 planned H2 stations + 23 (of 40 existing) CNG sites



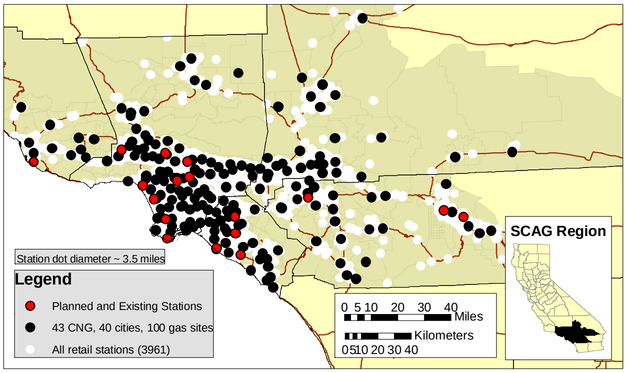
2.5% of stations in LA (100 stations total):
17 planned, 43 from CNG, 40 largest cites



3% of stations in LA (125 stations total):
17 planned, 43 from CNG, 40 largest cites, 25 gasoline locations



5% of stations in LA (200 stations total):
17 planned, 43 from CNG, 40 largest cites, 100 gasoline locations



Average Travel Time to the Nearest Station:

1% ~ 10 min; 3% ~ 6 min, 5% < 5 min

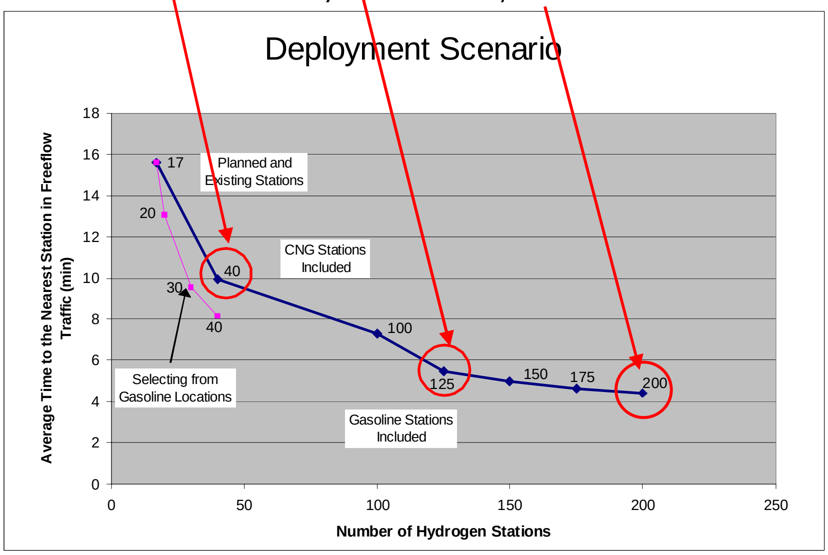
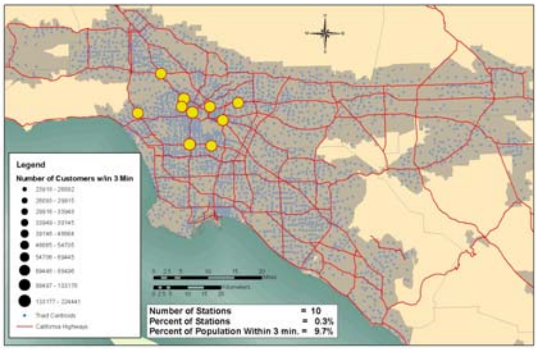
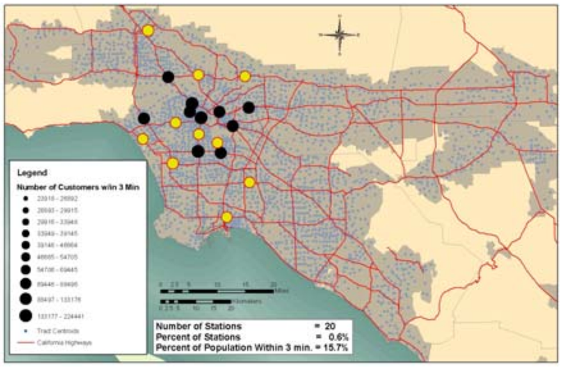


Figure 16

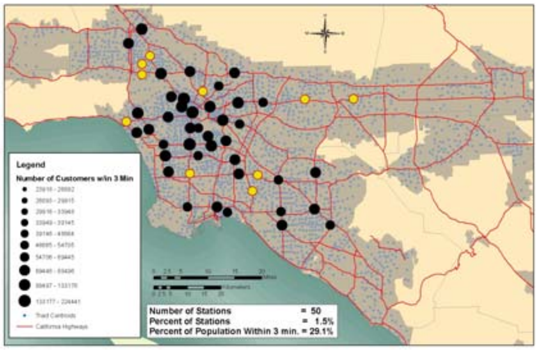
10 stations; 10% of people within 3 minutes



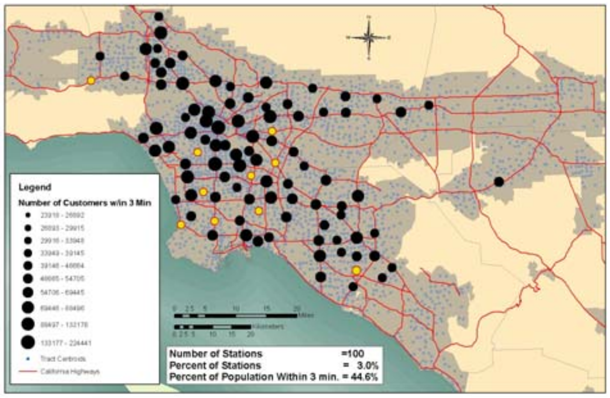
20 stations; 16% of people within 3 minutes



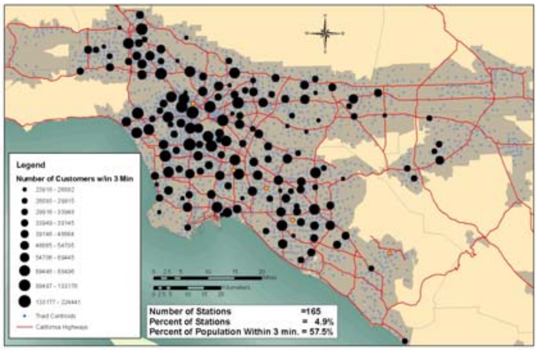
50 stations; 29% of people within 3 minutes



100 stations; 45% of people within 3 minutes



165 stations; 58% of people within 3 minutes



CONCLUSIONS AND FUTURE WORK

We have developed idealized and GIS-based analytical models for studying hydrogen delivery systems in cities. These models are used to estimate the truck travel distance and pipeline length for hydrogen delivery systems for real cities with different geographic and spatial characteristics. The idealized city model appears to adequately describe the distribution systems for four California cities: Sacramento, San Diego, the Bay Area, and Los Angeles. Modifications to the idealized city model yields results were seen to match well with those from a detailed GIS-based analysis of expected truck travel distances and pipeline lengths.

This work represents ongoing work toward verifying the UC Davis idealized city model using real city data. Additional cities will be analyzed to further verify and improve upon our idealized city models.

In future work we will further improve the idealized city model, by testing it with data from other US cities that have different populations and population densities. We will also consider infrastructures made up of a range of station sizes (unlike the uniform station size assumed in this analysis).

We also plan to develop equations for the design and costs for urban hydrogen delivery systems, suitable for inclusion in H2A and in NREL's regional hydrogen system models. This analytic framework that will allow NREL modelers to cost delivery infrastructure in terms of a readily available parameters about cities, markets and refueling infrastructure.

Task 2.

Through coordination and discussions with NREL and DOE analysts we identified several areas for future research. These include developing simple analytic formulations of our pipeline layout models suitable for inclusion in the H2A delivery model and studies of the interactions between hydrogen and the electricity system. We plan to continue coordination with NREL analysts as we conduct GIS-based studies of infrastructure deployment in Southern California.

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