VIII.5 Validation of "idealized city" Models for H2 Delivery in Urban Areas, with Real-City Data

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Objectives

- Assist the DOE in identifying promising paths for developing hydrogen infrastructure.
- Integrate existing UC Davis H_2 infrastructure models with other H_2 models funded by NREL, to address questions related to H_2 infrastructure development.
- Work with H2A core group to develop models of hydrogen delivery systems.

Technical Barriers

This project addresses the following technical barriers from the Systems Analysis section (of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(E) Lack of Understanding of the Transition of a Hydrocarbon-Based Economy to a Hydrogen-Based Economy

Accomplishments

TASK 1: Work with hydrogen analysts at NREL, to identify research areas for collaboration and integration.

- Met with NREL researchers in June 2005 to review UC Davis' infrastructure modeling tools, and how they relate to other NREL infrastructure modeling studies. Identified two areas for collaboration:
  - Validation of "idealized city" models developed at UC Davis for H_2 delivery in urban areas, with data from real cities *(also suggested by 2005 HFCIT Merit review of this project)*.
  - Develop equations for design and costs of urban H_2 delivery systems, suitable for inclusion in NREL's regional H_2 system models.

TASK 2: Validation of "idealized city" models for H2 delivery in urban areas, with real city data

- Current DOE models for hydrogen delivery in urban areas (such as the H2A delivery model) rely on idealized models of city geometry (circular city) and refueling station layout (evenly distributed). The layout of stations in a real city is much more complex than a simplified idealized city model (ICM).
- Question: How well do idealized city models predict hydrogen delivery system costs in real cities?
- Using real city geographic information system (GIS) data for gasoline stations and roads, used optimization methods to site stations for consumer convenience, and calculate delivery distances along actual city roads for trucks and pipelines.
- Compared results for delivery distances from ICM and real city data.
- Found good agreement between ICM and real city results for a variety of city sizes, shapes and population densities.
  - Trucks
    - Good agreement between ICM and real-city models.
  - Pipelines
    - Real-city pipeline length saturates as station number approaches the number of existing gasoline stations.
    - ICM agrees with real-city distribution network *if* stations are constrained to lie along an evenly spaced grid of major roads.
- Have developed an ICM suitable for use in NREL hydrogen delivery models.

TASK 3: Coordinate with H2A delivery team and DOE H2 transition analysis efforts

- Attended DOE H2 analysis workshops in Washington, D.C. (January 2006).

- Presentations to DOE H2 Transition Modeling Team (March 2006).
- Presentations to H2A Delivery Team (April 2006).

Introduction

Understanding the design and costs of hydrogen delivery systems is one of the key issues for modeling hydrogen infrastructure transitions. Current DOE models of hydrogen delivery in urban areas (such as the H2A delivery model) rely on highly idealized representations of city geometry (circular city) and refueling station layout (stations evenly distributed in space). The layout of stations in a real city is much more complex than those in idealized models. In this study, we explore how well ICMs predict hydrogen delivery system costs in real cities. The goal is to develop a simple model of hydrogen delivery that could be used in an EXCEL-based model like H2A, that matches well with results from more complex GIS-based models for station placement and delivery system design using real city data.

Approach

We compare results of two types of delivery infrastructure models developed at UC Davis: a "real city" model [1-3] and an "ideal city" model [4-9]. The "real city" model uses detailed GIS data for particular cities: gasoline station locations, population by census tract, roads and traffic flows. These are input to a spatial optimization model to find the best station locations and calculate hydrogen truck travel distances (along actual city roads) and pipeline network lengths (along actual city rights of way). In contrast, the ICM uses a small number of aggregated input data (city population, city size, number of stations) and assumptions about city geometry and station layout to find truck delivery distances and pipeline lengths.

We employ *distance* as a metric for comparing results from the two types of models. 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. We use the results of the comparison to improve the ICM to better describe real cities. The goal is to improve the ICM so that it allows us to quickly estimate infrastructure costs without having to use a complex, data and computationally intensive full GIS real city model.

Results

In Figure 1, we show the station layout calculated in the ICM. The city is modeled as a circle with stations evenly distributed. Given a small number of input parameters, the hydrogen demand, city radius and the number of stations, we can find the distances for truck travel and pipeline length, which allow us to calculate the delivery cost. This delivery model can be readily implemented in EXCEL and runs in less than 1 second.

By contrast, the real city model requires a full GIS description of the city, including gasoline station locations, roads, population by tract and traffic flows. For a specified number of stations, we choose a set of locations (from among existing gasoline stations) to minimize the average travel time for consumers located according to population tract data. (Minimizing travel time is taken as a proxy for maximizing consumer convenience, a key issue for hydrogen infrastructure placement.) Station layouts are shown for four real cities (Sacramento, San Diego, Bay Area and Los Angeles in Figure 2). Once the stations are located, we specify alternative locations for a hydrogen production site. The distances from this "depot" to the stations are found by tracing along actual city roads. The pipeline network is found using a minimum spanning tree algorithm to connect stations along existing roads into the shortest length system. The real city model requires detailed input data and takes considerable computation time to run, typically many hours.

In Figure 3 we compare the results for truck delivery distances estimated in the ICM and the real city model for four California cities (Los Angeles, San Diego, San Francisco and Sacramento). We plot truck travel distances (in units of city radii) versus number of stations. The ICM results are shown as a solid line.

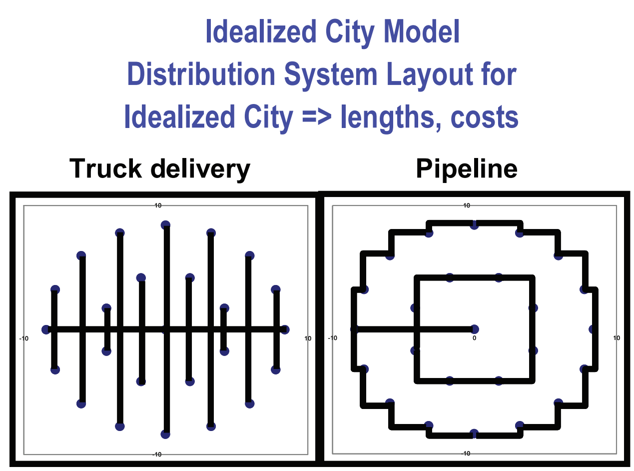

FIGURE 1. City geometry and Distribution System Layout for ICM for Truck and Pipeline Delivery

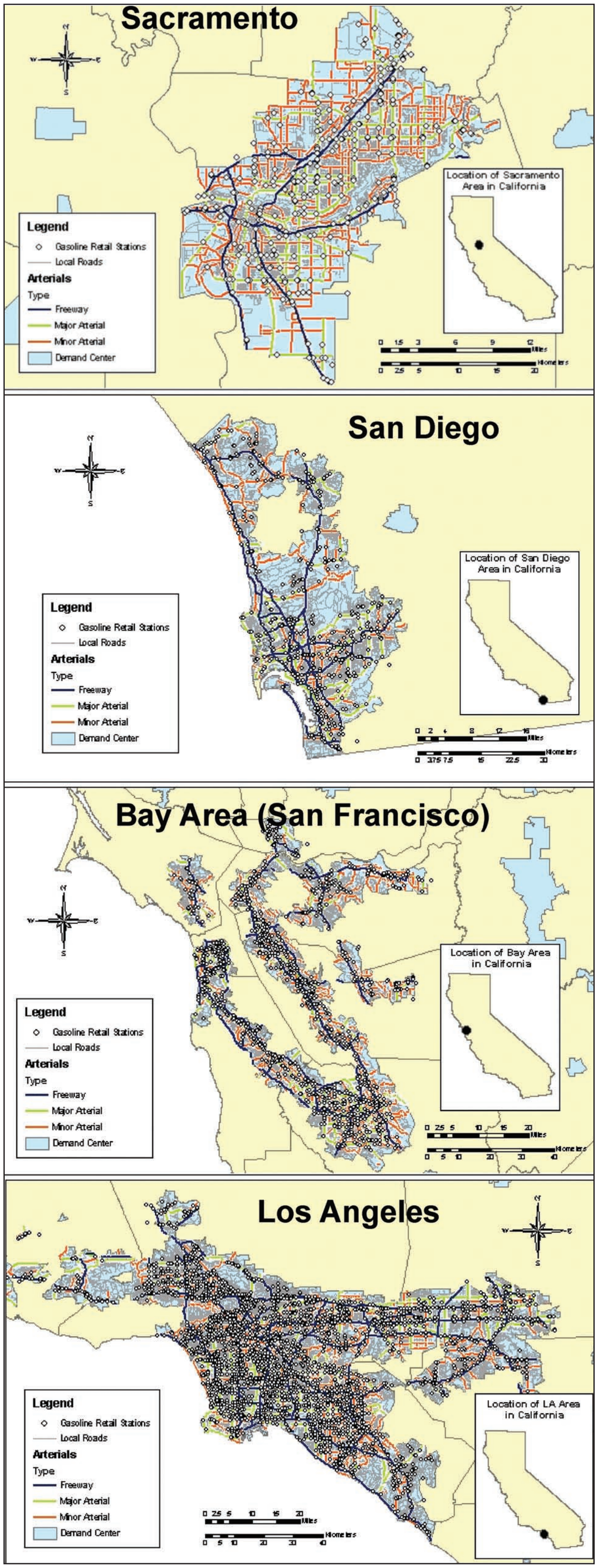

FIGURE 2. Station Layouts in Real Cities

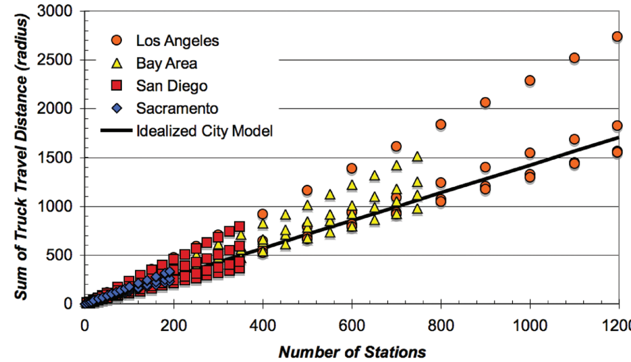

FIGURE 3. Truck Delivery Distances: Real-City vs. ICM with Four Different Depot Locations

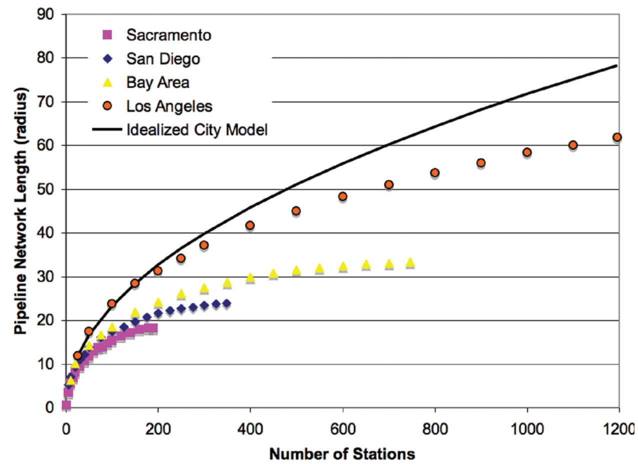

FIGURE 4. Length of Pipeline Networks Real City Model vs. ICM (no grid constraint)

The real city results for each city are shown as a series of dots. For each city, there are several dotted lines, corresponding to 4 different depot locations. Overall, the agreement between the idealized city model and the real city model are quite good for truck delivery.

In Figure 4, we compare the results for pipeline lengths for the idealized and real city models. Here we find that the idealized model significantly overestimates the pipeline network length. The reason for this is understood when we look at the constraints on the locations of refueling stations in real cities. In actual cities, gasoline stations are located only on major roads, where there is significant traffic, and the ability to deliver gasoline by truck. Stations (and pipelines) can only go along these roads, which limits the length of pipeline. In the original ICM, we had no constraints on the station location. To include this constraint, we impose an idealized square "grid" of main roads on the ideal city model, appropriately spaced, and require ideal city stations to lie along this grid. The grid spacing of main roads could be estimated in several ways. In the following table we summarize key city data that are used to find the grid spacing based, on the total length of major roads in the city.

	Sacramento	San Diego	Bay Area	Los Angeles
Area (km^2)	887.8	1,746.1	2,936.1	4,359.8
City Radius (km)	16.8	23.6	30.6	37.3
Arterial Road Length (km)	563.6	1,188.9	3,030.2	5,391.3
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	1,246	3,355
Gas Station Density ($/km^2$)	0.34	0.36	0.42	0.77

With the grid constrained ICM, we find much better agreement with real city results. This is illustrated in Figure 5 for four cities.

Conclusions and Future Directions

We have developed ICMs that adequately describe the hydrogen delivery systems for four "real" cities in California: Sacramento, San Diego, the Bay Area, and Los Angeles. The real city model and ICM lead to similar distances (and consequently costs) for truck distribution and pipeline network to a series of refueling stations. This verification and improvement of ICMs 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 much more quickly, and with a much less extensive data set.

- Planned for remainder of FY 2006
  - Validate with more cities.
  - Improve models (correlate grid spacing w/easily obtained data).
  - Look at distribution of station sizes and mixed delivery modes.
- Proposed for FY 2007

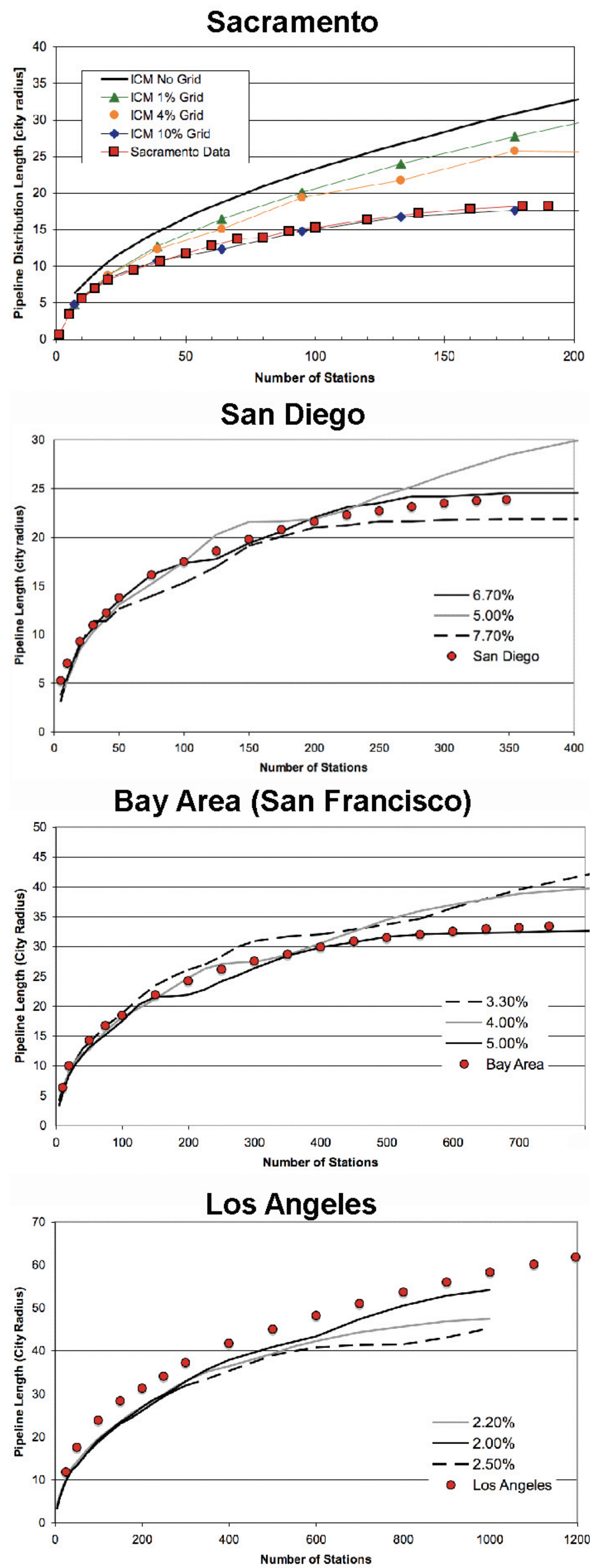

FIGURE 5. Length of Pipeline Networks Real City Model vs. ICM (including grid constraint)

- Collaborate on areas where UCD Models might be incorporated into next version of H2A delivery models
  - Station siting and sizing; distribution of station sizes.
  - Near-term station costs.
  - Pipeline lengths and layout.
- Improve and extend UC Davis regional transition models to assist in DOE Transition analysis efforts (case studies in California and other parts of the U.S.).

Special Recognitions & Awards/Patents Issued

1. In May 2006, Joan Ogden received a R&D Excellence award from the U.S. DOE Hydrogen Fuel Cells and Infrastructure Technologies Program for "Outstanding Achievement in Delivery Analysis" for her work with the H2A Delivery Team.

FY 2006 Publications/Presentations Related Directly to This Project

1. J. Ogden, "Hydrogen System Modeling at UC Davis," presentation at the National Renewable Energy Laboratory, Golden, CO, July 7, 2005.

2. J. Ogden and C. Yang, "Implementing a Hydrogen Energy Infrastructure: Storage Options and System Design," Proceedings of the Materials Research Society Fall Meeting, Boston, MA, November 28, 2005.

3. C. Yang, M. Nicholas and J.M. Ogden, "Comparison of Idealized and Real-World City Station Siting Models for Hydrogen Distribution," presented at the National Hydrogen Association meeting, Long Beach, CA, March 11-16, 2006.

4. C. Yang and J.M. Ogden, "*Determining the Lowest Cost H2 Delivery Mode,*"accepted for publication in the International Journal of Hydrogen Energy.

References

1. Nicholas, M. *Hydrogen Station Siting Strategies Using GIS*. in *20th International Electric Vehicle Symposium and Exposition*. 2003. Long Beach, CA.

2. Nicholas, M. *Siting and Network Evaluation Methods for Hydrogen Stations Using Geographical Information Systems*. in *National Hydrogen Association*. 2004. Los Angeles.

3. Nicholas, M., *Hydrogen Station Siting and Refueling Analysis Using Geographic Information Systems: A Case Study of Sacramento County*, in *Transportation Technology and Policy*. 2004, UC Davis: Davis, CA, p. 76.

4. Ogden, J.M., et al., *Technical and Economic Assessment of Transition Strategies Toward Widespread use of Hydrogen as an Energy Carrier*. 2005, Institute of Transportation Studies, UC Davis: Davis, CA.

5. Yang, C. and J.M. Ogden, *Determining the Lowest Cost H2 Delivery Mode.* 2006: Accepted for publication in the International Journal of Hydrogen Energy.

6. Yang, C. and J.M. Ogden. *Analyzing Natural Gas Based Hydrogen Infrastructure – Optimizing Transitions From Distributed To Centralized H2 Production*. in *National Hydrogen Association*. 2005. Washington D.C.

7. Johnson, N., et al., *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*. 2005. Washington, D.C.

8. Ni, J., et al. *Estimating Hydrogen Demand Distribution Using Geographic Information Systems (GIS)*. in *National Hydrogen Association*. 2005. Washington, D. C.

9. Yang, C. and J.M. Ogden. *A Simplified Integrated Model for Studying Transitions To A Hydrogen Economy*. in *NHA Hydrogen Conference and Expo*. 2004. Los Angeles, CA.