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Clean Hydrogen for Transportation Applications: Report

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Report for Task Order 5107

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Clean Hydrogen for Transportation Applications

Report

Prepared for

California Partners for Advanced Transit and Highways
Task Order 5107

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The contents herein are the collective results of contributions of all of the Hydrogen Pathways researchers.

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1. SECTION 1: HYDROGEN STATION OPTIONS FOR CALTRANS

1.1 Abstract

The California Department of Transportation, as part of their involvement in the California Hydrogen Highway initiative, is planning to construct a hydrogen station at their new maintenance facility in Sylmar, CA (Shop 7, at the junction of I-5 and I-405). This report was written to provide Caltrans information on the design and cost of various hydrogen station types. This information will be used to guide decision-making in choosing the station type and size to meet the anticipated hydrogen vehicle demand at their new facility.

Keywords
Vehicles, Environmental Impact, Technology Assessment.

1.2 Introduction

Overview
This report is organized as follows. First, there is a general discussion of the components of hydrogen fueling stations, necessary steps to build stations, and a breakdown of the costs involved. The next section describes station hardware options and gives recommendations for the type of stations the California Department of Transportation should consider. The next section gives cost results for each recommended station type. The report ends with brief conclusions.

Background
Hydrogen fueling stations are the building blocks of a hydrogen transportation infrastructure. While their primarily function is to provide hydrogen fuel for vehicles, this goal can be achieved in several different ways. For instance, some stations produce hydrogen on-site while others have fuel delivered from centralized production plants in liquid or gaseous form. Hydrogen can also be produced from a variety of feedstocks, such as water and electricity, natural gas, or bio-mass (e.g., agricultural waste, wood clippings).

Despite the many variations on station design, most stations contain the following pieces of hardware:

1. Hydrogen production equipment (e.g., electrolyzer, steam reformer) or storage equipment (if delivered)
2. Purifier: purifies gas to acceptable vehicle standard
3. Compressor: compresses gas to achieve high-pressure 5,000 pounds per square inch fueling and minimize storage volume
4. Storage vessels (liquid or gaseous)
5. Safety equipment (e.g., vent stack, fencing, bollards)
6. Mechanical equipment (e.g., underground piping, valves)
7. Electrical equipment (e.g., control panels, high-voltage connections).

Electrolyzers are devices that use electrical currents to dissociate water into oxygen and hydrogen. Steam reformers add steam to natural gas at high temperature and produce hydrogen and carbon dioxide. A vent stack is a vertical pole that allows hydrogen to be released above any equipment or buildings if the pressure is dangerously high. Bollards are posts set around hydrogen equipment to protect against vehicles crashing into station components.
Building stations also require the following tasks:

1. Engineering and design
2. Site preparation
3. Permitting
4. Installation
5. Commissioning (i.e., ensuring the station works properly).

Operating stations typically incur the following recurring expenses:

1. Equipment maintenance
2. Labor (station operator)
3. Feedstock costs (e.g., natural gas, electricity)
4. Insurance
5. Rent.

The economic analyses presented in this report include all of these costs when evaluating total station costs (Weinert, 2005).[1]

Station Options

While individual hydrogen fueling stations vary in their details, there are six basic station types. As indicated above, there is considerable overlap in station components; for example, almost all stations include compressors (devices which input gas at low pressure and output gas at significantly higher pressures), gaseous buffer storage (cylinders that store gas at pressure), and hydrogen dispensers (devices with nozzles that connect to vehicles and allow the hydrogen gas to flow from the station into the storage tanks on the vehicle). The major differences involve how the hydrogen is produced or delivered to the station. The basic station types are listed below along with a brief discussion of their defining features and benefits.

Mobile Refueler Station

Mobile refueling stations are self-contained units that can be moved to various locations for fuel dispensing. Generally these stations are filled with compressed hydrogen and sited at a particular location. When their storage is depleted, they are brought back to a central location for refueling. Their advantages are ease of siting and low cost. They cannot dispense large quantities of hydrogen without being refilled, so they are not cost effective for stations serving many vehicles.

Tube Trailer Station

Tube trailer stations have hardware sited in a permanent location, but their hydrogen storage component, a tube trailer, is periodically picked up and refilled at a central location. Generally, they are larger than mobile refuelers and hence provide more fuel between refills. Tube trailer stations are also a relatively cheap option for low-volume dispensing.

Liquid Hydrogen Station

Liquid hydrogen stations are similar to tube trailer stations, but their storage component, a cryogenic tank (storage device that keeps contents at very low temperatures usually in the liquid phase), is filled onsite from a liquid hydrogen delivery truck. Liquid hydrogen stations can serve a large number of vehicles, and generally they are more cost effective when sited relatively near a liquid hydrogen plant.

Reformer Station
Reformer stations produce hydrogen onsite from natural gas. These stations can serve a significant number of vehicles. Station costs depend largely on the capital cost of mid-size reformers that presently are built in low volume.

Electrolysis Station
Electrolysis stations produce hydrogen onsite using electricity and water. The electricity can come from the grid or from onsite power production (e.g., solar photovoltaics). These stations can be designed for zero emission, renewable fuel operation.

Energy Station
Energy stations combine hydrogen dispensing with electrical power production using hydrogen fuel (e.g., using fuel cells). In theory, any hydrogen station type could be coupled with stationary fuel cells, and therefore, be considered an energy station. Generally, energy station designs employ either reformers or electrolyzers. Energy stations can reduce the cost of hydrogen produced by allowing higher volume production.

1.3 <u>Results</u>

We recommend that Caltrans consider only three types of stations based on their anticipated fuel demand and their stated desire for renewable production: a mobile refueler (0-10 kg/day), an electrolyzer (10-30 kg/day), or an electrolysis-based energy station (30 kg/day + power demand (kW)). The figures below show the equipment involved for each of these types of stations.

Mobile Refueler Station

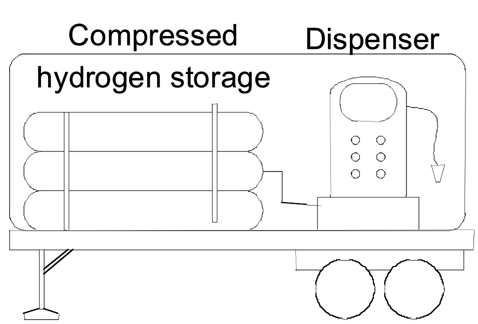

Figure 2: Schematic of Mobile Refueler

Mobile Refueler Station: This is the simplest type of station. It consists only of a high-pressure gaseous hydrogen storage and dispenser. If equipped with photovoltaics and a battery, these units require no site connection and can be completely mobile and self-sustaining.

Electrolyzer Station

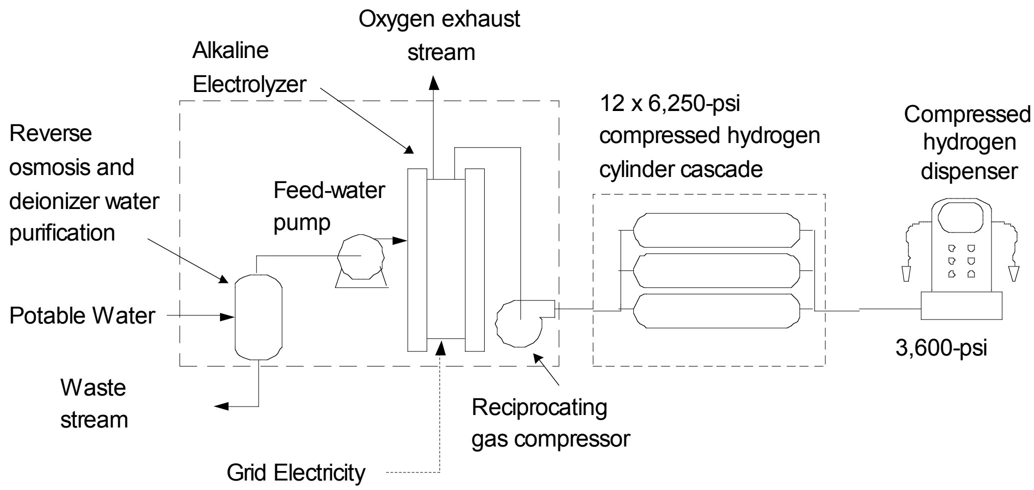

Figure 2: Schematic of Electrolyzer Station

Electrolyzer Station: This station can use either grid power or renewable electricity to produce its hydrogen. Water is fed to an alkaline electrolyzer. The output hydrogen is compressed and then stored. The stored hydrogen is dispensed onto vehicles. For this station, we assume either grid electricity or photovoltaic electricity (electricity generated by photovoltaic cells) provides power.

Energy Station

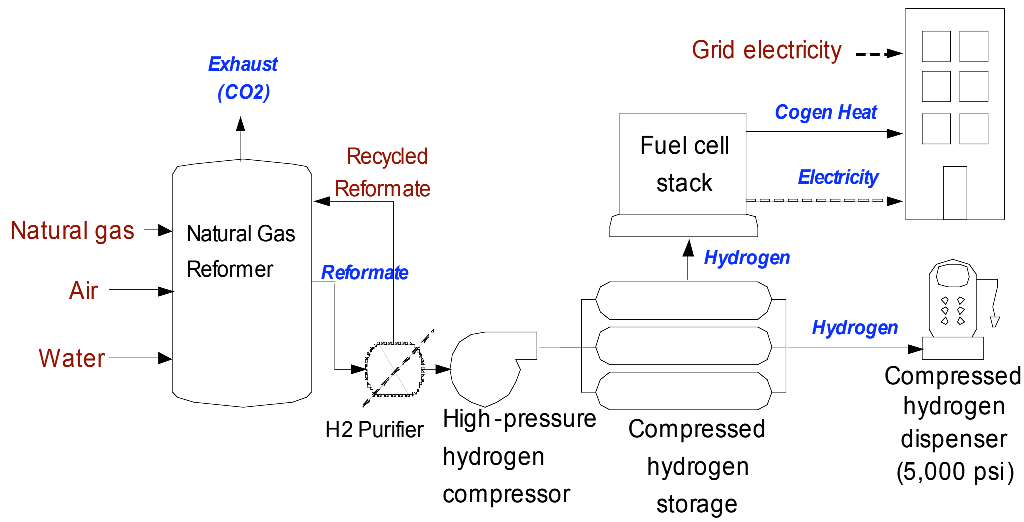

Figure 3: Schematic of Energy Station

Energy Station (ES): This type of station combines on-site hydrogen fuel production using either an electrolyzer or reformer (the diagram shows the reformer-type ES) and with electricity production capability using either a fuel cell or H2 ICE. By doing so, the station co-produces hydrogen fuel, electricity, and heating/cooling, yielding three sources of revenue. This type of station is best sited at a facility with premium (uninterruptible) electricity loads.

Station Costs for Recommended Stations

The cost for these types of stations has been calculated using a station cost model developed by one of the authors (Weinert). Equipment costs are based on manufacturers' quotes. Station costs are divided into four main categories: financing, installed capital, fixed operating cost and feedstock. ***Capital*** includes the levelized equipment cost and one-time, non-capital installation costs. ***Financing*** (i.e., fixed charge rate) includes the cost of borrowing the capital required to build the station assuming a certain return on the investment over *N* years (10% return on investment and 15 yrs is the baseline assumption). ***Fixed Operating Cost*** includes all recurring annual expenses at the station except feedstock costs. ***Feedstock*** includes the cost of fuel to the station (e.g. natural gas, electricity, gaseous hydrogen, liquid hydrogen). Annual Cost accounts for the capital (includes financing and installation) and operating costs, which is calculated using the following equations:

$$AC = OC + (CIC * CRF)$$

Where,

AC = Annual Cost ($/yr)
OC = Operating Cost ($/yr)
CIC= Capital + Installation Cost ($)
CRF = Capital Recovery Factor (%).

The graph below shows the annual costs in million dollars per year for each of the three recommended station types. The costs are disaggregated into financing charges, installed capital costs, fixed operating costs, and feedstock costs. The EL-ES 30 is an electrolyzer energy station with an output of 30 kgs hydrogen per day and an additional 42 kW of power. The EL-PV 30 is an electroyser station using photovoltaic power with an output of 30 kgs of hydrogen per day. The MOB 10 is a mobile refueler with an output of 10 kgs hydrogen per day.

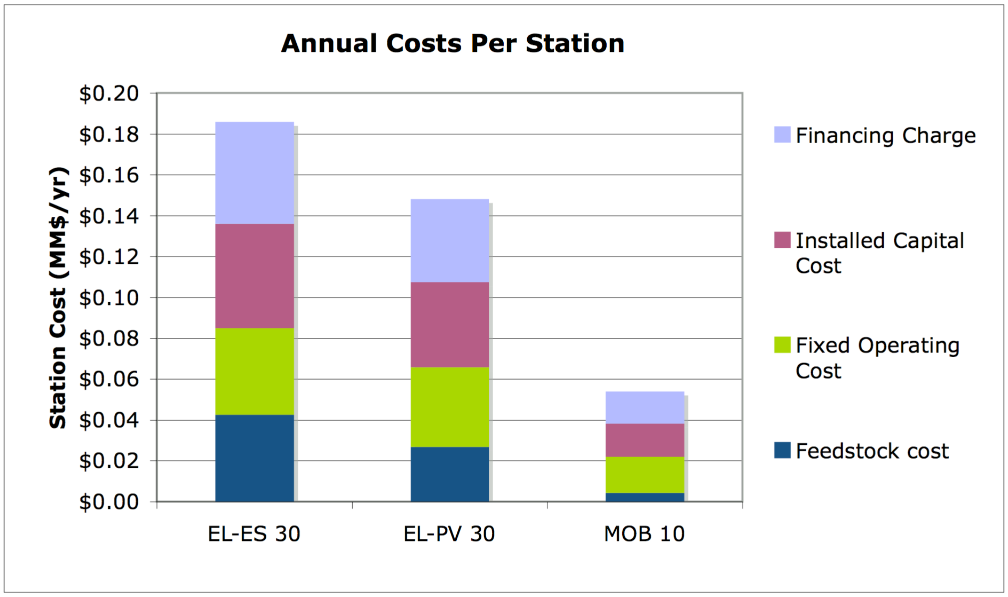

Figure 4: Annual station costs in million dollars per year for three station types. The assumptions for each scenario are provided in the Table below.

Net Economic Assumptions

Natural Gas Price ($/MMBtu)	$7.0
Electricity Price ($/kWh)	$0.10
Capacity Factor (%)	70%
Equipment Life	15 yrs
Return on Investment	10%
% of labor allocated to fuel sales	50%
Real Estate Cost ($/ft^2/month)	$0.50
Contingency (% of total capital cost)	20%

Table 1: Economic assumptions used in the cost model.

Detailed model outputs for each of the three recommended station types are shown below.

Mobile Refueler, 10 kg/day (2-3 veh/day)			
		$	**$/yr**
Mobile Refueler	39.7%	$162,804	
Safety Equipment	2.4%	$10,000	
Installation Costs	10.8%	$44,227	
Contingency	6.2%	$25,475	
Hydrogen Cost	7.9%		$4,289
Truck Delivery Costs	1.5%		$798
Fixed Operating Costs	31.5%		$16,984
Total	100.0%	**$242,506**	**$22,071**
Annual Cost ($/yr)	**$53,954**		

Table 5: Annualized cost for a Mobile Refueler Station.

Photovoltaic Electrolyzer, 30 kg/day (8-10 veh/day)			
		$	**$/yr**
Electrolyzer (includes purification)	13.1%	$147,301	
Storage System	4.6%	$51,348	
Compressor	2.4%	$27,611	
Dispenser	3.8%	$42,377	
Photovoltaic System	8.0%	$90,000	
Additional Equipment	5.9%	$66,738	
Installation Costs	12.4%	$139,431	
Contingency	5.6%	$62,710	
Electricity	18.2%		$26,949
Fixed Operating Costs	26.2%		$38,831
Total	100%	**$627,515**	**$65,780**
Annual Cost ($/yr)	**$148,282**		

Figure 6: Annualized cost for a Photovoltaic Electrolyzer Station.

Electrolyzer-Energy Station, 30 kg/day, (8-10 veh/day or 42 kW of power)			
Electrolyzer (includes purification)	15.2%	$147,301	
Storage System	3.6%	$51,348	
Compressor	2.0%	$27,611	
Dispenser	3.0%	$42,377	
PEM Fuel Cell	12.4%	175,546	
Additional Equipment	4.7%	$66,738	
Installation Costs	12.7%	$180,150	
Contingency	5.3%	$75,321	
Electricity	22.9%		$42,579
Fixed Operating Costs	22.9%		$42,509
Total	105%	**$766,393**	**$85,088**
Annual Cost ($/yr)	**$185,848**		

Figure 7: Annualized cost for an Electrolyzer Energy Station.

These costs are based on the following model assumptions:

Station Assumptions	2010 Retail	
Natural gas ($/MMBtu)	*$7.00*	/MMBTU
Electricity ($/kWh)	*$0.10*	/kWh
Demand charge ($/kW/month)	*$13.00*	/kW
Capacity Factor Increase	0%	
After-tax rate of return	10.0%	=d
recovery period in years	15	=n
Real Estate Cost ($/ft^2/month)	$0.50	/ft^2/month
Contingency	26%	of total installed capital cost (TIC)
Property Tax	1%	(% of TIC)
Capacity Factor	47%	

Capital Recovery Factor	13.1%	=CRF

Figure 8: Assumptions for the hydrogen station cost model.

The electrolyzer-energy station option costs over $37,000 more per year to own and operate than the photovoltaic electrolyzer station. Both stations are capable of dispensing the same volume of hydrogen (30 kgs per day). While the energy station has the additional capability of producing electricity, that electricity could presently be purchased from the grid at significantly lower cost. Energy stations are believed by some to hold the best promise to become cost effective among hydrogen station options. Choosing the energy station option makes sense as a high profile station demonstration not as the most economic way to dispense hydrogen to a fleet of vehicles.

The mobile refueler option is much less expensive per year but also services fewer vehicles. At full capacity the mobile refueler option costs slightly more than the photovoltaic electrolyzer option on a cost per kg of hydrogen basis. If the number of vehicles the station will serve is expected to remain at 2-3 for several years, than the mobile refueler option will satisfy the demand at considerably lower cost than the electrolyzer option.

1.4 Conclusions

Several hydrogen station options are described in this PATH report. The cost and design of three station options are analyzed in greater depth since they match the expected fuel and energy requirements of the Shop 7 facility. If Caltrans is interested in building a flag-ship station to serve demonstration and outreach purposes along with refueling, the electrolyzer-based energy station is an ideal choice. It incorporates a renewable energy component, several advanced technologies, and provides back-up power to the facility. There are very few hydrogen energy stations planned in the United States, and Caltrans would then own a high profile station. If cost is the primary criteria, the mobile refueler will satisfy vehicle fueling demand for 2-3 vehicles per day while the photovoltaic electrolyzer option will the demand for up to 6-8 vehicles per day.

1.5 References

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2. SECTION 2: HYDROGEN STATIONS AND REST STOPS

2.1 Introduction

The possibility of using Caltrans rest stops as hydrogen refueling areas was investigated in order to assess the extent to which Caltrans could assist in a transition from a gasoline based transportation system to one based on hydrogen. Rest stops are distributed throughout California and there is an opportunity to provide a comprehensive network of hydrogen stations across the state. The most important route is a north-south route from Mexico to Oregon since this route connects the state together, and provides access to other states and countries. Because the route along Interstate 5 is the least likely to be served by private interests, this route was chosen for analysis. A network of stations with an average distance of 46 miles separating stations could be constructed along Interstate 5. Since the access to a station is limited to one side of the freeway for rest stops, the average distance between rest stops on the same side of the interstate is 104 miles – within the range of most fuel cell vehicles. Because access to stations is limited to one side of the freeway, siting stations at rest stops is not a perfect solution. However, because the network of rest stops is so comprehensive, a unique opportunity exists to provide statewide access by the public to hydrogen.

2.2 Goals and Methodology

The California Hydrogen Highway is an initiative by backed by Governor Arnold Schwarzenegger to establish a network of hydrogen stations around the state in order to enable travel between and within regions using hydrogen as a transportation fuel. As originally conceived, the state of California hydrogen highways initiative focused on highways as the first places to site stations. Although station siting strategies have changed somewhat to include stations that enable intra-city travel, enabling inter-city travel along major highways is still of primary importance. Even though the rest stop analysis is not officially included in the hydrogen highways project, the end goal of enabling inter-city travel makes rest stop hydrogen stations an intriguing possibility.

Hydrogen stations siting can be split into two categories: intra-regional siting and inter-regional siting. The goals for each type are slightly different. Intra-regional siting refers to siting stations to facilitate local trips. Inter-regional siting refers to the siting of stations to facilitate trips between regions such as L.A. to San Francisco. The selection of Caltrans sites must be viewed in the context of an overall strategy for inter-regional and intra-regional siting.

A primary question in designing a hydrogen refueling infrastructure is: "how many stations do we need?" The answers are framed in their relation to the number of gasoline stations existing today, and range from 10% - 50% of existing stations depending on the type of region being studied. For urban areas, the range is 10% - 30% of existing stations[1][2][3][4][5]. For rural areas, there is only one estimate - 50% of existing stations[3].

The above estimates however, relate to the number of stations needed for intra-regional demand. Caltrans rest stop stations would be more appropriate to serve inter-regional demand. In the inter-regional context the relationship between existing stations and potential hydrogen refueling stations is less clear. The main goal is to facilitate travel between regions, and to a lesser extent, serve the surrounding communities. However, their geographic extent is much more limited than intra-regional stations. By their very nature, inter-regional stations are located on highways and interstates. The number of stations in the inter-regional context is more tied to the distance between stations on the interstate than to the number of existing stations.

Caltrans rest stop sites are best suited for inter-regional stations since they are along interstates. Siting hydrogen stations at rest stops should be constrained by a maximum distance and that maximum distance should be dictated by the technology of hydrogen vehicles. The maximum range of a hydrogen vehicle varies widely. Toyota Highlander FCHVs get a range of 180 miles[6]. However, ranges vary based on conditions such as hill climbing and air conditioner use. Because of this, a range of about 100-120 miles can be assumed.

To facilitate a 100-120 mile range, rest stop stations can be placed about 100-120 miles apart and safely provide fuel for inter-regional trips. Caltrans sites, however, present some interesting challenges to site hydrogen stations. Most locations consist of two rest stops – one on either side of the freeway. If a hydrogen station were sited on one side of the freeway, access from the other side of the freeway would be restricted. To overcome this problem, stations were sited approximately 60 miles apart, and the stations were sited on alternating sides of the interstate. Siting stations this way not only solves the problem of facilitating one way travel, but it also provides a measure of redundancy to the network should one of the hydrogen stations fail. Drivers could conceivably double back and refuel at a station on the other side of the interstate if a station failed on his or her side of the interstate.

The last issue is the route that the Caltrans hydrogen highway might take. A north-south route was preferred, for reasons discussed in the introduction, leaving 3 routes: Highway 101, Interstate 5, and Highway 99. Interstate 5 was chosen for two reasons. First, it is the most heavily used for Los Angeles to San Francisco travel. Second, Highway 99 would likely be served under the hydrogen highways project since the route is more heavily populated. Finding partners, such as fleet operators, may be easier on Highway 99 than on Interstate 5. The route along highway 99 runs through many cites and towns with a large number of fleets whereas the route along Interstate 5 runs through sparsely populated areas with fewer potential fleet customers. A network based on rest stops could be a way to leverage Caltrans's assets and provide service along Interstate 5 in a way that other providers could not. Additionally, Caltrans is not directly participating in the California Hydrogen Highway, providing rest stop refueling along Interstate 5 is a way for Caltrans to aid in the transition to hydrogen while not providing infrastructure that is redundant.

2.3 <u>Results</u>

The siting of stations using Caltrans rest stops was greatly simplified due to the fact that along the preferred route, there were few sites to choose from. The criteria for siting were based on the range of the car and access to the potential stations in either the north or south direction. The final map is shown in Figure 9 of suggested Caltrans rest stop stations.

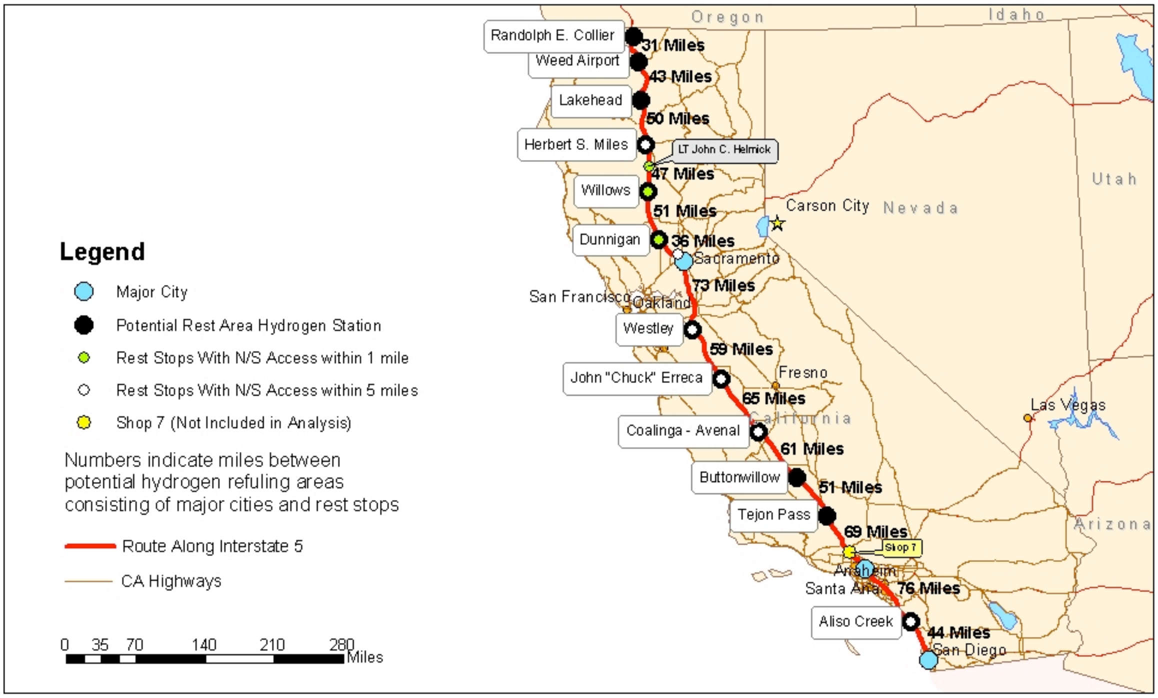

Figure 9 Completed map of proposed stations. All large black dots represent a proposed station. Some black dots have smaller dots inside. This is to indicate additional information indicated in the legend. Note – Distances between stations will likely be smaller near the major metropolitan areas of Sacramento, Stockton, Los Angeles and San Diego. Blue dots indicate city centers and do not represent the extent of suburban development.

In some cases the rough rule of 60 miles between stations was exceeded simply because there were no other rest stops from which to site a station (See Figure 10).

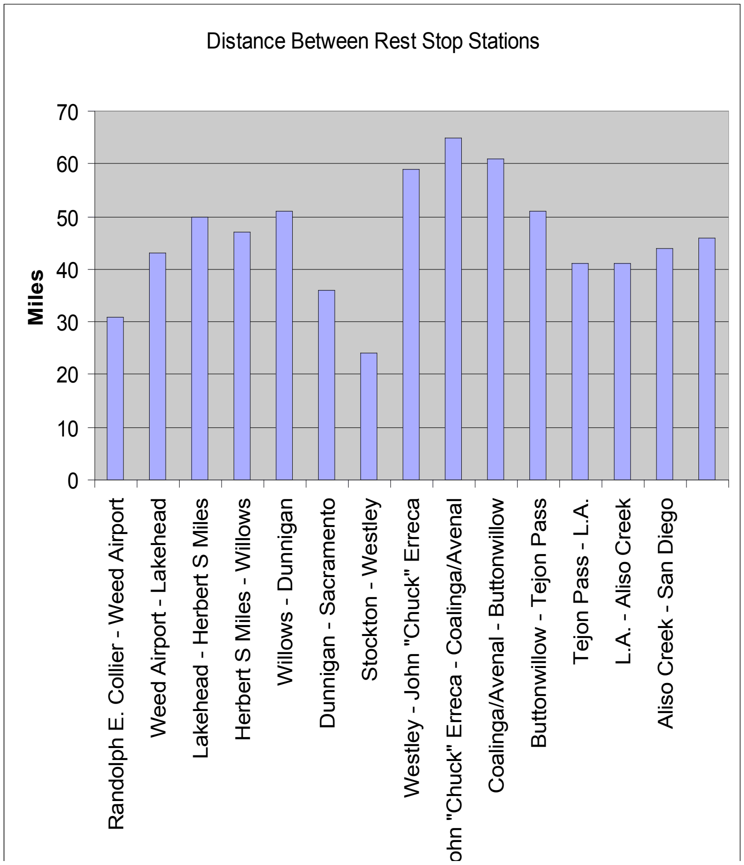

Figure 10 Distance between proposed Caltrans rest stop stations. Average distance between stations is 46 miles. This figure represents the distance between hydrogen refueling areas. These areas consist of rest stops and metropolitan areas assumed to have hydrogen.

The average distance between the selected Caltrans stations/city centers was 54 miles with a maximum of 73 miles and a minimum of 31 miles. This average reduces to 46 miles if one assumes that stations will be available in the suburbs surrounding a city center. Figure 10 represents the distances calculated using suburbs.

The estimation of 100-120 miles between stations on the same side of the freeway was also exceeded in some cases because of the lack of sites south of Sacramento. However, the distances between stations on the same side of the freeway did not exceed 130 miles – still within the range of many fuel cell vehicles. The distances for the stations on the same side of the freeway were only calculated for stretches between Caltrans sites that were assumed to have only north or south access (See Figures 11 and 12). It is important to reiterate that drivers with below average range still have the option to refuel at rest stops on the other side of the freeway if they cannot reach the station on the side of the freeway on which they are traveling.

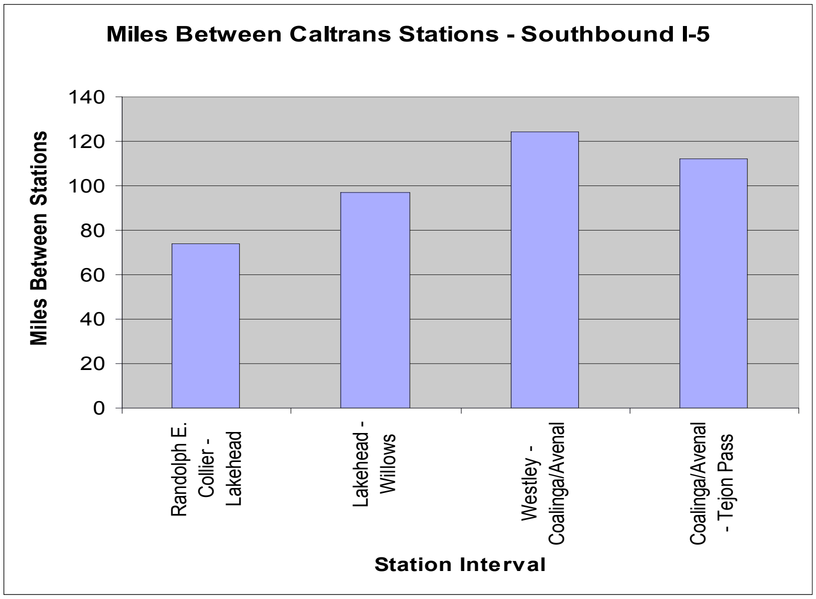

Figure 11 Distances between Caltrans sites with southbound access only. The average distance between stations is 102 miles. Even though the modeling target was 100-120 miles between stations, all of the above values are within the range of most fuel cell vehicles

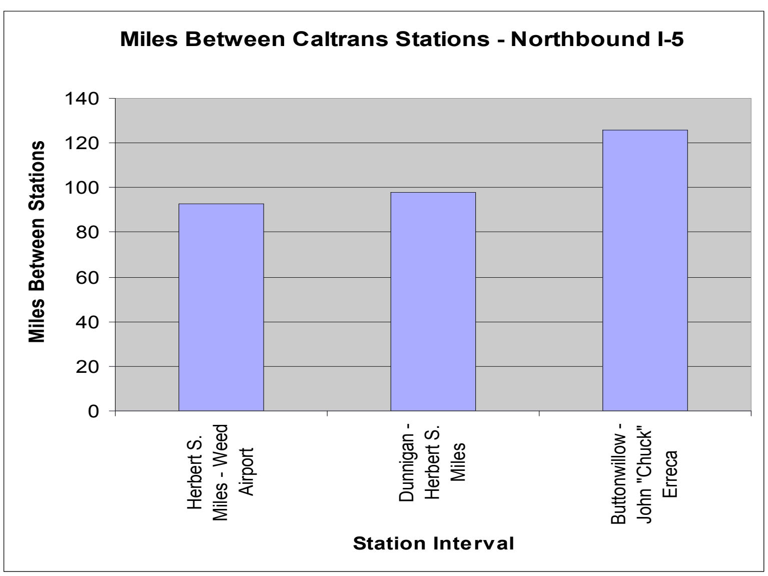

Figure 12 Distances between Caltrans sites with northbound access only. The average distance between stations is 106 miles.

Even though the distances between the stations exceed 100-120 miles in some cases, drivers still have the option to double back and refuel on the opposite side of the freeway. Notice in Figure 9 that many stations are within five miles of an interchange at which to reverse direction and refuel. Due to the initial scarcity of stations, hydrogen powered cars will almost certainly be equipped with a navigation system which includes refueling information. Perhaps in the future, information about the fuel availability at a particular station could be incorporated into the navigation system.

2.4 Conclusions

Using rest stops as hydrogen refueling locations could be an important component of hydrogen infrastructure in California. Though not a perfect solution due to the fact that the stations are not accessible from both sides of the freeway, the proximity of the rest stops to the freeway and the comprehensiveness of the rest stop network throughout California make rest stops attractive locations for hydrogen stations. Furthermore, the remoteness of many rest stop locations suggests that private businesses may not be able to provide fuel in many of these areas. Many issues, however, remain regarding the use Caltrans rest stops as refueling station sites. Caltrans rest stops are not continually staffed, and this creates problems with controlling access to the stations. Misuse or vandalism could pose problems to keeping the station in good working order. Although small stations would be relatively easy and inexpensive to incorporate into Caltrans rest stops, larger stations may require extensive modifications to the sites.

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A. APPENDIX: H2 PATHWAYS POOLED FUND ABSTRACT

This interim report is the result of work undertaken by the Hydrogen Pathways program (H2 Pathways) within the Institute of Transportation Studies at University of California Davis. The H2 Pathways program is an interdisciplinary research, education, and public process program with a specific focus on the use of hydrogen in the transportation sector. Within the first two years of the program, H2 Pathways has produced over 80 publications and presentations, engaged over 20 local, national, and international organizations as participants, and provided substantial guidance to public policy as it relates to hydrogen. H2 Pathways accomplishes this by integrating the research from a wide variety of researchers from disciplines such as engineering, economics, business, environmental science and more. The program is made up of four research tracks including Markets & Demand, Infrastructure Modeling, Policy and Business Strategy, and Environmental Analysis. As such, there is an ongoing series of research projects, each with their own interrelated scope, goals, timelines and outputs. This interim report is an attempt to provide a progress report on the major projects currently underway within the program, the recent accomplishments, and the plans going forward.

A.1. Key Words

Environmental Impact, Marketing, Policy, Risk Analysis, Vehicles, Emissions, Geographic Information Systems.

A.2. Investigating Hydrogen Infrastructure Design Using GIS (Johnson)

The use of hydrogen as a light-duty transportation fuel requires the development of a widespread regional hydrogen infrastructure, including production facilities, a distribution network, and refueling stations. In the case of fossil-based hydrogen production with carbon capture and sequestration, additional infrastructure is needed for CO2 disposal. We have developed an infrastructure model that identifies the major parameters that determine infrastructure cost and uses a geographic information system (GIS) to apply these parameters to optimize infrastructure design for a given region and hydrogen vehicle market penetration. The GIS-based infrastructure model development commenced within the H2 Pathways program in June 2004.

Presently, the model is applied to a regional case study of a potential coal-based hydrogen economy in Ohio with CO2 capture and sequestration. The objective is to model the optimal hydrogen infrastructure design for the entire state under different market penetration scenarios. GIS facilitates this analysis by allowing one to use existing spatially-referenced data, such as population distribution, coal resources, existing infrastructure, and CO2 sequestration sites, to calculate the location and magnitude of hydrogen demand and optimize the placement of production facilities and pipeline networks for transporting hydrogen and carbon dioxide. Engineering/economic models that identify the costs and technical performance of infrastructure components allow for the calculation of the costs, energy usage and emissions of different hydrogen infrastructure options. Based on these parameters, it is possible to identify the lowest cost infrastructure design for supplying hydrogen to users under multiple scenarios. The goal of this research is to increase understanding of the economics and design issues related to hydrogen infrastructure development under real-world constraints.

A.2.1 Specific progress and outputs from the reporting period (previous 3 months)

During the past three months, the research team has continued to develop a preliminary model for optimizing hydrogen infrastructure for a large region using GIS. This model includes a tool for modeling hydrogen demand and methods for optimizing production, distribution, and refueling station infrastructure based on geographic characteristics. The methods, current results, and recent progress were presented at the UC Davis Hydrogen Case Studies Workshop in June 2005.

Papers and Presentations

Ogden, J, N. Johnson, C. Yang, and J. Ni. Conceptual Design of a Fossil Hydrogen System with CO_2 Sequestration: Ohio Case Study. Presentation at the 4th National Carbon Sequestration Conference. May 2005. Arlington, VA.

Johnson, N., C. Yang, J. Ni, Z. Lin, and J. Ogden. Designing Hydrogen Infrastructure in Ohio Using GIS. Presentation at ITS-Davis Hydrogen Case Studies Workshop. June 2005. Davis, CA.

Models and model development

<u>Demand Center Calculator</u>
The demand center calculator was updated to automate more tasks and to isolate small island population clusters.

<u>Sensitivity Analysis for Demand Thresholds</u>
Sensitivity analyses were started in order to study the impacts on the overall infrastructure design cost of changing the density and aggregate thresholds used in the demand analysis at several market penetration levels.

<u>Model Extensions</u>
The model was applied to California to identify the potential demand centers within the state.

<u>Development of Decision Framework</u>
Research was conducted to begin defining constraints that the optimization model can apply in order to simplify its decision-making and, thus, streamline computation. An example of a possible constraint is the distance (between a central plant and demand center) at which various distribution methods are preferable for cities with various hydrogen demands. At this point, constraints have been identified for pipeline and liquid and gas truck distribution for cities of varying sizes and densities.

A.2.2 Planned progress and outputs for the following reporting period (next 3 months)

During the next three months, the researchers plan to continue to improve the demand center calculator and conduct sensitivity analyses on the thresholds used to define demand centers. In addition, the model will be expanded to look at additional market penetration levels and one additional region in which there is higher population density (e.g., the Northeast Corridor). In addition, the decision framework for the optimization will continue to be refined in order to provide additional constraints for the model. In the longer term, operations research (OR) techniques will be employed to optimize the pipeline network based on minimizing cost rather than distance. This will require the development of a pipeline cost model based on factors, such as land use, population density, and terrain and an optimization algorithm that considers these characteristics in addition to pipeline capacity. Planned output includes a detailed technical report on project methodology in September, 2005.

Papers and Presentations

Johnson, N., C. Yang, J. Ni, Z. Lin, J. Johnson, and J. Ogden. ITS Technical Report. September 2005.

Models and model development

<u>Refinement of Demand Center Calculator</u>
The code for the demand center calculator will continue to be streamlined in order to decrease processing time. July 2005.

<u>Sensitivity Analysis for Demand Thresholds</u>
Sensitivity analyses will be continued to study the impacts on the overall infrastructure design cost of changing the density and aggregate thresholds used in the demand analysis at several market penetration levels. The purpose is to identify whether the optimal threshold levels change with market penetration. July 2005.

<u>Model Extensions</u>
The model will be extended to examine more market penetration levels (July 2005) and one other region in which population density is higher (August 2005). The market penetration levels will likely include 5%, 10%, 25%, 50%, and 75%. The additional region may include the Northeast Corridor or Southern California.

<u>Development of Decision Framework</u>
Research will be continued for defining constraints that the optimization model can apply in order to simplify its decision-making and, thus, streamline computation. These constraints will be used to define a modeling decision framework beginning in July 2005. This process will likely continue throughout 2005.

A.3. Hydrogen Transition Modeling (Yang)

Hydrogen transition modeling is one of the major goals associated with the infrastructure analysis effort within the hydrogen pathways program at ITS-Davis. This modeling effort is extremely involved and incorporates a wide range of component models. These components include different hydrogen production technologies and feedstocks, hydrogen distribution systems and refueling station models. The main goal of the transition modeling is to develop a suitable framework in which supply infrastructure can be built up to meet an evolving demand (i.e. an infrastructure transition). This framework needs to incorporate organizational and decision components to choose between a wide range of alternative: possible choices (types of production feedstock and technology, distribution, and refueling station) and locations (for production plants, distribution systems, and refueling stations). These models will characterize the infrastructure designs in terms of costs, convenience, environmental impacts and other aspects to judge between possibilities and develop optimal and preferred strategies.

This modeling project is currently being carried out by two researchers: Zhenhong Lin, graduate student (PhD) in TTP program and Christopher Yang, Project Scientist in the Institute of Transportation Studies (ITS-Davis). Two separate approaches are currently being investigated: a simplified replacement problem from distributed H_2 production at refueling stations to central plant H_2 production with pipeline distribution (Yang), and a simplified operations research based optimization of the building infrastructure over time (Lin).

A.3.1 Current Project Status and Outputs:

Christopher Yang – Transitional Hydrogen Economy Replacement Model (THERM)
Due to changes in priorities further THERM model development and research dissemination hasn't proceeded as planned and documented in the last quarterly report. The status has not changed from the last report: The THERM model (continually developed since early 2004) is basically finished. A number of scenarios were run to examine the sensitivity of the costs of infrastructure development and replacement to a number of key parameters including city characteristics (population, size, density, growth profiles), infrastructure characteristics (size of production facilities and refueling stations) and exogenous cost factors (e.g. feedstock price). Preliminary results for the natural gas case (THERM-NG) were presented (as a poster) at the National Hydrogen Association Annual Meeting in Washington DC in March 2005.

Zhenhong Lin – Dynamic programming tools for optimal hydrogen infrastructure design over time. Zhenhong is currently using dynamic programming methods to define a modeling framework for optimal infrastructure network design in space and time. He has been working closely with Professor YueYue Fan of Civil and Environmental Engineering to frame the problem and incorporate simplifications and build and run a preliminary model with simplified example problems. (See Zhenhong's quarterly report for more info).

A.3.2 Planned progress and outputs:

The THERM model is basically finished but there will be some additional tweaking of the model, specifically related to the financial calculations. Also, additional runs will be implemented over the next several months in order to complete a thorough sensitivity analysis with THERM-NG of infrastructure replacement transitions to a number of parameters in order to determine which are most influential in determining infrastructure costs. Work will also continue on two related publications. The first is a very detailed ITS report on the replacement problem tools and methodology, which should be complete by the end of July 2005. The second is a shorter submission to a peer-reviewed journal (possibly *The International Journal of Hydrogen Energy*) on some of the main findings of the THERM-NG model to be submitted at the same time (July 2005). Additional work will also include the development of an analogous model, which will look at replacement options for other central plant options such as coal. This model will be in development in the next quarter.

In addition, Zhenhong and I will work together to define an example problem that both models (THERM and dynamic programming optimization model) can tackle in order to verify that both methods provide similar results. This will involve incorporating more detailed cost and technical data for process components into the optimization framework developed by Zhenhong. We will have updated results for some simple scenarios during the next quarter.

A.4. <u>Hydrogen and Electricity Study (Yang, McCarthy)</u>

This project will focus on identifying and understanding the integration and interactions between hydrogen production and electricity production in a developing and mature California hydrogen economy. This project is also part of a larger CEC study to evaluate advanced energy systems in California. There are several major tasks for this study. One major task is to review future projections for the growth of electricity and hydrogen demand in California, and to reconcile these demands with the potential supplies of primary energy feedstocks, preferably energy sources that are renewable and locally available. The second major task consists of characterizing the life-cycle cost and environmental impacts of using hydrogen for transportation in California. The final task involves modeling the co-production of hydrogen and electricity from a number of different feedstocks and conversion technologies, including natural gas reformation, biomass gasification, electrolysis from renewable electricity sources, and coal and biomass co-gasification. These different pathways will be analyzed to optimize the costs of hydrogen and electricity and determine the life-cycle environmental impacts.

The project will be carried out by Christopher Yang, a Project Scientist in the Institute of Transportation Studies (ITS-Davis), Ryan McCarthy, a graduate student (PhD) in Civil and Environmental Engineering, and Stephenie Ritchey, a graduate student (PhD) in Transportation Technology and Policy in collaboration and guidance from Joan Ogden, research co-director of the Hydrogen Pathways Program and Attilio Pigneri, a visiting research engineer from Italy.

A.4.1 Specific progress and outputs from the reporting period

This project has not yet been funded, though approval has been granted and funding should commence in the second quarter of 2005. Some preliminary work has begun on high level characterization of the electricity sector and we have presented and discussed the project with potential research partners, sponsors and collaborators.

Models and Analysis
We have developed a preliminary and rudimentary model of California's electricity sector through 2030 using the Long-range Energy Alternatives Planning (LEAP) software. The initial focus is on the electric system – characterizing and classifying existing and projected generation capacity supplying the state, and matching projected energy supply and demand and the petroleum refining sector - investigating evolving requirements for instate oil refining due to the increasing demand and new requirements for cleaner burning fuels. A point of interest is that the demand for hydrogen for use in refining will increase as a result of the additional refining requirements.

Papers, Presentations and Discussions

Christopher Yang. *Assessment of Strategies for Fuel and Electricity Production in a California Hydrogen Economy*. Presentation at a meeting with the South Coast Air Quality Management District (SCAQMD). May. 10, 2005. Diamond Bar, CA. This talk reviewed the hydrogen and electricity project as it relates to the interests of the SCAQMD.

Ryan McCarthy and Christopher Yang. *Assessment of Strategies for Hydrogen Fuel and Electricity Production: A California Case Study*. Poster presentation at the ITS-Davis Hydrogen Case Studies Workshop, Davis, CA, June 28-29. The poster, presented to our sponsors and other invitees to the case studies workshop, will outline the scope of the research project, and present preliminary results from a LEAP model of the California electric system.

In addition, we have had discussions with some potential collaborators and advisors for the larger project. We had a useful discussion Tom Kreutz, a researcher from Princeton, who has started an analysis of hydrogen slipstreams from large IGCC electricity plants. This collaboration will be important in the course of this project, trying to understand the economics of large central-scale electricity and hydrogen co-production plants. We have also spoken with Scott Murtishaw from Lawrence Berkeley National Lab regarding methods for characterization of the electricity sector.

Joan Ogden and Christopher Yang attended a meeting at the California Energy Commission in Sacramento with other researchers from Lawrence Livermore, Lawrence Berkeley, TIAX, GETF, and others to discuss collaboration on investigations of the impacts of alternative transportation fuels on the other energy sectors in California.

A.4.2 Planned progress and outputs for the following reporting period

Hydrogen and electricity literature review

There are a number of first steps to this project, which are expected to span the next quarter (July - September 2005). We will continue to develop our knowledge base with respect to electricity systems topics such as distributed generation, generation and storage options, and integrated resource planning. We are accomplishing this through a detailed literature review of electricity sector topics that are likely to be impacted during a large-scale shift towards hydrogen for transportation. While this review will be an ongoing process, the expected near-term product will be a write up of the initial literature review of the hydrogen and electricity topics of interest (end of September 2005).

In addition to this literature review, we will start to compile a broad database of relevant technologies and strategies that involve hydrogen and electricity. This database will describe each technology, applications where it might be used, status of the technology and estimated technical, economic and environmental characteristics. This database will be used to screen the technologies to determine the most promising technologies from a technical and economic perspective as well as identifying characteristics that may aid or hinder integration of hydrogen energy systems into the electricity sector.

Broad electricity system model development

We will continue to develop and expand a preliminary LEAP (Long-range Energy Alternatives Planning) software model discussed above to more fully describe California's energy sectors, electricity, petroleum refining and a future hydrogen economy. The model will include details of other sectors and projected hydrogen demand and supply trends. More detailed and recent data will be incorporated, and our modeling efforts will be combined with those of other organizations participating in the larger CEC project, including improving our access to relevant energy systems data (including demand projections for transport fuel and electricity).

Papers and Presentations

Our modeling work, and our work reviewing, summarizing, and extending the pertinent literature could lead to several potential presentations, ITS Research Reports, white papers, conference papers, or journal articles. Some possible topics include:

- A description of our LEAP model for California and initial findings
- Characterizing existing electricity system in terms of age, conversion technologies, costs, dispatch patterns, emissions, primary resources, and size
- Projecting future demand of electricity, natural gas, and transportation fuels
- Projecting future energy supply (sources, conversion technologies, dispatch, performance characteristics) and matching them with demand
- Analyzing the implications of various policies such as expansion of the renewable portfolio standard, or the development of the "Frontier" transmission line
- Detailed technological and performance (associated costs, emissions, etc…) summaries of hydrogen/electricity co-production pathways
- Extensions of these studies using Geographical Information Systems (GIS)

A.5. Assessing Reliability in Hydrogen Supply Pathways (McCarthy)

This project presents a new methodology to assess reliability in energy supply pathways. It takes from techniques currently used in the electricity, natural gas, and petroleum sectors and fits a broad, qualitative methodology to hydrogen systems. Potentially, the method can also be applied to competing energy product pathways (such as gasoline or future biofuel systems), allowing alternatives to be compared from a reliability standpoint based on a uniform framework.

Despite the broad applicability of the method and the potential research implications, this project is limited in scope to comparing reliability in two disparate hydrogen pathways. One is a centralized production pathway utilizing imported natural gas as a primary energy feedstock and distributing hydrogen via pipeline. The other pathway is based on forecourt hydrogen production via electrolysis, using grid-independent electricity produced from locally available renewable resources. Reliability is defined as consisting of two elements – *adequacy*, the ability of the system to supply peak demands, and *security*, the ability of the system to avoid unexpected interruptions. Metrics are chosen to value reliability in terms of these components, and are rated by a panel of experts. An aggregate of their ratings provides reliability scores from which the two pathways are compared.

A.5.1 Specific progress and outputs from the reporting period

Papers and Presentations
McCarthy, R.W. and J.M. Ogden (2005) *Assessing Reliability in Hydrogen Supply Pathways.* NHA Annual Hydrogen Conference 2005 Proceedings, Washington, D.C., March 29 – April 1. (http://www.its.ucdavis.edu/publications/2005/UCD-ITS-RP-05-12.pdf)
This paper describes the methodology developed to assess reliability in hydrogen energy systems, and presents results from an initial application of the methodology to the two pathways described in the project summary, above. (Submitted April 15, 2005)

McCarthy, R.W. and J.M. Ogden (unpublished) *Assessing Reliability in Hydrogen Supply Pathways.*
We expect to complete and submit a draft to the *International Journal of Hydrogen Energy* or *Energy Policy* before the end of this reporting period (before June 30, 2005). This paper is similar to that included in the NHA conference proceedings. It includes a brief description of the methodology, but its primary focus is on hydrogen-specific reliability considerations.

A.5.2 Planned progress and outputs for the following reporting period

Papers and Presentations
McCarthy, R.W. and J.M. Ogden (unpublished) Assessing Availability and Security in the Energy Sector.
This paper will focus on the importance of considering reliability in planning and policy making. It will consider reliability assessment methods throughout the energy sector broadly, not only for hydrogen, but also in electricity, natural gas, and petroleum systems. Completion and submission of this paper is on hold until the first (Assessing Reliability in Hydrogen Supply

Pathways) has been accepted. At that time, we will assess whether this paper is sufficiently different, and applicable to the journal.

A.6. <u>Hydrogen Production Cost and Technology Review and Summary (Lipman)</u>

Hydrogen is a highly promising energy carrier and fuel for vehicles and stationary power generation, but the potential expanded use of hydrogen involves a host of issues and challenges. Primary among these is the fundamental issue of how the hydrogen is itself produced and distributed. One of hydrogen's chief advantages - the ability to be made in various ways and with a diverse array of feedstocks - also complicates decision making with regard to planning for the development of hydrogen production and distribution infrastructure. This project assesses major options for producing hydrogen from fossil and renewable resources.

A.6.1 Specific progress and outputs from the reporting period (previous 3 months)

This research track element has been dormant for the past several months, other than a low ongoing level of activity to track the progress of hydrogen production technologies.

Other relevant items
Overlaps to some extent with CHREC and hydrogen energy station track elements.

A.6.2 Planned progress and outputs for the following reporting period (next 3 months)

No activities planned for this research track element in the next quarter. An updated review of hydrogen production technologies (building on a 2004 Lipman publication ITS-RR-04-10) may be undertaken in 2006.

A.7. <u>Hydrogen Energy Station Economic Analysis (Lipman)</u>

This project consists of economic and environmental analysis of hydrogen energy stations, including costs of electricity and hydrogen, costs compared with competing alternatives, and environmental performance of energy station operation. Various types of energy station technologies, system designs, and locations are being investigated using the CETEEM Matlab model.

A.7.1 Specific progress and outputs from the reporting period (previous 3 months)

Papers and Presentations
Progress made toward a revised energy station analysis report, planned for Summer of 2005.

J. Weinert presented poster paper at the Electric Vehicle Symposium conference that was based in part on this project element.

Models and model development
Continued progress in revising energy station economic and environmental analysis model (CETEEM) and selecting input data for the next set of energy station analysis. The model's economic analysis outputs are being refined and expanded, and additional input data are being developed. Data are being pursued to add alkaline fuel cell systems to the CETEEM analysis, to compare with PEM energy stations. A meeting was held with Cenergie Fuel Cells CEO Nick Abson to request technical specifications on their alkaline system. Data on the Japanese energy market are being prepared for comparison of U.S. vs. Japanese locations. Process of inputting data into Matlab from Excel "test matrix" spreadsheets is being modified to make easier and faster.

Other relevant items
Initial project runs (for the near term) are being prepared, and longer-term analysis cases will be added upon release of the H2A data, expected in July.

A.7.2 Planned progress and outputs for the following reporting period (next 3 months)
The following timeline indicates anticipated milestones for work on this project over following reporting period, and the next year:

April – June 2005: 1) revisions to CETEEM model structure; 2) input data analysis and selection; 3) model runs;

July 2005: 1) revised CETEEM model; and 2) analysis and documentation of PEM fuel cell energy station "near term" cases

August – October 2005: 1) analysis of "longer term" cases based on H2A analysis results, now expected in July and addition of alkaline fuel cell systems (if adequate data can be obtained)

November 2005: 1) documentation of "longer term" cases; 2) overall project report documenting recent analysis revisions, assumptions for cases analyzed, and research results; and 3) Powerpoint presentation of analysis methods/results.

January 2006: 1) analysis of high temperature fuel cell based energy stations initiated

July/August 2006: 2) initial results of high temperature fuel cell based energy station analysis

A.8. Hydrogen Fuel Cell Vehicle Market Research (Kurani)
The market research track consists of several integrated sub-projects. Hydrogen Pathways researchers working in the market research track initiated and completed tasks in several of these sub-projects during the past quarter. These tasks address the following major areas of the market research agenda: 1.) Mobile electricity (ME), 2.) Analogous environmental vehicle markets, and 3.) Linking research with education and outreach (E&O) programs. Some market research efforts planned for this quarter were postponed by the absence of Toyota's FCHVs during this and previous quarters.

1. *Mobile electricity in the context of innovative drivers for FCV markets:*
   ME may be a valued new service provided by electric-drive vehicles. If so, it may profoundly

reorganize the relationship between household (and work-related) activities, mobility, and locales, as well as the related energy use. Thus understanding ME is necessary both to understand markets for FCVs and the ultimate energy and related impacts.

Team members working on this sub-project include Brett Williams, Ken Kurani, and Tom Turrentine. Brett Williams has the primary responsibility for conceptual development and analysis of the tasks described below. Ken Kurani and Tom Turrentine play an advisory role and have conceptual and analytical responsibilities for other tasks in the ME sub-project.

a. Initiated specific market research tasks to characterize the size of the potential market for ME-services, and thus ME-enabled vehicles such as hydrogen fuel cell vehicles. (Detailed description of this overall program is provided in Brett William's dissertation proposal.)
b. Also began to develop co-funding for Hydrogen Pathways ME research through grant proposals to UCEI and UCTC.

2. *Analogous environmental vehicle markets:* In the near-complete absence of opportunities for citizens to interact with FCVs and the complete absence of opportunities for consumers to buy them, research on the role of hydrogen and FCV goals is being conducted in analogous setting. Goals such as sustainability, reduced emissions of greenhouse gases and criteria pollutants, and reduced petroleum consumption have been interjected into the market place through other alternative fuel vehicles and hybrid electric vehicles. These settings allow us to ascertain how consumers respond to vehicles to which these goals have been attached.

   Team members working on this sub-project include Rusty Heffner, Ken Kurani, and Tom Turrentine. Rusty Heffner has the primary responsibility for conceptual development and analysis of the tasks described below. Ken Kurani and Tom Turrentine play an advisory role and have conceptual and analytical responsibilities for other tasks in the environmental vehicle markets sub-project.

   a. Completed a series of 25 household interviews with buyers of hybrid electric vehicles. These interviews explore purchases of "environmental" vehicles and pilot test methods for future FCV research. Starting with hybrid vehicle purchases allows us to ground research in actual choices by consumers, prior to asking respondents to attempt to make hypothetical choices about future FCVs. Though related to FCV market research, this specific set of interviews was entirely funded by non-Pathways sources.

      Report of interim interview results presented at EVS-21 in early April 2005.

3. *Social Marketing and Research: Public Tracking Survey and E&O Programs*
   One of the defining features of social marketing is the explicit incorporation of research on the effectiveness of a given campaign into the overall structure and implementation of the campaign.

   One purpose of this sub-project is to initiate a public tracking study of citizen/consumer awareness, knowledge, and consideration of hydrogen and fuel cells, as well as the larger societal and environmental goals behind the development of alternatives to petroleum-based fuels. While the California Fuel Cell Partnership (CAFCP) has conducted an annual tracking survey of public awareness of hydrogen and fuel cells, results have been held as confidential information. Further, the CAFCP survey has been more narrowly focused on the activities of the partnership and has not surveyed the public on the more general goals of a transition to hydrogen.

Further, as ITS-Davis undertakes hydrogen and fuel cell vehicle demonstrations and education and outreach programs, this market research sub-project develops and implements self-evaluation tools for those programs. The intent is to develop a "culture" of self-evaluation in the design and implementation of these types of tactics (as well as overall social marketing campaigns).

Team members working on this sub-project include Tom Turrentine and Ken Kurani. Tasks a and b below were conducted in coordination with ITS-Davis' Toyota FCHV Demonstration Project and it's manager, Emily Winston. H2 Pathways Co-director Anthony Eggert also contributed to task a.

a. Scoped a major conceptual education and outreach paper.
b. Began a conversation with CAFCP about their annual tracking study and the possibility of ITS-Davis either supporting CAFCP in the future execution of that study. (The currently planned alternative is for the Pathways market research track to conduct an independent tracking study.) These are part of an overall effort to improve the quality of hydrogen and FCV E&O programs by incorporating explicit self-evaluation into such programs.

A.8.1 Specific progress and outputs from the reporting period (previous 3 months)

Papers and Presentations

Analogous environmental vehicle markets
Heffner, R.R., K.S. Kurani, T.S. Turrentine (2005) "Vehicle Image in Hybrid Vehicles." Presentation at EVS-21, Monaco. March.

> This paper describes interim results (of the first 10 interviews) based on initial concepts and theorizing regarding the role of different symbols that manufacturers, buyers, and non-buyers attribute to the early entrants in the hybrid electric vehicle market. Those "early entrants" are the vehicles (Toyota Prius, Honda Insight and Civic) and the people who buy them.

Social Marketing and Research: Public Tracking Survey and E&O Programs
Eggert, Kurani, Turrentine, and Winston—Abstract submitted to NHA (in the previous quarter). Ideas from the paper were incorporated into Eggert's presentation at NHA in early-April '05.

> Abstract called for the application of explicit social marketing frameworks to hydrogen and fuel cell education and outreach programs. Acknowledging that a great deal of E&O has been carried out, we cited some counter-transitional trends that suggest E&O

programs would benefit from evaluation components to track what information the public wants and whether they are getting it. From this specific example, an argument is made that the social marketing framework, as a guide to overall design and implementation, provides important strategic guidance.

Other relevant items—joint activities with the Toyota FCHV Demonstration Program
Questionnaires were distributed to 130 riders in the Toyota Fuel Cell Hybrid Vehicle at the 2005 UC Davis Picnic Day. Based on the analysis of the questionnaire responses, modifications were made to the questionnaire design. As additional education and outreach events are convened, the questionnaire will be re-deployed. The primary goal at this point is to create a survey to track the questions and opinions that participants have about hydrogen and fuel cell vehicles.

Based on vehicle availability, long-term placements of the Toyota FCHVs will begin this quarter. Initially, the Demonstration Program will be testing and finalizing procedures and protocols to handle vehicle loans and refueling. Additionally, the researchers will be exploring diary and journal designs to record significant consumer responses and encourage reflection on the role and meaning of hydrogen and fuel cell vehicles to the respondents.

A.8.2 Planned progress and outputs for the following reporting period (next 3 months)

Papers and Presentations
Analogous environmental vehicle markets
Heffner, Kurani, and Turrentine will begin a journal article detailing the findings of their complete set of interviews on the subject of symbols, and pro-environmental symbols in particular, on the early market for hybrid electric vehicles. Draft paper in preparation. Portions of this paper will be used by Kurani in his presentation at the 10th Biennial Conference on Transportation Energy and Environmental Policy in August 2005.

Mobile electricity in the context of innovative drivers for FCV markets:
Williams will prepare a draft paper on his analysis of broad possibilities and constraints in the California market for Vehicle-to-Grid and other ME markets. Focus here will be on socio-economic and demographic variables of buyers, characteristics of the vehicle and housing stocks, as well as regional conditions. Current plan is to submit the draft to the Transportation Research Board for presentation and publication at the January 2006 Annual Meeting. Drafts are due on August 1, 2005.

Other relevant items
Analogous environmental vehicle markets
Based on evolving plans for Heffner's dissertation, a decision will be made as to whether the next phase of research in this sub-project will be to solidify knowledge around existing symbolic attribution in the market place (by conducting a set of complementary and contrasting interviews with buyers of SUVs and hybrid-SUVs), or move to prospecting symbolic attribution of FCVs.

Social Marketing and Research: Public Tracking Survey and E&O Programs
Public Tracking Study: Kurani and Turrentine will proceed with the design of, what will for now be assumed to be, an independent and public tracking survey for California. We anticipate that

during this quarter, we will meet with CAFCP to share our interim design in the hopes of spurring further interest in their supporting a public study.

Evaluating E&O: The return of the Toyota FCHVs, education and outreach programs has resumed. As planned, these programs are adding evaluation—an assessment of whether we are addressing the questions audiences have about hydrogen and FCVs and how well we are conveying information and experience. This task is also intended to provide forums in which questions for other surveys may be pilot tested. Kurani, Turrentine, and Winston will continue to move to institutionalizing evaluation into all E&O activities—including the design of questionnaires tailored to specific types of E&O activities and audiences. This is intended to be an evolving and continuous process.

Integrated Studies
The integrated studies sub-project draws information and insights from all other sub-projects of the market research track to produce descriptions of FCV markets and market processes that may lead to FCV commercialization.

The integrated studies research plan will be re-written during this quarter to reflect several lessons learned over the preceding quarters. The new plan will shift of the Toyota Fuel Cell Vehicle Demonstration Program from a supporting to ancillary role in the market research. The new plan will incorporate increased engagement of laypersons in the design of "future contexts" in which questions will be posed about hypothetical vehicle purchase and use behavior. A new draft plan will be completed by the end of the quarter.

A.9. Hydrogen Station Siting Strategies for Urban and Rural Regions (Nicholas)

Building upon the work done for Hydrogen Highways, this project is a comparative analysis for metropolitan regions of differing density. The areas chosen for these comparative analyses are in California for convenience, even though the methods applied to examine these regions are applicable to anywhere in the nation. This work is part of the infrastructure modeling program. California as a case study will help develop techniques to apply elsewhere. Already, the methods are being applied to selected areas in France.

Additionally, station siting information can inform other areas of research, and can be benefited by other areas of research. Two areas are important for integration. First, consumer research will help identify customer locations, and improve station siting. Second, station siting information will help inform pipeline infrastructure analyses.

The analyses will examine the main metropolitan areas in California of Sacramento, San Francisco, Los Angeles and San Diego. The extent to which population density and geography affect station coverage and station investment needs is explored.

Station coverage needs are frequently expressed in terms of the percentage of existing stations needed for a minimum network. By evaluating hypothetical station networks in terms of the minimum average travel time to the nearest station, the number of existing stations has no effect on the sufficiency of a station network. The unique geography and population patterns determine the needs of a region. By comparing regions consistently in this manner, customer needs and economics can be more accurately forecast.

A.9.1 Specific progress and outputs from the reporting period (previous 3 months)

Creation of consistent statewide datasets

In keeping with the goals of the overall project, a consistent dataset is needed to compare the four main California regions. Previously, the dataset that produced the fastest results was used. This was accomplished using two primary methods. The first involved reducing the number of stations by K-means clustering. For example there are approximately 4000 stations in the LA region. To reduce computing time for station siting, the number of stations examined was reduced to 400 by using K-means clustering. The second method to reduce station siting computing time was to use a simplified traffic network. These networks are produced by traffic modelers in each of the four metropolitan regions independently. While the results gained using this type of network are consistent within the region being studied, the variability of the network creation from region to region makes comparisons difficult to make.

In order to make consistent datasets for comparison across regions, in California and elsewhere in the country, Streetmap, a road network that is consistent across the U.S. was used to create a driving time matrix. No clustering was used for the stations. The creation of this dataset is extremely time consuming and will have required approximately one and a half months when complete. The process is ongoing.

Steps Completed

- Created a travel time matrix for the Sacramento Metropolitan Area
- Created a travel time matrix for the San Diego Metropolitan Area.
- Creating a travel time matrix for the Los Angeles Metropolitan Area (75% complete)

Papers and Presentations

This work will be submitted to the 2006 TRB conference in Washington D.C.

Models and model development

This project enabled the first implementation of HySS1 station siting extension for use with the ArcView program. The HySS1 extension encompasses many of the processes and procedures used in the station siting process and organizes them into an easy to use interface. More importantly, this extension enables other researchers to more easily complete regional analyses of their own for any part of the country.

Consumer sensitivity to limited refueling networks

As part of the overall goal of understanding and comparing limited refueling networks, this project aims to quantify consumer reaction to limited refueling networks. The main question to be answered is the value a consumer places on fuel availability when making the initial purchase decision of a hydrogen vehicle. This information is useful in infrastructure planning to better determine the ramifications of different infrastructure strategies. For example, knowing how consumers will react to a specific station placement and the general availability of fuel can help determine the demand for fuel. In other words, customer locations are dependent on station placement to some degree, and station size is affected by station placement.

Steps Completed

- Project scoping completed.
- Proposal completed. "Consumer Choice and the Hydrogen Economy: An Integrated Geographic Model of Hydrogen Demand and Supply"

A.9.2 Planned progress and outputs for the following reporting period (next 3 months)

Using the methods developed for the projects described above and consistent with the description in section I, the analysis portion and a rough draft of the comprehensive study of California will be completed. Stations listed by the California Energy Commission will be used as possible hydrogen stations in each metropolitan area. As with previous studies average travel time and station locations will be chosen using the p-median formulation.

The project to determine consumer reaction to limited refueling networks will continue. A literature review will be completed and a methodology will be defined.

Papers and Presentations

A comparative study summarizing the refueling needs of California's four largest metropolitan areas will be submitted to the 2006 Transportation Research Board conference in Washington DC. Rough draft to be completed by July 31.

The consumer choice project will result in a paper presented in a peer reviewed journal. Journal TBD. Estimated completion date March 2006.

A.10. Techno-Economic Assessment of Waste Bio-Hydrogen in CA (Parker)

Biomass based hydrogen has some positive attributes as a transportation fuel. It has low well-to-wheels greenhouse gas emissions and the primary energy source is local and sustainable if implemented with good farming practices. Waste biomass is particularly compelling because it is co-produced with food products and is an environmental detriment if no economically viable end-use is found for it. For this reason, waste biomass feedstock can potentially be a negative or zero cost feedstock. This study is an economic optimization of a waste biomass-to-hydrogen industry in California. The transportation of the biomass feedstock and the product hydrogen is likely to make a significant contribution to total cost of the hydrogen. In order to obtain a good estimate of the availability of bio-hydrogen, transport distances need to be addressed. For this reason, a case study approach is being used. The case study will look at forestry, orchard, and vineyard thinning gasification, agricultural field residue gasification, dairy manure/biogas reforming, and landfill gas reforming.

The following is a brief description of the methodology. Available feedstock and demand centers will be characterized (type of feedstock and size of resource; location, size and density of demand) in a GIS database to determine the distances between them. Engineering-economic models of the conversion process (feedstock collection, feedstock transport, feedstock storage, conversion plant, and hydrogen transport to city-gate) will be developed or adapted from earlier work of the H2 Pathways group. The engineering-economic models will be scalable and will provide the cost per kg hydrogen given a configuration of the conversion process. The final tool to be developed will be an industry-optimizing model. This model will optimize the industry profit given a city-gate selling price of hydrogen and cost of feedstock by choosing the optimal size and location of the conversion plant and the demand center served by the conversion plant. This method will allow for the creation of a waste bio-hydrogen supply curves for different feedstock costs.

A.10.1 Specific progress and outputs from the reporting period (previous 3 months)

Promising first steps were taken on this project. Resource availability in California was analyzed through literature review and the feedstocks of interest for the research were identified (see Table 1). An initial single facility model was developed for rice straw.

The full GIS database of feedstocks and hydrogen demand center was not developed during this period as planned. The method and sources for creating the GIS database were identified for the agricultural residues but not for forestry wastes, animal manures, or landfill gas. Failures to complete these tasks were due to underestimating the tasks.

Papers and Presentations

Poster at the Hydrogen Case Studies Workshop, June 28th-29th

-Presenting initial results of the rice straw single facility case study.

Models and model development

Engineering-economic models of biomass gasification of woody biomass and stover-type biomass were developed. Engineering-economic models for the harvest, transport, and storage of rice straw were also developed. A transportation cost (both feedstock and hydrogen to city-gate) minimization model was employed to identify the most promising sites for conversion facility. A model was also developed in MatLab to calculate the average cost of hydrogen produced at the identified sites over all possible capacities.

Table 1:California Resources for Feedstocks to be Analyzed

Waste Product	Technical Resource (bdt/yr)	H_2 Potential (kg-H_2/day) * approximate estimates
Orchard and Vineyard Waste	1,771,238	420,000
Field and Seed Crops		
-Corn	366,445	77,000
-Wheat	489,999	102,000
-Rice	770,208	177,000
-Cotton	528,271	112,500
Food and Fiber Processing		
-Almond and Walnut Shells	315,728	73,000
-Fruit and Olive Pits	44,335	20,500
-Rice Hulls	275,164	53,000
-Cotton Gin Waste	125,427	24,000

Animal Manures		
-Dairy Cattle	1,823,175	173,000
-Poultry	950,726	137,500
Forestry		
-In-Forest	2,094,269	500,000
-Chaparral	3,077,638	668,000
-Mill Residue	2,025,000	472,000
Landfill Gas	-	670,000
Total		3,680,000

A.10.2 Planned progress and outputs for the following reporting period (next 3 months)

The next quarter will see the full development of the model and the writing of one paper. The paper will be based on current results of the rice straw case study and submitted to TRB. The modeling effort will progress initially as improving the current rice straw single-facility model, then to producing optimal solutions with more than one facility, and finally to expansion of the model to include all of the feedstocks.

The first step of model development will be to include local distribution and refueling costs in the current model. Station sites and demands will be identified through collaboration with Mike Nicholas and Nils Johnson. The hydrogen delivery mode choice will be improved by allowing mixed modes and improving the pipeline model to make logical networks instead of the spoke for each demand center currently used.

The multiple-facility optimization model will be the next step in model development. This step requires research into modeling methodologies. The month of August is designated for the task of developing the optimization model.

Finally the model will be expanded to include all of the feedstocks. This will require the development of engineering-economic models for each feedstocks harvest, transport, storage, and conversion. For the agricultural residues and woody feedstocks the gasification model for rice straw will be modified. For the manure and landfill gas, a biogas reformer model will need to be developed. Each new feedstock should require approximately one week to add to the model.

Papers and Presentations

A Spatially Explicit Economic Analysis of Hydrogen from Rice Straw in California –paper based on results current results, to be submitted to TRB - August 1, 2005

A.11. National Hydrogen Cost Study (Ni)

A.11.1 Specific progress and outputs from the reporting period (May 2005 ~ July 2005)

In this period, our focus is the calculation of hydrogen infrastructure cost (production, distribution, and storage). We will also conduct cost comparison of different H_2 production systems (centralized vs. on-site) as well as the distribution systems (truck vs. pipeline). The following is planned progress and output for this reporting period (May 2005 ~ July 2005)

Papers and Presentations

The H_2 cost study (production, storage, distribution) is the major task for this period. Based on the Census 2000 data of US top 73 most populous metropolitan areas, we first estimated H_2 demand (kg H_2/day) under different market penetration scenarios (e.g. 10% and 50%).

Combining the data of H2 demand, regional energy price from US Energy Information Administration, pipeline and truck delivery costs[1], we are able to determine the levelized cost for hydrogen distribution infrastructure. With the assumption on energy use of electricity and feedstock (e.g. natural gas, coal), we can also calculate the production and the storage cost of H2 system.

The results of this calculation will be on Excel spreadsheets and GIS (ArcMap) maps. The tentative working timeline for this period is: getting the required data in May, building the cost model in June and report writing in July. The final report will be the joint effort by Dr. Joan Ogden, Dr. Christopher Yang, Mr. Nils Johnson and Jason Ni. This paper may be used for internal review (hydrogen researchers and sponsors) and/or submission for NHA conference in 2006. In addition, a poster (including GIS maps) will be done to show the interim results on the Hydrogen Case Study workshop in June 28, 29 at UC Davis.

Models and model development

The final product of this period of work is a cost model for hydrogen infrastructure. As mentioned, we will combine the production cost with storage and distribution cost. Also, we will compare several scenarios as shown in the following:

PRODUCTION METHOD	DISTRIBUTION METHOD	MARKET PENETRATION RATE
Centralized SMR, CO_2 vented	Pipe/Truck	10%, 50%, 70%
Centralized SMR, CO_2 captured	Pipe/Truck	10%, 50%, 70%
Centralized Coal Gasifier, CO_2 vented	Pipe/Truck	10%, 50%, 70%
Centralized Coal Gasifier, CO_2 captured	Pipe/Truck	10%, 50%, 70%
On-Site SMR, CO_2 vented	-	10%, 50%, 70%

[1] Using Chris Yang's idealized city model for the pipeline/truck cost functions

As shown, the first four models are centralized production method for H_2. After we get the cost model, we will compare those models with the on-site production and see under what market penetration the centralize production will beat the on-site production in terms of the lowest cost. A series of GIS maps will also be generated to show that transition.

A.12. <u>Investigating the indirect global warming effect of NOx emissions (Riffel)</u>

The goal of this project is to investigate the overall global warming potential of NO_x emissions in terms of CO_2-equivalence factors. This net effect is the sum of numerous atmospheric and surface effects. Positive climate forcing effects include increased tropospheric ozone levels (O_3) due to reaction with VOC (volatile organic compounds), and increased N_2O levels from soil nitrogen fixing. Indirect negative climate forcing effects are decreased CO_2, decreases in methane levels and increased ambient lifetimes, and increased particulate nitrate levels. The overall expected effect is slightly negative climate forcing and sensitivity to emissions is uncertain. The goal is to provide detailed analysis of the implications of NO_x emissions on climate change for use in the Life-cycle Emissions Model (LEM) and air quality policy analysis.

A.12.1 Specific progress and outputs from the reporting period (previous 3 months)

The current focus of the analysis is the effect of NO_x emissions on methane and ozone concentrations in both the north and southern hemispheres. Specifically, we are interested in obtaining values of grams methane reduced per gram of NO_x emitted and grams ozone produced per gram NO_x emitted. Much research has been devoted to this question over the last decade and many models have been constructed to analyze this issue; unfortunately, literature values for these effects differ by more than order of magnitude and further investigation is necessary to understand the differing assumptions of the various available models and how these assumptions influence the relevant factors. Currently, I am sifting through the details of the models to understand their inner workings, assumptions and shortcomings. Probable culprits of disagreement in the literature include inadequate treatment of NO_x transport due to PAN (peroxyacetyl nitrate) formation, spatial resolution inadequacy and differences in initial configuration and location of NO_x emissions (geographic location and ground level vs. aloft).

A.12.2 Planned progress and outputs for the following reporting period (next 3 months)

Over the next three months I will finish analysis of the ozone and methane effects of NO_x emissions and begin drafting a comprehensive paper of the all of the effects (discussed above) of NO_x emissions for publication. I will also begin work on an emission project for light duty vehicles and trucks by determining and inputting emission factors for different categories of light duty vehicles (the truck section is nearly complete).

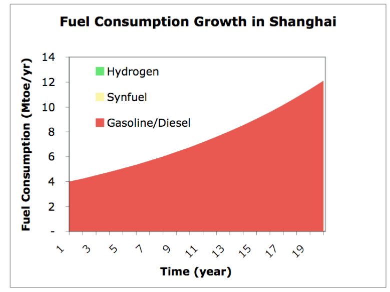
Papers and Presentations

Two papers are planned for the future, including a paper discussing the indirect NO_x climate forcing effects in detail and a paper that effectively condenses the content of Mark Delucchi's Appendix D of the LEM literature into an article. This latter publication will focus on the carbon dioxide equivalency factors of all greenhouse gases.

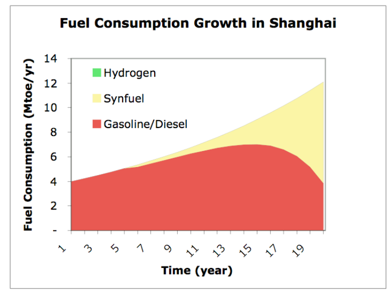
A.13. Fuel Transition Costs in China: Hydrogen Fuel Leapfrogging vs. Synfuels (Weinert)

This dissertation will evaluate and compare three fuel development scenarios for the city of Shanghai from a technical, economic, and environmental perspective:

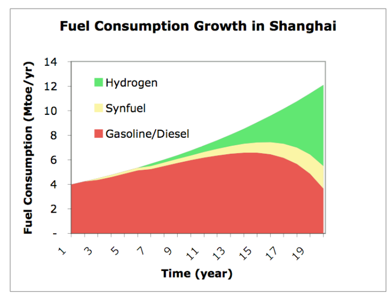
Scenario 1: Business as Usual –
Shanghai continues to build-up its gasoline/diesel infrastructure to serve the growing number of internal combustion engine vehicles. Alternative fuels play a small role in the transportation sector.



Scenario 2: Transition to Synthetic Liquid Fuels:
Shanghai builds a gasoline/diesel system but gradually transitions to liquid alternatives such as Fischer-Tropsch liquids and methanol using coal and natural gas feedstocks. Hydrogen plays a limited role in the transportation sector.



Scenario 3: 'Leap-frog' to Hydrogen: Shanghai invests in hydrogen fuel infrastructure (based on coal, natural gas, and biomass feedstocks) early and gradually transitions away from liquid fuels.



Some studies on alternative fuel infrastructure costs suggest the cost of installing new gasoline infrastructure would be similar to building new hydrogen infrastructure.2 If true, this could impact near-term infrastructure investment decisions. Few studies have explored the cost of building a synfuel-based infrastructure. No studies have yet compared these costs against each other.

The main goal of this research is to determine the trade-offs in cost and emissions of three different fuel paths pursued by Shanghai gov't and industry. Through this analysis, I will also determine what conditions need to be in place and at what time for the leapfrog scenario to be economical. The conditions to be considered are vehicle availability, fuel production/distribution availability, feedstock costs and supply.

[2] (Mintz et al. 2004, Thomas et al. 2001)

A.13.1 Specific progress and outputs from the reporting period (previous 3 months)

- Dissertation Proposal, version 1.4
- Literature Review on fuel transitions, hydrogen infrastructure in China, and liquid coal-based synfuel infrastructure

A.14. <u>Economics of Hydrogen Refueling Stations: Scale Economies and Learning Curves (Weinert)</u>

Joan and I have been working on a paper to submit to the International Journal of Hydrogen Energy. This paper will build off my Master's thesis and explore the affect of production volume and station scale on hydrogen cost. We plan to finish this paper by June.

In earlier work, we estimated costs for current stations (Weinert 2005 NHA), and longer term infrastructure costs (Ogden 1999). In this paper, we address the question of how long it will take for current hydrogen refueling infrastructure costs to come down to long-term levels. Several near to mid term H2 supply pathways are considered including:

- Central production of H2 from SMR
- Central production of H2 from biomass
    - For central hydrogen production we consider: delivery by mobile refuelers, tube trailers, LH2 trucks or pipeline
- Onsite production at refueling stations via small scale SMR,
- Onsite production at refueling stations via small electrolyzers

We have developed an economic model to estimate current costs for hydrogen stations, including equipment costs for stations, O&M costs, and non-equipment costs (permitting, etc.) as function of station size. We also estimate projected future costs for refueling stations, based on learning curves for equipment, and based on possibilities to reduce other costs such as permitting, (using experiences with CNG and gasoline as examples), as a function of the number of stations built (Weinert 2005– MS Thesis). Starting with scenarios for increasing hydrogen demand, we calculate the number and size of stations required over time (assuming that a minimum of 10% station coverage is needed for customer convenience). We then ask how much hydrogen and how many vehicles will be required to reach long-term costs. We find the cost of infrastructure over time for each option, and for a mix of station types. Finally, we estimate how much investment in refueling infrastructure would be needed over time to bring hydrogen refueling costs to long term projections.

A.14.1 Specific progress and outputs from the reporting period (previous 3 months)

Incomplete draft version of the report available

A.14.2 Planned progress and outputs for the following reporting period (next 3 months)

Continue working on the paper. Aim for completion in July.

Papers and Presentations

Economics of Hydrogen Refueling Stations: Scale Economies and Learning Curves*, Submit to IHJE*

Models and model development
Modify the Hydrogen Station Cost Model (developed in 2004)

A.15. Oil based Transportation Fuel Infrastructure Investment Projections (Ritchey)

This project consists of a well-to-tank economic analysis of the current transportation fuels infrastructure, mainly gasoline and diesel, for the purpose of comparison to perceived Hydrogen infrastructure costs. We wish to characterize investment requirements in both upstream and downstream transportation fuels pathways. The 'Upstream' pathway is defined as oil production processes that occur from the beginning stages of oil exploration to the final stages of the oil refining process. Global upstream investment requirements have been estimated and put forward by the International Energy Agency in the *World Energy Investment Outlook, 2003 Insights*. We would like to disaggregate these projected investments to enable regional (e.g. California) investment projections that are specific to the transportation sector of the economy. Similarly, we would like to have investment projections for the 'downstream' pathway, which includes processes that occur from the distribution of the refined product to the filling of a vehicle fuel tank. The projected investments over a given time period can then be combined, using demand profiles to obtain the total amount of required investment, which can then be used in comparison to investments required to build a Hydrogen fuel infrastructure.

A.15.1 Specific progress and outputs from the reporting period (April 1, 2005 – June 30, 2005)

The present reporting period has thus far focused on understanding the research question, searching for and reviewing relevant literature, and clarifying a research plan.

Papers and Presentations
The question originally motivating this research was whether or not there is in existence a study which estimates a total cost of the transportation fuels infrastructure as well as the investments that will be required to maintain the infrastructure in order to meet continuing and growing demand. The initial literature review turned up the IEA's *World Energy Investment Outlook, 2003 Insights*, which is an extensive analysis of global energy investment requirements and is based on the demand scenario used in the *World Energy Outlook, 2002*. I have begun a (white?) paper summarizing the *WEIO*'s projections for oil investment and expect to finish it by the end of the current reporting period.

Initial findings and progress presented to the Hydrogen Pathways Program Seminar: *Petroleum Infrastructure Future Investment Requirements*, May 26, 2005.

Models and model development
An appropriate analytic framework needs to be developed which enables the combination of upstream and downstream investment figures for a specific region, California for example. I am currently taking a course concerning integrated resource planning, which uses the Long-range Energy Alternatives Planning (LEAP) software as the analysis tool. I intend to determine the usefulness of this software in developing the desired framework by the end of this reporting period.

A.15.2 Planned progress and outputs for the following reporting period (July 1, 2005 – September 31, 2005)

A literature review for downstream costs and investment requirements needs to be conducted. If the search does not return desired information, relevant regional data to be used in an appropriate algorithm and framework, such as costs and investments associated with gasoline/diesel distribution and also refueling stations as well as data concerning future demand for gasoline/diesel, need to be collected. Collecting and analyzing this data in an appropriate framework will be the main focus of the next reporting period.

Papers and Presentations

A summary of the search results and next steps will be written and possibly presented during the next reporting period.

Models and model development

An overall goal in developing a model for this project could be to develop a model that can easily be modified to analyze different regional cases.

A.16. Exploring biomass and coal to hydrogen pathways (Wang)

Over the past 2 months, the following 4 hydrogen pathways have been explored, and special attention has been given to the hydrogen production modules, i.e., the biomass or coal to hydrogen conversion steps.

1) H2 from coal, without CO2 sequestration
2) H2 from coal, with CO2 sequestration
3) H2 from biomass, without CO2 sequestration
4) H2 from biomass, with CO2 sequestration

This task is part of the project of extending Lifecycle Emissions Model (LEM model) to include the brand new hydrogen pathways: coal to hydrogen, and biomass to hydrogen. The pathway step of hydrogen production is very important compared to other pathway step of the full fuel cycle in terms of energy use and emissions.

A.16.1 Specific progress and outputs from the reporting period (previous 2 months)

Extending LEM model to include coal and biomass to hydrogen pathways will provide researchers a tool to examine the full fuel cycle energy use and emissions associated with the hydrogen pathways. By doing a high-level literature review, the complete and detailed tables of energy and materials input-output for the conversion processes above have been made in the format of MS Word file, which play an important role in investigating the full hydrogen pathways.

A.16.2 Planned progress and outputs for the following reporting period (next 3 months)
The finished input and output tables will be made into Appendix K of the LEM documentation by Dr Mark Delucchi. The main report of currently-available LEM documentation can be found following the link:

http://its.ucdavis.edu/publications/2003/UCD-ITS-RR-03-17-MAIN.pdf

A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials. MAIN REPORT. Delucchi, Mark A. *ITS-Davis*. December 2003. Publication No. UCD-ITS-RR-03-17-MAIN REPORT.

A.17. Estimating social costs for hydrogen pathways (Wang)

This part of research will explore the social costs related to some certain hydrogen pathways (either currently popular hydrogen pathways like NG-to-H2 or potentially promising hydrogen pathways like coal-to-H2) from a lifecycle perspective.

Based on the environmental impacts of hydrogen pathways, social welfare losses (mainly attributable to human health damage) could be estimated in the following manner, i.e., so-called multistage damage function approach: source emissions (pollution source inventories)→ pollutant dispersion (atmospheric transfer/transformation models)→ impacts on human health (dose-response functions)→ monetary costs (economic evaluation).

A.17.1 Specific progress and outputs from the reporting period (previous 2 months)
Some literature associated with this huge topic has been reviewed. Applied to the research will be the damage function approach, or called impact pathway approach (IPA). Among the important literature are as follows.

1. ExternE report (1998): http://www.externe.info/

2. Some of ITS-Davis Social Cost series reports (1996), such as report 11: http://its.ucdavis.edu/publications/1996/rr-96-03-11.pdf

The Social Cost of the Health Effects of Motor-Vehicle Air Pollution. McCubbin, Donald R., Delucchi, Mark A. August 1996. Publication No. UCD-ITS-RR-96-03 (11).

A.17.2 Planned progress and outputs for the following reporting period (next 3 months)
The level of detail that the research requires in order to estimate the social costs still needs to be considered when I use some currently available damage-function results, pathway step emissions results, and atmospheric models for my further research.

A research proposal on how to deal with the association between social costs and hydrogen pathways' emissions will be drafted during the subsequent reporting period.

The model to estimate emissions and energy use associated with each pathway step of several typical hydrogen pathways will be established so that the emission inventories can be compiled, which is the first step of IPA approach to estimating social costs.

A.18. <u>Development of a Corporate Average Fuel Index (cafi) for the reduction of CO2 emissions from motor vehicles (Hughes)</u>

The dissertation project will evaluate the role of market based policies for the transportation fuel industry in a transition to a hydrogen based transportation system. The goal is to determine how policy may affect the development of a hydrogen based transportation system. In the case of addressing the challenge of global climate change in particular, a large number of policies have been proposed including: emissions standards, carbon taxes, vehicle technology mandates, feebates, fuel economy standards, marketable emission licenses and fuel composition standards. This project will evaluate a specific policy proposal, a corporate average fuel index (CAFI) whereby the carbon content of transportation fuels is quantified and fuel producers are subject to a CAFI standard for the fuels they sell. The system will include averaging, banking and trading (CAFI ABT) will be designed to provide fuel producers with increased flexibility in meeting the standard. The project will assess the properties of the CAFI system relative to other policy alternatives and will analyze the potential impact of such a system on the development of hydrogen fuel cell vehicles.

A.18.1 Specific progress and outputs from the reporting period (previous 3 months)

During the past quarter two draft reports have been completed. Each report represents initial progress on one of two main tracks of the research project: Social welfare implication of policies to control CO_2 emissions from light-duty vehicles, vehicle versus fuel regulation; and scenario analysis of a CAFI fuel standard and implied alternative fuel market penetration.

Draft Report: Vehicle versus Fuel Regulation in Policies to Control CO_2 Emissions from Light-Duty Vehicles

As a result of recent initiates to address concerns over global climate change, regulations to control carbon dioxide emissions from light-duty motor vehicles have become a topic of growing interest among local, regional and national policymakers. A key question is how to evaluate various alternatives in order to formulate policies which offer the largest benefits to society. Applied welfare economics provides a framework for considering this issue. Here, a simple model is developed to evaluate the social welfare effects of two major policy alternatives for controlling the emissions of carbon dioxide from motor vehicles namely, vehicle fuel standards and vehicle efficiency standards. An empirical example is developed using data for the United States and emission standards set by the California greenhouse gas law (AB 1493). Analysis of this example strongly suggests that fuel technology regulations provide significantly greater increases in social welfare relative to vehicle technology regulations for reasonable assumptions about future markets and technologies.

Draft Report: A Corporate Average Fuel Index for Reducing CO_2 Emissions from Light-Duty Vehicles

Emissions of greenhouse gases from transportation, primarily CO_2, represent a significant and growing share of worldwide emissions. It has been suggested that a fuel carbon composition standard or "corporate average fuel index" (CAFI) could be used to reduce CO_2 emissions from light-duty vehicles through the development of low carbon alternative fuels. In a CAFI system, the carbon content of transportation fuels are quantified and fuel sales are subject to an average performance standard. Emissions are reduced over time by requiring an increasing percentage of low carbon fuels as the CAFI standard is decreased.

This paper investigates the ability of a CAFI system to reduce CO_2 emissions from light-duty vehicles. Using California as a case study, the paper addresses two fundamental questions: 1.) What CAFI standards are required to achieve CO_2 emission reductions equivalent to those estimated for the California greenhouse gas law and 2.) What do these CAFI standards imply about the viability of a CAFI system in terms of the required penetration of alternative fuel and vehicle technologies? An empirical example is developed to demonstrate that CAFI can serve as an effective policy for reducing CO_2 emissions from light-duty vehicles. Achievement of relatively modest near-term emission reductions such as those developed in the context of the California greenhouse gas law implies significant investment in alternative fuel infrastructure and vehicles. However, because CAFI is currently the only comprehensive framework for quantifying and regulating the CO_2 emission characteristics of fuels, it can serve an important role as a long-term policy instrument for the transition to a lower carbon transportation system.

Papers and Presentations
Hughes, J.E., *Vehicle versus Fuel Regulation in Policies to Control CO_2 Emissions from Light-Duty Vehicles*, Draft Report, June 9, 2005.

Hughes, J.E., *A Corporate Average Fuel Index for Reducing CO_2 Emissions from Light-Duty Vehicles*, Draft Report, June 9, 2005.

A.18.2 Planned progress and outputs for the following reporting period (next 3 months)

During the quarter ending September 30, 2005, the draft reports described above will be refined and developed into final research reports. The goals of each research project are summarized below. The research team will seek feedback from Hydrogen Pathways program sponsors during the process of refining and finalizing the research. By the end of the quarter, the research team will have research reports available from distribution and will pursue publication of research results in scholarly journals.

<u>Optimal Regulation/taxation Relating for a System of Motor Vehicles and Fuels</u>
Using tools from social welfare economics, the social benefits and costs of regulating passenger vehicle GHG emissions at the vehicle level versus the fuel producer level versus a combined system will be analyzed. The goal is to determine the trade offs in terms of social surplus (and distribution effects, consumer and producer surplus) for regulating different components of the fuel-vehicle system as a means of guiding policy. While determining exact relationships and

quantities is difficult given uncertainty in determining supply and demand curves for markets within the transportation fuels system, the goal of the work is to illustrate relationships based on values of fundamental properties of the market (e.g. price elasticity of fuel).

Scenario Analysis of a CAFI Fuel Standard and Alternative Fuel Market Penetration
As an initial analysis of the properties of a corporate average fuel index (CAFI) for the control of GHG emissions from motor vehicles, I propose a scenario analysis of various GHG reduction targets. The analysis consists of two parts: 1.) For given GHG emission targets (e.g. "Kyoto like" 1990 passenger vehicle emission levels by 2020) determine various schedules of CAFI standards that would be required to meet emissions goals based on estimates for future motor vehicle travel, and 2.) For the various CAFI standard schedules, determine the implicit levels of market penetration of alternative transportation fuels and vehicles that would be required (e.g. hydrogen fuel cell vehicles with 80/20 SMR green electrolysis mix or dedicated CNG vehicles). The goal is to illustrate the potential of a CAFI system on reducing GHG emissions without yet addressing the issues of cost-effectiveness or efficiency.

Throughout, the project I will continue to be important to engage Hydrogen Pathways program sponsors in issues relating to this project and long-term GHG reduction policy in transportation. One near-term goal is to establish contact with interested individuals at sponsor organizations to explore opportunities for collaboration and information exchange (perhaps as part of the upcoming Asilomar conference).

Papers and Presentations
Working papers completed for both projects described above: *Vehicle versus Fuel Regulation in Policies to Control CO_2 Emissions from Light-Duty Vehicles* and *A Corporate Average Fuel Index for Reducing CO_2 Emissions from Light-Duty Vehicles*.

Models and model development
Social Welfare Policy Model for Regulation of LDV CO_2 Emissions
CAFI Scenario Model

A.19. Hydrogen Technology Learning Centers for FL, CA and NY (Hughes)

The UC Davis hydrogen technology learning center will focus on the creation of an exportable interdisciplinary curriculum for hydrogen education on the university level. The goal is to create materials that can be broadly distributed and used to provide future leaders in the hydrogen economy with experience in: methods of energy and cost life-cycle analysis; energy and transportation policy dynamics; energy infrastructure modeling; market research and consumer behavior; and hydrogen safety, codes and standards.

As part of the Hydrogen Technology Learning Centers project, I am working to develop and educational curriculum and educational material for a Hydrogen Pathways university level graduate course. In addition, I am involved in planning two additional deliverables for the program, a series of hydrogen educational modules for middle and high school students and a university level fuel cell systems laboratory course.

Other relevant items
The majority of the work is co-funded through State Technologies Advancement Collaborative (STAC) Program: Energy Efficiency Research, Development, Demonstration, and Deployment Projects (03-STAC-1)

A.19.1 Planned progress and outputs for the following reporting period (next 3 months)
During the next quarter, the team will continue to develop content for the various lectures and topic areas of the hydrogen economy graduate course. These will include: lectures; background reading materials; practice problem and homework sets; and a detailed description (and example) of the final hydrogen system design project.

A.20. URL Location for Relevant References

A Near-Term Economic Analysis of Hydrogen Fueling Stations. Weinert, Jonathan. *ITS-Davis.* April 2005. UCD-ITS-RP-05-06. http://www.its.ucdavis.edu/publications/2005/UCD-ITS-RR-05-06.pdf

Assessing Reliability In Hydrogen Supply Pathways. McCarthy, Ryan; Ogden, Joan. *Partnering for the Global Hydrogen Future, NHA Conference*. April 2005. UCD-ITS-RP-05-12. http://www.its.ucdavis.edu/publications/2005/UCD-ITS-RP-05-12.pdf

Estimating Hydrogen Demand Distribution Using Geographic Information Systems (GIS). Ni, Jason; Johnson, Nils; Ogden, Joan; Yang, Chris; Johnston, Joshua. *Partnering for the Global Hydrogen Future, NHA Conference*. April 2005. UCD-ITS-RP-05-19. http://www.its.ucdavis.edu/publications/2005/UCD-ITS-RP-05-19.pdf

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