VII.8 Analysis of the Hydrogen Production and Delivery Infrastructure as a Complex Adaptive System

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Subcontractors:

- BP, Naperville, IL
- Ford Motor Company, Dearborn, MI
- Protium Energy Technologies, Orefield, PA

Start Date: June 15, 2005
Projected End Date: June 30, 2009 (no-cost extension approved through December 31, 2009)

Objectives

- Use agent-based modeling (ABM) to provide insights into likely infrastructure investment patterns.
- Deal with chicken-or-egg aspect of early transition.
- Provide answer to the question, "Will the private sector invest in hydrogen infrastructure?"

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:

(A) Future Market Behavior
(C) Inconsistent Data, Assumptions and Guidelines

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 5:** Complete analysis and studies of resource/feedstock, production/delivery and existing infrastructure for various hydrogen scenarios. (4Q, 2009)
- **Milestone 25:** Complete the Agent Based Modeling System for infrastructure analysis of hydrogen fuel and vehicles (4Q, 2008)

Accomplishments

- Introduced centralized hydrogen production to the ABM.
- Analyzed the influences on the date of entry of centralized hydrogen production.
- Discovered significant impacts of investor agent's satisficing behavior.
- Introduced into the ABM corporate-level investment decision making in addition to simple project evaluation as the full basis for investment choices.

Introduction

The purpose of this project work is to analyze investment in hydrogen infrastructure during the early transition to a hydrogen economy using an agent-based modeling and simulation (ABMS) technique. ABMS is a micro-simulation technique that facilitates representation of heterogeneity in terms of many characteristics of the actors (agents) involved in the transition to a hydrogen infrastructure. These characteristics can include size, beliefs and preferences, expectations, goals, and location, among the most important. ABMS simplifies the modeling of learning by agents. In distinction from conventional modeling approaches currently applied to the hydrogen economy, ABMS relies on different objective functions (goals) for different agents; it also allows for different reactions to unmet expectations, different learning from the emerging economic environment, and different responses based on agent characteristics. It is easy to specify putty-clay capital (an investment in an earlier period of a simulation cannot change into another technology in a subsequent period), which is both realistic and facilitates analysis of quasi-rent changes (stranded investments). Altogether, ABMS is a well-suited vehicle to apply sophisticated economic models in an environment involving actors with widely differing characteristics and goals.

Early transition is expected to be a time of considerable uncertainty, when reasonable investors might hold widely differing expectations and could have different goals. An additional feature of early transition is the existence of a chicken-or-egg problem, in which potential investors in infrastructure want to wait for hydrogen vehicles to emerge on the market, but potential vehicle buyers want to wait until fuel is widely available. ABMS is a convenient tool for exploring these interactions via simulation, since analytical expressions for solutions to models with only modest complications are intractable.

Approach

The project began as a 3-year project with preliminary model results due in the second year, but the project was re-oriented before it began, its first year budget was reduced by nearly 60 percent, and initial funding was delayed. The revised first year goal of the project was to provide an answer to the question, "Will the private sector invest in hydrogen infrastructure?" and to focus on California as a likely region of early transition.

To accomplish the revised first year goal, the project developed a framework that focused on investments as business decisions and used that framework as a basis for preliminary assessment of profitability. In a parallel effort, efforts were begun to prepare the ABM for detailed simulations in the project's second year. Work in the second year was delayed by a continuing resolution, which restricted staffing. Full funding began in the third year. A revised completion date of June 30, 2009 has been approved. A no-cost extension until December 31, 2009 also has been approved.

Results

Background Review of the Model Structure

The model is composed of two major modules, a driver module which simulates behavior of driver agents, and an investor module which simulates the decisions of the investor agent who supplies hydrogen to the Los Angeles market. The model uses a geographic information system platform of the Los Angeles metropolitan area based on one-mile grids. Driver agents are located at residential sites corresponding to Los Angeles residential densities. They decide whether to purchase a hydrogen vehicle on the basis of vehicle cost relative to a conventional vehicle, fuel availability, and taste for greenness. Hydrogen production is modeled with investor agents, who make investments in either 1,500 kg/d distributed steam methane reforming stations or centralized production on the basis of their expectations of hydrogen vehicle adoption. They form their expectations from observing past growth in hydrogen vehicles and correct mistakes in expectations from period to period.

Completion of the Model

The prototype model of 2007-08 was completed during 2008-09.

Simulation Results

Results of four important simulations are reported. The first two, the influences of the sticker price of the hydrogen vehicle and of the price of gasoline, are largely market influences, although both can be affected to some extent by policy. The third simulation examines a temporary tax credit policy. The fourth simulation reported here, involving a parameter called the familiarity premium, demonstrates the importance of the preferences of potential hydrogen vehicle purchasers.

Declining Sticker Price

Sensitivity to declining sticker price, shown in Figure 1, shows the effect on sales penetration of moving "too early," that is, of marketing the hydrogen fuel cell

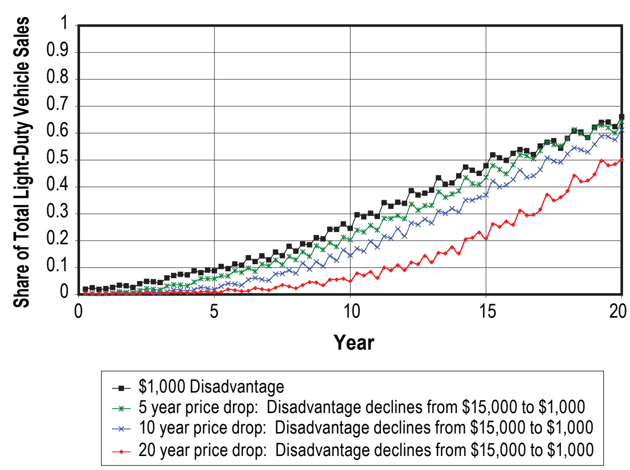

FIGURE 1. The Effect of Declining Sticker Price on Hydrogen Vehicle Sales Growth

vehicle to a mass audience before technological and scale-economy factors have succeeded in making it cost-competitive with a conventional gasoline vehicle. Jumping the gun by five years has a small (8%) effect on 20-year sales penetration, but if the price remains relatively high for the first 20 years of mass production, it will cause sales to lag more substantially.

Price of Gasoline

In the benchmark scenario, the gasoline price averages $5.50 per gallon over the period analyzed. Two additional scenarios are tested: one in which the gasoline price averages $8.00/gallon and the driver agents save 22.8 cents per mile by driving a hydrogen vehicle and one in which gasoline averages $3.00/gallon and driver agents save only 5.6 cents per mile. The higher savings per mile translates to roughly $8,000 over the life of the vehicle in expected savings for the average agent, who drives 12,150 miles a year (the benchmark savings for the average agent is about $4,500). The low savings per mile translates to roughly $1,400 in expected savings over the life of the vehicle. In Figure 2, the high savings scenario increases hydrogen vehicle market share by roughly one-third, to 90% by the 20th year after introduction. The low savings scenario lowers market share in the 20th year to 32%.

Temporary Tax Credit

Figure 3 shows the consequence of eliminating the vehicle tax credits after ten years. While the drop in the percent of sales once the tax credit is terminated looks drastic, the hydrogen share of vehicle sales continues to climb without a credit, reaching 78 percent of sales after 20 years with the $3,500 credit and 83 percent with the $7,000 credit. The temporary tax credit hastens the growth of the hydrogen vehicle stock, which in turn hastens driver agents' familiarity with the vehicle and bolsters the impact of the bandwagon effect. Without a tax credit, the hydrogen vehicle stock would comprise about 5 percent of the total vehicle stock after 10 years. The tax credits raise the stock at 10 years to 17 percent and 34 percent, which in turn raises the level of the hydrogen share of sales above the no-credit benchmark case for each of the remaining ten years in the simulation.

Familiarity Premium

The familiarity premium is the amount a potential buyer would have to be paid to buy a hydrogen vehicle if he were completely unfamiliar with it. Hydrogen vehicle market share grows more rapidly in the scenario with the lower familiarity premium. In Figure 4, market share reaches 84% by the 20th year, 18% higher than the 20th year market share in the benchmark scenario.

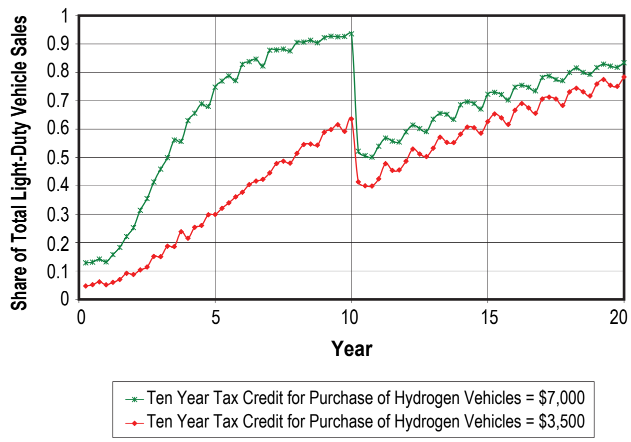

FIGURE 3. Effect of Temporary Tax Credits on Hydrogen Vehicle Sales Penetration

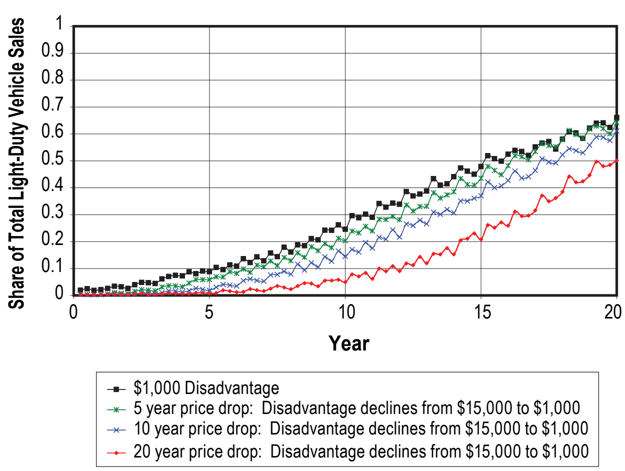

FIGURE 2. The Effect of Gasoline Price on Hydrogen Vehicle Sales Growth

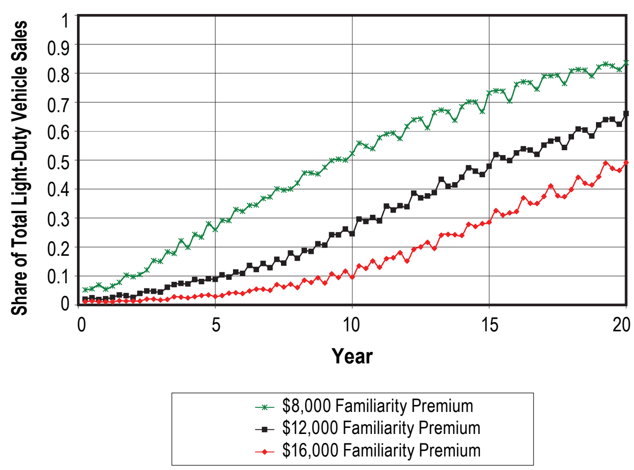

FIGURE 4. The Effect of Familiarity Premium on Hydrogen Vehicle Sales Growth

In the weak bandwagon effect scenario, adoption is substantially slowed, with market share only reaching 49% in the 20th year.

Conclusions and Future Directions

In most of the scenarios studied in this report, hydrogen vehicles ultimately saturate the light-duty vehicle market in Los Angeles. However, these asymptotic market shares generally are reached after the end of the 20-year period reported graphically here. Whether driver agents or investor agents maximize perfectly, or whether they exhibit some behaviors that, strictly speaking, are irrational, has little impact on the ultimate market outcome, although these behaviors can slow down adoption, particularly during the first 10 years of the transition.

In the benchmark scenario, hydrogen vehicles account for 60% of sales within 20 years. However, depending on the values of parameters characterizing driver agent or investor agent attitudes, the 20-year market penetration can range from 35% to 80%. The magnitude of the familiarity premium to driver agents is particularly important to early adoption of hydrogen vehicles. A two-fold variation in the value driver agents place on familiarity with the hydrogen vehicle results in a range of hydrogen vehicle shares of sales from 30% to 80% after 20 years. Alternative degrees of driver preference for greenness, as well as the dispersion of that preference through the population, result in hydrogen vehicle shares of sales ranging from 40% to 70% after 20 years. Nonetheless, none of the driver agent characteristics studied had the capacity to kill the transition. The strength of the bandwagon effect among driver agents has more impact between the 10th and 15th years of the transition than it does by 20 years. Soon thereafter, differences in that behavioral attitude will retain no influence on the transition.

Many of the alternative practices of the investor agents had little impact on the pace of adoption of hydrogen vehicles during the first 20 years. There is little sensitivity to the investor agent's method of estimating demand for hydrogen, and differences in the sophistication of his expectations formation yields a range of 20-year market penetrations of 45% to 60%. However, while these different investor agent practices do not have major depressing effects on the pace of market penetration, none of the variations studied have the capacity to greatly hasten penetration. This said, one attitude of the investor agent does have the capacity to greatly retard or even kill the transition – very high discount rates on the part of upper management. Discount rates equivalent to very short pay-back periods could keep market penetration to the range of five to 20 percent after 20 years.

External influences can have major impacts on the pace, and even the fate, of the transition. Gasoline prices remaining as low as $3.00 per gallon for the first 20 years can effectively stall the transition. Conversely, however, a $5.00 per gallon gasoline price would see the hydrogen vehicle market share rise to 60% in 20 years, and an $8.00 price would put it at 90%. The price of the hydrogen vehicle relative to the gasoline vehicle has an equally powerful influence. If the hydrogen vehicle remains only $1,000 higher than the equivalent gasoline vehicle, the hydrogen vehicle share will reach 60% in 20 years, while if it is $5,000 higher, the share will not exceed 10% after 20 years. On the other side of those possibilities, if the hydrogen vehicle's price were $3,000 below the gasoline vehicle's price, market penetration would reach 95% in 20 years.

In sum, the answer to the original question, "Will the private sector invest in hydrogen infrastructure?" is, "It depends." If fuel prices, vehicle production costs, and a number of driver and investor parameters are favorable, the private sector will invest in the infrastructure necessary to support the transition to hydrogen.

FY 2009 Publications/Presentations

1. Mahalik, M., C. Stephan, G. Conzelmann, M. Mintz, G. Tolley, and D. Jones, "Modeling Investment Strategies in the Transition to a Hydrogen Transportation Economy," *Proceedings of the NHA Conference and Hydrogen Expo*, Columbia, SC, March 30 – April 3, 2009.