ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Technovation ∎ (∎∎∎∎) ∎∎∎–∎∎∎

technovation

www.elsevier.com/locate/technovation

Modeling technology diffusion of complementary goods: The case of hydrogen vehicles and refueling infrastructure

Patrick E. Meyer*, James J. Winebrake

Department of STS/Public Policy, Rochester Institute of Technology, 92 Lomb Memorial Drive, Rochester, NY 14623, USA

Abstract

Hydrogen has emerged as a possible transportation fuel for addressing long-term, sustainable energy supply, security, and environmental problems. Yet, there are a number of barriers that need to be overcome if hydrogen vehicles are ever to penetrate transportation markets, not the least of which is the development of a vehicle–infrastructure system. Hydrogen vehicles and refueling infrastructure are complementary goods and must both successfully penetrate transportation markets for either to be successful. This paper describes a system dynamics model created to investigate the vehicle–infrastructure phenomenon currently inhibiting the growth of hydrogen transportation systems. Four scenarios explore the phenomenon through analysis of vehicle adoption, infrastructure development rates, and hydrogen market conditions. We conclude that a coordinated policy approach that simultaneously encourages both the purchase of hydrogen vehicles and the building of hydrogen infrastructure is the most effective approach for rapid vehicle–infrastructure adoption.

Keywords: Hydrogen energy; Complementary goods; Alternative fuels; Technology diffusion

1. Introduction

Some experts predict that the 100 year reign of petroleum as the dominant transportation fuel will soon come to an end due to depleting reserves, unlikely future discoveries, mounting prices, instable markets, and the escalating availability of alternatives (Campbell and Laherrere, 1998; Deffeyes, 2003; Hirsch, 2008; Laherrere, 2001; Witze, 2007; Yergin, 2006). Although global transportation systems are still highly dependent on petroleum, increasing oil scarcity, international energy security, and the desire and need to reduce environmentally degrading emissions have forced or will soon force many nations into considering long-term transportation alternatives (Smill, 2003; Yergin, 2006).

In the United States (US), where petroleum fuels almost 97 percent of the transportation sector, government bodies and other stakeholders have expressed particular concerns about petroleum price shocks or supply disruptions that could have widespread negative economic impacts including trade deficits, decreased industrial investment, and increased unemployment (DOE, 2005; Hirsch, 2008; TRB, 2006). These concerns are heightened in the face of increasing world petroleum demand in India, China, Russia, and Brazil (Bleischwitz and Fuhrmann, 2006; Hirsch et al., 2006; Noreng, 2006; Winebrake, 2002). Moreover, recent work by the Intergovernmental Panel on Climate Change establishes a much stronger connection between anthropogenic emissions of greenhouse gases from transportation and climate change (IPCC, 2007).

In this context, nations have been investing heavily in exploring non-petroleum-based alternative fuels as a way to enhance energy security and reduce emissions of air pollutants and greenhouse gases (EIA, 2007). *Hydrogen* has emerged as a possible 'fuel of choice' for addressing these long-term, sustainable energy supply and environmental problems (Clark and Rifkin, 2006; Dunn, 2002; Johansson

*Corresponding author. Present address: Center for Energy and Environmental Policy, University of Delaware, 278 Graham Hall, Newark, DE 19716, USA. Tel.: +1 585 797 5206; fax: +1 302 832 3098.

E-mail addresses: patrickmeyer@gmail.com (P.E. Meyer), jjwgpt@rit.edu (J.J. Winebrake).

0166-4972/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.technovation.2008.05.004

Please cite this article as: Meyer, P.E., Winebrake, J.J., Modeling technology diffusion of complementary goods: The case of hydrogen vehicles and refueling infrastructure. Technovation (2008), doi:10.1016/j.technovation.2008.05.004

Nomenclature

C	price per mile
f	fuel price attractiveness factor
J	set of available vehicle types
j	specific vehicle type
l	life of vehicle
m	market share baseline
r	refueling station percentage
s	station density attractiveness factor
v	vehicle price attractiveness factor
δ	attractiveness coefficient
ε	elasticity
ρ	price of vehicle
ς	price slope

et al., 1993; Myers et al., 2003; Turner, 1999; Winebrake, 2002).

Whether hydrogen vehicles ever gain footing in global transportation markets remains to be seen. There are a number of barriers that need to be overcome, not the least of which is the development of an efficient and affordable fuel production and distribution infrastructure. This hydrogen vehicle–infrastructure system represents a classic case of complementary goods. In this system, consumers will not purchase hydrogen vehicles if there is no refueling infrastructure to service the vehicles; at the same time, infrastructure development will not occur if there are no vehicles in operation to support it. This dilemma has been dubbed the "chicken and egg" phenomenon in the alternative fuels literature (DOE, 2002; Marchetti, 2006; Melaina, 2003; Melendez and Milbrandt, 2006; Mintz et al., 2003; Rifkin, 2002; Sperling, 1988; Zhao and Melaina, 2006).

In this paper, we use system dynamics (SD) modeling to better understand and evaluate the diffusion of hydrogen technology in this complementary goods context. The model is focused on the US, but could be applied to other countries with minimal or no modifications. Through a demonstration of this model, we analyze the role of technology deployment and policy in the context of hydrogen vehicles and infrastructure. From this analysis, we suggest that a coordinated policy approach is needed to encourage hydrogen market penetration in US transportation systems. These results can be generalized to gain a greater understanding of complementary goods diffusion in large-scale, technological systems.

2. Background

2.1. Why hydrogen transportation?

The US currently uses about 21 million barrels of crude oil per day, mostly to satisfy demands in the transportation sector (EIA, 2008). Similar to other industrialized nations, the US transportation industry is almost 97 percent dependent on petroleum (DOE, 2005; Mintz et al., 2003; Romm, 2006) and 60 percent of that fuel is imported (EIA, 2008). In the first week of January 2008, oil prices breached $100 per barrel for the first time (BBC, 2008; Shenk and Subrahmaniyan, 2008). Assuming this price and the most recent consumption statistics, the US spends nearly $15 billion on oil *per week* (EIA, 2008). Despite the high cost of oil, alternative fuel use in the US in 2005 accounted for only 421 million gallons of gasoline equivalent, or about 0.3 percent of total vehicle fuel consumption (Davis and Diegel, 2007; EERE, 2008).

This dependence on petroleum in the US transportation sector also presents numerous environmental problems (EPA, 2006a, b; Winebrake and Creswick, 2003). In 2005, the US transportation sector was responsible for about 2000 million metric tons of carbon dioxide emissions, or about 33 percent of the total carbon dioxide emissions nationally (Davis and Diegel, 2007). This proportion has increased every year since 1990 and is expected to continue to increase; transportation is projected to account for almost half of the 40 percent rise in carbon dioxide emissions forecast for 2025 (Davis and Diegel, 2007; EIA, 2005). Additionally, conventional gasoline and diesel vehicles contribute to emissions of carbon monoxide, oxides of nitrogen and sulfur, particulate matter, and numerous toxic emissions that have a negative impact on human health and the environment (Bleischwitz and Fuhrmann, 2006; EPA, 2006b).

Because of these energy security and environmental concerns, there has been recent interest in the US in hydrogen as an energy carrier. This interest is driven by two main factors. First, hydrogen can be produced in a number of different ways. The National Research Council identifies seven existing and potential methods by which hydrogen may be produced: (1) reformation of natural gas to hydrogen, (2) conversion of coal to hydrogen, (3) use of nuclear energy to produce hydrogen, (4) electrolysis, (5) use of wind energy to produce hydrogen, (6) production of hydrogen from biomass, and (7) production of hydrogen from solar energy (NRC, 2004). Hydrogen from a variety of sources produces diversity in transportation energy supply allowing the nation to be less susceptible to petroleum price or supply shocks (Wietschel et al., 2006).

Second, hydrogen used in a fuel cell produces zero end-use vehicular emissions (Wang, 2002; Winebrake and Creswick, 2003). Furthermore, life-cycle analyses have shown that many hydrogen pathways achieve significant emissions reductions compared to traditional fuels across the entire fuel cycle (Wang, 2002; Winebrake and Meyer, 2008; Wu et al., 2006).

Because of the aforementioned benefits, hydrogen is being pursued in multiple sectors, but most prominently in the realms of distributed generation and transportation (Rifkin, 2002). The general emergence of distributed generation is being driven by economics, electric grid reliability concerns, and the development of new technologies such as hydrogen fuel cells (Casazza and Delea, 2003). It is predicted that fuel cells will likely begin to be widely introduced into power systems between 2008 and 2018 (Casazza and Delea, 2003). However, fuel cells may hold the highest potential in the transportation sector where the combination of a flexible hydrogen production pathway and the overall cleanliness of hydrogen fuel cells hold the potential to solve the most pressing transportation problems. It should be noted that the advancements in both stationary and mobile fuel cell applications will likely have positively reinforcing impacts on each technology's future development.

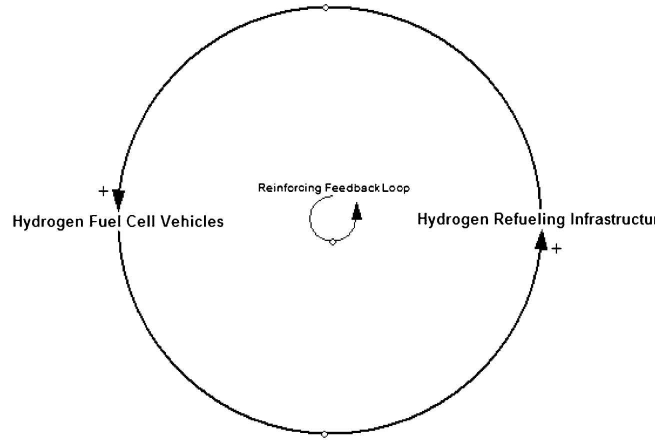

Fig. 1. Hydrogen vehicle–infrastructure causal loop diagram.

2.2. Complementary goods and convenience costs in transportation

Despite the aforementioned benefits of hydrogen as a transportation fuel, there are many barriers hindering the introduction of hydrogen into transportation systems. The US Department of Energy's (DOE) *A National Vision of America's Transition to a Hydrogen Economy—To 2030 and Beyond* (2002) identifies numerous barriers to hydrogen market penetration, including the lack of hydrogen infrastructure; the lack of hydrogen production, storage, and conversion devices; and, consumer preferences for low-cost energy sources. These barriers are echoed by Romm (2006) who identifies high first cost of vehicles, high fuel costs, and limited refueling stations as major problems. These contribute to the above-mentioned "chicken and egg" phenomenon whereby investments in hydrogen vehicles will not be made without complementary investments in hydrogen refueling infrastructure; yet, investments in refueling infrastructure will not be made without complementary investments in hydrogen vehicles (DOE, 2002; Marchetti, 2006; Melaina, 2003; Melendez and Milbrandt, 2006; Mintz et al., 2003; Rifkin, 2002; Sperling, 1988; Zhao and Melaina, 2006).

To further understand this phenomenon, consider the concept of *complementary goods*. Complementary goods are goods which operate in a system and must be consumed together (Katz and Shapiro, 1994; Saloner and Shepard, 1995). Examples of such goods are DVD players and their complementary disks, computer hardware and complementary software, and of course, vehicles and their complementary refueling infrastructure. The systematic effects of complementary goods in the context of alternative fuel vehicles (AFVs) and their associated infrastructure was first presented by Winebrake and Farrell (1997), who showed that such complementarity creates network effects that could lead to "clusters" of AFVs in certain locations in the US. The concept has recently been studied in the Swiss natural gas vehicle (NGV) industry (Frick et al., 2007) and is a primary reason why the NGV market never took hold in Canada (Flynn, 2002).

Without sufficient penetration of *both* goods in a complementary goods system, the purchase and use of one of the complementary goods becomes highly inconvenient. This inconvenience introduces a new set of costs to the consumer known as "convenience costs" (Winebrake and Farrell, 1997). For example, in early US NGV markets, convenience costs associated with the extra time required to travel to and refuel one's NGV (due to the low density of NGV refueling stations) canceled out benefits associated with cheap natural gas fuel (Winebrake, 2000, 2002). These costs may play an extremely important role in the development of hydrogen vehicle markets. Refueling stations must be conveniently located to reduce convenience costs associated with refueling (Winebrake and Farrell, 1997).

The relationship of complementary goods in a simple hydrogen vehicle-fueling station causal loop diagram is shown in Fig. 1. This figure depicts a reinforcing feedback loop. Currently, this loop is operating in a negative direction. There are limited incentives to build refueling stations when vehicle populations are low; and there are limited incentives to produce or purchase vehicles when the refueling infrastructure is lacking. However, with certain interventions, this system can move in a positive direction (Winebrake and Farrell, 1997). For example, government policies that incentivize hydrogen FCV purchases may stimulate refueling infrastructure development, which would thereby lead to more vehicle purchases, leading to more stations, leading to more vehicles purchases, and so on.

3. Methods: technology diffusion and systems dynamics modeling

3.1. Technology diffusion models

This paper presents a technology diffusion model aimed at analyzing the complementary vehicle–infrastructure

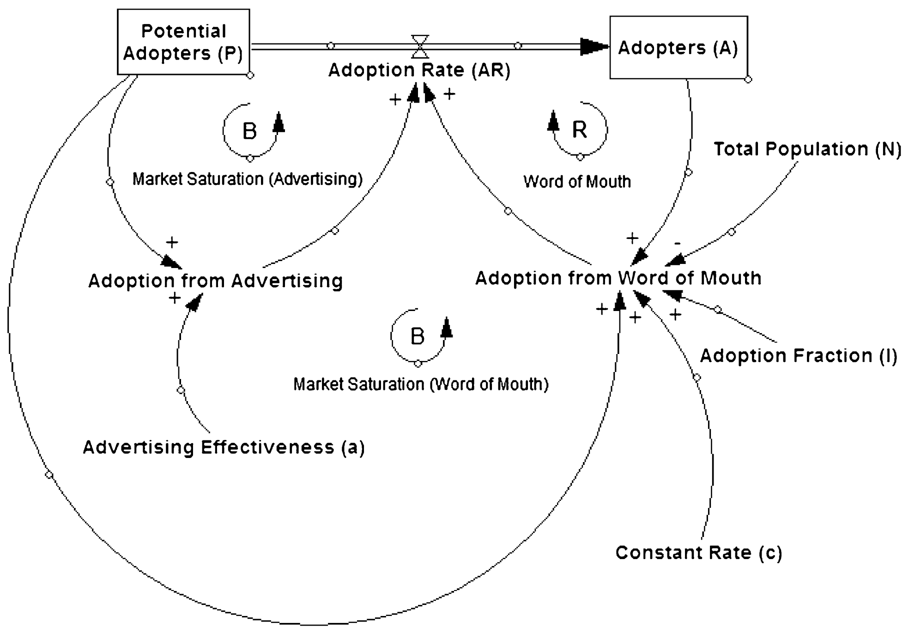

Fig. 2. The Bass diffusion model.

relationships exhibited in a hydrogen transportation system. The SD environment is a good one for evaluating such systems and has been regularly applied to the mainstream diffusion of innovations and new technologies (Rogers, 1983; Sterman, 2000; Valente, 1993).

The technology diffusion process has been formulated as the one exhibiting logistic growth (“s-shaped curve”) characteristics. The application of this type of functional form has a long history and broad application, including research in agricultural technologies (Griliches, 1957), the spread of disease (Bailey, 1957, 1975; Monin et al., 1976), rumors (Daley and Kendall, 1965), and news (Deutschmann and Danielson, 1960).

When applied to technology diffusion, logistic growth depicts a process in which there are initially only a few “early adopters” of an innovation. As the population of adopters increases (slowly at first) more information about the technology is shared among existing and potential users and the rate of adoption increases under the influence of reinforcing feedback. At some point along the curve, the increase in new adopters becomes self-sustaining. This has been referred to as the *critical mass* (Allen, 1988; Flynn, 2002; Markus, 1987; Valente, 1993) or the *tipping point* (Sterman, 2000) and refers to a point after which the technology achieves permanent market penetration. The curve ultimately flattens as the technology reaches its market saturation point (Valente, 1993).

This concept has been studied in depth by Bass (1969) in his diffusion model. The Bass diffusion model is shown in a causal loop diagram in Fig. 2 (adapted from Sterman, 2000). The model has proven to have a high capacity of forecasting power despite its simple structure (Mahajan et al., 1990).

During technology diffusion, the “early majority” will emulate the practices of the early adopters, and this is the key to widespread acceptance of technology (EERE, 2007; Rogers, 1983). Policies aimed at reaching the early majority need to be designed to ensure that diffusion will reach the critical mass of adopters (Valente, 1993). When this critical mass is reached, the technology diffuses to other end-users, manufacturers, retailers, consultants, builders, and households and policy incentives become less necessary (EERE, 2007).

Recent work by Struben and Sterman (2007) develops a behavioral dynamics model which explores the transition from conventional vehicles to AFVs and uses basic technology diffusion concepts similar to those developed by Bass. Although Struben and Sterman’s model incorporates feedback from the development of fueling infrastructure, the primary focus of their model regards behavioral dynamics such as word of mouth, social exposure, and the willingness of consumers to consider AFVs. Struben and Sterman demonstrate the development of refueling infrastructure through the lens of social dynamics (i.e. advertisement, social exposure, perceived utility of vehicle platforms, and refueling effort).

3.1.1. Vehicle-oriented hydrogen diffusion models

Basic concepts of technology diffusion have been incorporated into many models of hydrogen vehicle penetration (McDowall and Eames, 2006). This literature tends to be disproportionately vehicle oriented with an overall disregard for the importance of refueling infrastructure’s complementary role in vehicle acceptance. Some examples of these models include: (1) the *TAFV Alternative Fuels and Vehicles Choice Model* (AFVC), which uses AFV attributes integrated with a consumer choice model to forecast AFV market penetration (Greene, 1994, 2001); (2) the *Cost of Hydrogen under Alternative Infrastructures* (CHAIN) model, which estimates hydrogen pathway costs on a *total fuel-cycle* basis (Mintz, 2002; Mintz et al., 2003); (3) the DOE Hydrogen Analysis Group efforts to develop a modeling tool for analyzing hydrogen alternatives at the system, technology, or component level, but not vehicle–infrastructure dynamics (EERE, 2006; Ogden et al., 2004); (4) the *Transitional Hydrogen Economy Replacement Model* (THERM) being developed by the Institute of Transportation Studies Hydrogen Pathways Program at UC Davis to analyze different scenarios related to hydrogen production (Yang, 2006); (5) the HyTrans Model, recently developed by the DOE, which simulates the functioning of competitive markets by maximizing producers' profits and consumers' welfare (Greene and Leiby, 2007); and (6) applications of the analytic hierarchy process (AHP) to explore the commercialization possibilities of hydrogen technologies in a multi-attribute decision making environment (Winebrake and Creswick, 2003).

Although useful in their respective contexts, these models do not adequately develop the dynamic relationship between vehicles and infrastructure (as complementary goods) needed to understand the effectiveness of technology development and policy in a hydrogen vehicle–infrastructure system. Although some of the above models, such as the HyTrans Model and the recent work by Struben and Sterman, specifically discuss and simulate fueling infrastructure dynamics, we believe that the model developed here, which has been constructed more explicitly through the frame of the complementary goods phenomenon, serves to increase the precise knowledge of the feedback and complications which arise when two goods (i.e. vehicles and infrastructure) must be simultaneously developed.

3.2. The H_2VISION model

3.2.1. Model overview and limitations

The hydrogen (*H_2*) *V*ehicle and *I*nfrastructure *S*imulator for *I*ntegrated and *O*perational Transportation *N*etworks (*H_2VISION*) makes use of SD techniques to simulate the diffusion paradigm associated with hydrogen FCVs and refueling infrastructure. Developed in STELLA® System Modeling Research Software, H_2VISION explores: (1) the fundamental dynamics of the vehicle–infrastructure, complementary goods phenomenon, and long-term mainstream hydrogen technology diffusion; (2) consumer preferences regarding FCVs and convenience costs associated with refueling infrastructure; (3) the potential role that policies aimed at hydrogen technologies may play in market development (i.e. bulk vehicle procurement, monetary incentives, and mass building of refueling stations); and (4) the role of fleet operators, governments, and other investors as *early adopters* of hydrogen technologies.

H_2VISION uses data on demographics, consumer preferences, and vehicle and station attributes and generates market share estimates for each vehicle and infrastructure type. H_2VISION makes use of consumer preference formulas and relationships originally developed by Greene (1994), updated in Greene (2001), and most recently used in Greene and Leiby (2007). With H_2VISION, we can evaluate long-term hydrogen market penetration for a specific area under various technology and policy scenarios.

It should be noted that H_2VISION does not consider home- or residential-refueling options due to the high estimated cost associated with such methods; the National Renewable Energy Laboratory has reported cost estimates of five refueling methods and the two home-refueling (via electrolysis) options ranked the most costly (NREL, 1999). Thus H_2VISION explores refueling via refueling stations only. Further, H_2VISION does not directly consider spillover effects into the transportation sector from hydrogen technology advancements in other industries. For example, fuel cells hold particular promise in the realm of distributed power generation, but the development of distributed generation fuel cells has not been included in H_2VISION at this time. Lastly, H_2VISION does not directly consider the impact of externalities such as the price of oil. However, as will be explained, H_2VISION inputs and overall model structure are flexible enough to indirectly incorporate almost any externality. For example, an increase in the price of oil can be incorporated into the model by increasing the gasoline price for conventional vehicles; or, advancements in distributed power generation can be incorporated by decreasing the price of FCVs (assuming a breakthrough in power generation would have positive externalities, making FCVs more economically attractive).

3.2.2. Causal loop diagram

Fig. 3 presents a causal loop diagram for H_2VISION. This figure portrays the various vehicle–infrastructure–consumer relationships in the model. The diagram consists of multiple variables and six separately identifiable loops—four of which are "reinforcing" and two of which are "balancing". The reinforcing loops form the core structure of the diagram, and arguably cause the existing inertia in today's alternative fuels transportation markets. That is, conventional vehicle markets are positively reinforcing in a manner that allow them to dominate market share, while alternative vehicle markets are negatively reinforcing making it difficult to overcome barriers to market entry. The balancing loops and external variables serve as conduits by which the polarity of the reinforcing loops may be altered. Tables A1 and A2 located in the Supplementary Appendix provide a detailed description of each variable and each feedback loop, respectively.

3.2.3. The SD H_2VISION model

The H_2VISION SD model is separated into three sections: (1) the *Core H_2VISION Model*, (2) the *Refueling*

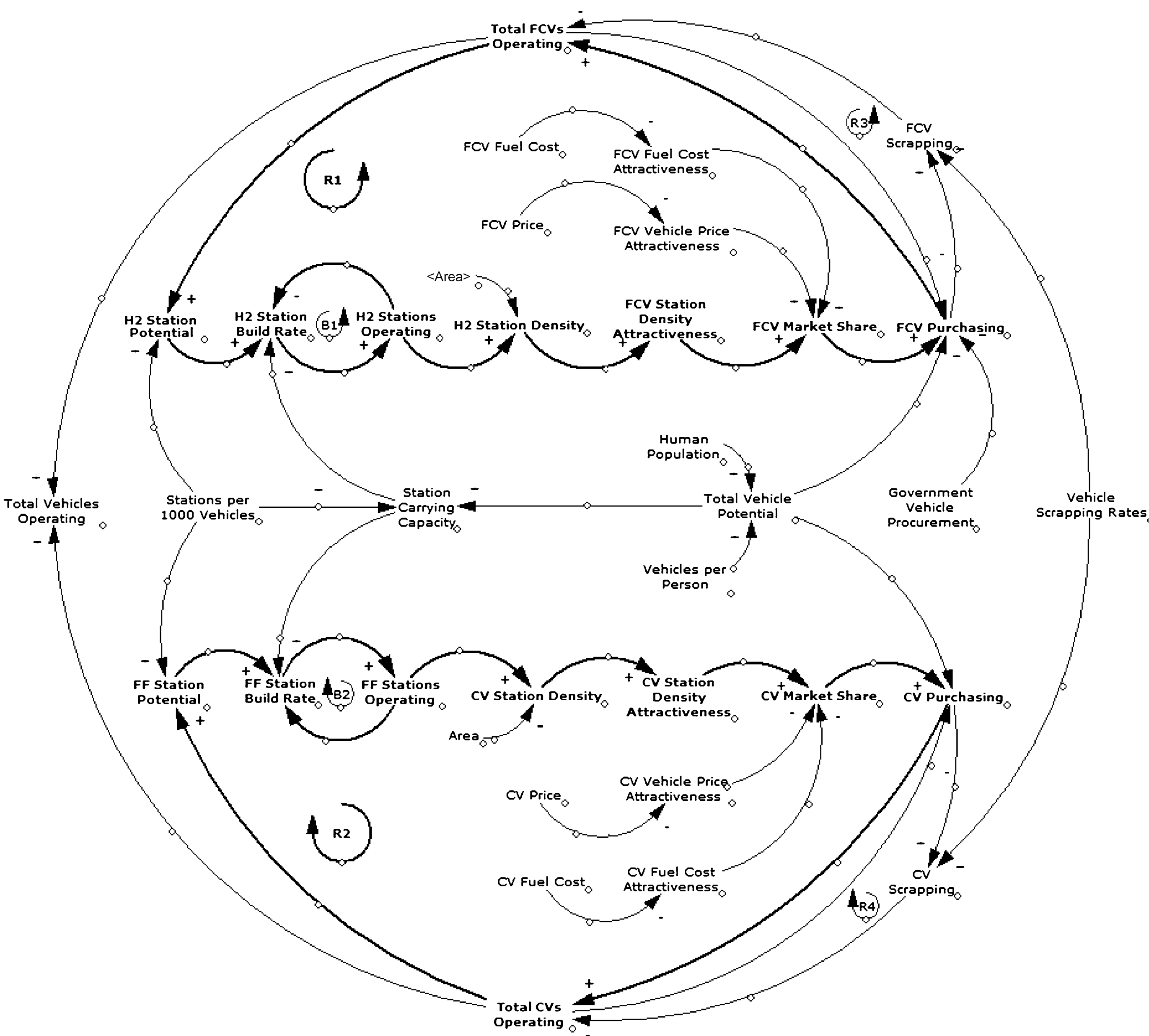

Fig. 3. H_2 VISION causal loop diagram.

Station Market Shares sub-model, and (3) the *Vehicle Market Shares sub-model*. The core model is a stock-and-flow design and captures the FCV and conventional vehicle (CV) populations, vehicle aging and scrapping, and demographics within the simulation area. Output from the core model includes total vehicles operating by type (FCV or CV). For simplicity, we do not distinguish among vehicle classes, and we include only two types of vehicles (FCV and CV). The model could be expanded to include other vehicle types and distinguish among vehicles classes. However, we do not believe that such disaggregation is needed for the purposes of this paper—that is, to demonstrate the vehicle–infrastructure dynamic and draw general conclusions about how that dynamic thwarts technology adoption in complementary goods systems and how technologies and policies may affect system inertia.

The *cohort* modeling structure we use has also been applied to vehicle population deterioration (purchasing and scrapping) and to determine air pollution and vehicle emissions at different stages of vehicle life (Deaton and Winebrake, 2000).

Fig. 4 presents the core H_2VISION model as it appears in the STELLA® system modeling software. Table A3 located in the Supplementary Appendix provides details of each variable in the *Core H_2VISION Model* along with a description of information regarding units and equation of the variable.

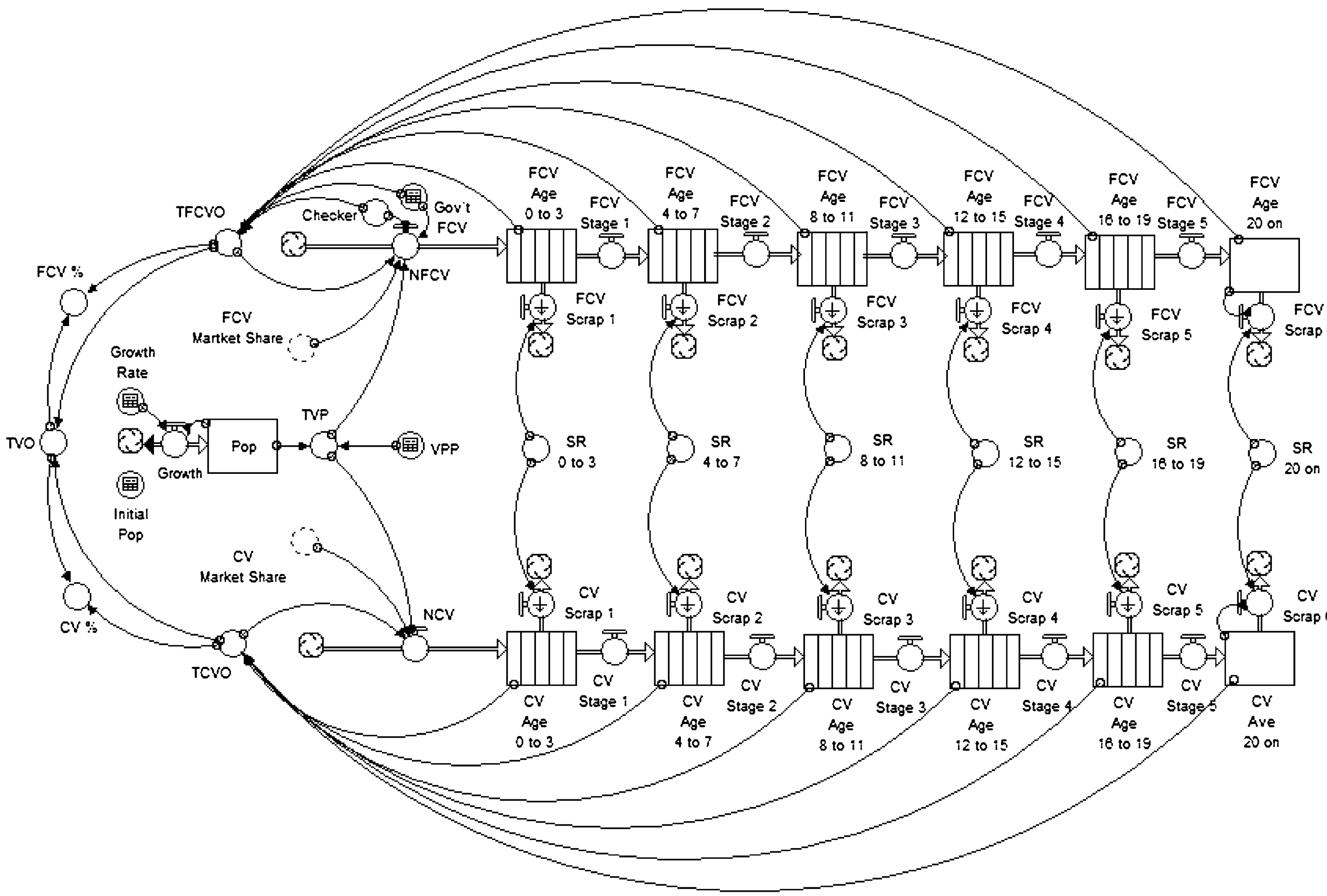

Fig. 4. Core H_2 VISION model.

The *Refueling Station Market Shares* sub-model (RSMS-SM) captures the hydrogen (H2) and fossil fuel (FF) refueling station populations, the potential number of new stations based on vehicles on the road, and the station carrying capacity—and outputs essential data regarding total stations operating and the portion of those stations that are H2 or FF stations. Fig. 5 presents RSMS-SM as it appears in the STELLA® system modeling software. Table A4 located in the Supplementary Appendix provides details on each variable in RSMS-SM along with a description and vital information on units and equation of the variable.

The *Vehicle Market Shares* sub-model (VMS-SM) is a consumer preference model that captures the market shares of FCVs and CVs. The shares are found by first calculating three "attractiveness factors" (related to consumer preferences): *fuel cost attractiveness* (FCA), *vehicle price attractiveness* (VPA), and *station density attractiveness* (SDA). Our consumer preference model structure falls under the class of *discrete choice analysis* (DCA) and assumes that the probability of choosing a particular vehicle type is calculated as the probability that that vehicle type has a higher utility than the other available alternatives (Michalek et al., 2003). In our model, consumers make adoption decisions based on the utility or attractiveness of FCVs or conventional vehicles and corresponding infrastructure. Using logit model formulations, we identify the probability that a given consumer will purchase one vehicle type over other types as

$$\Pr(j|J) = \frac{e^{u_j}}{\sum_{j \in J} e^{u_j}}$$

where j is one vehicle type in a set of vehicle types J (see Michalek et al., 2003).

The utility function that we use is based on a linear consumer choice equation that includes items present in Greene's (1994, 2001) work, such as cost per mile (determined by fuel price), vehicle price, and refueling station density (called "fuel availability" by Greene). We call these terms "attractiveness factors" in our model. The utility function is defined as

$$u_j = \beta_1 f_j + \beta_2 v_j + \beta_3 s_j$$

where f is the fuel price attractiveness factor, v is the vehicle price attractiveness factor, and s is the station density attractiveness factor. The attractiveness factors are further defined hereunder.

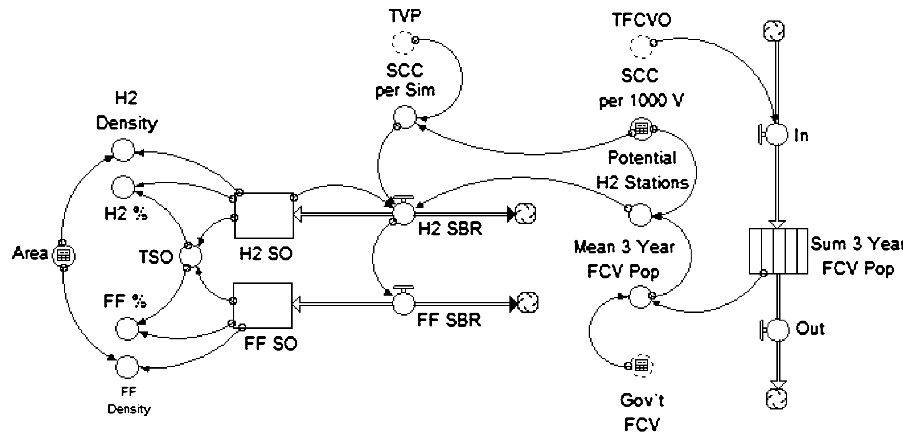

Fig. 5. Refueling station market shares sub-model (RSMS-SM).

The fuel price attractiveness factor (*f*) is defined as

$$f = \delta_j C_j$$

where C_j is the price per mile of vehicle *j* and δ is the attractiveness coefficient of vehicle *j* with respect to *f*. The attractiveness coefficient is defined as

$$\delta = l_j \left(\frac{\varsigma}{100}\right)$$

where l_j is the vehicle life of vehicle *j* (in miles) and ς is the price slope. The price slope is defined as

$$\varsigma = \frac{\varepsilon}{\rho_j(1-m)}$$

where ρ is the price of vehicle *j* and ε is the elasticity at the market share baseline *m*.

The vehicle price attractiveness factor (*v*) is defined as

$$v = \rho_j \varsigma$$

where ρ is the price of vehicle *j* and ς is the price slope as defined above.

Lastly, the station density attractiveness factor (*s*) is defined as

$$s = \delta_0 e^{\delta_{10}(r_j/100)}$$

where δ_0 is the attractiveness coefficient at 0 percent refueling station density, δ_{10} is the attractiveness coefficient at 10 percent refueling station density, and r_j is the percent of refueling stations able to service vehicle type *j* versus the total stations in operation. δ_0 is further defined as

$$\delta_0 = -(\rho_0 \varsigma)$$

and δ_{10} is defined as

$$\delta_{10} = \frac{[\ln(\rho_{10}\varsigma) - \ln(\rho_0\varsigma)]}{10\%}$$

where ρ_0 is the consumer price penalty associated with 0 percent station density, ρ_{10} is the consumer price penalty associated with 10 percent station density, and ς is the price slope as defined above.

Fig. 6 presents VMS-SM as it appears in the STELLA® system modeling software. Table A5 located in the Supplementary Appendix provides details on each variable in VMS-SM along with a description and information on units and the in-model equation of the variable.

It should be noted that the AFCV Model incorporates 11 variables by which to determine market share: vehicle price, fuel cost, vehicle range, top speed, acceleration, multifuel capability, home refueling availability, maintenance cost, luggage space, fuel availability, and make/model availability. In this analysis it has been assumed that all but three of these variables are equal between CVs and FCVs. H_2VISION incorporates the three factors which are most likely to differ between the vehicle types in real-world scenarios: vehicle price, fuel cost, and fuel availability (station density). The flexibility of the model structure allows for the incorporation of other consumer preference variables as determined appropriate by the analyst.

4. Application of the model for diffusion analysis

4.1. Scenario overview

This section presents four scenarios using H_2VISION to illustrate the role of complementary goods (vehicles and infrastructure) in hydrogen FCV markets. The driving variables in our scenario analysis are: (1) the level of early FCV adoption, (2) the level of early infrastructure development, and (3) the attractiveness of hydrogen in transportation markets as defined by hydrogen fuel and vehicle costs. Through our scenario analysis, we can investigate the role that each of these variables has in hydrogen FCV market penetration. Table 1 presents a summary of the four scenarios.

H_2VISION is constructed so that any demographic area can be simulated. We conduct our analysis for an area of approximately 60 square miles, which is representative of a mid-size US city. We assume an initial population of 565,000 people growing at about 0.6 percent per year,

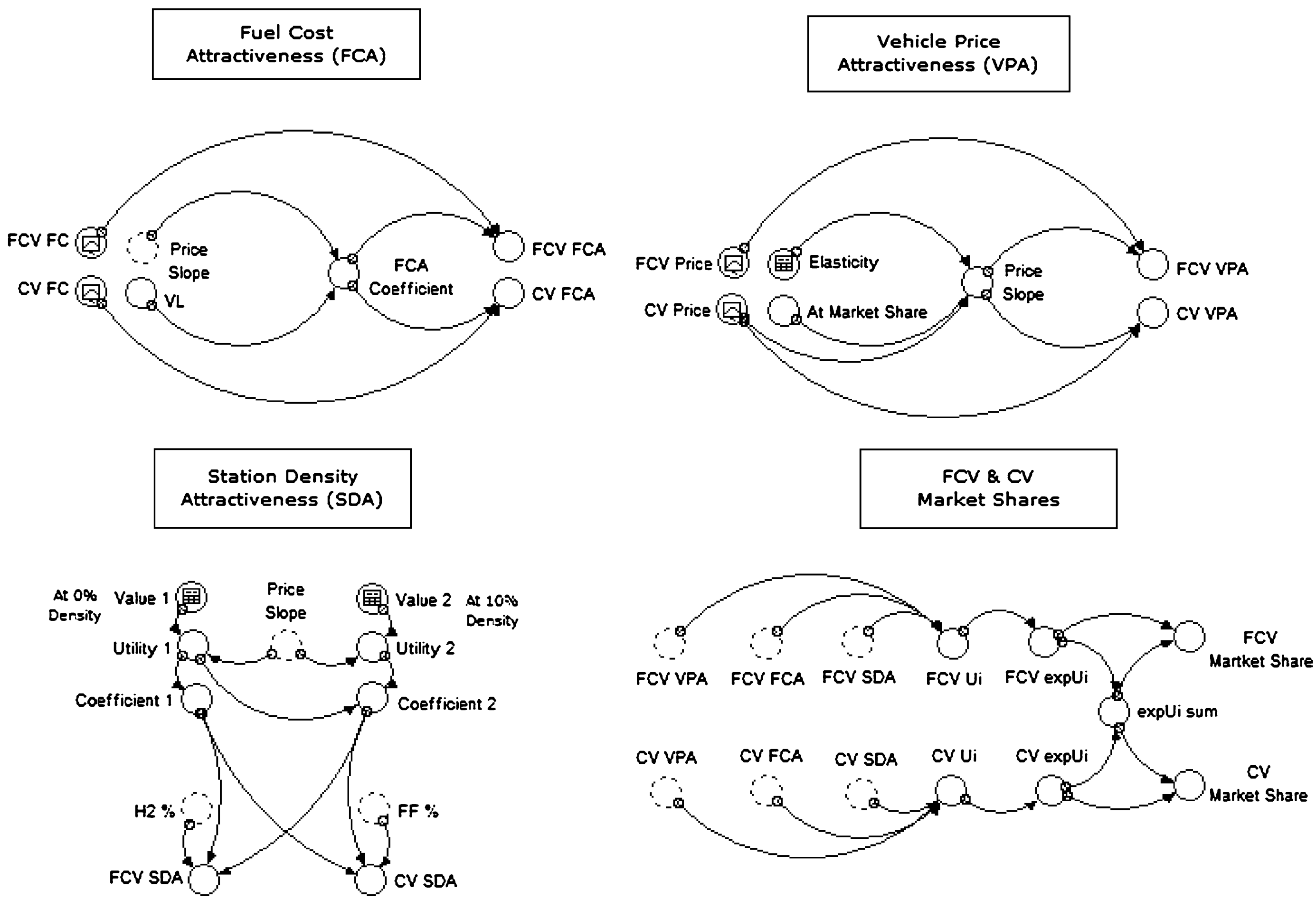

Fig. 6. Vehicle market shares sub-model (VMS-SM).

based on Washington, DC demographic estimates (USCB, 2005). We assume that citizens own approximately 0.8 vehicles per person (Davis and Diegel, 2007; USCB, 2005). Table 2 presents the initial values for each scenario.

Consumers in different areas will exhibit different consumer preference functions that may make AFVs more or less attractive. Variability in consumer demographics can be represented in the chosen utility function coefficients. Further, the specific scenarios chosen to explore vehicle–infrastructure dynamics may vary from region to region, but the actual functions of the model would remain the same regardless of the exact demographic area to which it is applied. We note that H_2VISION is intended to provide general market trends for FCVs and associated infrastructure, so readers should not overly scrutinize the exact numerical results in our scenario results, but should view the overall trends of market success or failure and consider how the given initial conditions led to such results.

4.2. Scenario 1: infrastructure investment in challenging markets

In *Scenario 1: infrastructure investment in challenging markets* (S1), efforts to spur hydrogen market growth are focused almost entirely on infrastructure; 20 H_2 stations are constructed in a market in which FCVs (vehicles and fuel) are economically unfavorable. The selection of 20 initial H_2 stations was done so to represent a situation in which there would be far greater hydrogen stations that the current situation, but less than the current conventional vehicle-to-station ratio. To explain, if 20 hydrogen refueling stations were built in the greater Washington, DC area, the number of alternative fuel stations would increase fivefold from 5 current stations (ethanol, biodiesel, and natural gas stations) to 25 stations. (Refueling station data from Davis and Diegel, 2007.) With 25 alternative fuel stations, this would represent a situation with an 18,000-to-1 conventional vehicle-to-alternative refueling station ratio, which is about 13 times less than the national average of 1400-to-1 conventional vehicle-to-conventional station ratio. Thus, while the construction of 20 hydrogen stations may seem aggressive, an area with nearly a half-million vehicles would actually need about 260 alternative refueling stations in order for the stations to be as equally accessible as conventional stations.

It is further assumed in this scenario that a FCV costs \$3000 more than a CV and H_2 fuel costs \$0.02 per mile more than conventional fuel. S1 assumes that full attention

Table 1
Summary of four scenarios

Scenario number	Scenario title and attributes	Scenario description
1	Infrastructure investment in challenging markets • Infrastructure investment: high • FCV investment: low • H_2 market conditions: poor	This scenario represents a situation in which 20 H_2 stations are constructed in an uncertain and unfavorable FCV market.
2	Infrastructure and FCV investments in competitive markets • Infrastructure investment: high • FCV investment: moderate • H_2 market conditions: moderate	This scenario represents a situation in which 20 H_2 stations are constructed in a market which offers monetary incentives on FCVs and hydrogen fuel.
3	FCV investment in competitive markets • Infrastructure investment: very low • FCV investment: high • H_2 market conditions: moderate	This scenario represents a situation in which there is a substantial initial introduction of FCVs and market conditions/ monetary incentives favor the development of FCVs and hydrogen infrastructure.
4	FCV investment in challenging markets • Infrastructure investment: very low • FCV investment: high • H_2 market conditions: poor	This scenario represents a situation in which there is a substantial initial introduction of FCVs but market conditions do not favor hydrogen vehicles or infrastructure.

(through investment) is given initially to infrastructure development and none to supporting the purchasing of FCVs. Table 2 presents S1 inputs.

As shown in Fig. 7, S1 results in a situation where mass building of stations has some effect through the early stages of FCV markets. The construction of 20 stations is enough to reduce the convenience costs associated with a very limited refueling station density, but the effect is not substantial enough to reach permanent FCV market penetration due to the high vehicle and fuel costs. In the long run, the FCV population collapses and H_2 stations reduce to zero. Note that we assume that stations are distributed homogenously throughout the region and not clustered in one location. That is, for any given consumer the cost of refueling their vehicle is partly a function of the time to get to the station where the time is a function of the number of stations in the area. The consumer's utility is a function of the number of stations *in a given area*, not accounting for clustering of stations at any one point within the area.

With less than 10 H_2 stations operating, the H_2 stations represent only 2 percent of the total number of conventional and hydrogen fueling stations in the area. The failure of the H_2 markets in this scenario is due to an overemphasis placed on infrastructure and a general disregard for vehicle economics. In this case, the FCVs are simply too expensive to buy and refuel—regardless of there being a large investment in infrastructure—and thus FCVs are considered uneconomical. Here, the concept of complementary goods is validated—too much attention is paid to one good (infrastructure) and not enough to the complementary good (FCVs), proving detrimental to long-run market development.

4.3. *Scenario 2: infrastructure and FCV investment in competitive markets*

In *Scenario 2: infrastructure and FCV investment in competitive markets* (S2), efforts to spur hydrogen market growth are applied to both infrastructure and vehicle initiatives; 20 hydrogen refueling stations are built in a market in which FCVs and their fuel are economically *favorable*. Table 2 presents S2 inputs. As shown in Fig. 8, S2 results in a significant increase of FCVs; infrastructure investors respond to FCV purchases by building additional stations quickly, which allows FCV and H_2 stations to reach a sustainable level.

4.4. *Scenario 3: FCV investment in competitive markets*

Scenario 3: FCV investment in competitive markets (S3) evaluates a situation with policy-driven incentives that allow FCVs to be economically favorable in comparison to CVs, but no major infrastructure investments are provided (only 1 initial station is built). As identified in Table 2, S3 was run with the "default" H_2VISION settings, which includes initial FCV purchases, high FCV investment, and attractive H_2 market conditions.

As shown in Fig. 9, S3 results in near-full hydrogen market penetration. There is a relatively slow growth of FCVs and H_2 stations; around year 30, FCVs have achieved only about a 4 percent market penetration. Between year 30 and 40 however, the adopter population escalates. An exponentially greater number of adopters buy FCVs for about half a decade and then the rate of adoption levels off—forming the s-shaped growth curve—the shape of which is consistent with technology diffusion literature (Bass, 1969; Griliches, 1957; Rogers, 1983) and the length of which is consistent with hydrogen literature (DOE, 2002; Romm, 2006).

4.5. *Scenario 4: FCV investment in challenging markets*

Scenario 4: FCV investment in challenging markets (S4) represents a situation in which there is a relatively large

Table 2
Scenario inputs and initial values

Variable	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Units
Area	61.4	61.4	61.4	61.4	Square miles
Initial population	565,000	565,000	565,000	565,000	People
Population growth rate	0.6	0.6	0.6	0.6	Percent
Vehicles per person	0.80	0.80	0.80	0.80	Vehicles
Stations per 1000 vehicles	0.9	0.9	0.9	0.9	Stations
Initial FCV purchases	*0*	*0*	1900	1900	Vehicles
Utility value at 0% density	−30,000	−30,000	−30,000	−30,000	Dollars
Utility value at 10% density	−3000	−3000	−3000	−3000	Dollars
Elasticity	−5	−5	−5	−5	Ratio of proportional change
CV price	20,000 (constant over time)	20,000 (constant over time)	20,000 (constant over time)	20,000 (constant over time)	Dollars
FCV price	*23,000 (constant over time)*	17,000 (constant over time)	17,000 (constant over time)	*23,000 (constant over time)*	Dollars
CV fuel cost	*5 (constant over time)*	7.5 (constant over time)	7.5 (constant over time)	*5 (constant over time)*	Cents per mile
FCV fuel cost	*7 (constant over time)*	3 (constant over time)	3 (constant over time)	*7 (constant over time)*	Cents per mile
Run time	50 (0–49)	50 (0–49)	50 (0–49)	50 (0–49)	Years
Initial FCVs (set)	*0*	*0*	1900	1900	Vehicles
Initial CVs (derived)	449,000	449,000	449,000	449,000	Vehicles
Initial H2 stations (set)	*20*	*20*	1	1	Stations
Initial FF stations (set)	*390*	*390*	410	410	Stations

Alterations italicized.

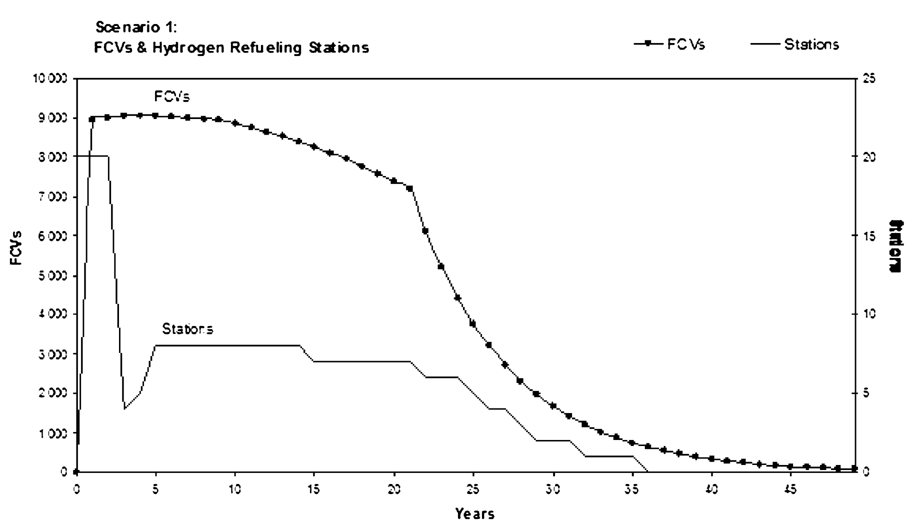

Fig. 7. Scenario 1 graphical results.

initial FCV investment despite there being no monetary incentives provided for FCVs. Minimal infrastructure is initially constructed (only 1 station) to support the vehicle population and FCVs and hydrogen fuel are more expensive than CV price and fuel. Specifically, S4 assumes an initial purchase of approximately 1900 FCVs, a FCV cost $3000 more than CV, and FCV fuel cost $0.02 per mile more than conventional fuel. Table 2 presents S4 inputs. This scenario might mimic a case where government fleets purchase a large number of FCVs in order to stimulate market development in an otherwise challenging market environment.

As shown in Fig. 10, S4 results in a stagnant hydrogen market. The initial large purchase of FCVs and the initial refueling station have minimal impact and the population of adopters does not escalate. During the first year of the simulation there are approximately 70 purchases of FCVs. This small purchase represents the early adopters in the population. However, the purchases are not great enough to reach permanent FCV market penetration or trigger the

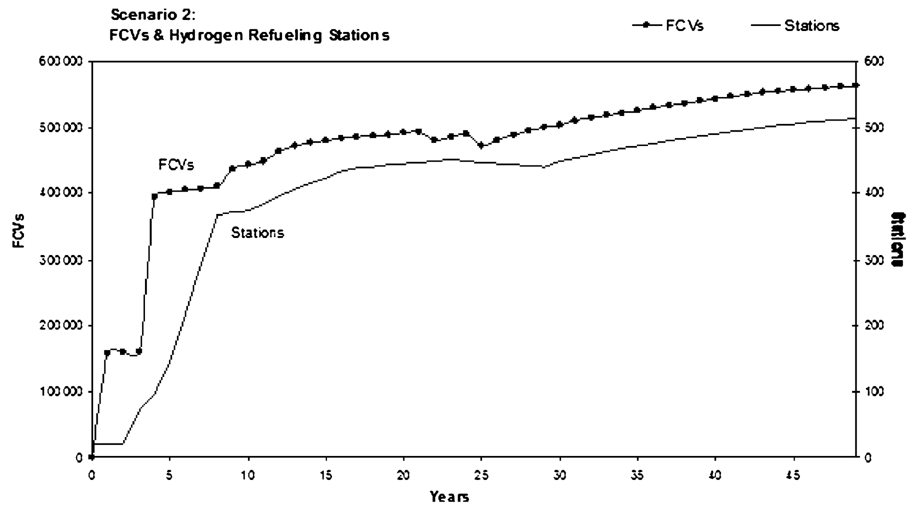

Fig. 8. Scenario 2 graphical results.

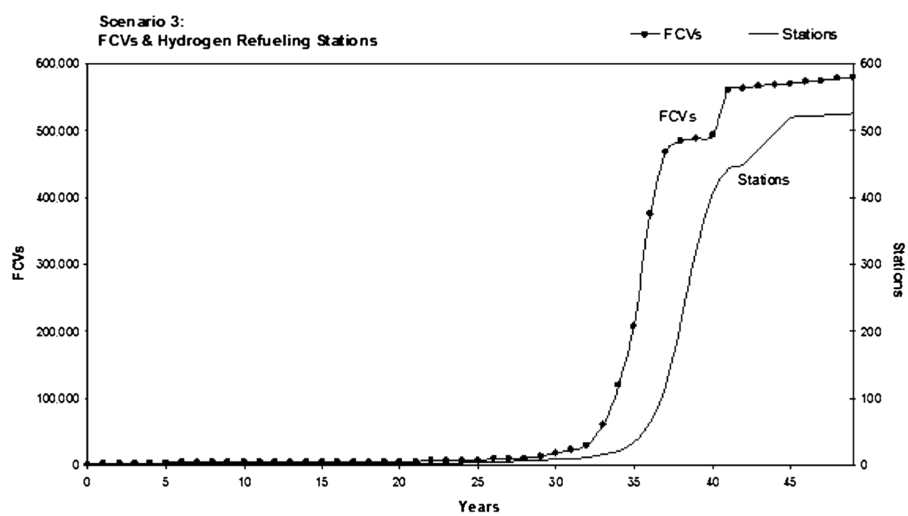

Fig. 9. Scenario 3 graphical results.

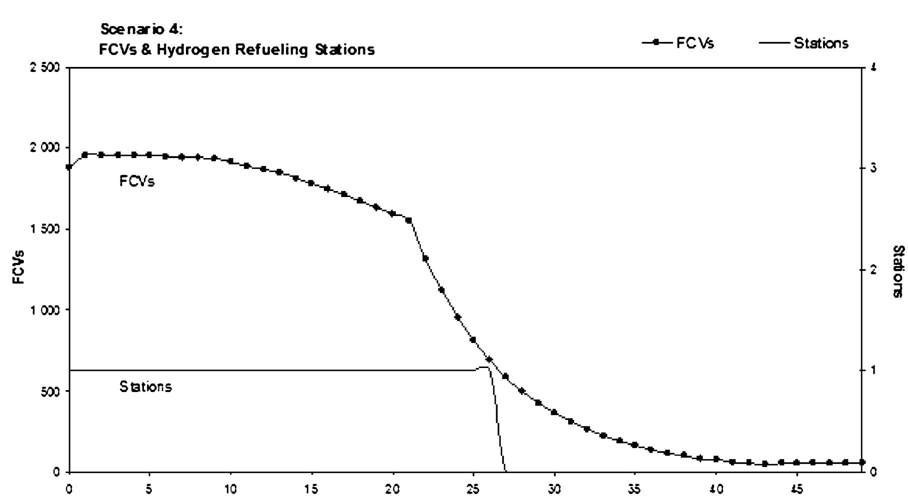

Fig. 10. Scenario 4 graphical results.

early majority adopters. Around year 5, the FCV population begins to decline due to vehicle scrapping, and around year 25, the refueling station is forced to close due to lack of FCVs in the market. The FCV population asymptotically approaches zero.

5. Implications and conclusion

In this paper, we use SD modeling to explore the technology diffusion of complementary goods. Our model (H_2VISION) allows us to explore an important case of complementary goods: hydrogen FCVs and their supporting decentralized refueling infrastructure. We restate that the model is not a logistic planning tool and is not intended to provide exact forecasting or predictions of future events. Instead, it is intended to investigate and offer general trends of vehicle and infrastructure diffusion over a long-term period.

As previously identified, the four scenarios developed under this project explore the dynamics of the vehicle–infrastructure complementary goods phenomenon currently inhibiting the growth of FCVs and refueling infrastructure through three attributes: level of FCV adoption, level of infrastructure development, and favorability of hydrogen market conditions.

A number of conclusions can be drawn from the scenario results. Consider that out of the four scenarios, only S2 and S3 yield a successful FCV market penetration. The only major attribute in common between these scenarios is the favorability of hydrogen market conditions. The scenarios differ in that S2 focuses on initial infrastructure and S3 focuses on initial FCVs. Focusing on infrastructure (S2) leads to faster hydrogen vehicle adoption and station construction. However, *both* scenarios yield complete hydrogen technology saturation in the long run and thus both are successful. This implies that FCV market conditions will be extremely important for any FCV success.

S1 and S4 identify situations in which market penetration does not occur. In both S1 and S4, market conditions do not favor FCVs. Regardless of whether investments are made on infrastructure (S1) or vehicles (S4), permanent FCV market penetration is not achieved. Thus, these scenarios imply that investments affecting only one of the complementary goods may not be sufficient for FCV diffusion to occur.

The scenarios show that incentives must affect both vehicles and infrastructure to yield market penetration. Providing greater infrastructure incentives leads to faster hydrogen vehicle adoption and infrastructure construction, but only if vehicles and fuel are also economically incentivized. Investing in initial vehicle purchases will also yield FCV adoption, but at a slower rate, and again, only if vehicles and fuel are economically incentivized. Investing solely in infrastructure or solely in vehicles will not yield adoption. Ignoring the cost of the vehicles or cost of hydrogen fuel also will not yield adoption. Thus, vehicle- and fuel-oriented incentives must be accompanied by infrastructure-oriented incentives; and infrastructure-oriented incentives must be accompanied by vehicle- and fuel-oriented incentives. Any incentivization that lacks attention to the respective complementary good will yield zero or drastically limited market penetration rates.

If market penetration of FCVs is to occur within the next half-century, it is vitally important that investors (federal, state, and local governments, fleet operators, energy and fuel companies, etc.) simultaneously act as a first-use consumers of FCVs *and* refueling infrastructure developers. This conclusion is echoed by Winebrake (2002): ''If hydrogen is ever to achieve significant market penetration, then coordinated, systematic market development is needed.'' Therefore, our results imply a coordinated policy approach that encourages both the purchase of FCVs and the building of hydrogen infrastructure and provides insights into related factors for technology diffusion of complementary goods. Although the model does not point to, nor have we evaluated *specific* policies, our results shed light on the potential role of governments and fleet operators in assisting systematic market development by supporting the deployment of hydrogen technologies, undertaking bulk procurement of FCVs, offering subsidies for infrastructure construction or directly funding the construction of new stations, offering tax credits on civilian FCV purchases, and offering subsidies on hydrogen fuel production and delivery.

Although many believe that ''the hydrogen economy is within sight'' (Rifkin, 2002) and that ''the future for hydrogen is now and not in 20–30 years'' (Clark and Rifkin, 2006), we have shown that because of the complementary nature of FCVs and their supporting infrastructure, several variables must align if we expect to see technology diffusion of FCVs in vehicle markets. This paper explores the nature of that relationship. From our research, we show how simultaneous investment or policies aimed at *both* complementary goods are needed for such goods to penetrate markets. This is particularly true in transportation markets, where market competition includes well-entrenched, competitive goods and services that make market penetration particularly challenging.

Appendix A. Supplementary materials

The online version of this article contains additional supplementary data. Please visit doi:10.1016/j.technovation.2008.05.004.

References

Allen, D., 1988. New telecommunications services: network externalities and critical mass. Telecommunications Policy 15, 257–271.

Bailey, N.T.J., 1957. The Mathematical Theory of Epidemics. Charles Griffen, London.

Bailey, N.T.J., 1975. The Mathematical Theory of Infectious Diseases and its Applications. Charles Griffen, London.

Bass, F.M., 1969. A new product growth for model consumer durables. Management Science 16, 215–227.

BBC, 2008. Single trader behind oil record. BBC World News International Version London: The British Broadcast Corporation. Retrieved 19 February 2008, from: 〈http://news.bbc.co.uk/2/hi/business/7169543.stm〉.

Bleischwitz, R., Fuhrmann, K., 2006. Introduction to the special issue on 'hydrogen' in 'energy policy'. Energy Policy 34 (11), 1223–1226.

Campbell, C., Laherrere, J., 1998. The End of Cheap Oil. Scientific American.

Casazza, J., Delea, F., 2003. Understanding Electric Power Systems: An Overview of the Technology and the Marketplace. Wiley, Hoboken, NJ.

Clark, W.W., Rifkin, J., 2006. A green hydrogen economy. Energy Policy 34 (17), 2530–2639.

Daley, D.J., Kendall, D.G., 1965. Stochastic rumors. Journal of the Institute of Mathematical Applications 1, 42–55.

Davis, S.C., Diegel, S.W., 2007. Transportation Energy Data Book (No. 26). Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, TN.

Deaton, M.L., Winebrake, J.J., 2000. Dynamic Modeling of Environmental Systems. Springer, New York.

Deffeyes, K.S., 2003. Hubbert's Peak: The Impending World Oil Shortage. Princeton University Press, Princeton, NJ.

Deutschmann, P.J., Danielson, W.A., 1960. Diffusion of knowledge of the major news story. Journalism Quarterly 37, 345–355.

DOE, 2002. A National Vision of America's Transition to a Hydrogen Economy—To 2030 and Beyond. United States Department of Energy, Washington, DC.

DOE, 2005. Hydrogen, Fuel Cells & Infrastructure Technologies Program: multi-year research, development and demonstration plan. US Department of Energy Office of Energy Efficiency and Renewable Energy, Washington, DC.

Dunn, S., 2002. Hydrogen futures: toward a sustainable energy system. International Journal of Hydrogen Energy 27 (3), 235–264.

EERE, 2006. Systems Analysis: H2A Model. *Hydrogen, Fuel Cells & Infrastructure Technologies Program.* US Department of Energy Office of Energy Efficiency and Renewable Energy, Washington, DC. Retrieved 16 April 2006, from: 〈http://www.eere.energy.gov/hydrogenandfuelcells/analysis/model.html〉.

EERE, 2007. Impact Evaluation Framework for Technology Deployment Programs. US Department of Energy, Energy Efficiency and Renewable Energy, Washington, DC.

EERE, 2008. Alternative Fuels and Advanced Vehicles Data Center. US DOE Office of Energy Efficiency and Renewable Energy, Washington, DC Retrieved 19 February 2008 (2008, 7 February).

EIA. 2005. Alternative Fuels Website. Energy Information Administration. Retrieved 16 April 2006, from: 〈www.eere.energy.gov〉.

EIA, 2007. Annual Energy Oulook 2007 Overview. Department of Energy, Washington, DC.

EIA, 2008. Petroleum Navigator: Crude Oil and Petroleum: Product Supplied. US Energy Information Administration, Washington, DC Retrieved 19 February 2008.

EPA, 2006a. 2002 National Emissions Inventory (2002 NEI Version 2). Environmental Protection Agency, Washington, DC.

EPA, 2006b. Control of hazardous air pollutants from mobile sources; proposed rule. Federal Register 71 (60).

Flynn, P., 2002. Commercializing an alternate vehicle fuel: lessons learned from natural gas for vehicles. Energy Policy 30 (7), 613–619.

Frick, M., Axhausen, K.W., Carle, G., Wokaun, A., 2007. Optimization of the distribution of compressed natural gas (CNG) refueling stations: Swiss case studies. Transportation Research Part D 12, 10–22.

Greene, D., 1994. Alternative Fuels and Vehicles Choice Model. Oak Ridge National Laboratory, Oak Ridge, TN.

Greene, D., 2001. TAFV Alternative Fuels and Vehicles Choice Model Documentation. Oak Ridge National Laboratory, Oak Ridge, TN.

Greene, D., Leiby, P., 2007. Integrated Analysis of Market Transformation Scenarios with HyTrans. Oak Ridge National Laboratory, Oak Ridge, TN.

Griliches, Z., 1957. Hybrid corn: an exploration in the economics of technological change. Econometrica 25, 501–522.

Hirsch, R.L., 2008. Mitigation of maximum world oil production: shortage scenarios. Energy Policy 36 (2), 881–889.

Hirsch, R.L., Bezdek, R., Wendling, R., 2006. Peaking of world oil production and its mitigation. A.I.Ch.E. Journal 52 (1), 2–8.

IPCC, 2007. Climate Change 2007: The IPCC 4th Assessment Report. Intergovernmental Panel on Climate Change.

Johansson, T., Kelly, H., Reddy, A., Williams, R., 1993. Renewable Energy: Sources for Fuels and Electricity. Island Press, Washington, DC.

Katz, M., Shapiro, C., 1994. System competition and network effects. Journal of Economic Perspectives 8 (2), 93–115.

Laherrere, J., 2001. Estimates of oil reserves. In: Paper presented at the EMF/IEA/IEW Meeting. IIASA, Laxenburg, Australia.

Mahajan, V., Muller, E., Bass, F.M., 1990. New product diffusion models in marketing: a review and directions for research. Journal of Mark 54, 1–26.

Marchetti, C., 2006. Long-term global vision of nuclear-produced hydrogen. International Journal of Nuclear Hydrogen Production and Application 1 (1), 13–19.

Markus, M.L., 1987. Toward a "critical mass" theory of interactive media: universal access, interdependence and diffusion. Communication Research 14, 491–511.

McDowall, W., Eames, M., 2006. Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: a review of the hydrogen futures literature. Energy Policy 34 (11), 1236–1250.

Melaina, M.W., 2003. Initiating hydrogen infrastructures: preliminary analysis of a sufficient number of initial hydrogen stations in the US. International Journal of Hydrogen Energy 28 (7), 743–755.

Melendez, M., Milbrandt, A., 2006. Hydrogen Infrastructure Transition Analysis. US Department of Energy National Renewable Energy Laboratory.

Michalek, J., Papalambros, P., Skerlos, S. A study of emission policy effects on optimal vehicle design decisions, 2003. In: Paper presented at the ASME 2003 Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Chicago, IL.

Mintz, M., 2002. Establishing a Hydrogen Distribution Infrastructure. Systems Assessment. Argonne National Lab: US Department of Energy Office of Energy Efficiency and Renewable Energy. Retrieved 16 April 2006, from: 〈http://transtech.anl.gov/v2n2/hydrogen-distribution.html〉.

Mintz, M., Molburg, J., Folga, S., Gillette, J., 2003. Hydrogen distribution infrastructure. AIP Conference Proceedings (671), 119–132.

Monin, J.P., Benayoun, R., Sert, B., 1976. Initiation to the Mathematics of the Processes of Diffusion, Contagion, and Propagation (M. Brandon, Trans.). The Hague, Mouton.

Myers, D., Ariff, G., Kuhn, R., James, B., Paster, M., 2003. Hydrogen from Renewable Energy Sources: Pathway to 10 Quads For Transportation Uses in 2030–2050. Directed Technologies, Inc. and US Department of Energy, Arlington, VA.

Noreng, O., 2006. Crude Power: Politics and the Oil Market. I.B. Tauris, London.

NRC, 2004. The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs. National Research Council and National Academy of Engineering of the National Academies, Washington, DC.

NREL, 1999. Survey of the Economics of Hydrogen Technologies. National Renewable Energy Laboratory, Golden, CO.

Ogden, J., Mintz, M., Ringer, M., 2004. H2A scenarios for delivering hydrogen from a central production plant to light duty vehicles. In: Paper presented at the NHA Conference, Los Angeles, CA.

Rifkin, J., 2002. The Hydrogen Economy: The Creation of the Worldwide Energy Web and the Redistribution of Power on Earth. Tarcher/Penguin, New York.

Rogers, E.M., 1983. Diffusion of Innovations. The Free Press, New York.
Romm, J., 2006. The car and fuel of the future. Energy Policy 34 (17), 2609–2614.
Saloner, G., Shepard, A., 1995. Adoption of technologies with network effects: an empirical examination of the adoption of automated teller machines. RAND Journal of Economics 26 (3), 479–501.
Shenk, M., Subrahmaniyan, N. (2008, 2 February). Oil touches $100 a barrel on supply concern, increased demand. Bloomberg.com, New York, NY. Retrieved 20 February 2008, from: 〈http://www.bloomberg.com/apps/news?-pid=20601085&refer=Europe&sid=aX8NEC_T7Zfg〉.
Smill, V., 2003. Fossil Fuel Futures. The MIT Press, Cambridge, MA.
Sperling, D., 1988. New Transportation Fuels: A Strategic Approach to Technological Change. University of California Press, Berkeley and Los Angeles, CA.
Sterman, J.D., 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World. McGraw-Hill, New York.
Struben, J.J.R., Sterman, J.D., 2007. Transition Challenges for Alternative Fuel Vehicle and Transportation Systems. MIT Sloan School of Management, Cambridge, MA.
TRB, 2006. Critical Issues in Transportation. The National Academies, Washington, DC.
Turner, J.A., 1999. A realizable renewable energy future. Science 285, 687–689.
USCB, 2005. National and State Population Estimates. In: A. Annual Estimates of the Population for the United States and States, 2000 to July 1, 2005 (NST-EST2005-01) (Ed.). US Census Bureau.
Valente, T.W., 1993. Diffusion of innovations and policy decision-making. Journal of Communication 43 (1 Winter).
Wang, M., 2002. Fuel choices for fuel-cell vehicles: well-to-wheels energy and emissions impacts. Journal of Power Sources 112 (1), 307–321.
Wietschel, M., Hasenauer, U., Groot, A.d., 2006. Development of European hydrogen infrastructure scenarios—CO_2 reduction potential and infrastructure investment. Energy Policy 34 (11), 1284–1298.
Winebrake, J.J., 2000. Requiem or respite? An assessment of the current state of the US alternative fuel vehicle market. Strategic Planning for Energy and the Environment 19 (4), 43–62.
Winebrake, J.J., 2002. Hype or holy grail? The future of hydrogen in transportation. Strategic Planning for Energy and the Environment 22 (2), 20–34.
Winebrake, J.J., Creswick, B.P., 2003. The future of hydrogen fueling systems for transportation: an application of perspective-based scenario analysis using the analytic hierarchy process. Technological Forecasting and Social Change 70 (4), 359–384.
Winebrake, J.J., Farrell, A., 1997. The AFV credit program and its role in future AFV market development. Transportation Research-D 2 (2), 125–132.
Winebrake, J.J., Meyer, P., 2008. Assessing the total fuel cycle energy and environmental impacts of alternative transportation fuels. The New York State Energy Research and Development Authority, Albany, NY.
Witze, A., 2007. That's oil, folks.... Nature 445 (7123), 14–17.
Wu, Y., Wang, M., Sharer, P., Rousseau, A., 2006. Well-to-wheels results of energy use, greenhouse gas emissions, and criteria air pollutant emissions of selected vehicle/fuel systems. SAE 2006 Transactions (Journal of Engines) 115 (3).
Yang, C. 2006. Transitional hydrogen economy replacement model (THERM). Infrastructure Modeling. UC Davis, Davis, CA. Retrieved 16 April 2006, from: 〈http://hydrogen.its.ucdavis.edu/research/track2/〉.
Yergin, D., 2006. Ensuring energy security. Foreign Affairs 85 (2), 69–82.
Zhao, J., Melaina, M., 2006. Transition to hydrogen-based transportation in China: lessons learned from alternative fuel vehicle programs in the United States and China. Energy Policy 34 (11), 1299–1309.

Patrick Meyer is a doctoral candidate at the Center for Energy and Environmental Policy at the University of Delaware, Newark, DE. He holds a BS in Public Policy and a MS in Science, Technology, and Public Policy from the Rochester Institute of Technology, Rochester, NY. His current research pertains to energy sustainability, hydrogen as an alternative transportation fuel, infrastructure and vehicle relationships in industrialized and developing nations, and technology–society–environment relationships.

James Winebrake is a professor and chair of the Department of Science, Technology, & Society/Public Policy at the Rochester Institute of Technology, Rochester, NY. He currently is Director of the University-National Park Energy Partnership Program and co-Director of the RIT Environmental Computing and Decision Making Lab.

Please cite this article as: Meyer, P.E., Winebrake, J.J., Modeling technology diffusion of complementary goods: The case of hydrogen vehicles and refueling infrastructure. Technovation (2008), doi:10.1016/j.technovation.2008.05.004