HYDROGEN PRODUCTION AND DELIVERY INFRASTRUCTURE AS A COMPLEX ADAPTIVE SYSTEM

RCF Economic and Financial Consulting, Inc.
Argonne National Laboratory

Final Report

Award Number DE-FG36-05GO15034

June 2010

TABLE OF CONTENTS

PART ONE: INTRODUCTION

PART TWO: THE MODEL

PART THREE: SENSITIVITY TO MODEL PARAMETERS

PART FOUR: SENSITIVITY TO MARKET AND POLICY INFLUENCES

PART FIVE: VALIDATION

PART SIX: SUMMARY AND CONCLUSIONS

PREFACE

In 2005, the Hydrogen, Fuel Cells and Infrastructure Technologies Program of the Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy contracted with RCF Economic and Financial Consulting, Inc. to develop an Agent-based Model (ABM), in cooperation with Argonne National Laboratory, on the construction of hydrogen infrastructure as hydrogen vehicles penetrate the U.S. light-duty vehicle market. Industry cooperators were Ford Motor Company, BP, Protium Energy Technologies, and John E. Johnston (formerly Planning Executive for ExxonMobil's Corporate Strategic Research Laboratories).

A principal product of this project is the agent-based model “Hydrogen Infrastructure Complex Adaptive Systems” (H2CAS). The model benefitted from earlier work on other topics using agent-based modeling at the Center for Energy, Environmental, and Economic Systems Analysis (CEEESA) at Argonne National Laboratory, and from a similar model previously developed at Ford Motor Company. Conventional methods to address technology introduction rely on traditional optimization procedures such as simple cost minimization assuming perfect knowledge. There are too many interactions among the participating entities in the hydrogen transition to be captured with these techniques. The agent-based model simulates the behavior and interactions of a large number of individuals (agents) and studies the macro-scale consequences of these interactions. The agents represent a diverse group of actors with different tastes, resources, strategies, and risk preferences. Agents use rules of thumb and other realistic informal estimation techniques. They may be biased. Corrective actions occur as agents learn from their experience. They adapt over time.

The study team was charged with answering the questions, “Will the private sector be likely to undertake this infrastructure investment on its own, and with sufficient promptness to satisfy national energy and foreign policy goals?” and “If not, what policy actions would be effective?”

To answer these questions, projections are given of how hydrogen infrastructure will grow and how hydrogen vehicles will penetrate the market under alternative conditions. Sensitivity scenarios are presented pertaining to such influences as the cost of hydrogen vehicles relative to non-hydrogen vehicles, the price of gasoline, risk attitudes of senior managers at companies involved in hydrogen supply technologies, and behavior of consumers. The effectiveness of policies that would affect adoption is estimated.

Part One introduces the report and discusses other applications of agent-based modeling.

Part Two gives an overview of the model. The model offers the ability to introduce a variety of characteristics of people who might purchase hydrogen vehicles (driver agents). On the infrastructure side of the problem, the agent-based approach allows the firms that provide hydrogen for vehicles (investor agents) to make investment decisions that are not strictly maximizing. Instead they use satisficing rules of thumb and other approximations, making decisions that are “good enough” if not perfect. This allows investor agents to behave more like real business people, who face circumstances that are too complicated to allow perfect maximize.

Part Three reports simulation results of the model with, first, a benchmark set of parameters and then with variations allowing study of sensitivity to numerical values of model parameters.

Part Four reports results of simulations examining a number of market and policy parameters, including the sticker price of the hydrogen vehicle, vehicle fuel prices, tax credits, carbon taxes, and seed stations at the beginning of the simulation provided with policy help.

Part Five is concerned with validation. The simulations of the present study are compared to experiences with a number of other innovations, many of which have encountered chicken-or-egg effects that characterize the introduction of hydrogen. The investigation includes a variety of consumer durables plus experiences with compressed natural gas vehicles, Japanese imports, and hybrid vehicles.

Part Six summarizes the results of the study and draws conclusions regarding ability to supply infrastructure that will permit market penetration of hydrogen vehicles..

Technical appendices report the mathematical structure of the driver module (Appendix A) and investor module (Appendix B) and summarize major influences on the future price of hydrogen vehicles (Appendix C).

ACKNOWLEDGEMENTS

The team at RCF was led by George Tolley and included Donald Jones, Naveen Singhal, Mihai Sturdza, Catherine Mertes, Mark Grenchik, David Jarvis, and several other RCF staff members. The team at Argonne National Laboratory was led by Guenter Conzelmann, and included Marianne Mintz, Craig Stephan (formerly of Ford), Matthew Mahalik, Thomas Veselka, and Audun Botterud. The hydrogen model made use of the Argonne team's experience with agent-based modeling and an earlier model of hydrogen vehicle adoption developed at Ford Motor Company by Craig Stephan and John Sullivan.

Generous and valuable contributions were made by the industry cooperators, who included Dean Fry of BP; Craig Stephan and John Sullivan of Ford Motor Company; John Johnston formerly of ExxonMobil; and Venki Raman of Protium Energy Technologies.

Very helpful comments on the draft report were provided by the peer reviewers, who were Shannon Baxter-Clemmons of the South Carolina Hydrogen and Fuel Cell Alliance, Maria Curry-Nkansah of the Imago Energy Consultancy Group, and George Parks of FuelScience LLC.

Fred Joseck of DOE was a constant source of valuable feedback and help. Midterm decisions benefitted greatly from comments in semi-annual Fuel Pathways Integration Technical Team (FPITT) meetings in Washington, D.C., Golden, CO, and Naperville, IL over the course of the project.

ABSTRACT

An agent-based model of the transition to a hydrogen transportation economy explores influences on adoption of hydrogen vehicles and fueling infrastructure. Attention is given to whether significant penetration occurs and, if so, to the length of time required for it to occur. Estimates are provided of sensitivity to numerical values of model parameters and to effects of alternative market and policy scenarios. The model is applied to the Los Angeles metropolitan area

In the benchmark simulation, the prices of hydrogen and non-hydrogen vehicles are comparable. Due to fuel efficiency, hydrogen vehicles have a fuel savings advantage of 9.8 cents per mile over non-hydrogen vehicles. Hydrogen vehicles account for 60% of new vehicle sales in 20 years from the initial entry of hydrogen vehicles into show rooms, going on to 86% in 40 years and reaching still higher values after that. If the fuel savings is 20.7 cents per mile for a hydrogen vehicle, penetration reaches 86% of new car sales by the 20th year. If the fuel savings is 0.5 cents per mile, market penetration reaches only 10% by the 20th year. To turn to vehicle price difference, if a hydrogen vehicle costs $2,000 less than a non-hydrogen vehicle, new car sales penetration reaches 92% by the 20th year. If a hydrogen vehicle costs $6,500 more than a non-hydrogen vehicle, market penetration is only 6% by the 20th year. Results from other sensitivity runs are presented.

Policies that could affect hydrogen vehicle adoption are investigated. A tax credit for the purchase of a hydrogen vehicle of $2,500 tax credit results in 88% penetration by the 20th year, as compared with 60% in the benchmark case. If the tax credit is $6,000, penetration is 99% by the 20th year. Under a more modest approach, the tax credit would be available only for the first 10 years. Hydrogen sales penetration then reach 69% of sales by the 20th year with the $2,500 credit and 79% with the $6,000 credit.

A carbon tax of $38 per metric ton is not large enough to noticeably affect sales penetration. A tax of $116 per metric ton makes centrally produced hydrogen profitable in the very first year but results in only 64% penetration by year 20 as opposed to the 60% penetration in the benchmark case. Provision of 15 seed stations publicly provided at the beginning of the simulation, in addition to the 15 existing stations in the benchmark case, gives sales penetration rates very close to the benchmark after 20 years, namely, 63% and 59% depending on where they are placed.

EXECUTIVE SUMMARY

INTRODUCTION

This final report presents results of the *Analysis of the Hydrogen Production and Delivery Infrastructure as a Complex Adaptive System (Award Number E-FC36-05GO15034),* conducted for the Fuel Cell Technologies Program of the Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy.

The project is concerned with the ability to provide infrastructure necessary to support a hydrogen transportation system. The start-up of a hydrogen transportation system encounters a chicken-or-egg problem of what comes first, drivers of hydrogen cars or investors in hydrogen fueling infrastructure. The central purpose is to answer:

> *Whether the private sector will supply the infrastructure to permit a transition to hydrogen consistent with national goals and, if not, what policy actions would be effective.*

APPROACH

The methodology used is Agent-based Modeling (ABM). ABM actors use realistic approximations in making decisions, rather than using perfect optimization that assumes impossible requirements of complete knowledge. ABM permits the introduction of great variety in the analysis of interactions among the many different actors in an economic system. The model in this study was developed jointly between RCF Economic and Financial Consulting, Inc. and Argonne National Laboratory.

The model simulates the interactions of drivers of hydrogen vehicles and investors providing hydrogen fueling infrastructure, during years when adoption of hydrogen vehicles is occurring. It provides a tool for estimating how different circumstances will affect the growth of the hydrogen economy.

OUTLINE OF REPORT

Part One of the report provides an introduction. Part Two provides an overview of the model including a description of the geographic area, driver agent and investor agent behavior, the model simulation process, hydrogen production technology, and the hydrogen fuel station siting process. Part Three describes the study’s benchmark adoption scenario and reports on sensitivity to numerical estimates of driver and investor behavioral parameters. Part Four reports on the sensitivity to market influences and policies. Part Five is concerned with validation of the model through comparison of its prediction of hydrogen vehicle adoption with observed adoption of previous innovations for durable goods. Part Six summarizes the major empirical findings of the study, presents conclusions on the central question of prospects for adequate provision of hydrogen infrastructures, and discusses the usefulness of the study in the future. Appendix A contains further details regarding driver agents. Appendix B contains further on investor agents.

Appendix C presents an analysis of the sources of declines in cost of producing hydrogen vehicles that would allow them to enter the mass market.

OVERVIEW OF THE MODEL

As discussed in Section 2.1, the Agent-based Model (ABM) developed for the study contains 130 parameters which consist of 92 cost parameters from DOE's H2A model, 17 driver behavior parameters, 10 investor behavior parameters, and 11 price and policy variables.

The model area is a 100-by-50-mile rectangular area centered on the Los Angeles, California, metropolitan area. Within the model area, there are two types of agents: potential buyers of hydrogen vehicles (driver agents) and potential investors in hydrogen fuel infrastructure (investor agents).

Driver agents make decisions regarding whether or not to purchase hydrogen vehicles each quarter within each simulation year. At the beginning of a simulation, driver agents own only non-hydrogen vehicles. Driver agents observe the few hydrogen fueling stations which are sited as seed stations as part of the model. Driver agents then decide whether to replace their non-hydrogen vehicles with hydrogen-powered vehicles depending on their individual differences and on the location of stations where they can buy hydrogen fuel. Those hydrogen vehicles are then fueled throughout the simulation year. Investor agents observe the fueling behavior of driver agents, revise their expectations regarding the strength of demand based on the sales they observe, and then decide where and how many new fuel stations to build in the next simulation year. Driver agents then view the stations that have been added and once again make decisions about purchasing hydrogen vehicles. The process repeats for each year of the simulation.

DRIVER AGENTS

As discussed in Section 2.2, driver agents represent vehicle drivers living and working in the model area. The driver agents live and work in different locations, have different incomes, varying knowledge about hydrogen vehicles, varying attitudes toward the environment, and other characteristics. Drivers differ in their proclivities to buy hydrogen vehicles and in their proximity to hydrogen stations. The adoption path of hydrogen vehicles will depend on how driver agents react to hydrogen fuel stations supplied by investor agents.

The model contains approximately 7 thousand drivers, each representing 1,000 vehicles in order to approximate 7 million vehicles in the model area. At the beginning of the simulation, nearly all driver agents own only conventional vehicles. In each simulation, drivers make trips, refueling as needed. Drivers replace some part of the vehicle fleet each period during a simulation, using the driver utility function to determine whether they would consider themselves better off with a new hydrogen vehicle or another non-hydrogen vehicle.

The driver agent utility function has seven terms:

1. Sticker price difference

2. Fuel cost advantage
3. Disadvantage due to limited familiarity
4. Bandwagon effect
5. Greenness
6. Inconvenience
7. Worry

The sticker price difference is the price of a hydrogen vehicle minus the price of a comparable non-hydrogen vehicle. The fuel cost advantage is the present value of any fuel cost savings resulting from driving a hydrogen vehicle. The disadvantage due to limited familiarity results from a driver agent's hesitation to purchase a hydrogen vehicle due to a lack of knowledge about it. The bandwagon effect occurs when a potential buyer's beliefs about the performance of a new product are influenced by those who have already purchased the product. Greenness represents driver agent preferences, if any, toward hydrogen vehicles due to environmental considerations. Inconvenience may result from a limited availability of hydrogen refueling options. Worry may result from concern for running out of fuel because of limited availability of hydrogen refueling options.

When few hydrogen stations are available in early periods, inconvenience and worry figure noticeably in utility calculations. As a simulation proceeds, more fueling stations are sited and these concerns lessen. As drivers buy hydrogen vehicles, other drivers who are able to observe their performance become more comfortable with them in subsequent periods as the disadvantage due to unfamiliarity is reduced.

INVESTOR AGENTS

As discussed in Section 2.3, investor agents supply the hydrogen infrastructure necessary for refueling hydrogen vehicles purchased by the driver agents. Investor agents cannot foresee hydrogen fuel sales with certainty. Realistically investors must resort to simplifications and approximations. These are a central feature of the model in the present study, providing a contrast to many traditional economic theories that assume perfect foresight or depart from reality in modeling behavior toward the future in other ways. The simplifications and approximations take a variety of forms. They include back-of-the-envelope calculations and rules of thumb. An investor agent is subject to over- or under-optimistic biases. An investor learns from experience and may change in degree of optimism or pessimism from one period to the next. Decisions are influenced by broader corporate goals of upper management, such as near-term earnings performance that affects share values of the company regardless of the long-term promise of an investment. The terms satisficing and bounded rationality are sometimes used to describe these types of influences on decisions departing from the assumption of perfect maximization.

HYDROGEN PRODUCTION TECHNOLOGIES

Also discussed in Section 2.3, several potential hydrogen production technologies were evaluated during this study. The major technologies included in the model are distributed stream methane reforming and centralized stream methane reforming. Alternative technologies include electrolysis, coal gasification and biomass gasification. Steam methane reforming (SMR) consists of heating methane to 700^{o} - $1{,}100^{o}$ C which separates it into carbon monoxide and hydrogen.

Steam methane reforming is used in the model because our evaluation shows that it is the most likely hydrogen production technology for the model area centered on the Los Angeles metropolitan area. H2A models indicate that SMR is less expensive than either electrolysis or coal gasification. It is unlikely that sufficient volumes of biomass would be available to produce all the hydrogen needed in the latter years of the simulation via biomass gasification. Analysis in this study indicates that switching technologies midway through the simulation period, from biomass to SMR, would entail a higher cost than starting with SMR. Modeling the use of both biomass gasification and SMR is possible but is beyond the scope of the present study.

With distributed SMR production, small reforming units are located at each refueling site. With centralized SMR production, a large reformer serves many refueling sites by pipeline or truck delivery.

The investor faces a choice between building distributed SMR stations, and building centralized plants along with a pipeline infrastructure for delivery of fuel. To make the choice between the two technologies, the investor compares the levelized cost of producing hydrogen using the centralized technology with the levelized cost using distributed stations. Investor agents choose the method of production based on projected sales volume and the lowest-cost method for that volume. The investor charges a price for fuel that is equal to the average cost of producing hydrogen.

STATION SITING

As further discussed in Section 2.3, the model area is divided into 5,000 1x1-mile cells. The investor agent is restricted to siting stations in 156 cells located at major highway intersections and at the midpoints of highway segments. Each cell may have as many stations as the investor chooses to site there.

In the first year of the simulation, it is assumed there are only seed stations. Investor agents consider siting stations annually from the second year onward. The procedure used to make decisions regarding how many stations to site and at which locations uses a process to forecast the expected hydrogen fuel sales and profitability of all possible new station locations, ranks locations, and calculates the effect of siting a station. The procedure is repeated each year of the simulation for all possible new station locations.

THE BENCHMARK SCENARIO

As discussed in Section 3.1, the benchmark case represents a 40 year scenario where hydrogen vehicles and fuel become competitive with traditional vehicles. The benchmark case provides an example of a set of prices of vehicles and fuels for hydrogen and non-hydrogen vehicles that would result in cost competitiveness and allow the beginning of a take-off. It is to be emphasized that the model does not attempt to predict the exact year when the required competitiveness will be achieved. The benchmark scenario is presented as a baseline estimate using the parameters in the following table:

Main Parameters Used in Benchmark Scenario

Parameter	**Value**
Driver Agent Parameters	
Disadvantage Due to Limited Familiarity[a,f]	$12,000
Bandwagon Effect Coefficient [a]	0.1
Bandwagon Effect Dispersion [a]	2.2
Greenness Central Tendency[b,f]	$250
Greenness Dispersion[b]	10
Investor Agent Parameters	
Fueling Station Capital Cost[c,f]	$4,806,357
Fueling Station Fixed O&M Costs[c,f]	$236,598
Fueling Station Salvage Value[c]	0
Investor Discount Rate[d]	10%
Hydrogen Selling Price[e,f]	$3.63/kg
Fueling Station Operating Capacity[c]	1,278 kg/day

[a] For additional discussion see Section A.2.3 in Appendix A, "Disadvantage Due to Limited Familiarity and Bandwagon Coefficient, P_{jt}^{F} and q_j."

[b] For additional discussion see Section A.2.4 in Appendix A, "Greenness, T_j."

[c] Station nameplate capacity of 1,500 kg/day from DOE H2A model.

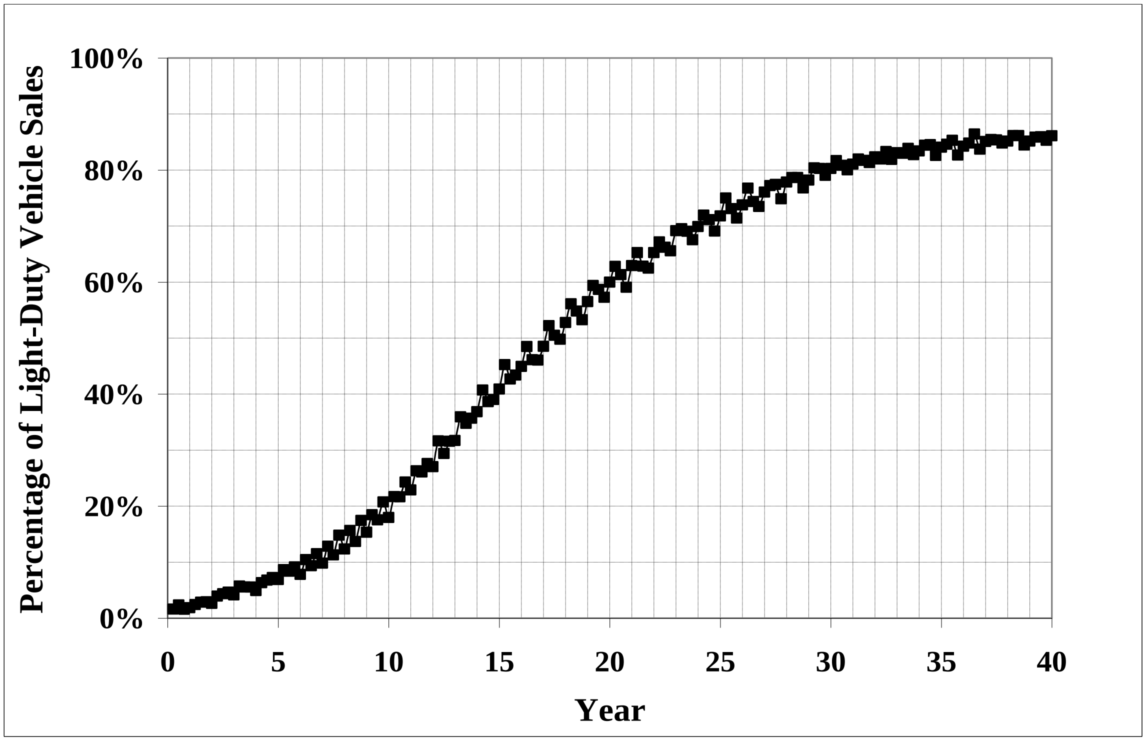
[d] DOE H2A model.

[e] For additional discussion see Section B.1 in Appendix B, "Price Charged for Hydrogen Fuel."

[f] In 2009 dollars.

Using these baseline estimates, the figure below shows annual hydrogen vehicle sales as a percent of all light-duty vehicle sales over a forty year simulation period. Hydrogen vehicle sales under the benchmark scenario reach a market penetration of 86% after 40 years.

Benchmark Hydrogen Vehicle Sales Penetration over 40 Years



SENSITIVITY TESTING FOR DRIVER BEHAVIOR PARAMETERS

As discussed in Section 3.2, results of sensitivity analyses for the driver agents show that driver agent behavior can have a significant effect on the rate at which hydrogen vehicles are adopted. The strength of the disadvantage due to *limited familiarity* has a large initial influence acting to slow sales growth, which is overcome over time due importantly to the *bandwagon effect* or the impact of drivers who have already bought a hydrogen vehicle on drivers who have not bought one yet. The influence of *greenness* or driver willingness to pay a premium for an environmentally friendly vehicle is somewhat smaller but still significant.

SENSITIVITY TESTING FOR INVESTOR BEHAVIOR PARAMETERS

As discussed in Section 3.3, results of the sensitivity analyses for investor agents show that the *upper management discount rate* can have a large influence on the number of fuel stations built and consequently on hydrogen vehicle sales. The upper management discount rate reflects the attitudes of investors including degree of risk aversion, and the degree of optimism or pessimism about the viability of hydrogen vehicle expansion. In contrast, sensitivity of the model to the *staff discount rate* used in preparing investment evaluations submitted for consideration by upper management appears to be relatively small, because the staff uses a narrower range of textbook discount rates. Relatively limited effects are also found for sensitivity to the investor's *rapidity of learning*, method of predicting *first year sales at new stations*, and method of forming *growth expectations*. All the latter may have large effects for one year, particularly early in the simulation when investor experience is limited, but the unfolding of actual events corrects investor mistakes relatively rapidly. The *number of investors* has a limited effect because a single investor is already acting much like a pure competitor in view of the threat of entry of other investors and of regulation if monopolistic practices are observed.

EFFECTS OF REALISTIC APPROXIMATIVE DECISIONS

Section 3.4 asked: What is the effect of realistic, approximative decision making, sometimes called satisficing, in place of traditional, full optimization on the results? Obtaining a strict answer is not feasible because calculating the fully optimized path would be impossibly complicated. However, having perfect information about the growth rate of demand for hydrogen, and about fueling locations with the greatest potential for spurring hydrogen vehicle adoption, would eliminate important complications. An upper bound on these effects can be obtained by re-running the simulation assuming that hydrogen stations are found at every location. The lack of availability of hydrogen would then not be a hindrance to adoption.

The effect of the investor's lack of perfect knowledge about demand in delaying the provision of infrastructure would no longer be operative. Adoption of hydrogen vehicles would still not be instantaneous because drivers would still have to learn about the performance of hydrogen vehicles, which is the driver's contribution to delay in adoption, not the investor's. If we compare the hydrogen vehicle saturation level at a given year, say the 20th, in the re-run simulation with that in the original simulation, we obtain an estimate of the maximum possible delay that the investor's satisficing behavior has caused. The results of the comparison reveal that the maximum possible effect is a relatively modest 2-year delay by the 20th year.

SENSITIVITY TESTING FOR POLICY AND MARKET INFLUENCES

Part Four reports on sensitivity scenarios for policy and market influences. The market influences studied include changes to the *sticker price* of hydrogen vehicles, and changes to the *price of gasoline*. Additional market changes not foreseen at the present time will inevitably occur in the future. The model of this study can be useful beyond providing a prediction of future conditions as seen at the present time. Sensitivity of model results to differences in market conditions indicates how model results will be affected by different market conditions as they emerge in the future, increasing the value of the study as a tool for use beyond the year of the present study. The policy scenarios studied include *tax credits* for hydrogen vehicle purchase, *loan assistance* to investors, the effect of possible *carbon taxes*, and *additional seed stations*.

Market Developments: S*ticker price differences* (Section 4.1) have important effects on the adoption of hydrogen vehicles. A decline sticker price disadvantage beginning with a $14,000 hydrogen vehicle price disadvantage that declines to $0 by year 5 or 10 still allows sales penetrations over 50% by the 20th year. A non-declining price disadvantage of $6,500 precludes a hydrogen take-off.

Market Developments: *Fuel cost savings* (Section 4.2) play an important role in the adoption of hydrogen vehicles. Sufficiently low savings will prevent take-off, while very high savings will hasten a take-off. The results are driven by the price of gasoline and suggest that future gasoline prices could be a crucial market consideration determining hydrogen vehicle penetration.

Policies: *Permanent tax credits* (Section 4.3.1) dramatically hasten sales penetration. *Temporary tax credits* (Section 4.3.2) that end after 10 years still result in higher sales than in the benchmark case with no tax credits, because so many more hydrogen vehicles are purchased earlier and, operating through the bandwagon and familiarity effects, continue to affect vehicle choice after the expiration of the tax credits.

Policies: *Carbon taxes* (Section 4.4) have limited effects. An additional 15 stations available at the beginning of the simulation has a perceptible, though not major, but alternative locations of the seed stations have little impact on sales penetration.

MODEL VALIDATION

As discussed in Part Five, research was conducted on adoption of other durable goods innovations to see if the adoption path predicted for hydrogen vehicles in this study is similar to those for other innovations. A comparative study was conducted on the adoption paths of consumer durables products as a whole. Adoption experiences and lessons learned were gathered for specific vehicle innovations including CNG vehicles, penetration of Japanese vehicles in the U.S. market, and hybrid vehicles.

Overall, we judge the validation tests to be favorable to the Agent-based model of this study. The adoption paths for hydrogen vehicles in the simulations of this study have been found to have a typical S-shaped adoption curve similar to the empirical adoption paths calculated for other consumer durables. The S-curve for hydrogen vehicles exhibits a slower rate of adoption than for the average of all consumer durables. This is to be expected because automobiles including hydrogen vehicles have a much longer life and are thus subject to slower turnover than other durable goods. A lesson from the three vehicle case studies (CNG vehicles, Japanese vehicles, and hybrids) is that gain to the consumer from an innovation and, in the case of Japanese imports, government policy can have a powerful influence on the rate of adoption.

BOTTOM LINE ISSUE OF THIS STUDY: ADEQUACY OF PRIVATE SECTOR INFRASTRUCTURE SUPPLY

In addition to summarizing the study, Part Six takes stock of the implications of the study for the key question (Section 6.9): *Will the private sector supply the necessary infrastructure to permit a transition to a hydrogen transportation economy?* This study indicates that the private sector transition will provide the necessary infrastructure, provided prerequisite technological and market conditions are met. The effect of technological and market conditions takes on added importance because the model of this study indicates that a transition to hydrogen transportation in the relatively favorable benchmark case will require a number of years.

This seemingly favorable answer however leads to two follow-up questions. *First, is the rate of adoption rapid enough to satisfy the national goal of extricating from dependence on foreign oil?* The rapidity of transition depends on how favorable the pre-requisite conditions are. If the price of gasoline is higher than it has been historically or there is a near-term favorable technological breakthrough greatly reducing the cost of producing hydrogen vehicles, drivers will have substantial incentives to switch to hydrogen vehicles, acting to speed the adoption process. On the other hand, if conditions are just barely favorable, the result may not be very different in terms of policy from no take-off at all. Adoption may proceed so slowly that it is deemed unsatisfactory from the point of view of reducing foreign dependence.

The results lead to a second follow-up question: *If the transition to hydrogen is not deemed satisfactory, what policies are available to speed it up?* Tax credits, a carbon tax and government assistance with seed stations have been used to illustrate the effects of policies aimed at speeding up the transition. Government assistance policies in the form of tax credits for the purchase of hydrogen vehicles have been found to be quite potent. A temporary tax credit, extending for the first 10 years of the transition, would provide a very significant boost. The early period of high hydrogen shares of sales with the temporary credits will increase the stock of hydrogen vehicles earlier in the transition. Carbon taxes and government assistance in building seed stations have less effect.

FUTURE WORK

As discussed in Section 6.10, this study has applied an agent-based approach to modeling hydrogen infrastructure supply, using real world decision processes that do not assume unrealistic optimization. Given the resource limitations of the study, help was given by our industry cooperators in choosing which of the many facets of decision-making to concentrate on. A large number of possibilities exist for studying other approximative decisions that drivers and investors may be concerned with beyond those considered here.

Our results have been presented in such a way that they can be adapted to future conditions. While reliably predicting events and policy concerns 10 or 15 years in the future is at best difficult, the model of this study provides a way to analyze effects of a wide range of future possibilities. It is a tool to aid in evaluation of policies that will arise in the future and that can be adapted to changing conditions in the future.