VIII.11 System Dynamics: HyDIVE (Hydrogen Dynamic Infrastructure and Vehicle Evolution) Model

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Objectives

- Quantify the effect of limited fueling station coverage on hydrogen vehicle demand.
- Estimate the required vehicle price, fuel cost, and make/model availability to achieve, in equilibrium, various DOE sales targets for two station configurations.

Technical Barriers

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

(A) Future Market Behavior

Contribution to Achievement of DOE Systems Analysis Milestones

This project will contribute to achievement of the following DOE Systems Analysis milestones from the Systems Analysis section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- **Milestone 4**: Complete a "lessons learned" study of the development of other infrastructures which apply to hydrogen fuel and vehicles. (4Q, 2008)
- **Milestone 5**: Complete analysis and studies of resource/feedstock, production/delivery and existing infrastructure for various hydrogen scenarios. (4Q, 2009)

Accomplishments

- Estimated the forecast "equilibrium" vehicle sales parametrically for two station configurations (400 stations and 750 stations in the Los Angeles area), three fuel prices, three vehicle cost differences, and three levels of vehicle model availability (for a total of 54 "equilibrium" vehicle sales forecasts).
- Quantified the sensitivity of consumers to various spatial attributes of fueling station convenience.

Introduction

The National Renewable Energy Laboratory (NREL) has been developing a spatial, dynamic model called HyDIVE™ (Hydrogen Dynamic Infrastructure and Vehicle Evolution) to permit rigorous analysis of the interdependence between hydrogen fuel cell vehicle (FCV) demand growth and hydrogen fueling station coverage. The foundation for HyDIVE™ was developed by researchers at the Massachusetts Institute of Technology [1], with partial funding from NREL. NREL has since expanded and modified the model to suit its analysis needs. Early analyses with HyDIVE™ [2] revealed that consumer sensitivity to the reduced convenience afforded by limited hydrogen fueling station coverage is a key driver of growth dynamics. However, the degree to which consumers will be sensitive to the reduced vehicle utility that results from limited hydrogen station coverage is not well understood, and has not been adequately addressed in the literature. This work addresses that research gap.

Approach

HyDIVE™ is a spatial, behavioral, and dynamic market simulation model. The modeling methodology is system dynamics, a field invented in the 1950s at the Massachusetts Institute of Technology to analyze the time-changing behavior of complex systems. Macro-level market behavior is determined by micro-level decisions of individual "economic agents" (e.g., station owners and vehicle purchasers) explicitly represented in the model.

Discrete choice analysis was used to statistically estimate the parameters of the vehicle choice model.

Consumers were presented with various products, each with specified attributes such as price, and were asked to choose the product they were most likely to purchase. By collecting numerous responses, and by varying the levels of product attributes per an efficient design of experiment, we can ascertain the relative contribution of each attribute to the likelihood of product purchase.

Results

Tables 1 and 2 illustrate the forecast "equilibrium" vehicle sales parametrically for two station configurations (400 stations and 750 stations in the Los Angeles area), three fuel prices, three vehicle cost differences, and three levels of vehicle model availability. Initial HyDIVE™ analysis indicates that to achieve (in equilibrium) the target DOE sales volumes [3] for 2020 and 2022[1] (with 400 and 750 stations, respectively), that hydrogen fuel cell power trains must be offered in roughly 20 vehicle models[2] at a price (net of incentives) equivalent to a comparable performance gasoline vehicle (about 15% cheaper for the 2022 target), with fuel price in the $2 to $3/kg range. The forecast sales volumes per HyDIVE™ are upper bound, equilibrium forecasts (for a given constant number of fueling stations), would not necessarily correspond with the 2020 or 2022 target *year* for those sales volumes (due to other dynamics not yet incorporated that would tend to delay the forecast sales), and may be optimistic because consumers tend to overstate willingness to pay or make sacrifices in convenience for environmental benefits.

Figure 1 illustrates the calculated sensitivity of consumers to the various vehicle and station convenience attributes considered in the discrete choice analysis. The "reference case" in Figure 1 corresponds with having 100% availability of hydrogen fueling stations and the same vehicle price and fuel cost. Sensitivities to these parameters vary, however, for different reference cases. In general, the sensitivities tend to be greater at lower levels of initial station coverage. The following insights were gleaned through the analysis of the consumer sensitivity to various vehicle and station convenience attributes (see Figure 1) as one deviates from the reference case of perfect parity on all attributes relative to a gasoline internal combustion engine:

- Even though long-distance trips[3] represent a very small fraction of a consumer's trips; an inability to take such trips has a significant impact on a

[1] Target vehicle sales provided by DOE for 2020 (in the Los Angeles area) were 55,000, 130,000, and 160,000 for scenarios 1, 2, and 3, respectively. Target vehicle sales provided by DOE (in the Los Angeles area) for 2022 were 85,000, 150,000, and 210,000 for scenarios 1, 2, and 3, respectively.
[2] Current analysis assumes the vehicle models would be similar to the top 20 vehicle models. If offered in less popular models, more vehicle models would need to offer a hydrogen fuel cell power train.
[3] Long-distance trips are defined as those longer than one-half the vehicle range from the driver's home (about 150 miles for a vehicle with a 300-mile range).

TABLE 1. Los Angeles Area Forecast Hydrogen FCV Sales, Scenario Targets (400 Station Layout)

Los Angeles Area: Forecast Hydrogen FCV Sales and Scenario Targets			HyDIVE™ Equilibrium Upper Bound Sales/Year[1]
# Vehicle Models[2]	Vehicle Price (% diff. rel. to gas ICE)[3]	H2 Price ($/kg, before taxes)[4]	w/400 Stations
10	−15	2	130,000
10	−15	3	123,000
10	−15	4	117,000
10	0	2	112,000
10	0	3	105,000
10	0	4	99,000
10	15	2	94,000
10	15	3	87,000
10	15	4	81,000
15	−15	2	163,000
15	−15	3	155,000
15	−15	4	147,000
15	0	2	141,000
15	0	3	133,000
15	0	4	124,000
15	15	2	118,000
15	15	3	110,000
15	15	4	102,000
20	−15	2	191,000
20	−15	3	181,000
20	−15	4	172,000
20	0	2	165,000
20	0	3	155,000
20	0	4	145,000
20	15	2	138,000
20	15	3	129,000
20	15	4	119,000

[1] This static forecast is considered to be an upper bound, equilibrium level per HyDIVE™ calculations. See Welch 2007 for the caveats associated with using this equilibrium value. Hydrogen FCV performance is assumed to be equivalent to gasoline ICEs. For this initial estimate, hydrogen FCVs compete only with gasoline ICEs (i.e., not with gasoline–electric hybrids). Competition with gasoline–electric hybrids would reduce these forecast sales volumes somewhat, depending on the success level of hybrid vehicles.
[2] For calculating equilibrium vehicle sales, FCVs are assumed to be offered in vehicles similar to the top selling gasoline ICE models. If offered in less popular models, forecast sales would be lower. Hydrogen FCV range is assumed to be 300 miles in this table only.
[3] Price difference (including incentives) is relative to that of an equivalent performance gasoline ICE.
[4] The actual price paid at the pump, for the purpose of forecasting, is assumed to include an additional $0.55/kg for state and federal taxes (about $0.55/gal for gasoline in California). The gasoline price, which affects the relative fuel cost savings and therefore hydrogen FCV sales, is assumed to be $2.64/gal [$2.67/gal], including taxes, per AEO's high price scenario for 2020 [2022] (EIA 2006). A fuel economy ratio of 2.4 is assumed (per DOE guidance) for hydrogen FCVs over conventional gasoline ICEs (again, hybrid competition is not yet included).

TABLE 2. Los Angeles Area Forecast Hydrogen FCV Sales, Scenario Targets (750 Station Layout)

Los Angeles Area: Forecast Hydrogen FCV Sales and Scenario Targets			HyDIVE™ Equilibrium Upper Bound Sales/Year[1]
# Vehicle Models [2]	Vehicle Price (% diff. rel. to gas ICE)[3]	H2 Price ($/kg, before taxes)[4]	w/750 Stations
10	−15	2	155,000
10	−15	3	148,000
10	−15	4	141,000
10	0	2	135,000
10	0	3	128,000
10	0	4	120,000
10	15	2	115,000
10	15	3	107,000
10	15	4	100,000
15	−15	2	195,000
15	−15	3	186,000
15	−15	4	177,000
15	0	2	170,000
15	0	3	161,000
15	0	4	151,000
15	15	2	144,000
15	15	3	135,000
15	15	4	125,000
20	−15	2	228,000
20	−15	3	218,000
20	−15	4	207,000
20	0	2	199,000
20	0	3	188,000
20	0	4	177,000
20	15	2	169,000
20	15	3	158,000
20	15	4	147,000

[1] This static forecast is considered to be an upper bound, equilibrium level per HyDIVE™ calculations. See Welch 2007 for the caveats associated with using this equilibrium value. Hydrogen FCV performance is assumed to be equivalent to gasoline ICEs. For this initial estimate, hydrogen FCVs compete only with gasoline ICEs (i.e., not with gasoline–electric hybrids). Competition with gasoline–electric hybrids would reduce these forecast sales volumes somewhat, depending on the success level of hybrid vehicles.
[2] For calculating equilibrium vehicle sales, FCVs are assumed to be offered in vehicles similar to the top selling gasoline ICE models. If offered in less popular models, forecast sales would be lower. Hydrogen FCV range is assumed to be 300 miles in this table only.
[3] Price difference (including incentives) is relative to that of an equivalent performance gasoline ICE.
[4] The actual price paid at the pump, for the purpose of forecasting, is assumed to include an additional $0.55/kg for state and federal taxes (about $0.55/gal for gasoline in California). The gasoline price, which affects the relative fuel cost savings and therefore hydrogen FCV sales, is assumed to be $2.64/gal [$2.67/gal], including taxes, per AEO's high price scenario for 2020 [2022] (EIA 2006). A fuel economy ratio of 2.4 is assumed (per DOE guidance) for hydrogen FCVs over conventional gasoline ICEs (again, hybrid competition is not yet included).

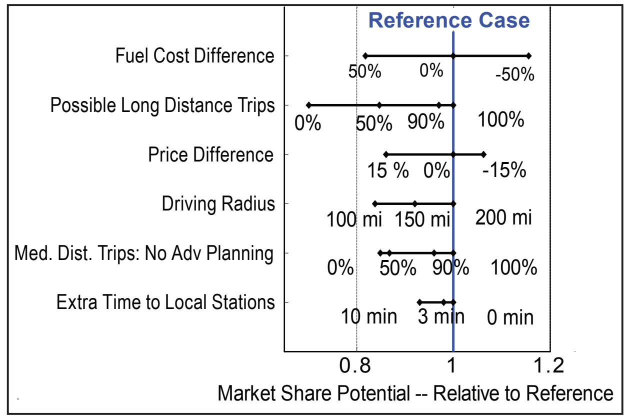

FIGURE 1. Attribute Sensitivity Chart—Reference Case = 100% Availability of Hydrogen Fuel

consumer's likelihood of purchasing a vehicle. For example, roughly a 30% *reduction* in market share is forecast if one reduces the possible long-distance trips from 100% to 0% (e.g., due to limited station coverage). Conversely, about a 43% (1/(1-0.3)) *increase* in market share is forecast if one increases from 0% to 100% the possible long-distance trips.

- Fueling station coverage for "medium-distance trips"[4] is also a significant factor in determining a consumer's likelihood to purchase a hydrogen vehicle. For example, if there is no fueling station coverage for long-distance trips (e.g., >150 miles), and if there are no stations in the medium-distance region (e.g., 20 to 150 miles from home), about a 45% reduction in market share is estimated relative to having 100% station coverage for medium- and long-distance trips.
- The effect of changing the fueling station coverage for medium-distance trips is highly nonlinear. Such nonlinearity indicates that a high degree of station coverage in the medium-distance region is required before a significant increase in forecast market share results (i.e., increasing coverage of medium distance trips from 50% to 100% has a greater effect than increasing coverage from 0% to 50%).
- *Increases* in vehicle price result in more significant changes in forecast market share than do *decreases* in vehicle price (relative to the price of an equivalent performing gasoline vehicle). Recognition of this effect suggests that government incentives to make hydrogen vehicles "price-equivalent" may be important, but that diminishing returns may be experienced with attempts to further stimulate sales

[4] Medium-distance trips are defined as those between 20 miles and one-half the vehicle range (e.g., 150 miles for a vehicle with a 300-mile range) from home.

via incentives that make hydrogen vehicles *cheaper* than conventional gasoline vehicles.[5]

- The data indicate that the effect of extra time traveled to local stations is not as large as anticipated, and that below five to ten minutes to the nearest station, the effect on vehicle purchase probability of improving station coverage is not large. Future analyses will cross-check this result, as it has implications for station introduction strategies.
- A fuel cost difference of +/- 50% is calculated to have roughly a 15-20% impact on the likelihood of vehicle purchase. Future analyses will compare this elasticity effect with the body of literature on elasticity of demand to fuel costs.
- A decrease in vehicle range from 400 miles to 200 miles (200 mile driving radius to 100 mile driving radius) is estimated to reduce forecast vehicle sales by roughly 16%. Further reductions in vehicle range are expected to have a highly nonlinear impact on vehicle sales, but data were not collected outside this range, so nonlinearity was not detected.

Conclusions and Future Directions

- This analysis quantified that fueling station coverage can be a significant barrier to market penetration of hydrogen vehicles and that careful consideration of the dynamic interdependence between fueling station growth and hydrogen vehicle growth is vital to informing transition strategy and policy.
- Future work will use a modified characterization of fueling station coverage that will focus on illustrating via maps the various levels of station convenience to cross-check the results of this analysis.
- Future work will also include other relevant dynamics into HyDIVE™ such that dynamic analysis, which can inform policy and strategy decisions, can be performed to complement the static analyses reported herein.

Special Recognitions & Awards/Patents Issued

1. 2007 U.S. Department of Energy (DOE) Hydrogen Program Research and Development Award for "Outstanding Contributions to Hydrogen Scenario Analysis," presented at the DOE Annual Hydrogen Program Merit Review, Washington, D.C., May 2007.

[5] Such may not be the case if the reference vehicle price *also* changes, via mechanisms such as so-called fee-bates, whereby a fee is charged to lower efficiency vehicles and rebates are provided to higher efficiency vehicles.

FY 2007 Publications/Presentations

1. Welch, C. "Discrete Choice Analysis: Hydrogen Fuel Cell Vehicle Demand Potential." Presented at the DOE 2010-2025 Scenario Analysis Meeting, Washington, D.C., January 31, 2007. Available at www.eere.energy.gov/hydrogenandfuelcells/analysis/pdfs/scenario_analysis_welch1_07.pdf.

2. Welch, C. "Quantifying Consumer Sensitivity to Hydrogen Refueling Station Coverage." Presented at the U.S. DOE Annual Hydrogen Program Merit Review, Arlington, VA, May 2007. Available at www.nrel.gov/docs/fy07osti/41553.pdf.

3. Welch, C. "System Dynamics: HyDIVE (Hydrogen Dynamic Infrastructure and Vehicle Evolution) Model." Presented at the U.S. DOE Annual Hydrogen Program Merit Review, Arlington, VA, May 2007. Available at www.nrel.gov/docs/fy07osti/41553.pdf.

3. Welch, C. "Using HyDIVE to Analyze Hydrogen Scenarios." NREL/TP-560-41363. Golden, CO: National Renewable Energy Laboratory, Forthcoming 2007.

References

1. Gronich, S. "2010-2025 Scenario Analysis." Presented at the DOE 2010-2025 Scenario Analysis Meeting, August 9, 2006, Washington, D.C. Available at www1.eere.energy.gov/hydrogenandfuelcells/analysis/pdfs/gronich_scenario_analysis.pdf.

2. Struben, J.J. "Identifying Challenges for Sustained Adoption of Alternative Fuel Vehicles and Infrastructure." *MIT Sloan Research Paper No. 4625-06* 2006. Available at SSRN: http://ssrn.com/paper=927012.

3. Welch, C. "Lessons Learned from Alternative Transportation Fuels: Modeling Transition Dynamics." NREL/TP-540-39446. Golden, CO: National Renewable Energy Laboratory, February 2006.