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Vehicle & infrastructure relationships in hydrogen transportation networks: Development of the H2VISION modeling tool

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Vehicle & Infrastructure Relationships in Hydrogen Transportation Networks: Development of the H_2VISION Modeling Tool

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Abstract

The political instability of acquiring oversea oil resources, the need to reduce greenhouse gas emissions, and the desire for inexpensive energy have recently driven a shift of focus towards hydrogen energy. It has become increasingly evident that there are significant barriers facing the development of a hydrogen-based energy system – a system commonly referred to as the "hydrogen economy". The small quantities of hydrogen fuel cell vehicles that have been deployed to date are not numerous enough to facilitate the growth of a substantial refueling infrastructure. Additionally, the underdeveloped and extremely limited infrastructure has imposed significant convenience costs upon consumers. These convenience costs, in turn, inhibit further purchases of hydrogen fuel cell vehicles – creating what has been dubbed the "chicken and egg" phenomenon.

To analyze the vehicle-infrastructure chicken and egg phenomenon and assist in the creation of future hydrogen-related policies, this thesis presents the H_2VISION systems model. H_2VISION is designed to explore: (1) the role of various government policies aimed at hydrogen deployment (vehicle procurement, monetary incentives, or mass-station building); (2) the specific role of government as a first-use and innovative adopter of hydrogen technologies; (3) the effect of consumer preferences regarding vehicles and convenience costs regarding infrastructure on hydrogen markets; and (4) the short- and long-term results of mainstream hydrogen technology diffusion.

Using H_2VISION, multiple scenarios with varying demographic, market, and policy conditions are analyzed with an aim to isolate specific factors inhibiting the growth hydrogen markets. It is found that investments in infrastructure may yield more

rapid market growth in comparison to investments in vehicles. However, it is concluded that funding cannot be applied solely to infrastructure and instead must be systematically applied to all aspects of hydrogen markets (vehicles, fuel, infrastructure, etc.). Only with a systematic and widespread application of funding will government policies facilitate the successful growth of the hydrogen economy.

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Notation

Table 1: Notation

Abbreviation or Acronym *(alphabetical)*	**Definition**
AFV	Alternative Fuel Vehicle
ANVP	Annual New Vehicle Purchases
B1, B2, etc.	Balancing Causal Loop
CC	Carrying Capacity
CV	Conventional Vehicle
D.C.	Washington, D.C.
DOE	US Department of Energy
FC	Fuel Cost
FCA	Fuel Cost Attractiveness
FCV	Fuel Cell Vehicle
FF	Fossil Fuel
FF Station	Fossil Fuel Refueling Station
Gov't	Government
H2 or H_2	Hydrogen
H2 Station or H_2 Station	Hydrogen Refueling Station
H_2VISION	Hydrogen Vehicle and Infrastructure Simulator for Integrated and Operational Transportation Networks
NGV	Natural Gas Vehicle
Pop	Population
R1, R2, etc.	Reinforcing Causal Loop
SBR	Station Build Rate
SDA	Station Density Attractiveness
SO	Stations Operating
T	Time
TCVO	Total Conventional Vehicles Operating
TFCVO	Total Fuel Cell Vehicles Operating

Table 2: Notation cont.

TVP	Total Vehicle Population
TVPO	Total Vehicle Population Operating
Ui	Utility
V	Vehicles
VL	Vehicle Life
VPA	Vehicle Price Attractiveness
VPP	Vehicles Per Person

Vehicle & Infrastructure Relationships in Hydrogen Transportation Networks: Development of the H_2VISION Modeling Tool

Patrick E. Meyer

1. Introduction

The United States is currently dependent on imported oil to fuel the nation's transportation systems. This heavy dependence threatens the economic well-being of the country; petroleum price shocks or supply disruptions have widespread negative economic impacts including, but not limited to, trade deficits, decreased industrial investment, and increased unemployment (DOE 2005).

Bleischwitz and Fuhrmann (2006) argue that the nation is presented with significant challenges when it comes to assuring a *secure and affordable* energy supply. These challenges are exacerbated by a high world market demand, impending scarcities of oil and gas as well as prevailing market deficits. Indeed, considering that the United States imported approximately $251.6 billion worth of oil in 2005, oil imports represent a very significant portion of the nation's trade deficit (Ibbotson 2006). Furthermore, emerging economies such as India, China, and others will increase demand in world oil markets and lead to future shortages in energy supply and increases in prices (Winebrake 2002; Bleischwitz and Fuhrmann 2006).

Due to the widely-recognized negative implications of maintaining an economy dependent on foreign-oil, there has been considerable recent advocacy to increase domestic production of renewable energy and diversify energy supply sources. *Hydrogen* has been the focus of many of these discussions; "over the past several years … hydrogen has emerged as the 'fuel of choice' for solving civilization's long-term, sustainable energy supply problems" (Winebrake 2002).

As will be discussed later, hydrogen does not occur naturally as a gas on Earth. To use hydrogen as a gaseous transportation fuel it must first be converted or produced from natural sources; this production process requires energy input. Thus, experts claim that for any country to become *energy independent* it must not only seek a hydrogen future, but a future where hydrogen is produced from renewable energy sources (Clark and Rifkin 2005).

Hydrogen is the simplest and most plentiful element in the universe and when burned, or used in a fuel cell, produces almost no pollution (EERE 2003). Due to the element's availability, hydrogen has the potential to both reduce dependency on foreign oil while reducing pollution from greenhouse gas emissions (DOE 2002). It is because of this potential that "in virtually all advanced economies, there is considerable interest and enthusiasm over the concept of a 'hydrogen economy' and the prospect of hydrogen-fueled vehicles. Not since the mid-1970s, when the term 'hydrogen economy' was first coined, have we seen anything like the current level of research activity and discussion in the popular press" (Mintz, Molburg et al. 2003). Indeed, the concept of the "hydrogen economy" has today infiltrated all mediums (mainstream media, news, academia, government reports, etc.). Much of the term's recent popularity can be credited to Jeremy Rifkin's <u>The Hydrogen Economy</u>, which achieved "bestseller" status in 2002 (Rifkin 2002).

It is not all talk, however – there has been action as well. In fact, a number of hydrogen-powered fuel cell vehicles (fuel cells being the prominent method for utilizing hydrogen in transportation) are being tested and developed around the globe (DOE 2002). It has been almost a decade since Chicago, in 1998, became the first city in the US to use hydrogen fuel cells to power public transit buses (DOE 2002) and fuel cell development has continued since then. Japanese automobile manufacturer Honda has recently made headlines as likely being the first company to be able to mass produce hydrogen fuel cell cars. At the 2006 Detroit Motor Show, the company announced that their FCX Concept vehicle resembles a hydrogen-powered car they will produce in three to four years time (Science 2006).

In addition to Honda, other car manufacturers Hyundai, Ford, General Motors, Toyota, and DaimlerChrysler have all announced that they are developing fuel cell vehicles for personal use (DOE 2002). With the exception of Honda, who has plans for a fuel cell vehicle in a matter of years, major car companies have said they will be able to mass produce a fuel cell vehicle within 10 to 15 years (Science 2006). But one thing is absolutely clear: the potential and opportunity to develop the hydrogen economy is upon us *today*.

As will be discussed in depth throughout this paper, a significant problem exists when it comes to simultaneously developing hydrogen vehicles and refueling infrastructure. If development does not occur in a correct fashion, the efforts of the aforementioned car manufacturers to mass produce hydrogen vehicles may prove ineffective in capturing vehicle market share. Addressing the dilemma surrounding the simultaneous development of hydrogen vehicles and infrastructure – dubbed by some the “chicken and egg” phenomenon – the following sections develop in detail the broad concept of technology innovation, specific application to innovation and mainstream deployment of hydrogen vehicles and infrastructure, consumer trends and reactions to hydrogen innovation, and the role of government in assuring that car manufacturers’ efforts to mass produce hydrogen vehicles come to full fruition.

Specifically, to analyze the vehicle-infrastructure chicken and egg phenomenon and assist in the creation of future hydrogen-related policies, this thesis presents the H_2VISION system model. H_2VISION is designed to explore: (1) the role of various government policies aimed at hydrogen deployment (vehicle procurement, monetary incentives, or mass-station building); (2) the specific role of government as a first-use and innovative adopter of hydrogen technologies; (3) the effect of consumer preferences regarding vehicles and convenience costs regarding infrastructure on hydrogen markets; and (4) the short- and long-term results of mainstream hydrogen technology diffusion.

As will be fully developed, it is found that investments in infrastructure may yield more rapid market growth in comparison to investments in vehicles. However, it is concluded that funding cannot be applied solely to infrastructure and instead must be systematically applied to all aspects of hydrogen markets (vehicles, fuel, infrastructure, etc.). Only with a systematic and widespread application of funding will government policies facilitate the successful growth of the hydrogen economy.

2. Why Hydrogen?

On 21 April 2006, the world price of oil closed above 75 dollars a barrel in New York for the first time. Upon hearing this news, finance ministers from the Group of Seven (G7) leading industrial countries[1] met to discuss the economic impacts and necessary actions that nations may have to take to combat inflation.[2] Although the ministers agreed that a long-term solution was necessary to curb negative economic impacts associated with oil shortages, the only solution they could offer is to increase transparency, production, drilling, and investment in existing oil markets and fossil fuel technologies (BBC 2006). The finance ministers' solution piercingly contrasts with much academic work (cited below) which argues that fossil fuels *cannot* offer a long term solution to the current world energy crisis.

The United States currently uses about 20 million barrels of oil per day (DOE 2005). The American transportation industry is 97 percent dependent on petroleum (Mintz, Molburg et al. 2003; DOE 2005; Romm 2005) and 60 percent of that is imported (DOE 2005). Assuming a cost of only \$60 per barrel of oil (considerably lower than the price as of late April 2006), America spends a total of about \$8 billion on oil *per week* (DOE 2005).[3] This equates to \$416 billion per year, or approximately 3.5 percent of the nation's gross domestic product. In 2002, alternative fuel use accounted for only 395

[1] Interestingly, Russia (the 8th member of the G8) did not participate in the G7 oil talks. Present at the conference were: Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States.
[2] An increase in oil prices usually causes an inward shift in short run aggregate supply and puts upward pressure on price level. Large increases in the price of crude oil can cause an inflationary shock throughout the national (and world) economy.
[3] Includes imported and domestic oil sources.

million gallons of gasoline, or about 0.2 percent of total vehicle fuel consumption (EIA 2005). If oxygenate additives such as ethanol and methyl tertiary butyl ether (MTBE) are included, alternative fuels still account for only about 3 percent of total fuel consumption (Zhao and Melaina 2006).

There have been significant advances in technologies aimed at reducing emissions from conventional fuel vehicles. However, due to the aforementioned disproportionate dominance of fossil fuels in the transportation sector, conventional fuel vehicles still account for a very large percent of total air pollution (Winebrake and Creswick 2003). In fact, in the 1990s, the transportation sector had the fastest growth in carbon dioxide emissions of any major sector of the American economy, and transportation is projected to account for almost half of the 40 percent rise in carbon dioxide emissions forecast for 2025 (EIA 2005). Carbon dioxide isn't the only problem; conventional vehicles contribute to emissions of carbon monoxide, oxides of nitrogen, exhaust particles, and numerous other pollutants that have a negative effect on human health (Bleischwitz and Fuhrmann 2006). Carbon pollutants also contribute to global warming. Some experts claim that emission level reductions in the order of 50 percent or more are required to limit future climate change (Bleischwitz and Fuhrmann 2006).

The American transportation sector lags behind other economic sectors and "is arguably, one of the last bastions of petroleum dependence in the US economy" (Mintz, Molburg et al. 2003). But due to recent international events, coupled with an increased interest in national security, many argue that *now* is the time to begin the full development and implementation of the hydrogen economy (Clark and Rifkin 2005). Keeping in mind the aforementioned points on the quantity of petroleum consumed and the pollution associated with using the petroleum in the transportation sector, consider that "recent interest in hydrogen is due to two realizations:

1. Hydrogen fuel is essentially limitless, as hydrogen can be derived by electrolyzing water (ideally through the use of renewable energy technologies); and,
2. Hydrogen fuel is clean burning, as the oxidation of hydrogen yields only water" (Winebrake and Creswick 2003).

As the first of the two above realizations identifies, hydrogen does not occur naturally as a gas on Earth but is combined with other elements. Water, for example, is a combination of hydrogen and oxygen and through electrolysis, the water can be split into hydrogen and oxygen (Clark and Rifkin 2005). Although less environmentally sound, hydrogen can also be converted from "hydrocarbons" such as gasoline, natural gas, methanol, and propane (EERE 2003). The fact that hydrogen is available from a wide range of different feedstocks is beneficial – making the nation less economically vulnerable to fluctuations in any one or two of the fuel pathways (Wietschel, Hasenauer et al. 2006).

The electricity necessary for hydrogen conversion can easily be produced from renewable energy sources such as waste, wind, hydropower, geothermal, wave, biomass, or solar, or a non-carbon source such as nuclear energy (Clark and Rifkin 2005; Bleischwitz and Fuhrmann 2006; Zhao and Melaina 2006). The fact that hydrogen can be derived by using a variety of energy sources is also beneficial in that it allows for diversity of the transportation energy supply, opportunities for new technologies and players in energy markets, a broadening of energy choices, and an increase in overall economic growth (DOE 2005).

A small number of producers have recognized the benefits of hydrogen as a transportation fuel; as of 2002 there were 11 plants which had the capacity to produce over 280 tonnes of liquid hydrogen per day in North America. This hydrogen is distributed by truck, rail, and barge – but in the future will most likely be supplied via pipeline (DOE 2002). There are already a few hydrogen pipelines in use in the U.S. by Air Liquide Group, Air Products and Chemicals Inc., and Praxair Inc., located in Texas, Louisiana, California, and Indiana. These pipelines have proven to be efficient means to transport hydrogen and serve as excellent case-studies of success (DOE 2002).

The installed costs for a renewable energy refueling station in 2003 were about $1 million per station. Impressively, in 2004, the costs were reduced to approximately $700,000 and continue to decline (Clark and Rifkin 2005). Including liquefied petroleum gas, natural gas, electric, and ethanol stations, there are approximately 5000 alternative refueling stations in the US (EERE 2005). However, as of 2003 there were only 100 hydrogen refueling stations operating in the US (Clark and Rifkin 2005), compared to the 160,000 to 170,000 conventional stations (Zhao and Melaina 2006). One prominent problem of market development remains in the lack of fuel cell vehicles, which number so few that refueling stations are “economically unfeasible” (Clark and Rifkin 2005). The next section discusses the specific barriers facing the hydrogen economy and explores reasons why, even with falling costs, developing the hydrogen market remains a prominent challenge.

3. Barriers to the Hydrogen Economy

3.1. The “Chicken and Egg” Phenomenon

Numerous authors have identified several barriers to the hydrogen economy. Discussing alternative fuel vehicles (AFVs) overall, Zhao and Melaina (2006) argue that the slow development of AFV markets is due to:

1. Insufficient availability of refueling infrastructure;
2. The relatively low price of oil; and,
3. The relatively high upfront costs of most AFVs.

Similarly, the US Department of Energy’s *A National Vision of America’s Transition to a Hydrogen Economy – To 2030 and Beyond* (2002) identifies numerous specific barriers to the hydrogen economy:

1. Inability to build and sustain national consensus on energy policy priorities;
2. Lack of a hydrogen infrastructure and the substantial costs of building one;
3. Lack of commercially available, low cost hydrogen production, storage and conversion devices, such as fuel cells;
4. Hydrogen safety issues;

5. Competing energy sources and technologies;
6. Current availability of relatively low cost fossil fuels; and,
7. Simultaneous consumer preferences for both a clean environment and affordable energy supplies.

Many of these barriers are echoed by Romm (2005) who names six specific hindrances to AFV market penetration:

1. High first cost for vehicles;
2. On board fuel storage issues;
3. Safety and liability concerns;
4. High fueling costs;
5. Limited refueling stations; and,
6. Improvements in the competition.

Many of the factors listed above contribute to what many have described as a “chicken and egg” phenomenon within the hydrogen economy (DOE 2002; Mintz, Molburg et al. 2003; Zhao and Melaina 2006). The problem can be summarized as follows: “manufacturers are unwilling to produce vehicles without an in-place fueling infrastructure and fuel producers are unwilling to build that infrastructure without some certainty that vehicles requiring those fuels will be in operation” (Mintz, Molburg et al. 2003). Indeed, even when fuel cell vehicles are ready for release into the market, if consumers do not have access to a station to refuel their vehicle, the public will not accept hydrogen as an alternative (DOE 2002).

3.2. Complimentary Goods

To further understand the chicken and egg phenomenon, consider the concept of *complementary goods.* Complimentary 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 disks to use in the players, computer hardware and software by which to access the hardware, left and right shoes, and of course, cars and fuel. In terms of hydrogen transportation markets, fuel cell vehicles (FCVs) and hydrogen refueling infrastructure must be thought of as complimentary goods in the context of a *system*. Without FCVs, the refueling infrastructure would be useless; without the infrastructure, FCVs would be equally useless.

In its natural state, hydrogen transportation networks operate in a state reinforcing negative feedback. That is, there are no incentives to build refueling stations or manufacture vehicles due to the lack of the other, complementary good. In such systems, positive externalities can affect the polarity of feedback within the system, to assist in overcoming the negative feedback (Winebrake and Farrel 1997). An example, to be discussed in depth in the following sections of this paper, is government policy which funds research and development and/or provides monetary incentives for the purchasing of FCVs or construction of refueling infrastructure.

But the question remains: which comes first – the vehicles or the infrastructure? Some sources argue that if a FCV were to be purchased in a given area, the existence of the FCV may provide incentives to fuel providers to develop refueling infrastructure (Winebrake and Farrel 1997). The increase in infrastructure development would entice potential adopters to purchase FCVs and, in turn, additional infrastructure would be constructed. On the other hand, due to the fact that vehicles are only one part of the total transportation system, it may be necessary to first have a reliable and *convenient* refueling infrastructure in place before vehicles are purchased (Winebrake 2000). There are, of course, additional concerns associated with adopting this "build it and they will come!" prospective – the prospective that if refueling infrastructure is built, then consumers will automatically adopt FCVs to use such infrastructure (Winebrake 2002).

Thus, although the construction of infrastructure is vitally important, the chicken and egg phenomenon cannot be solved by solely adopting the "build it and they will come" attitude due to the concept of *convenience costs*. Convenience costs – also known as *transaction costs* – are costs that are associated with trading. To explain, deficiencies may exist which serve as impediments to the conducting of beneficial trade; the costs of conducing such deficient trades are called transaction costs (Stokey and Zeckhauser 1978). As in the case of alternative fuel markets, transaction, or convenience costs can prevent free markets from yielding efficient outcomes.

Transaction costs may stem from the time that must be spent bargaining or negotiating an outcome, or obtaining a good (Stokey and Zeckhauser 1978). If these costs are great enough, they may even prevent a market from being established. This is the case with alternative fuel vehicles; historically, with alternative fuel vehicles, "convenience costs are primarily due to increased time associated with traveling to an AFV station" (Winebrake 2002). These costs play an extremely important role in the development – or lack thereof – of hydrogen markets. Indeed, "the *real* fueling costs faced by [FCV owners] depend highly on fueling infrastructure availability. Refueling facilities must be conveniently accessible to fleet operators in order to reduce any convenience costs associated with refueling operations" (Winebrake and Farrel 1997).

For example, if a fuel provider were to build a hydrogen refueling station in a given metropolitan area, those people living within a mile or so of the station would most likely find the station's existence and placement very convenient. Due to the availability of the refueling station, there would be no additional transaction cost associated with using the hydrogen station in comparison to the existing conventional stations. Thus, these people may purchase a FCV to use at the hydrogen station for their daily local commute. However, those people who live ten or twenty miles from the station would have almost no incentive to purchase a FCV to use the station. In fact, people living further from the station will perceive the distance that must be traveled to access the station as a financial penalty. The further the distance that must be traveled to access the station, the greater the transaction cost and financial penalty associated with the distance. Thus, if only one station is constructed, most consumers will not adopt FCVs due to the high economic convenience costs associated with accessing the station.

Thus the chicken and egg phenomenon persists. As will be explored in the remainder of this paper, perhaps the answer lies in the simultaneous systematic development of vehicles *and* infrastructure. Many argue that such a development can only occur through aggressive government subsidies and assistance (DOE 2002; Clark and Rifkin 2005; Romm 2005; Hisschemoller, Bode et al. 2006; Zhao and Melaina 2006). The following section will discuss the opportunities government has to play a significant role in breaking through the chicken and egg phenomenon by acting as first-use and innovative adopters of hydrogen technologies.

4. Government Role in Transitioning to the Hydrogen Economy

Clark and Rifkin (2005) describe a future hydrogen economy based on “green” energy technologies – a “future” that they claim will be “present” sooner than most people realize. To make the future present, Clark and Rifkin outline eight critical opportunities that need to be optimized in creating the hydrogen economy. The first on the list of requirements is the necessary involvement of governments at all levels:

> “Innovations and advanced technologies emerge historically when government helps clear the way for the introduction of mass markets. Since the end of [World War II], the industrialized nations have all used government research and development monies to support the commercialization of everything from diesel fuels to the Internet. Government incentives, tax breaks, and procurement are critical to the commercialization of new technologies.” (Clark and Rifkin 2005)

The necessary role of government is echoed by others:

> “Governments may take the transition of the energy system in their own hands. [The government] might guide a collaborative attempt to implement hydrogen options that require huge infrastructure investments. A joint public-private effort to invest as ‘early movers’ in a pre-competitive state,

> may be effective in realizing a transition path to a sustainable energy system" (Hisschemoller, Bode et al. 2006).

Indeed, "alternative fuel vehicles inevitably require government incentives or mandates to succeed" (Romm 2005). As the DOE (2002) acknowledges, construction of a hydrogen infrastructure will take considerable time and resources; infrastructure will begin with smaller pilot projects and then expand to local, regional, and ultimately national and international applications. However, this expansion is unlikely to occur without a "push" of some sort:

> "The natural pace of turnover of existing capital in our infrastructure is relatively slow; there is a reluctance to alter traditional systems. These factors introduce uncertainties and risk and interfere with making changes. Existing inertia in our energy system has made it difficult for policy makers and business executives to make strategic decisions about long term energy requirements, which has led to delays in decision making, and has made it hard for business to commit large financial resources to energy investments" (DOE 2002).

At the root of the "existing inertia in our energy system," there exist two prominent market failures which inhibit the formulation of hydrogen markets and justify the intervention of the government: (1) significant barriers to entry, such as slow capital turnover and relatively few producers/suppliers of energy and transportation technology, and (2) externalities, such as the gross economic and environmental impact of using imported petroleum, are not addressed in the current fuel markets.

Stokey and Zeckhauser (1978) explain that “externalities, and the market failures they generate, are a major reason for government intervention in private markets. The most familiar and most widely discussed externalities relate to the environment. Given present pricing arrangements, we cannot expect market processes to yield air and water that are sufficiently pure.” These arguments are echoed by Zhao and Melaina (2006) in the context of the hydrogen economy; they state that market failures justify government intervention and require aggressive policies that support the simultaneous development of hydrogen vehicles and infrastructure.

Thus, government policies should take advantage of one of the most basic contributions governments could make: the creation of niche markets (Hisschemoller, Bode et al. 2006). Although, as will be discussed in the following section, the government has had mixed results with investing in AFV systems, the government could play a valuable role as a “first-use customer.” In 2002 federal, state, and local governments within the United States owned a total of 4,790,000 cars and trucks as part of fleets of 15 vehicles or more (Davis and Diegel 2004). Thus there exists the potential for the government to purchase, own, and operate almost 5 million hydrogen fuel cell vehicles.

As Clark identifies, in addition to procurement, the government must offer monetary incentives such as tax breaks to ensure market development. The incentives approach is appropriate for many reasons, but particularly when consumers’ behavior (burning fossil fuels) generates externalities (pollution) (Stokey and Zeckhauser 1978). Showing its support for the development of the hydrogen economy, the 2005 Energy Policy Act (the first energy act in 13 years) offers tax credits up to $3,400 per fuel cell vehicle based on fuel savings potential (Whitehouse.gov 2005). Additionally, the Act establishes a 30 percent credit, up to $30,000 for investments in hydrogen refueling stations (HR6 2005; Meyer 2005). These incentives show that the United States government is interested in developing the hydrogen economy, but history has proven that even *more aggressive* monetary incentives and procurement policies must be developed if the transition to a hydrogen economy is to be realized in the near future. Furthermore, as will be discussed in the following section, analyzing the state of natural gas vehicle markets has proven that incentives may be entirely wasted if consumer convenience costs associated with refueling availability are not also addressed.

5. The Natural Gas Market: Lessons Learned

The failure of the natural gas vehicle market in the 1980s serves as an excellent case study of what can go wrong when introducing an AFV into mainstream markets. Although the problems associated with the mainstream penetration of natural gas vehicles (NGVs) are numerous and complex on many levels, two prominent reasons have been at the forefront of recent analysis: (1) the failure of government to uphold their end of the commercialization process; and (2) the failure of the overall industry to recognize the importance of convenience costs associated with refueling infrastructure.

Flynn (2002) conducted a comprehensive analysis of the failure of natural gas vehicles (NGVs) to capture market share and makes important conclusions regarding the implications of the failure. As Flynn explains, throughout the 1980s, oil prices relative to natural gas prices and favorable public policy programs created a situation in which it was advantageous for high mileage vehicles to convert to natural gas. Due to the various market incentives, the growth rate of NGVs was steep and conversions more than doubled between 1984 and 1985. Unfortunately, sales growth was not great enough to achieve a “critical mass”, or “tipping point,” and the small number of vehicles made natural gas fuel and infrastructure suppliers unprofitable; they were forced to exit the market when startup funds were exhausted (Flynn 2002). (The concept of critical mass and tipping point will be explained in depth in following section.)

In the case of NGVs, although the government provided incentives for purchasing vehicles, the incentives were not aggressive enough to have a major impact in the markets. While the government’s under-funded NGV policies may have been intentional due to the fact that NGVs were viewed by some as only a stepping stone to more advanced AFVs, the funding even fell short of promoting NGVs as a bridge to new technologies. Indeed, NGVs provide a prime example in which "it could be argued that, whereas the market may fail in realizing innovations that trigger transitions towards more sustainable energy efficient systems, government does not have a very good track record either" (Luiten 2001). Flynn argues that promotional programs need to be designed for market effectiveness – and programs aimed at promoting NGVs were not. Policies must be designed in a manner that will guarantee achievement of the "critical point of commercial viability" (Flynn 2002).

Furthermore, Flynn argues that in the case of a new fuel or vehicle type, the promoters of the fuel needs to also focus on infrastructure and ensure to that the infrastructure system is profitable. He explains that infrastructure is far more important to existing and prospective customers than future improvements in technology. The NGV situation provides a principle example of a scenario where convenience costs associated with refueling were almost entirely ignored. As explained in the previous sections, there are significant convenience costs associated with the inconvenience of a limited availability of refueling stations. Natural gas refueling stations were hard to find, "even in urban areas that boast of 'extensive' natural gas refueling infrastructure" (Winebrake 2000). In the case of NGVs, these costs added up over time and canceled out benefits associated with cheap fuel. As time passed, more attention was paid to addressing convenience cost issues, but the bottom line is that "for NGVs, these issues received little attention quite late" (Flynn 2002).

Besides the lack of attention to infrastructure and consumer convenience costs, where else did NGVs go wrong? Flynn concludes that NGVs were hailed as being economical and more environmentally friendly than gasoline vehicles in 1984. These economic and environmental praises were partially true and partially false. The bottom line, however, is that NGVs were considerably over-hyped; full economic and environmental benefits were never attained. Applying this to the prospect of the hydrogen economy, it is important that hydrogen advocates acknowledge the short-term barriers associated with hydrogen. It is a popular notion today that hydrogen is economical and more environmentally friendly than gasoline. As with NGVs in 1984, neither claim is unconditionally true for hydrogen in 2006. Hydrogen can *eventually* be considerably more economical than gasoline and can *eventually* be made from environmentally clean renewable energy sources. Until these options become a full reality, the nation must be wary of the “hydrogen hype” now prominent among government, industry, and media hydrogen advocates (Winebrake 2002).

Vitally important aspects of NGV markets were overlooked, leading to a stagnant vehicle and infrastructure market. Due to the lack of government policies aggressive enough to reach a tipping point in the markets and the failure to recognize the importance of refueling convenience costs, the potential opportunities that NGVs possessed were never fully realized. As will be discussed in the following sections, the system model developed for this project allows for the exploration of different levels of government policy aggressiveness and the impact that refueling station density (and associated convenience costs) has on mainstream hydrogen diffusion. First, however, we will further develop the concept of technology diffusion, systems dynamics, and the “tipping point.”

6. Technology Diffusion and the Tipping Point

> "The challenge facing us all is how to move from generalizations about accelerating learning and systems thinking to tools and processes that help us understand complexity, design better operating policies, and guide change in systems from the smallest business to the planet as a whole. However, learning about complex systems when you also live in them is difficult. We are all passengers on an aircraft we must not only fly but redesign in flight." (Sterman 2000)

To understand the complex nature of systems, the sources of policy resistance, and to design more effective policies, many analysts have used the method of *system dynamics* (Sterman 2000). In the last few decades, system dynamics has been regularly applied to the mainstream diffusion of innovations and new technologies (Rogers 1983), but the concept of the "diffusion paradigm" has been studied since the 1950s. As explained by Valente (1993):

> "The diffusion paradigm emerged in rural sociology to promote agricultural research results to farmers. Diffusion research was conducted to evaluate and improve Agricultural Extension Services so that research on agricultural innovations could be more rapidly communicated to farmers, and thereby improve the productivity of US farming."

In 1957, Griliches applied the concept of innovation diffusion to hybrid corn production with the goal of learning about the ways technological change occurs in the US agricultural industry. Specifically, Griliches applied logistic growth functions to the data using three parameters he dubbed *origins*, *slopes*, and *ceilings*. Origins were associated with supply factors; slopes were associated with rate of acceptance by users; and, ceilings were associated with demand factors affecting the long-run equilibrium position (Griliches 1957). Griliches' work resulted in the first application of an "s-shaped" logistic growth curve to the diffusion of an innovation – a methodology that was later applied to the spread of disease (Bailey 1957; Bailey 1975; Monin, Benayoun et al. 1976), rumors (Daley and Kendall 1965), and news (Deutschmann and Danielson 1960).

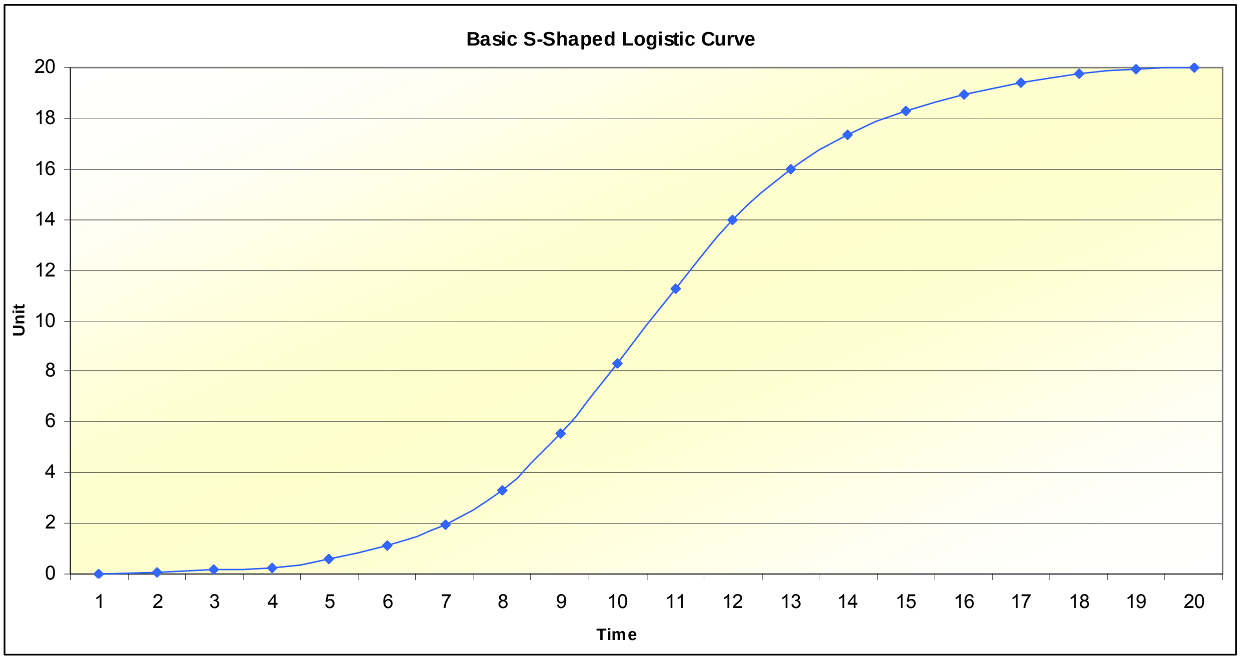
Two vitally important criteria for achieving s-shaped growth have been identified by Sterman (2000). First, to generate s-shaped growth, the negative feedback loops within the system must not include any significant time delays (negative and positive feedback loops will be discussed in depth in the *Causal Loop Diagram* section of this paper). If time delays exist, the system will create a growth curve which "overshoots and oscillates" instead of taking on an s-shape. Second, to generate s-shaped growth, the carrying capacity must be fixed. That is, the growth curve "cannot be consumed by the growth of the population" (Sterman 2000).[4]

Noting the above two criteria for s-shape, consider the following simplified explanation of s-shaped growth: the s-shaped logistic growth curve represents a process in which there are initially only a few adopters of an innovation. The population

[4] It is important to note (here, and as will be explained in further depth later) that the carrying capacity in the H_2VISION system model *is not* fixed. It is instead derived from other variables within the model and thus the carrying capacity changes in conjunction with values of the other variables. If the model's carrying capacity were derived independently, it would violate the second of Sterman's criteria for s-shape growth; instead, its dependent nature within the model allows for abiding of Sterman's criteria.

of adopters increases – slowly at first – and then relatively quickly until about the halfway point. At that point there become fewer potential adopters left in the population, the growth rate of the curve slows, and levels off at some saturation level (or carrying capacity) (Valente 1993). Figure 1 displays an example of a basic s-shaped logistic growth curve for *units* over *time*.

Figure 1: Basic S-Shaped Logistic Curve



To fully understand the concept of s-shaped growth of a population, it is also important to understand the *net fractional growth rate* underlying the growth of the population. To explain, s-shaped growth occurs when the net fractional growth rate of a population falls from an initial positive value, passes through zero when the population equals the carrying capacity, and then becomes negative when the population is greater than the carrying capacity (Sterman 2000). If graphed, “the net growth rate will have a shape roughly like an inverted bowl: net growth is zero when the population is zero, rises with increasing population up to a maximum, falls to zero at the carrying capacity, and continues to drop, becoming increasingly negative, when population exceeds carrying capacity” (Sterman 2000).

There is a point on the s-shaped growth curve where the increase in new adopters becomes self-sustaining. This point has been referred to as the *critical mass* (Markus 1987; Allen 1988; Valente 1993) or the *tipping point* (Sterman 2000). At this point, positive feedback within the system dominates negative feedback and the population of adopters becomes dominant (Sterman 2000). This concept has been studied in depth by Bass (1969) in his “diffusion model” (Lee, Cho et al. 2006).

The Bass diffusion model has proven to have a high capacity of forecasting power despite its simple structure (Mahajan, Muller et al. 1990). In his highly-regarded paper, Bass applies a logistic growth model to the growth of initial purchases of a wide range of products. By concentrating on initial and new purchases of consumer products over time Bass is able provide solid rationale for long-range forecasting (Bass 1969). Bass classifies adopters of an innovation as *innovators*; *early adopters*; *early majority*; *late majority*; and *laggards*, based on the timing of adoption by various groups. Ultimately, an adopter is either an innovator (an initial adopter who adopts independently of the social system), or an imitator (the latter classes who are influenced by pressures of the social system). The resulting growth is that of a classic s-shaped curve, “[demonstrating] vividly the slowing down of growth rates as sales near the peak” (Bass 1969).

The purpose of identifying the work completed by researchers such as Bass and Griliches is twofold:

1. To explain the basic notions of s-shaped growth, the tipping point, and technology diffusion – three concepts that are at the core of the H_2VISION model.
2. To further develop the concept of government involvement in promoting new technologies.

That is, policies aimed at promoting innovation of technologies need to be designed to ensure that diffusion will reach the critical mass of adopters (Valente 1993). Only when the tipping point is reached will policy incentives become less necessary and the technology penetrate the mainstream. As Valente explains, if the tipping point is known beforehand, policies can be managed and withdrawn once the point is reached, saving money and resources that would be unnecessarily spent on a market that is capable of self sustaining. It is arguable – as will be later shown – that the tipping point of hydrogen markets can not be reached in a reasonable timeframe without the immediate help of government policies. Knowing when the tipping point occurs is a very valuable public policy tool (Valente 1993) and should be well-understood by government prior to formulating or enacting any hydrogen-related policies.

The basic concepts of technology diffusion have been incorporated into many system models. The following section will discuss technology diffusion models and analysis that pertain specifically to alternative fuel vehicles and hydrogen technology.

7. Current Hydrogen Technology and Diffusion Models

McDowall and Eames (2006) recently published a review of existing hydrogen futures literature and claim that “there is rich contemporary literature, spanning articles in academic peer reviewed journals and official or semi-official policy documents … to works of popular advocacy, exploring the future potential of hydrogen energy.” The review also analyzes a diverse range of future scenarios – including most major hydrogen forecasts, scenarios, visions, pathways, and roadmaps conducted in the last decade. McDowall and Eames conclude that “rapid transitions to hydrogen occur only under conditions of strong governmental support combined with, or as a result of, major ‘discontinuities’ such as shifts in society’s environmental values, ‘game changing’ technological breakthroughs, or rapid increases in the oil price or speed and intensity of climate change” (McDowall and Eames 2006).

Others agree that there are increasing numbers of studies available that examine the technical and economic aspects of the hydrogen economy (Clark and Rifkin 2005). The DOE at least partially agrees with these experts: In last year’s *Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-year Research Development and Demonstration Plan* the DOE claims that systems analysis has been used multiple times to evaluate possible alternative hydrogen futures – assessing hydrogen system issues, and the specific developments of the production, delivery, storage, fuel cells, and safety technologies – but there lacks a “macro-system model” to assess the overall transition from the exiting infrastructure to one including hydrogen (DOE 2005). In other words, the DOE claims that analysts have yet to systematically assess or link together the big-picture issues concerning the transition to the hydrogen economy.

Indeed, others disagree with the aforementioned notion of an increasing availability of hydrogen studies and further convey that there is instead a significant lack of integrated knowledge available regarding the transition to any sustainable energy system (whether it be fueled by hydrogen or any other renewable source) (Hisschemoller, Bode et al. 2006). Some suggest that researchers who would otherwise study the infrastructure-based issues may be shying away from the topic due to the fact that environmental and storage concerns have not yet been entirely resolved. "Why study infrastructure when environmental and storage issues haven't yet been tackled?" (Mintz, Molburg et al. 2003) Answering their own rhetorical question, the authors state:

> "If one accepts the premise of a coming hydrogen transition and the need to begin making the necessary investments now, strategic planning cannot wait for resolution of many of these [environmental and storage] issues. Rather, energy, economic and environmental analyses must be undertaken in concert with research on improved production, storage and distribution technologies." (Mintz, Molburg et al. 2003)

In other words, research in only one area could prove detrimental to overall progression; research must be conducted in all areas and progress must be made on all fronts (environmental, economic, technological, etc.).

Although disagreements exist on the existence, quantity, and impact of existing hydrogen research, it is clear that some progress *has* been made; vehicle manufacturers and energy providers have begun to identify strategies to decrease risks and rationalize large up-front costs of infrastructure (Mintz, Molburg et al. 2003). The following sections identify a handful of existing analyses, models, and simulators currently being developed or used to analyze and overcome these risks. Table 3 briefly summarizes the analyses and models to be discussed.

Table 3: Summary of Existing Hydrogen Analyses, Models, and Simulators

Analysis, Model, or Simulator	***Purpose***
Alternative Fuels and Vehicles Choice Model (AFCV)	Determines market share for various alternative fuel vehicles based on consumer preferences and vehicle capabilities.
Cost of Hydrogen under Alternative Infrastructures Model (CHAIN)	Estimates various hydrogen pathway costs on a total fuel-cycle basis.
DOE Hydrogen Analysis (H2A) Group	Analyzes hydrogen alternatives at the system, technology, or component level.
Transitional Hydrogen Economy Replacement Model (THERM)	Analyzes different scenarios for the transition from distributed to centralized hydrogen production.
The Analytic Hierarchy Process (AHP)	Explores the commercialization possibilities of hydrogen technologies through scenario analysis techniques.
Wind Deployment Systems Model – Hydrogen (WinDS-H2)	Analyzes market potential for hydrogen production from wind technologies.

7.1. Alternative Fuels and Vehicles Choice Model

The *Alternative Fuels and Vehicles Choice Model* (AFCV) was developed by David L. Greene at Oak Ridge National Laboratory's Center for Transportation Analysis in 1994 – and has since become an important tool for forecasting market penetration of alternative fuels and vehicles. Utilizing attributes of alternative fuels and vehicle technologies – along with key assumptions about consumer behavior – the model calculates the expected market share that each vehicle technology will occupy. The data relies on existing studies of consumer choice of conventional and alternative fuels, analysis of surveys of consumer preferences for alternative fuels, existing technology assessments for alternative fuel vehicles, and assumptions about key factors such as the discount rate and value over time (Greene 1994). Although the model can be used to calculate the market share of conventional vehicles versus fuel cell vehicles, it “does not attempt to represent the dynamic process of new vehicle purchases and the aging and retirement of vehicle stock” (Greene 1994).

It is important to note that the structure and equations of H_2VISION *System Sub-Model B* are derived from the AFVC model (H_2VISION will be explained in depth in the following section). Specifically, the equations for the following H_2VISION variables are derived from AFVC model variables with similar or the same name:

- fuel cost attractiveness coefficient;
- fuel cell vehicle fuel cost attractiveness;
- conventional vehicle fuel cost attractiveness;
- consumer elasticity (constant);
- at market share (constant);
- consumer price slope;
- fuel cell vehicle price attractiveness;
- conventional vehicle price attractiveness;
- utility 1 (and corresponding coefficient);
- utility 2 (and corresponding coefficient);
- fuel cell vehicle station density attractiveness;
- conventional vehicle station density attractiveness;

- fuel cell vehicle total consumer utility;
- conventional vehicle total consumer utility;
- fuel cell vehicle exp. consumer utility;
- conventional vehicle exp. consumer utility;
- sum of all exp. consumer utility;
- fuel cell vehicle market share;
- conventional vehicle market share.

The short and full name, a brief description, and the underlying equation of each of the above variables are explained in depth in Appendix A3.3.

7.2. Cost of Hydrogen under Alternative Infrastructures Model

The *Cost of Hydrogen under Alternative Infrastructures* (CHAIN) model was developed by Argonne National Lab and is able to estimate hydrogen pathway costs on a *total fuel-cycle* basis (Mintz 2002). For example, in recent research using CHAIN, Argonne researchers estimated distribution costs for the following four hydrogen pathways:

1. Uranium to thermochemical hydrogen production via advanced nuclear reactors;
2. Natural gas to hydrogen via steam methane reforming at large centralized plants;
3. Natural gas to hydrogen via distributed steam methane reforming; and,

4. Coal gasification (Mintz 2002).

Importantly, the modeled pathways include any additional infrastructure that would be needed to support the feedstock, production, and delivery of the fuel to customers (Mintz, Molburg et al. 2003). However, the focus of the research was on the cost of refueling via various pathways, not on the development of infrastructure and its relation to consumer preference for fuel cell vehicles.

7.3. DOE Hydrogen Analysis (H2A) Group

DOE's *Hydrogen Analysis Group* is developing a modeling tool for analyzing hydrogen alternatives at the system, technology, or component level (EERE 2006). Developed as a Microsoft Excel spreadsheet model, the tool analyzes capital costs, performance, other pertinent costs (fuel, electricity, labor, parts, etc.), equipment lifetime (and economic lifetime) (Ogden, Mintz et al. 2004). Output data on each alternative is provided in terms of cost, performance, benefit, and risk impact – the latter of which is vitally important in terms of infrastructure and vehicle investment.

7.4. Transitional Hydrogen Economy Replacement Model

The *Transitional Hydrogen Economy Replacement Model* (THERM) is currently being developed by the Institute of Transportation Studies Hydrogen Pathways Program at UC Davis (Yang 2006). The model will analyze different scenarios for the transition from distributed to centralized hydrogen production. It will consider current natural gas pathways as a point of comparison and a future option for hydrogen production and distribution. “THERM is used to estimate the infrastructure transition costs as a function of a relatively small number of parameters for various demand scenarios. The analysis investigates how transition costs and timing depend on factors such as the size and geographic density of demand, and the market penetration rate” (Yang 2006).

7.5. The Analytic Hierarchy Process

The *Analytic Hierarchy Process* (AHP) has been used to explore the commercialization possibilities of hydrogen technologies (Winebrake and Creswick 2003). Using scenario analysis techniques, AHP is extended using “perspective-based scenario analysis” (PBSA) to measure the impact of issues associated with hydrogen vehicle operation, production/distribution, resources, economic issues, and the environment. Winebrake and Creswick’s project focuses on fuel processor technologies that will be available in 15 to 20 years.

7.6. Wind Deployment Systems Model – Hydrogen

The National Renewable Energy Laboratory’s *Wind Deployment Systems Model* (WinDS) has recently been modified to include hydrogen pathways (WinDS-H2) and addresses complexities associated with analyzing market potential for hydrogen production from wind (NREL 2006). Unconventional models such as WinDS-H2 are necessary if there is to be any planning for a hydrogen economy based on “green” technologies, but are notably complex: “The market potential of hydrogen from wind depends on wind issues – wind resources, transmission access, and integration of the intermittent generation into the electric grid – as well as the complexities of hydrogen production, storage and transport and competition with other sources of hydrogen” (NREL 2006).

The above described analysis, models, and simulators deal with the choice of hydrogen technologies (Winebrake and Creswick 2003; Ogden, Mintz et al. 2004; EERE 2006), fuel pathway costs and benefits (Mintz 2002; Mintz, Molburg et al. 2003; NREL 2006; Yang 2006), and consumer preferences regarding alternative fuel and vehicle choice (Greene 1994). As explained, Green’s AFVC model served as a vitally important building block for H_2VISION; a number of H_2VISION equations were derived directly from similar equations within the AFCV model. However, the other models explained in this section did not directly fortify H_2VISION in any way. In fact, the other models instead serve to prove that there is a gap in current research projects. The work conducted under this project fills the gap.

Specifically, existing models do not develop the relationship between government alternative vehicle and fuel policies, government as a first-time purchaser of technologies, or consumer preferences, adoption patterns, and convenience costs and their effect on mainstream hydrogen technology diffusion. As will be discussed in the following section, H_2VISION, the system model developed for this project, addresses these previously-neglected, yet vitally important areas.

8. H_2VISION

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 systems dynamics techniques to simulate the diffusion paradigm associated with hydrogen fuel cell vehicles (FCVs) and fueling infrastructure. Developed in STELLA® System Modeling Research Software[5], H_2VISION accepts user inputs regarding demographics, consumer preferences, and vehicle and station data – and outputs the number of conventional vehicles (CVs), FCVs, and respective refueling infrastructure. Outputs are presented in terms of market share percentage for each vehicle and infrastructure type. H_2VISION makes use of consumer preference formulas and relationships developed by Greene (1994) available in the *Alternative Fuels and Vehicles Choice Model* mentioned earlier in this paper. The specific variables used by Greene are identified and explained in the following sections.

The primary goal and purpose of H_2VISION is twofold:

1. To identify the potential role of government in the growth of the hydrogen economy and penetration of FCVs into the mainstream consumer market.

[5] To view H_2VISION, a user must have either the STELLA® software or the isee Player installed on their computer. A 30-day save-disabled free trial version of Stella is available on the ISEE Systems website at http://www.iseesystems.com/community/downloads/STELLA/STELLADemo.aspx. The isee Player is free and can be downloaded at http://www.iseesystems.com/softwares/player/iseeplayer.aspx. Full versions of STELLA® may also be purchased via the website; discounts are available for Qualified Educational Institutions.

(See the *Government Role in Transitioning to the Hydrogen Economy* section of this paper for more information on government potential.)

2. To explore the dynamics of the "chicken and egg" phenomenon and consumer convenience costs currently inhibiting the growth of the FCV and hydrogen refueling infrastructure system. (See the *Barriers to the Hydrogen Economy* section of this paper for more information on the chicken and egg phenomenon.)

At the most simplistic level, H_2VISION allows users to input data regarding three basic parameters:

1. Demographic conditions;
2. Price fluctuations in vehicle price and fuel cost (due to natural economic factors or government intervention); and,
3. Government procurement of FCVs.

As described in detail in previous sections of this report, there is a current lack of literature and study regarding the relationship between hydrogen market penetration, infrastructure deployment, and consumer preferences. Many hydrogen-related policies are carried out without proper understanding of how markets and consumers will react to the effects of those policies. Additionally, many existing policies are aimed solely at vehicle incentives with less attention on infrastructure needs. As previously discussed, this was the core problem associated with natural gas vehicle markets in the 1980s and their failure to reach critical mass.

H_2VISION allows policy and decision makers, business leaders, hydrogen advocates, and citizens, to enter information relating to a specific simulation area and obtain vehicle and infrastructure results regarding the effects that a public policy may have on existing markets. Given certain inputs, underdeveloped markets similar to those associated with natural gas vehicle markets will result. Given more "favorable" inputs, H_2VISION can forecast FCV and hydrogen refueling infrastructure market penetration on a short- or long-term basis.

This section will explain in detail:

1. The H_2VISION Causal Loop Diagram; and
2. The H_2VISION System Model.

8.1. Causal Loop Diagram

8.1.a. Causal Loop Diagram Summary

The H_2VISION Causal Loop Diagram presents the primary components of the H_2VISION System Model in an easy-to-understand diagram. The major feedback loops are identified, along with major external components affecting those loops. The Causal Loop Diagram was developed in Vensim®: The Ventana Simulation Environment.[6] Figure 2 is a screenshot of the Causal Loop Diagram from the Vensim® interface. Although this provides a basic view of the diagram, it is recommended that Vensim® be downloaded, installed, and the H_2VISION Causal Loop Diagram be viewed in the Vensim® environment. This will allow for a clearer viewing of the components, loops, and respective polarity within the diagram.

As shown in Figure 2, the Causal Loop Diagram consists of multiple variables and six separately identifiable loops – four of which are "reinforcing" and two of which are "balancing". The reinforcing loops *R1: Core FCV and H2 Station Causal Loop* and *R2: Core CV and FF Station Causal Loop* form the core structure of diagram, and facilitate the existing inertia in today's transportation systems. That is, conventional vehicle markets are positively reinforcing in a manner that they dominate market share – while alternative vehicle markets are negatively reinforcing in a manner that it is

[6] Vensim® is free for educational purposes and may be downloaded at http://www.vensim.com/freedownload.html.

difficult overcome barriers to market entry. The balancing loops and external variables serve as vehicles by which the polarity of the reinforcing loops may be altered.

In the following section, Table 3 and Table 4 summarize the variables and parameters of the Causal Loop Diagram. Specifically, Table 4 lists: (1) each variable in the H_2VISION Causal Loop Diagram; (2) a brief description of each variable; (3) the units of measurement of that variable; (4) the equation of the variable (note that "user entered" means that the variable is a constant number which is altered by the user in the System Model); and (5) whether the variable is a primary component of a feedback loop and if so, which loop.

Table 5 lists: (1) each reinforcing and balancing loop in the causal loop diagram; (2) the full name of each loop as used in the following sections; (3) the internal, or primary, components of the loop (the core components; those that actually formulate the loop); and, (4) the external, or second level, components of the loop (these are those components that are one "level" outside of the core loop that have a direct impact on the loop itself).[7]

8.1.b. Causal Loop Diagram Structural Details

For a detailed explanation of the structure of each loop contained in the Causal Loop Diagram, see Appendix A which provides a variable-by-variable analysis of each relationship within the diagram.

[7] External (second level) components may or may not be influenced by additional components (i.e. third, fourth level etc.) in the causal diagram. For simplicity, third and fourth level components have not been discussed below – but can be easily determined by examining the causal loop diagram.

Figure 2: Causal Loop Diagram

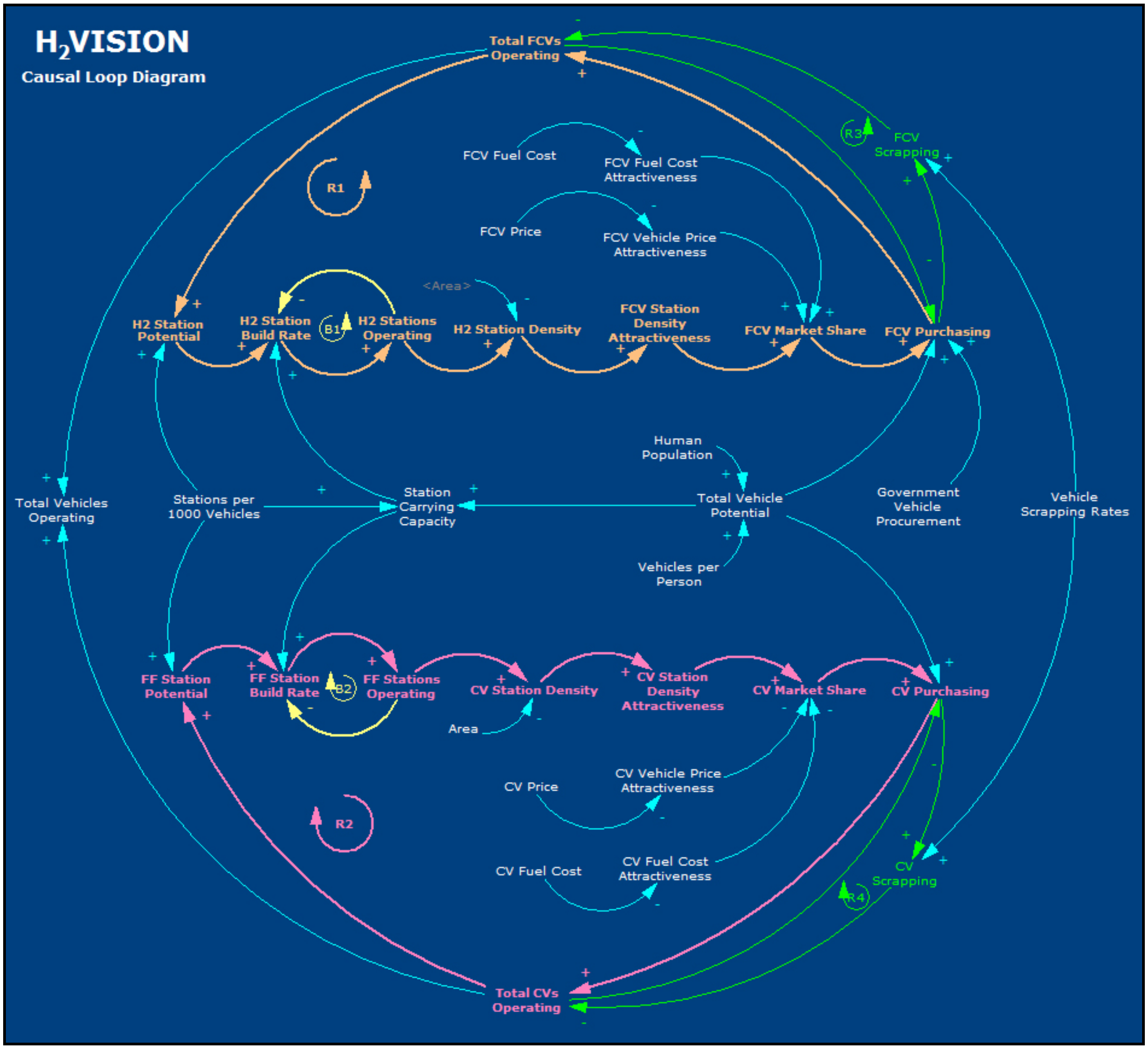


Table 4: Causal Loop Variables

Variable *(alphabetical)*	**Description**	**Units**	**Equation**	**Component of Loop?**
Area	The square mile area of the simulation area.	$miles^2$	(user entered)	no
CV Fuel Cost	The cost of fuel for a CV.	cents / mile	(user entered)	no
CV Fuel Cost Attractiveness	One of three "attractiveness values" affecting *CV Market Share*. *CV Fuel Cost Attractiveness* is based on *CV Fuel Cost*; as cost of fuel increase, attractiveness to purchase a CV decreases.	attractiveness value	CV Fuel Cost Attractiveness = *f*(CV Fuel Cost)	no
CV Market Share	The share of the total vehicle market belonging to CVs based on the three "attractiveness values". Market share will increase or decrease dramatically based on the density of refueling stations, the cost of fuel, and the price of a new vehicle.	percent	CV Market Share = *f*(CV Fuel Cost Attractiveness, CV Vehicle Price Attractiveness, CV Station Density Attractiveness)	R2
CV Price	The price of a new CV at the dealer.	dollars	(user entered)	no
CV Purchasing	The rate at which new CVs are purchased based on *CV Market Share* and *CV Scrapping*. Scrapped CVS will always be repurchased if it is necessary to do so to fulfill the market share. If market share is already met, scrapped CVs will instead be replaced with FCVs.	vehicles *(CVs)*	CV Purchasing = (CV Market Share * Total Vehicle Potential) – Total FVs Operating	R2, R4
CV Scrapping	The number of operating CVs that are scrapped at time *t* based on number of CVs operating and *Vehicle Scrapping Rates*.	vehicles *(CVs)*	CV Scrapping = CV Purchasing *(i.e. Operating)* * Vehicle Scrapping Rates	R4

Variable *(alphabetical)*	**Description**	**Units**	**Equation**	**Component of Loop?**
CV Station Density Attractiveness	One of three "attractiveness values" affecting *CV Market Share*. *CV Station Density Attractiveness* is based on *FF Station Density*; as density increase, attractiveness to purchase a CV increases.	attractiveness value	CV Station Density Attractiveness = *f*(FF Station Density)	R2
CV Vehicle Price Attractiveness	One of three "attractiveness values" affecting *CV Market Share*. *CV Vehicle Price Attractiveness* is based on *CV Price*; as the price of a CV increases, attractiveness to purchase a CV decreases.	attractiveness value	CV Vehicle Price Attractiveness = *f*(CV Price)	no
FCV Fuel Cost	The cost of fuel for a FCV.	cents / mile	(user entered)	no
FCV Fuel Cost Attractiveness	One of three "attractiveness values" affecting *FCV Market Share*. *FCV Fuel Cost Attractiveness* is based on *FCV Fuel Cost*; as cost of fuel increase, attractiveness to purchase a FCV decreases.	attractiveness value	FCV Fuel Cost Attractiveness = *f*(FCV Fuel Cost)	no
FCV Market Share	The share of the total vehicle market belonging to FCVs based on the three "attractiveness values". Market share will increase or decrease dramatically based on the density of refueling stations, the cost of fuel, and the price of a new vehicle.	percent	FCV Market Share = *f*(FCV Fuel Cost Attractiveness, FCV Vehicle Price Attractiveness, FCV Station Density Attractiveness)	R1
FCV Price	The price of a new FCV at the dealer.	dollars	(user entered)	no
FCV Purchasing	The rate at which new FCVs are purchased based on *FCV Market Share* and *FCV Scrapping*. Scrapped FCVS will always be repurchased if it is necessary to do so to fulfill the market share. If market share is already met, scrapped FCVs will instead be replaced with CVs. At time 0, *FCV Purchasing* will include *Government Vehicle Procurement*.	vehicles *(FCVs)*	FCV Purchasing = (FCV Market Share * Total Vehicle Potential) – Total FCVs Operating	R1, R3
FCV Scrapping	The number of operating FCVs that are scrapped at time *t* based on number of FCVs operating and *Vehicle Scrapping Rates*.	vehicles *(FCVs)*	FCV Scrapping = FCV Purchasing *(i.e. Operating)* * Vehicle Scrapping Rates	R3

Variable *(alphabetical)*	**Description**	**Units**	**Equation**	**Component of Loop?**
FCV Station Density Attractiveness	One of three "attractiveness values" affecting *FCV Market Share*. *FCV Station Density Attractiveness* is based on *H2 Station Density*; as density increase, attractiveness to purchase a FCV increases.	attractiveness value	FCV Station Density Attractiveness = *f*(H2 Station Density)	R1
FCV Vehicle Price Attractiveness	One of three "attractiveness values" affecting *FCV Market Share*. *FCV Vehicle Price Attractiveness* is based on *FCV Price*; as the price of a FCV increases, attractiveness to purchase a FCV decreases.	attractiveness value	FCV Vehicle Price Attractiveness = *f*(FCV Price)	no
FF Station Build Rate	The rate at which new FF stations are built or decommissioned.	stations / time	FF Station Build Rate = FF Station Potential – FF Stations Operating	R2, B2
FF Station Density	The number of FF stations operating in one square mile.	stations / area	FF Station Density = FF Stations Operating / Area	R2
FF Station Potential	The potential number of FF stations that can be built based on *Total CVs Operating*. For example, if every 1000 vehicles required 1 refueling station and there were 5000 CVs operating, then the *FF Station Potential* would be 5 stations.	stations	FF Station Potential = Total CVs Operating * Stations per 1000 Vehicles / 1000	R2
FF Stations Operating	The total number of FF stations in operation at time *t*. The number of stations operating is based on the station build rate, which may be positive or negative. Thus, the number of FF stations in operation may increase or decrease over time.	stations *(FFs)*	FF Stations Operating = FF Stations Operating + (FF Stations Operating * FF Station Build Rate)	R2, B2
Government Vehicle Procurement	The number of FCVs procured by the government at time 0.	vehicles *(FCVs)*	(user entered)	no
H2 Station Build Rate	The rate at which new H2 stations are built or decommissioned.	stations / time	H2 Station Build Rate = H2 Station Potential – H2 Stations Operating	R1, B1
H2 Station Density	The number of H2 stations operating in one square mile.	stations / area	H2 Station Density = H2 Stations Operating / Area	R1

Variable *(alphabetical)*	**Description**	**Units**	**Equation**	**Component of Loop?**
H2 Station Potential	The potential number of H2 stations that can be built based on *Total FCVs Operating*. For example, if every 1000 vehicles required 1 refueling station and there were 5000 FCVs operating, then the *H2 Station Potential* would be 5 stations.	stations	H2 Station Potential = Total FCVs Operating * Stations per 1000 Vehicles / 1000	R1
H2 Stations Operating	The total number of H2 stations in operation at time *t*. The number of stations operating is based on the station build rate, which may be positive or negative. Thus, the number of H2 stations in operation may increase or decrease over time.	stations *(H2s)*	H2 Stations Operating = H2 Stations Operating + (H2 Stations Operating * H2 Station Build Rate)	R1, B1
Human Population	The population of people within the simulation area.	people	(user entered)	no
Station Carrying Capacity	The maximum number of total refueling stations that can operate in the simulation area. The carrying capacity is based on the total vehicle potential, which is a factor of the population and the number of vehicles owned per each person.	stations / vehicles	Station Carrying Capacity = Total Vehicle Potential * Stations per 1000 Vehicles / 1000	no
Stations per 1000 Vehicles	The number of stations required to support 1000 vehicles.	stations	(user entered)	no
Total CVs Operating	The total number of CVs that are on the road at time *t*.	vehicles *(CVs)*	Total CVs Operating = CV Purchasing – CV Scrapping	R2, R4
Total FCVs Operating	The total number of FCVs that are on the road at time *t*. This includes *all* FCVs operating; government and civilian owned.	vehicles *(FCVs)*	Total FCVs Operating = FCV Purchasing – FCV Scrapping	R1, R3
Total Vehicle Potential	The maximum number of vehicles that will be purchased in the simulation area based on the human population and the average number of vehicles owned per each person.	vehicles	Total Vehicle Potential = Human Population * Vehicles per Person	no
Total Vehicles Operating	The total number of vehicles that are on the road at time *t*. This includes *all* vehicles; FCVs (government and civilian owned) and CVs.	vehicles	Total Vehicles Operating = Total FCVs Operating + Total CVs Operating	no

Variable *(alphabetical)*	**Description**	**Units**	**Equation**	**Component of Loop?**
Vehicle Scrapping Rates	The rate at which FCVs and CVs are scrapped per *t*.	vehicle / time	Vehicle Scrapping Rates = (default values)	no
Vehicles per Person	The average number of vehicles owned per each person.	vehicles / person	(user entered)	no

Table 5: Causal Diagram Balancing and Reinforcing Loops

Short Name *(Color in Diagram)*	**Balancing or Reinforcing** *(+ or -)*	**Full Name**	**Internal Components**	**External Components Influencing Loop**
R1	Reinforcing *(+)*	Core FCV and H2 Station Causal Loop	Total FCVs Operating; H2 Station Potential; H2 Station Build Rate; H2 Stations Operating; H2 Station Density; FCV Station Density Attractiveness; FCV Market Share; FCV Purchasing; Total FCVs Operating.	Stations per 1000 Vehicles; Station Carrying Capacity; FCV Fuel Cost Attractiveness; FCV Vehicle Price Attractiveness; Total Vehicle Potential; Government Vehicle Procurement; FCV Scrapping.
R2	Reinforcing *(+)*	Core CV and FF Station Causal Loop	Total CVs Operating; FF Station Potential; FF Station Build Rate; FF Stations Operating; FF Station Density; CV Station Density Attractiveness; CV Market Share; CV Purchasing; Total CVs Operating.	Stations per 1000 Vehicles; Station Carrying Capacity; CV Fuel Cost Attractiveness; CV Vehicle Price Attractiveness; Total Vehicle Potential; CV Scrapping.
R3	Reinforcing *(+)*	FCV Scrapping Causal Loop	FCV Scrapping; Total FCVs Operating; FCV Purchasing; FCV Scrapping.	Vehicle Scrapping Rates; FCV Market Share; Total Vehicle Potential; Government Vehicle Procurement.

Short Name *(Color in Diagram)*	**Balancing or Reinforcing** *(+ or -)*	**Full Name**	**Internal Components**	**External Components Influencing Loop**
R4	Reinforcing *(+)*	CV Scrapping Causal Loop	CV Scrapping; Total CVs Operating; CV Purchasing; CV Scrapping.	Vehicle Scrapping Rates; CV Market Share; Total Vehicle Potential.
B1	Balancing	H2 Station Building Causal Loop	H2 Stations Operating; H2 Station Build Rate; H2 Stations Operating.	Station Carrying Capacity; H2 Station Potential.
B2	Balancing	FF Station Building Causal Loop	FF Stations Operating; FF Station Build Rate; FF Stations Operating.	Station Carrying Capacity; FF Station Potential.

8.2. System Model

The H_2VISION system model consists of two "levels" – the *user interface level* and the *system model level*. Upon entering H_2VISION via the STELLA® software, the user will initially see the *user interface level*. It is recommended that the user first "run" the model via the *user interface level* to understand the fundamental inputs and outputs before viewing the *system model level*. (Experienced users may navigate immediately to the system model level by clicking the "View System Model Level" button.)

8.2.a. The User Interface Level

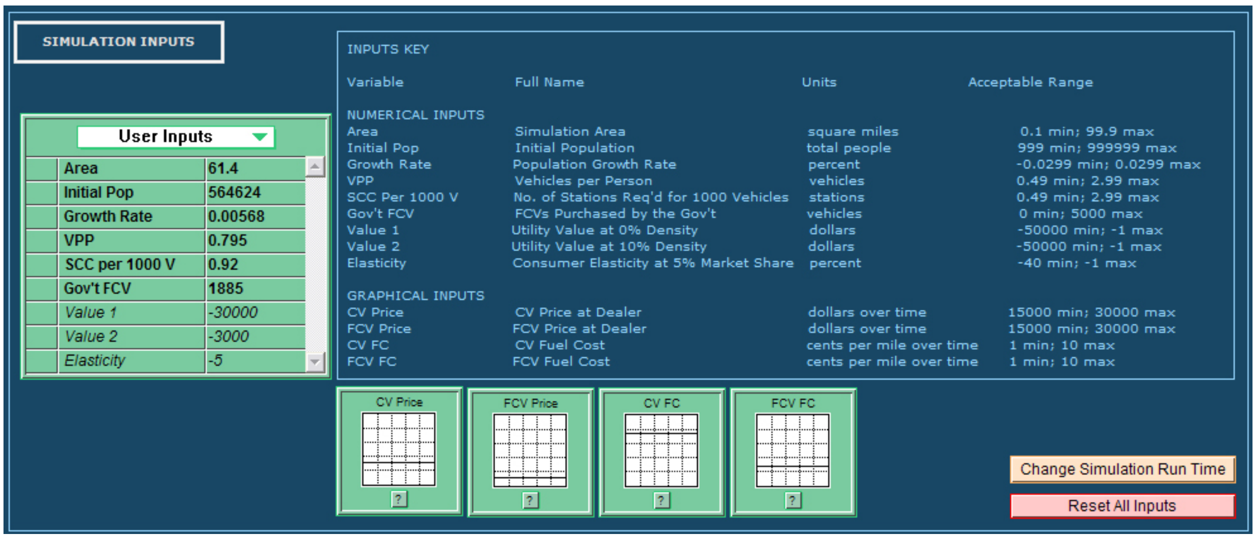
This section describes the *user interface level* from which the user may manipulate user inputs and run the model. The following are brief instructions how to navigate the user interface level:

1. Click the "Begin Simulation" button.

2. In the *Simulation Inputs* section, the user may customize H_2VISION assumptions and default values to reflect their specific simulation area. The *Simulation Inputs* section is shown in Figure 3.

   There are 13 values which the user may alter; Table 6 identifies the short and full name, the units, and the minimum and maximum acceptable range of each user-alterable variable in the model. The *Numerical Inputs* are entered as numbers in a "list input device". The *Graphical Inputs* are entered as graphical relationships with respect to time in a "graphical input device". The user may also click the "Change Simulation Run Time" button to alter the length of the simulation, the simulation run speed, and other run specifications.

Figure 3: User Interface Simulation Inputs



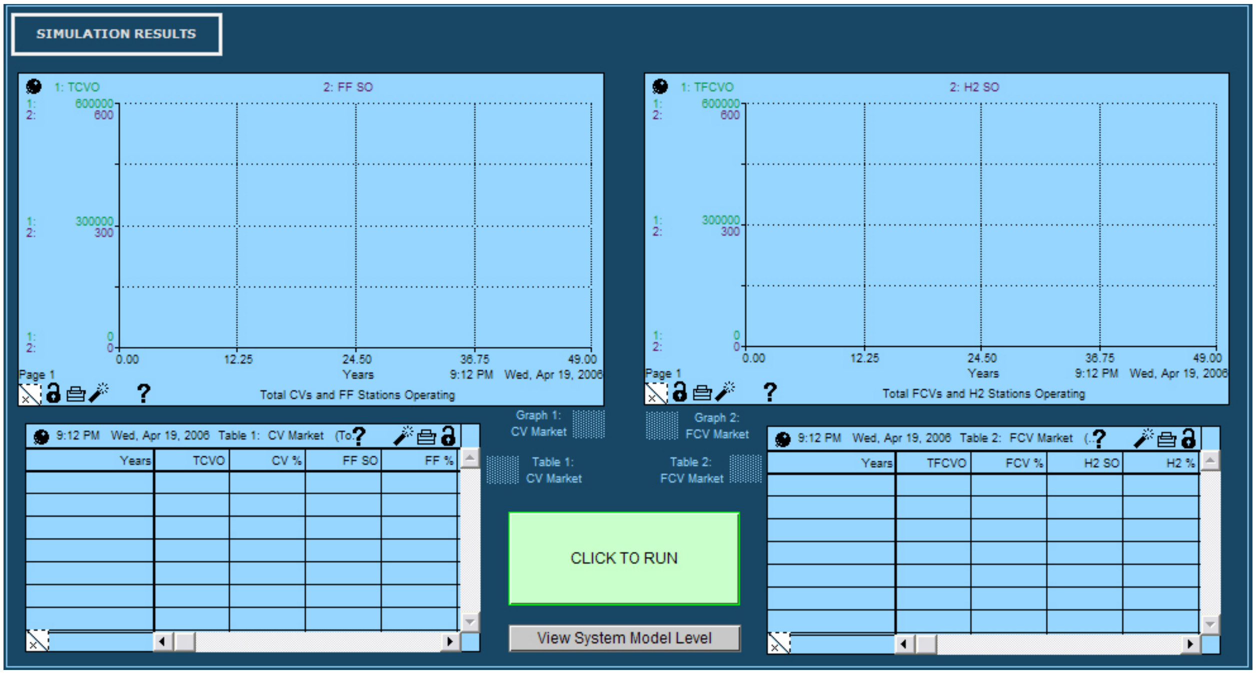
Screenshot from H_2VISION; STELLA® Research Software (Wallis, Chichakly et al. 2002)

Table 6: User Interface Inputs Key

Variable	***Full Name***	***Units***	***Min Value***	***Max Value***
Numerical Inputs				
Area	Simulation Area	square miles	0.1	99.9
Initial Pop	Initial Population	total people	999	999999
Growth Rate	Population Growth Rate	percent	-0.0299	0.0299
VPP	Vehicles per Person	vehicles	0.49	2.99
SCC Per 1000 V	No. of Stations Req'd for 1000 Vehicles	stations	0.49	2.99
Gov't FCV	FCVs Purchased by the Gov't	vehicles	0	5000
Value 1	Utility Value at 0% Density	dollars	-50000	-1
Value 2	Utility Value at 10% Density	dollars	-50000	-1
Elasticity	Consumer Elasticity at 5% Market Share	percent	-40	-1
Graphical Inputs				
CV Price	CV Price at Dealer	dollars over time	15000	30000
FCV Price	FCV Price at Dealer	dollars over time	15000	30000
CV FC	CV Fuel Cost	cents per mile over time	1	10
FCV FC	FCV Fuel Cost	cents per mile over time	1	10

3. After altering the desired user inputs, click the "Click to Run" button located at the bottom of the *Simulation Results* section. The simulation will run and the results will be displayed both in graphical and tabular format. The *Simulation Results* section is shown in Figure 4.

Figure 4: User Interface Simulation Results



Screenshot from H_2VISION; STELLA® Research Software (Wallis, Chichakly et al. 2002)

Graph 1: CV Market graphs the total conventional vehicles operating (TCVO) and the total fossil fuel stations operating (FF SO) over the course of the simulation. *Table 1: CV Market* displays the TCVO, FF SO, and also the percentage of the total vehicle population that are CVs and the percentage of the total station population that are FF stations.

Graph 2: FCV Market graphs the total fuel cell vehicles operating (TFCVO) and the total hydrogen stations operating (H2 SO) over the course of the simulation. *Table 2: FCV Market* displays the TFCVO, H2 SO, and also the percentage of the total vehicle population that are FCVs and the percentage of the total station population that are H2 stations.

4. After viewing the results, the user may click the “View System Model Level” button located at the bottom of the *Simulation Results* section. This button will navigate the user to the *System Model Level* which will be discussed in the following section.

8.2.b. The System Model Level

One may notice at initial glance that the default values incorporated in H_2VISION reflect a scenario which is unlikely in the immediate future. That is, the default values represent a situation in which FCVs are considerably less expensive than CVs, hydrogen fuel is considerably less expensive than conventional fuel, and the government makes a substantially large purchase of FCVs. The reason for having set the default values to such “favorable” market conditions is so that upon a first-time run, the user will see the model “in action.” In other words – and as explained in the *Scenarios* section of this paper – the default values allow for a complete market penetration of FCVs to occur. Thus, the default values *do not* reflect the author’s notion of normal market conditions – but instead, ideal market conditions.

Recognizing the aforementioned point, H_2VISION default values represent an ideal situation in which the government offers tax credits on FCV price, subsidies on FCV fuel, and an aggressive 20 percent FCV procurement policy. For macro-level demographic variables, default values are roughly based on national figures and averages for the years 2002 through 2005. For demographic variables specific to a given area, default values roughly based on characteristics of Washington, D.C. for the year 2002. H_2VISION *is not* made to work specifically with Washington, D.C. – but instead, the city was chosen as a medium-sized city representative by which to fortify default values.

The default values are summarized in Table 7 and explained in depth in Appendix B.

Table 7: Assumptions and Default Variable Summary

Variable	*Value*
Scrap Rate Age 0 to 3	0.00%
Scrap Rate Age 4 to 7	0.95%
Scrap Rate Age 8 to 11	4.60%
Scrap Rate Age 12 to 15	7.00%
Scrap Rate Age 16 to 19	9.60%
Scrap Rate Age 20 on	15.00%
Gov't FCV	1885
CV Age 0 to 3	107,281
CV Age 4 to 7	108,628
CV Age 8 to 11	96,957
CV Age 12 to 15	81,695
CV Age 16 to 19	36,135
CV Age 20 on	17,956
Initial Pop	564,624
Growth Rate	0.568%
VPP	.795
Area	61.4
Station CC Per 1000 V	0.92
FF SO	413
H2 SO	1
Elasticity	-5
FCV Price	17,000
CV Price	20,000
FCV Fuel Cost	3.0
CV Fuel Cost	7.5
Value 1	-30000
Value 2	-3000

8.2.c. System Model Structural Details

The H_2VISION System Model is separated into three sections: (1) the Core H_2VISION Model; (2) the Refueling Station Market Shares Sub-Model; and (3) the Vehicle Market Shares Sub-Model. The user may double-click on any variable to view the initial value or equation of that variable and a description of the variable (to view the description, double click the variable then click *Document*).

See Appendix C for a detailed discussion regarding the three sections of the model including lists of each variable in H_2VISION along with their full name, description, units, equation, and whether or not the variable is user alterable on the user interface level.

9. Sensitivity Analysis

Sensitivity analysis is a process by which variables in a model are manipulated to determine the degree of influence that each variable has on the results of a simulation. This is useful in that it allows for a more detailed understanding of varying outcomes of simulations that could occur given differing user-inputs (Winebrake and Creswick 2003). As developed by Deaton and Winebrake (2000), sensitivity analysis is a four-step process:

1. Identify the *exogenous variables* in the system. These are the variables whose values do not depend on other quantities in the system, but are instead set by the user or the model builder.
2. For each exogenous variable, make a series of model runs, changing the value of the variable over a fixed range or plus or minus a certain percentage great enough to yield noticeable changes in results (in this case, plus or minus 25 percent).
3. Observe and compare the system behavior and outcome for each run. Determine the extent to which the system behavior changes whenever each exogenous variable is changed. Changes in the system can manifest themselves in the overall *shape* or *level* of the response. Here we will focus on *level*, and determine the percentage change of two stocks (FCVs and H_2 stations operating) at a particular point in time (time = 49), when comparing runs from the lowest setting (-25%) and the highest setting (+25%) of the exogenous variables.

4. Identify the variables that have the most impact and those that appear to have little impact. Provide rationale for the way each variable is classified.

The process of conducting a sensitivity analysis within H_2VISION, along with the respective results, is presented in Table 8. Specifically, Table 8 identifies each exogenous variable, rationale, stock value, manipulated value, result, percent change, and leverage. Results and percent changes are determined for both FCVs and H_2 Stations Operating (H_2 SO). Leverage is classified as none, low, or high.

Low leverage variables are those which have a minimal impact on the system (Deaton and Winebrake 2000). The value of these variables can be changed, within a range determined on the *User Interface Level*, without significantly affecting the overall system. As identified by Deaton and Winebrake, "the low-leverage variables are important because they provide options for policy makers to change the system in ways that may have important economic or other benefits without adversely affecting the system." For example, through the sensitivity analysis, it is concluded that *Population Growth Rate* is a low leverage variable; altering its value (within limits) has minimal impact on long-run simulation results.

High leverage variables, on the other hand, are those variables whose values have a significant impact on the system's behavior. When the values of these variables are changed even slightly, the system behavior will change dramatically. These variables are also important because they "provide the best opportunities for policy makers to impact a system. If policies or technologies can be instituted that exert even a slight impact on a high-leverage variable, the change to the overall system could be significant" (Deaton and Winebrake 2000). This theory holds true in H_2VISION; policies exerting even a slight impact on a high-leverage variable, such as vehicle price or fuel cost, have tremendous impacts on the results of the simulation. For example, increasing the value of *FCV Price* by 25 percent will result in a -99.9 percent change in fuel cell vehicles operating at time 49 (in other words, a 25 percent price increase in FCVs will create a situation in which almost no FCVs are purchased by consumers).

The findings that consumers are highly sensitive to even the slightest changes in price factors or elasticity is consistent with literature (Greene 1994). Furthermore, consumers are also highly sensitive to the number of vehicles that can be supported at each station (or the number of stations available to support the population of vehicles). Consumers are the least sensitive to demographical (population) changes. It should be noted that *area* has a leverage rating of “none” only because of the structure of the model. In reality, altering the size of the simulation area would have considerable impact on many factors, most notably station density.

Table 8: Sensitivity Analysis Table

Exogenous Variable *(units)*	**Rational**	**Value +25%** **Stock Value** **Value -25%**	**Result** *(TFCVO at t=49)*	**Percent Change**	**Result** *(H2 SO at t=49)*	**Percent Change**	**Leverage** *(none, low, or high)*
Area *(square miles)*	*Area* will have no impact on the total number of FCVs or H2 stations operating due to the structure of the model. It *will* have a substantial effect on station density, but this does not effect TFCVO because the "attractiveness value" is based on the *percent* of the stations that are H2s or FFs.	76.75 61.40 46.05	580,799 580,799 580,799	0.00% - - - - - 0.00%	527 527 527	0.00% - - - - - 0.00%	**none**
Initial Population *(people)*	*Initial Population, Population Growth Rate,* and *Vehicles per Person* will have a relatively low effect on the long run results of the simulation. These demographic values have a direct impact on the total vehicle potential and the maximum number of vehicles that will be operating in the system; and vehicle population grows relative to human population. However, unless population, growth rate, or VPP are *drastically* altered, the effects are low relative to other variables discussed here.	705,780 564,624 423,468	730,565 580,799 420,459	+25.79% - - - - - -27.61%	659 527 376	+25.05% - - - - - -28.65%	**low**
Population Growth Rate *(percent)*		0.710 0.568 0.426	617,152 580,799 482,325	+6.26% - - - - - -16.95%	558 527 220	+5.88% - - - - - -58.25%	**low**
Vehicles per Person *(vehicles)*		0.9938 0.7950 0.5963	730,602 580,799 420,494	+25.79% - - - - - -27.60%	659 527 376	+25.05% - - - - - -28.65%	**low**
Stations per 1000 Vehicles *(stations)*	*Stations per 1000 Vehicles* will have a high effect on the long run results of the simulation if lowered. If the value is too low, as is the case here, then too many vehicles will be required to spark the growth of a new station. Thus, the tipping point is not reached and full market penetration does not occur. If the value is raised, the effects are minimal.	1.15 0.92 0.69	554,864 580,799 7,327	-4.47% - - - - - -98.74%	624 527 4	+18.41% - - - - - -99.24%	**high**

Exogenous Variable ***(units)***	**Rational**	**Value +25% Stock Value Value -25%**	**Result** ***(TFCVO at t=49)***	**Percent Change**	**Result** ***(H2 SO at t=49)***	**Percent Change**	**Leverage** ***(none, low, or high)***
Government FCV Procurement *(vehicles)*	*Government FCV Procurement* will have a high effect on the long run results of the simulation if lowered. If government does not procure enough FCVs at the beginning of the simulation, not enough stations are built to spark the growth of the FCV markets (due to station density). Thus, the tipping point is not reached and full market penetration does not occur.	2356 1885 1414	564,221 580,799 19,384	-2.85% - - - - - -96.66%	504 527 8	-4.36% - - - - - -98.48%	high
Value at 0% Density *(dollars)*	The dollar value at which a consumer values having refueling stations available to refuel their vehicle has a high effect on the long run results. If the value is decreased (i.e. consumers are *more* "inconvenienced" by having a low station density) then there is significantly less or no incentive to purchase an FCV. If either *Value 1* or *Value 2* are significantly reduced, then either the tipping point will not be reached, or no purchases will occur in the first place.	-22,500 -30,000 -37,500	570,463 580,799 215	-1.78% - - - - - -99.96%	517 527 0	-1.90% - - - - - -100.00%	high
Value at 10% Density *(dollars)*		-2,250 -3,000 -3,750	563,675 580,799 8,795	-2.95% - - - - - -98.49%	504 527 6	-4.36% - - - - - -98.86%	high
Elasticity	*Elasticity* has a high effect on the long run results of the simulation. A higher (more negative) value greatly reduces the growth of the FCV market due to "sticky" customers who are unwilling to switch from CVs to FCVs. In this case either the tipping point will not be reached, or no purchases will occur in the first place.	-3.75 -5.00 -6.25	570,245 580,799 352	-1.83% - - - - - -99.94%	514 527 0	-2.47% - - - - - -100.00%	High

Exogenous Variable *(units)*	**Rational**	**Value +25% Stock Value Value -25%**	**Result *(TFCVO at t=49)***	**Percent Change**	**Result *(H2 SO at t=49)***	**Percent Change**	**Leverage *(none, low, or high)***
CV Price *(dollars; considered constant over time)*	*CV Price, FCV Price, CV Fuel Cost, and FCV Fuel Cost* have high effects on the long run results of the simulation. This shows that consumers are extremely reactive to changes in vehicle price or fuel cost. A plus or minus price difference of 25% of the vehicle price can result in either a monopoly of that type of vehicle, or zero sales over the course of the simulation. Due to the high sensitivity and overall importance of these price variables in H_2VISION, particular attention should be paid to these variables when running a simulation.	25,000 20,000 15,000	568,377 580,799 35	-2.14% - - - - - -99.99%	509 527 0	-3.42% - - - - - -100.00%	High
FCV Price *(dollars; considered constant over time)*		21,250 17,000 12,750	506 580,799 571,764	-99.91% - - - - - -1.56%	0 527 518	-100.00% - - - - - -1.71%	High
CV Fuel Cost *(dollars per mile; considered constant over time)*		0.0938 0.0750 0.0563	572,703 580,799 1,427	-1.39% - - - - - -99.75%	517 527 1	-1.90% - - - - - -99.81%	High
FCV Fuel Cost *(dollars per mile; considered constant over time)*		0.0375 0.0300 0.0225	4,143 580,799 568,599	-99.29% - - - - - -2.10%	3 527 507	-99.43% - - - - - -3.80%	High

10. Scenario Analysis

10.1. Scenarios Introduction

The purpose of scenarios is not to give definitive answers as to what will or will not happen in the future. Instead, they serve to:

> "broaden the perspectives of decision-makers and stakeholders, helping them to understand more of the world around them. Players who understand the world better and see signs of change earlier will make better decisions. The use of scenarios can serve as guidance for the implementation of policies and measures conducive to obtaining a desirable future position or avoiding non-desirable outcomes." (Wietschel, Hasenauer et al. 2006)

That is, *Scenario Analysis* is a methodology used to shed light on possible futures to fortify and expand an available information base, but is not intended to be used as a *predictive* tool. The use of scenario analysis with systems models can allow for a fortification of a model, a method for validating a model, and a method to explore the limitations of a model.

This section develops and documents the scenario analysis conducted via H_2VISION simulations. Six scenarios were conducted; four "Vehicle Dynamics Scenarios" and two "Refueling Infrastructure Dynamics Scenarios". The Vehicle Dynamics Scenarios primarily explore the first goal of H_2VISION: to identify the potential role of government as first-use customers in the growth of the hydrogen economy and penetration of FCVs into the mainstream consumer market. The Refueling Infrastructure Dynamics Scenarios primarily explore the second goal of H_2VISION: to explore the dynamics of the chicken and egg phenomenon currently inhibiting the growth of FCVs and refueling infrastructure.

10.2. Vehicle Dynamics Scenarios

The first four scenarios, dubbed the "Vehicle Dynamics Scenarios", explore the impact that government can have on hydrogen markets by acting as first-use innovative adopters of hydrogen technologies, offering monetary incentives in the form of tax breaks or fuel subsidies, or assisting with the construction of a small number of refueling stations to support their fleets.

Table 9 and Table 10 provide overviews of the Vehicle Dynamics Scenarios, presenting a summary and layout of *Scenarios 1* through *4*. The following section provides a detailed description of each scenario.

Table 9: Vehicle Dynamics Scenarios Summaries

Scenario Number	**Scenario Name**	**Scenario Description**
1	Archetypical FCV Future	This scenario represents a archetypical – or an ideal – situation in which the government makes a *substantial* initial purchase of FCVs and market conditions/monetary incentives *favor* the development of FCVs and hydrogen infrastructure.
2	Practical FCV Future	This scenario represents a relatively practical situation in which the government makes a *small* purchase of FCVs and the market conditions/monetary incentives *do not favor* FCVs or hydrogen infrastructure.
3	Practical-Plus FCV Future	This scenario is similar to *Scenario 2*, except that here the government makes a *substantial* initial purchase of FCVs instead of a small purchase. Like *Scenario 2*, market conditions/monetary incentives *do not favor* FCVs or hydrogen infrastructure.
4	Improbable FCV Future	This scenario represents a situation in which the government *does not* purchase any FCVs, but market conditions/monetary incentives *favor* FCVs and hydrogen infrastructure. As explained in the following section, this scenario is improbably in "real-world" terms, but serves to test the boundaries of the model's capabilities.

Table 10: Vehicle Dynamics Scenarios Grid

		Scenario Grid	
Government Procurement	Substantial	Scenario 3: Practical-Plus FCV Future	Scenario 1: Archetypical FCV Future
	Low or None	Scenario 2: Practical FCV Future	Scenario 4: Improbable FCV Future
		Unfavorable	Favorable
		FCV Market Conditions	

10.2.a. Scenario 1: Archetypical FCV Future

The *Archetypical FCV Future* scenario represents an “ideal” situation in which the government acts as a first-use innovative adopter by making a substantial initial purchase of FCVs at the beginning of the simulation. Furthermore, the government offers monetary incentives on vehicles and fuels which favor the development of hydrogen markets. As identified in Table 11, *Scenario 1* was run with the default H_2VISION settings: an aggressive government procurement policy, a FCV price heavily supported by government tax credits, and a FCV fuel cost heavily supported by fuel subsidies (or other monetary credits).[8]

[8] Note that all six scenarios are run on a time horizon of 50 years (time 0 to 49). The results from this 50 year time range are presented. Although unlikely, it is possible that from time 50 onward the model would provide unexpected and unreported results.

Table 11: Scenario 1 Inputs & Initial Values

Variable *(derived variables are* not *directly user-alterable)*	**Default Value**	**Scenario Value** *(alterations in **bold-italic**)*	**Units**
Area	61.4	61.4	square miles
Initial Population	564624	564624	people
Population Growth Rate	0.00568	0.00568	percent
Vehicles per Person	0.795	0.795	vehicles
Stations per 1000 Vehicles	0.92	0.92	stations
Government FCV	1885	1885	vehicles
Utility Value at 0% Density	-30000	-30000	dollars
Utility Value at 10% Density	-3000	-3000	dollars
Elasticity	-5	-5	percent
CV Price	20000 (constant over time)	20000 (constant over time)	dollars
FCV Price	17000 (constant over time)	17000 (constant over time)	dollars
CV Fuel Cost	7.5 (constant over time)	7.5 (constant over time)	cents per mile
FCV Fuel Cost	3 (constant over time)	3 (constant over time)	cents per mile
Run Time	50 (0 to 49)	50 (0 to 49)	years
Initial FCVs (derived)	1885 (gov't FCV)	1885 (gov't FCV)	vehicles
Initial CVs (derived)	448876	448876	vehicles
Initial H2 Stations (derived)	1	1	stations
Initial FF Stations (derived)	412	412	stations

As explained previously, these default settings – although arguably unlikely in the immediate future – allow the model to be viewed "in action." For more a more detailed explanation of H_2VISION default settings, see the section of this paper entitled *"Default Scenario" Variable Settings*.

As shown in Table 12 and Figure 5, the *Archetypical FCV Future* results in near-full hydrogen market penetration. At time 49 approximately 80 percent of operating vehicles are FCVs and 100 percent of operating refueling stations are hydrogen stations. When graphed, the population of total fuel cell vehicles operating portrays a s-shaped growth curve – the fundamentals of which are described in detail in the section of this paper entitled *Technology Diffusion and the Tipping Point*.

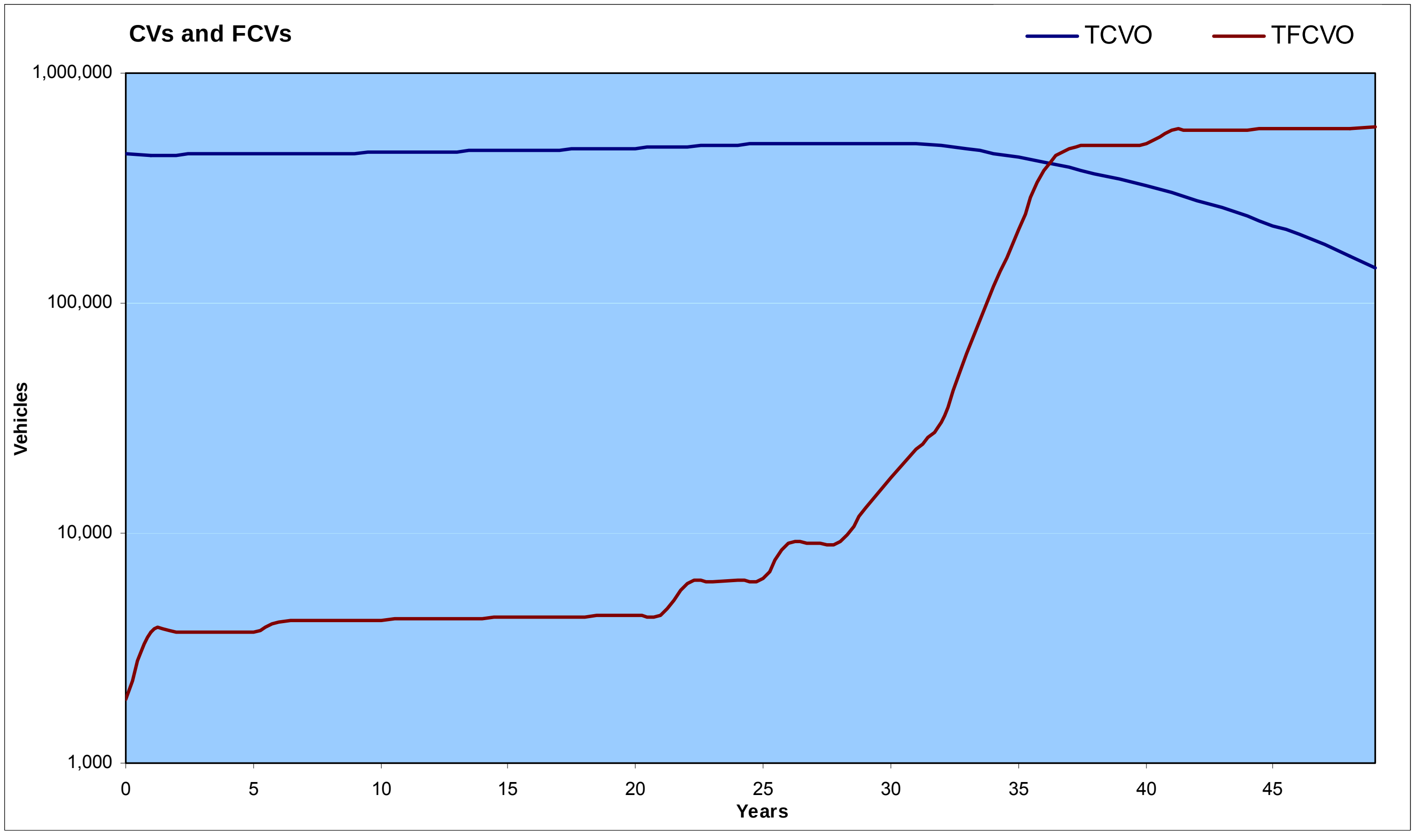
Deciphering the results in more detail, we see a relatively slow growth of FCVs and H_2 stations; around year 30, FCVs have achieved only about a 4 percent market penetration. Between year 30 and 40 however, the adopter population escalades. An exponentially greater number of adopters buy FCVs for about half a decade and then the rate of adoption levels off when the market approaches saturation – forming the s-shaped growth curve. The shape of the growth curve is consistent with the technology diffusion literature (Griliches 1957; Bass 1969; Rogers 1983) and the length is consistent with hydrogen literature. DOE (2002) states that a complete transition to a hydrogen economy may take several decades to unfold; Romm (2005) states that FCVs will most likely not achieve a market penetration greater than 5 percent until at least 2030.

In the *Archetypical FCV Future*, the government acts as a first-use customer to assist in the development of the hydrogen markets. The results indicate an epidemic; a “solving” of the chicken and egg phenomenon; a complete market saturation of FCVs. However, at initial glance it is difficult to determine whether the government’s initial purchase has a substantial effect on the long-term growth of the market or if the purchase was a primary source of overcoming the inhibiting factors associated with the chicken and egg phenomenon. *Scenarios 2*, *3* and *4* will attempt to isolate the effect of government procurement in the long-term scenario, provide a more clear understanding of the government’s role in hydrogen technology diffusion, and further explore the chicken and egg phenomenon.

Table 12: Scenario 1 Tabular Results

Years	TCVO	CV %	FF SO	FF %	TFCVO	FCV %	H2 SO	H2 %
0	448,652	99.60%	412	99.80%	1,885	0.40%	1	0.20%
1	442,199	99.20%	412	99.80%	3,725	0.80%	1	0.20%
2	441,942	99.20%	412	99.80%	3,725	0.80%	1	0.20%
3	443,445	99.20%	411	99.50%	3,725	0.80%	2	0.50%
4	444,145	99.20%	411	99.50%	3,725	0.80%	2	0.50%
5	445,877	99.20%	410	99.30%	3,725	0.80%	3	0.70%
6	445,306	99.10%	410	99.30%	4,132	0.90%	3	0.70%
7	446,308	99.10%	410	99.30%	4,156	0.90%	3	0.70%
8	447,551	99.10%	410	99.30%	4,179	0.90%	3	0.70%
9	449,007	99.10%	410	99.30%	4,203	0.90%	3	0.70%
10	450,609	99.10%	410	99.30%	4,193	0.90%	3	0.70%
11	452,352	99.10%	410	99.30%	4,217	0.90%	3	0.70%
12	454,240	99.10%	410	99.30%	4,241	0.90%	3	0.70%
13	456,276	99.10%	410	99.30%	4,265	0.90%	3	0.70%
14	458,334	99.10%	410	99.30%	4,270	0.90%	3	0.70%
15	460,513	99.10%	410	99.30%	4,291	0.90%	3	0.70%
16	462,782	99.10%	410	99.30%	4,315	0.90%	3	0.70%
17	465,152	99.10%	410	99.30%	4,340	0.90%	3	0.70%
18	467,765	99.10%	410	99.30%	4,347	0.90%	3	0.70%
19	470,417	99.10%	410	99.30%	4,370	0.90%	3	0.70%
20	473,101	99.10%	410	99.30%	4,394	0.90%	3	0.70%
21	475,829	99.10%	409	99.00%	4,419	0.90%	4	1.00%
22	479,266	98.80%	409	99.00%	6,032	1.20%	4	1.00%
23	483,483	98.70%	409	99.00%	6,132	1.30%	4	1.00%
24	487,168	98.70%	409	99.00%	6,224	1.30%	4	1.00%
25	490,680	98.70%	408	98.80%	6,308	1.30%	5	1.20%
26	491,214	98.20%	408	98.80%	9,047	1.80%	5	1.20%
27	494,369	98.20%	408	98.80%	9,087	1.80%	5	1.20%
28	497,145	98.20%	407	98.50%	9,171	1.80%	6	1.50%
29	496,239	97.50%	406	98.30%	12,779	2.50%	7	1.70%
30	494,212	96.60%	405	98.10%	17,402	3.40%	8	1.90%
31	490,966	95.50%	404	97.80%	23,180	4.50%	9	2.20%
32	486,351	94.10%	401	97.10%	30,309	5.90%	12	2.90%
33	467,631	88.60%	397	96.10%	60,113	11.40%	16	3.90%
34	448,390	79.00%	392	94.90%	119,238	21.00%	21	5.10%
35	428,680	67.30%	379	91.80%	208,498	32.70%	34	8.20%
36	408,498	52.10%	349	84.50%	375,939	47.90%	64	15.50%
37	387,878	45.30%	295	71.40%	468,736	54.70%	118	28.60%
38	366,915	43.10%	198	47.90%	484,996	56.90%	215	52.10%
39	345,677	41.50%	91	22.00%	488,209	58.50%	322	78.00%
40	324,213	39.60%	6	1.50%	493,622	60.40%	407	98.50%
41	302,588	35.00%	0	0.00%	561,448	65.00%	442	100.00%
42	280,986	33.20%	0	0.00%	564,381	66.80%	449	100.00%
43	259,658	31.40%	0	0.00%	566,795	68.60%	473	100.00%
44	238,665	29.50%	0	0.00%	569,181	70.50%	496	100.00%
45	218,144	27.60%	0	0.00%	570,876	72.40%	519	100.00%
46	198,232	25.70%	0	0.00%	572,985	74.30%	521	100.00%
47	179,219	23.70%	0	0.00%	575,543	76.30%	523	100.00%
48	160,786	21.80%	0	0.00%	578,383	78.20%	525	100.00%
49	142,927	19.70%	0	0.00%	580,799	80.30%	527	100.00%

Figure 5: Scenario 1 Graphical Results
(Please note the logarithmic y-axis scale.)



10.2.b. Scenario 2: Practical FCV Future

The *Practical FCV Future* scenario represents a "practical" real-world scenario facing alternative fuel vehicles and demonstrates many of the core concepts associated with the vehicle-side of the chicken and egg phenomena. In this scenario, the government makes a relatively small purchase of FCVs for use in federal or state fleets; the FCV price is considerably more expensive than CV price (even with government tax credits); and, FCV fuel cost is more expensive than CV fuel cost (due to high costs of producing and distributing hydrogen). Estimates show that FCV costs are expected to be about \$2,000 to \$4,000 greater than CV costs (depending on incorporation of on-board reforming technologies) (Thomas, Lomax et al. 2000). We will assume a middle-ground FCV cost of \$3,000 more than CV cost. Furthermore, this scenario assumes a government purchase of only 100 FCVs (with no station building) and FCV fuel cost 2 cents per mile more expensive than CV fuel cost. Table 13 summarizes Scenario 2 inputs.

As shown in Table 14 and Figure 6, the *Practical FCV Future* scenario results in a stagnant hydrogen market; there is a small population of FCV adopters but the population never reaches significant levels. The state of the hydrogen market demonstrated here represents a market suffering from one form of the chicken and egg phenomenon. That is, there exists a significant barrier to the market (high vehicle and fuel price) which is prohibiting consumers from purchasing FCVs and there is no demand for – or construction of – refueling infrastructure. Thus, the problem is twofold: (1) although the government acted as innovators and purchased 100 vehicles, the quantity of purchase was not substantial enough to trigger the building of an initial refueling station; and (2) the price differences between FCVs and CVs (and their fuel) are too great for a large number of consumers to switch to FCVs.

Table 13: Scenario 2 Inputs & Initial Values

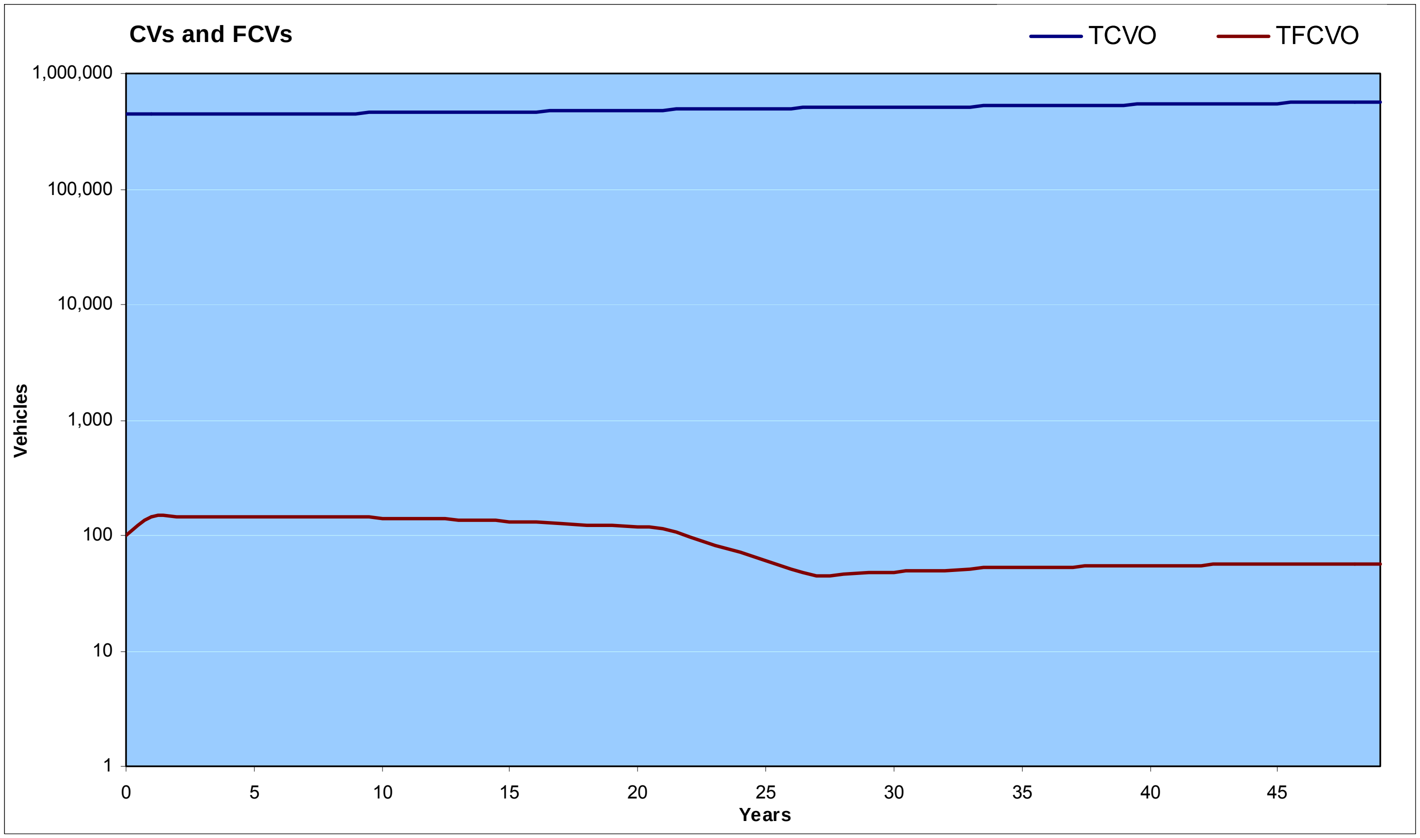
Variable *(derived variables are* not *directly user-alterable)*	**Default Value**	**Scenario Value** *(alterations in **bold-italic**)*	**Units**
Area	61.4	61.4	square miles
Initial Population	564624	564624	people
Population Growth Rate	0.00568	0.00568	percent
Vehicles per Person	0.795	0.795	vehicles
Stations per 1000 Vehicles	0.92	0.92	stations
Government FCV	1885	***100***	vehicles
Utility Value at 0% Density	-30000	-30000	dollars
Utility Value at 10% Density	-3000	-3000	dollars
Elasticity	-5	-5	percent
CV Price	20000 (constant over time)	20000 (constant over time)	dollars
FCV Price	17000 (constant over time)	***23000 (constant over time)***	dollars
CV Fuel Cost	7.5 (constant over time)	***5 (constant over time)***	cents per mile
FCV Fuel Cost	3 (constant over time)	***7 (constant over time)***	cents per mile
Run Time	50 (0 to 49)	50 (0 to 49)	years
Initial FCVs (derived)	1885 (gov't FCV)	***100 (gov't FCV)***	vehicles
Initial CVs (derived)	448876	448876	vehicles
Initial H2 Stations (derived)	1	***0***	stations
Initial FF Stations (derived)	412	412	stations

One will notice, however, that during the first year of the simulation there are 45 civilian purchases of FCVs. These civilian purchases represent the small population of *early adopters*; the people who want to set a trend and are attracted to purchase a FCV even though the vehicle and fuel cost is substantially uneconomical and there are no refueling stations in existence. Regardless of the government and civilian purchases, they are not great enough to reach a *tipping point* in market penetration or trigger the *early majority* adopters. By year 7, the FCV population begins to decline due to vehicle scrapping and eventually levels off around 50 vehicles due to balancing of a very small population of purchasers and a constant scrapping rate. (The long-run balancing of FCV purchasing and scrapping may be considered problematic and is discussed in detail in the *Validity Concerns* section of this paper.)

Table 14: Scenario 2 Tabular Results

Years	TCVO	CV %	FF SO	FF %	TFCVO	FCV %	H2 SO	H2 %
0	448,652	100.00%	412	100.00%	100	0.00%	0	0.00%
1	442,378	100.00%	412	100.00%	145	0.00%	0	0.00%
2	443,747	100.00%	412	100.00%	145	0.00%	0	0.00%
3	445,261	100.00%	412	100.00%	145	0.00%	0	0.00%
4	446,899	100.00%	412	100.00%	145	0.00%	0	0.00%
5	448,646	100.00%	412	100.00%	145	0.00%	0	0.00%
6	449,401	100.00%	412	100.00%	145	0.00%	0	0.00%
7	450,422	100.00%	412	100.00%	144	0.00%	0	0.00%
8	451,689	100.00%	412	100.00%	144	0.00%	0	0.00%
9	453,165	100.00%	412	100.00%	143	0.00%	0	0.00%
10	454,790	100.00%	412	100.00%	142	0.00%	0	0.00%
11	456,539	100.00%	412	100.00%	140	0.00%	0	0.00%
12	458,450	100.00%	412	100.00%	139	0.00%	0	0.00%
13	460,502	100.00%	412	100.00%	137	0.00%	0	0.00%
14	462,583	100.00%	412	100.00%	135	0.00%	0	0.00%
15	464,766	100.00%	412	100.00%	132	0.00%	0	0.00%
16	467,059	100.00%	412	100.00%	130	0.00%	0	0.00%
17	469,448	100.00%	412	100.00%	127	0.00%	0	0.00%
18	472,085	100.00%	412	100.00%	124	0.00%	0	0.00%
19	474,747	100.00%	412	100.00%	121	0.00%	0	0.00%
20	477,455	100.00%	412	100.00%	118	0.00%	0	0.00%
21	480,204	100.00%	412	100.00%	115	0.00%	0	0.00%
22	485,601	100.00%	412	100.00%	98	0.00%	0	0.00%
23	489,691	100.00%	412	100.00%	83	0.00%	0	0.00%
24	493,443	100.00%	412	100.00%	71	0.00%	0	0.00%
25	496,926	100.00%	412	100.00%	60	0.00%	0	0.00%
26	500,196	100.00%	412	100.00%	51	0.00%	0	0.00%
27	503,301	100.00%	412	100.00%	44	0.00%	0	0.00%
28	506,179	100.00%	412	100.00%	46	0.00%	0	0.00%
29	508,895	100.00%	412	100.00%	47	0.00%	0	0.00%
30	511,503	100.00%	412	100.00%	48	0.00%	0	0.00%
31	514,044	100.00%	412	100.00%	49	0.00%	0	0.00%
32	516,573	100.00%	412	100.00%	50	0.00%	0	0.00%
33	519,098	100.00%	412	100.00%	51	0.00%	0	0.00%
34	521,638	100.00%	412	100.00%	52	0.00%	0	0.00%
35	524,207	100.00%	412	100.00%	52	0.00%	0	0.00%
36	526,820	100.00%	412	100.00%	53	0.00%	0	0.00%
37	529,475	100.00%	412	100.00%	53	0.00%	0	0.00%
38	532,178	100.00%	412	100.00%	54	0.00%	0	0.00%
39	534,931	100.00%	412	100.00%	54	0.00%	0	0.00%
40	537,763	100.00%	412	100.00%	55	0.00%	0	0.00%
41	540,659	100.00%	412	100.00%	55	0.00%	0	0.00%
42	543,613	100.00%	412	100.00%	55	0.00%	0	0.00%
43	546,620	100.00%	412	100.00%	56	0.00%	0	0.00%
44	549,930	100.00%	412	100.00%	56	0.00%	0	0.00%
45	553,361	100.00%	412	100.00%	56	0.00%	0	0.00%
46	556,857	100.00%	412	100.00%	57	0.00%	0	0.00%
47	560,379	100.00%	412	100.00%	57	0.00%	0	0.00%
48	563,899	100.00%	412	100.00%	57	0.00%	0	0.00%
49	567,402	100.00%	412	100.00%	57	0.00%	0	0.00%

Figure 6: Scenario 2 Graphical Results
(Please note the logarithmic y-axis scale.)



10.2.c. Scenario 3: Practical-Plus FCV Future

The *Practical-Plus FCV Future* scenario represents a situation which is slightly better than practical. That is, *Scenario 3* is identical to *Scenario 2: Practical FCV Future*, except that in *Scenario 3*, there is a “bonus” in the form of government making a FCV purchase of substantial size instead of small. Thus, as with *Scenario 2*, the government acts as *innovators* and makes a substantial purchase of FCVs to assist in overcoming the chicken and egg phenomena. In this case the government purchases enough FCVs to warrant the building of 1 refueling station, but still does not support the FCV price or fuel cost through monetary incentives.

Table 15: Scenario 3 Inputs & Initial Values

Variable *(derived variables are* not *directly user-alterable)*	**Default Value**	**Scenario Value** *(alterations in **bold-italic**)*	**Units**
Area	61.4	61.4	square miles
Initial Population	564624	564624	people
Population Growth Rate	0.00568	0.00568	percent
Vehicles per Person	0.795	0.795	vehicles
Stations per 1000 Vehicles	0.92	0.92	stations
Government FCV	1885	1885	vehicles
Utility Value at 0% Density	-30000	-30000	dollars
Utility Value at 10% Density	-3000	-3000	dollars
Elasticity	-5	-5	percent
CV Price	20000 (constant over time)	20000 (constant over time)	dollars
FCV Price	17000 (constant over time)	***23000 (constant over time)***	dollars
CV Fuel Cost	7.5 (constant over time)	***5 (constant over time)***	cents per mile
FCV Fuel Cost	3 (constant over time)	***7 (constant over time)***	cents per mile
Run Time	50 (0 to 49)	50 (0 to 49)	years
Initial FCVs (derived)	1885 (gov't FCV)	1885 (gov't FCV)	vehicles
Initial CVs (derived)	448876	448876	vehicles
Initial H2 Stations (derived)	1	1	stations
Initial FF Stations (derived)	412	412	stations

Due to the lack of monetary incentives on FCVs or hydrogen fuel in this scenario, the FCV price is considerably more expensive than CV price and FCV fuel cost is more expensive than CV fuel cost. Specifically, *Scenario 3* assumes a government purchase of 1885 FCVs (with 1 station), a FCV cost $3,000 more than CV, and FCV fuel cost 2 cents per mile more expensive than CV fuel cost. Table 15 summarizes the *Scenario 3* inputs.

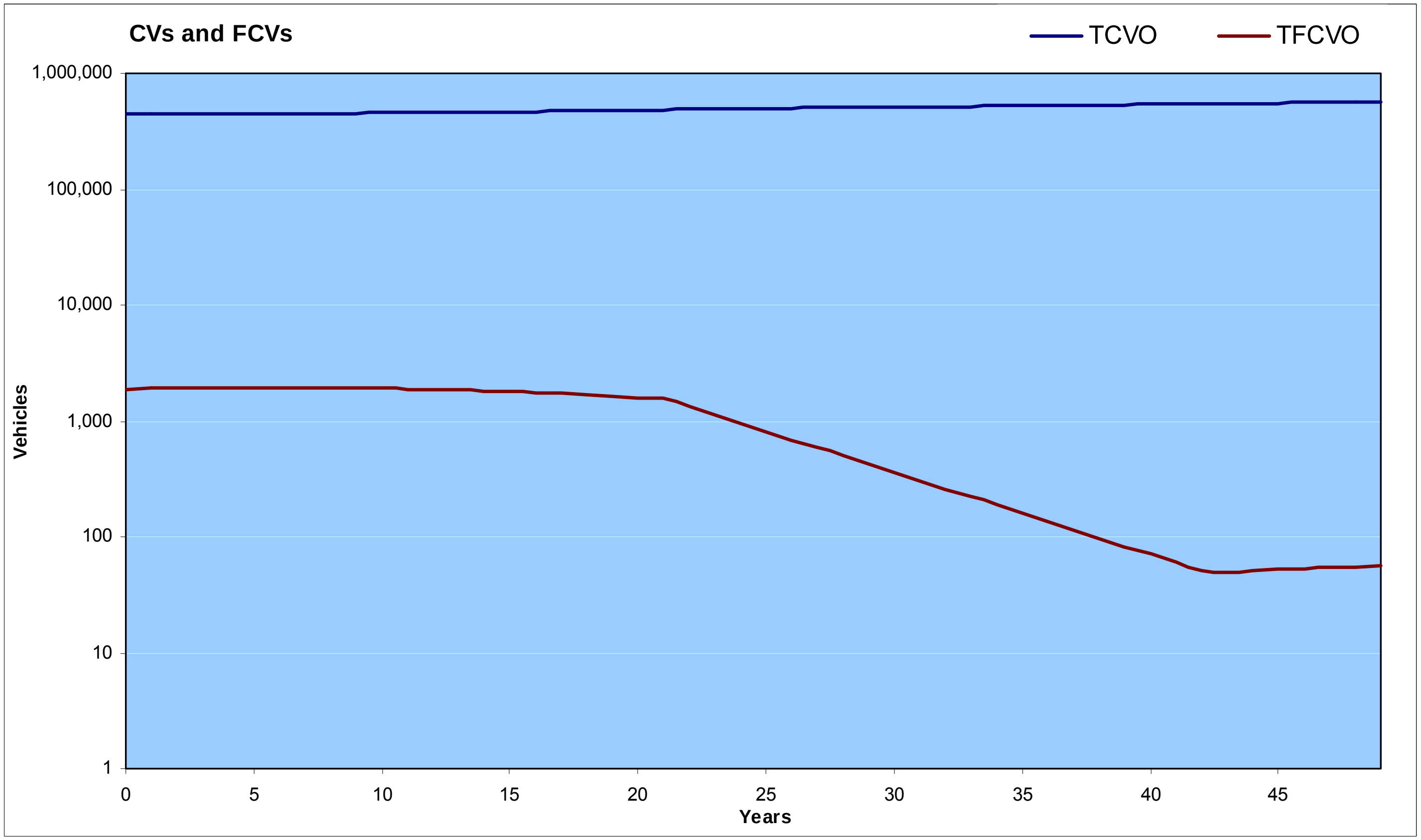
As shown in Table 16 and Figure 7, the *Practical-Plus FCV Future* scenario results in a stagnant hydrogen market similar to that observed in *Scenario 2*. The government "bonus" provided with the larger purchase of FCVs and the building of 1 refueling station allows for *Scenario 3* to operate at a higher market penetration rate compared to *Scenario 2* – but the impact is minimal and the population of adopters still does not escalate. The problem prohibiting market growth is due to the price differences between FCVs and CVs (and their fuel). Although the government acted as innovators and purchased 1885 vehicles and built 1 refueling station, the price differences still prohibit civilians from purchasing FCVs.

During the first year of the simulation there are 69 civilian purchases of FCVs (slightly greater than those in *Scenario 2*). As with the case in *Scenario 2*, this small civilian purchase represents the *early adopters* in the population; the people who want to set a trend and are attracted to purchase a FCV even though the vehicle and fuel cost is substantially uneconomical. Additionally, this population represents those civilians that are willing to purchase FCVs even though there is only 1 refueling station in the 61 square mile simulation area. However, the purchases are not great enough to reach a *tipping point* in market penetration or trigger the *early majority* adopters. By year 6, the FCV population begins to decline due to vehicle scrapping and at year 27, the refueling station is forced to close due to lack of FCVs in the market. As with *Scenario 2*, the FCV population eventually levels off around 50 vehicles due to balancing of a very small population of purchasers and a constant scrapping rate. (The long-run balancing of FCV purchasing and scrapping may be considered problematic and is discussed in detail in the *Validity Concerns* section of this paper.)

Table 16: Scenario 3 Tabular Results

Years	TCVO	CV %	FF SO	FF %	TFCVO	FCV %	H2 SO	H2 %
0	448,652	99.60%	412	99.80%	1,885	0.40%	1	0.20%
1	442,354	99.60%	412	99.80%	1,954	0.40%	1	0.20%
2	443,723	99.60%	412	99.80%	1,954	0.40%	1	0.20%
3	445,237	99.60%	412	99.80%	1,954	0.40%	1	0.20%
4	446,875	99.60%	412	99.80%	1,954	0.40%	1	0.20%
5	448,622	99.60%	412	99.80%	1,954	0.40%	1	0.20%
6	449,376	99.60%	412	99.80%	1,949	0.40%	1	0.20%
7	450,397	99.60%	412	99.80%	1,945	0.40%	1	0.20%
8	451,664	99.60%	412	99.80%	1,940	0.40%	1	0.20%
9	453,140	99.60%	412	99.80%	1,935	0.40%	1	0.20%
10	454,765	99.60%	412	99.80%	1,913	0.40%	1	0.20%
11	456,514	99.60%	412	99.80%	1,891	0.40%	1	0.20%
12	458,425	99.60%	412	99.80%	1,869	0.40%	1	0.20%
13	460,477	99.60%	412	99.80%	1,846	0.40%	1	0.20%
14	462,558	99.60%	412	99.80%	1,814	0.40%	1	0.20%
15	464,740	99.60%	412	99.80%	1,782	0.40%	1	0.20%
16	467,034	99.60%	412	99.80%	1,749	0.40%	1	0.20%
17	469,423	99.60%	412	99.80%	1,717	0.40%	1	0.20%
18	472,059	99.60%	412	99.80%	1,676	0.40%	1	0.20%
19	474,721	99.70%	412	99.80%	1,635	0.30%	1	0.20%
20	477,429	99.70%	412	99.80%	1,593	0.30%	1	0.20%
21	480,178	99.70%	412	99.80%	1,552	0.30%	1	0.20%
22	485,577	99.70%	412	99.80%	1,320	0.30%	1	0.20%
23	489,667	99.80%	412	99.80%	1,122	0.20%	1	0.20%
24	493,418	99.80%	412	99.80%	954	0.20%	1	0.20%
25	496,900	99.80%	412	99.80%	811	0.20%	1	0.20%
26	500,170	99.90%	412	99.80%	689	0.10%	1	0.20%
27	503,275	99.90%	413	100.00%	586	0.10%	0	0.00%
28	506,181	99.90%	413	100.00%	498	0.10%	0	0.00%
29	508,896	99.90%	413	100.00%	423	0.10%	0	0.00%
30	511,504	99.90%	413	100.00%	360	0.10%	0	0.00%
31	514,045	99.90%	413	100.00%	306	0.10%	0	0.00%
32	516,574	99.90%	413	100.00%	260	0.10%	0	0.00%
33	519,099	100.00%	413	100.00%	221	0.00%	0	0.00%
34	521,639	100.00%	413	100.00%	188	0.00%	0	0.00%
35	524,208	100.00%	413	100.00%	160	0.00%	0	0.00%
36	526,820	100.00%	413	100.00%	136	0.00%	0	0.00%
37	529,476	100.00%	413	100.00%	115	0.00%	0	0.00%
38	532,179	100.00%	413	100.00%	98	0.00%	0	0.00%
39	534,932	100.00%	413	100.00%	83	0.00%	0	0.00%
40	537,763	100.00%	413	100.00%	71	0.00%	0	0.00%
41	540,659	100.00%	413	100.00%	60	0.00%	0	0.00%
42	543,613	100.00%	413	100.00%	51	0.00%	0	0.00%
43	546,620	100.00%	413	100.00%	49	0.00%	0	0.00%
44	549,930	100.00%	413	100.00%	51	0.00%	0	0.00%
45	553,361	100.00%	413	100.00%	52	0.00%	0	0.00%
46	556,858	100.00%	413	100.00%	53	0.00%	0	0.00%
47	560,379	100.00%	413	100.00%	54	0.00%	0	0.00%
48	563,900	100.00%	413	100.00%	55	0.00%	0	0.00%
49	567,400	100.00%	413	100.00%	56	0.00%	0	0.00%

Figure 7: Scenario 3 Graphical Results
(Please note the logarithmic y-axis scale.)



10.2.d. Scenario 4: Improbable FCV Future

The *Improbable FCV Future* scenario represents a situation in which the government does not make a purchase of FCVs but there is a naturally favorable market to FCV development. It is acknowledged that a scenario where FCV costs are considerably less than CV costs is unlikely in the immediate future (Winebrake 2002). However, this combination of inputs has been used to demonstrate bounds of the model. Specifically, the *Improbable FCV Future* scenario assumes the government purchases zero FCVs, but a FCV price $3,000 *less expensive* than CVs, and a FCV fuel cost 4.5 cents per mile *less expensive* than CV fuel cost. Table 17 summarizes *Scenario 4* inputs.

As shown in Table 17 and Figure 8, the *Improbable FCV Future* scenario results in a hydrogen market which is growing at a very slow rate: at year 1, FCVs occupy 0.3 percent of the market and do not approach 1 percent penetration until year 45. The problem prohibiting the growth of the market is twofold: (1) the lack of a substantial government purchase at the beginning of the simulation; and (2) the lack of a station built at the beginning of the simulation. Both of these factors amount to a situation in which the chicken and egg phenomenon reigns true; no consumers will purchase FCVs and no infrastructure builders will construct stations due to there being no FCVs on the road. That is, even with relatively inexpensive FCVs and a heavily subsidized fuel cost, a large number of consumers prove to be uninterested in purchasing FCVs because there is no where to refuel those vehicles! Specifically, due to the very slow FCV adopter growth rate in this scenario, it takes 5 years for there to be enough consumer

FCVs on the road before 1 H_2 station is built and another 35 years(!) before a second station is built.

Table 17: Scenario 4 Inputs & Initial Values

Variable *(derived variables are* not *directly user-alterable)*	**Default Value**	**Scenario Value** *(alterations in **bold-italic**)*	**Units**
Area	61.4	61.4	square miles
Initial Population	564624	564624	people
Population Growth Rate	0.00568	0.00568	percent
Vehicles per Person	0.795	0.795	vehicles
Stations per 1000 Vehicles	0.92	0.92	stations
Government FCV	1885	***0***	vehicles
Utility Value at 0% Density	-30000	-30000	dollars
Utility Value at 10% Density	-3000	-3000	dollars
Elasticity	-5	-5	percent
CV Price	20000 (constant over time)	20000 (constant over time)	dollars
FCV Price	17000 (constant over time)	17000 (constant over time)	dollars
CV Fuel Cost	7.5 (constant over time)	7.5 (constant over time)	cents per mile
FCV Fuel Cost	3 (constant over time)	3 (constant over time)	cents per mile
Run Time	50 (0 to 49)	50 (0 to 49)	years
Initial FCVs (derived)	1885 (gov't FCV)	***0 (gov't FCV)***	vehicles
Initial CVs (derived)	448876	448876	vehicles
Initial H2 Stations (derived)	1	***0***	stations
Initial FF Stations (derived)	412	412	stations

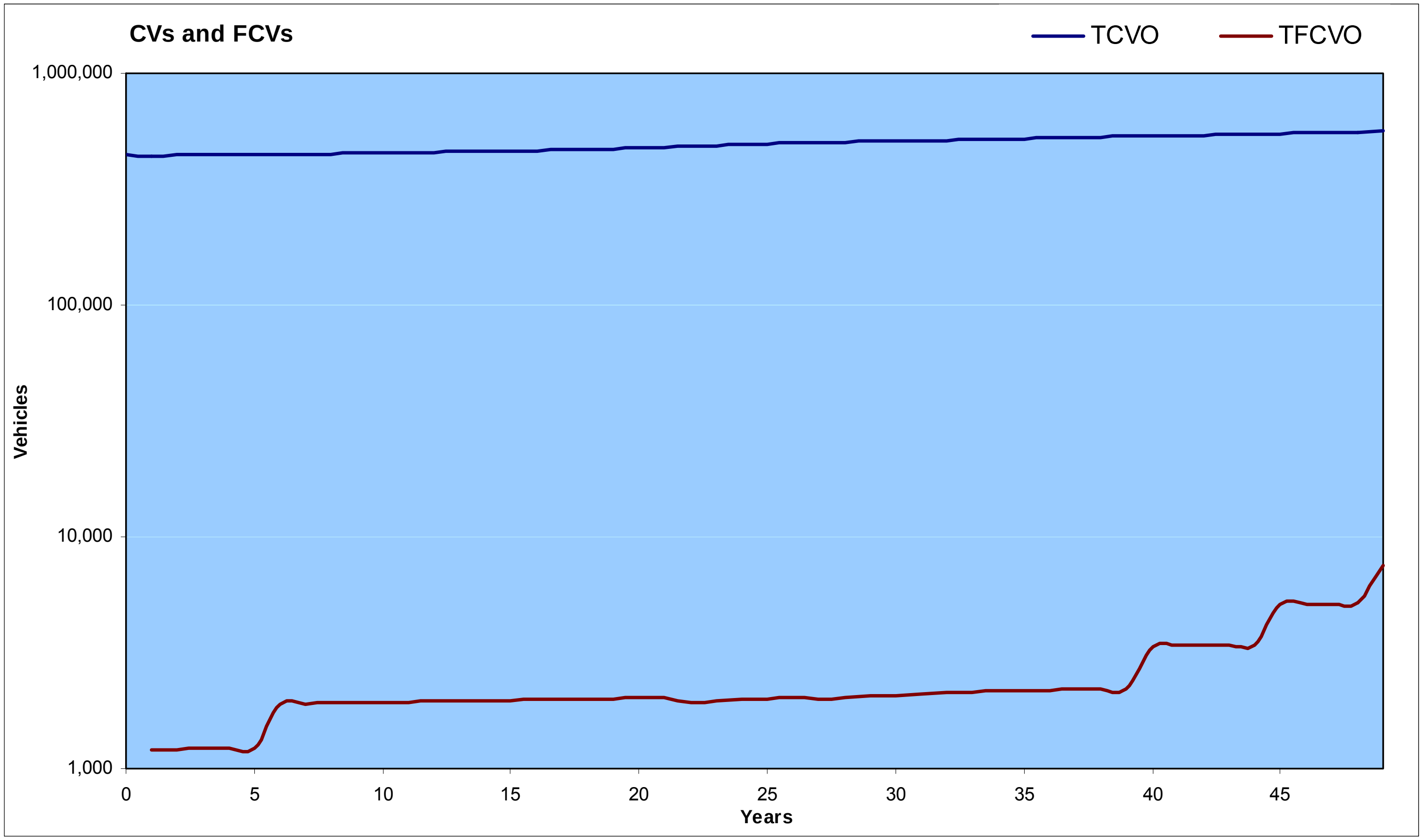
There are two reasons why this scenario is dubbed the "Improbable FCV Future." First, during the first year of the simulation there are over 1,200 civilian FCV purchases even though there are no stations active and no where to refuel these vehicles. H_2VISION yields these results due to the incorporation of the Greene (1994) assumption and equations (for more information on Greene, see the section of this paper entitled *Alternative Fuels and Vehicles Choice Model*). The nature of the Greene equations is that adopters choose to adopt FCVs based on (1) station density; (2) vehicle price, and (3) fuel cost. Thus, even with a negative $30,000 value associated with having no stations in existence, 0.3 percent of the population will risk purchasing a FCV simply because in this scenario the FCVs are so inexpensive compared to CVs. The concern that there are FCV purchases even when there are no stations active is addressed further in the *Validity Concerns* section of this paper.

Second, it is highly improbable that there would be a situation where FCVs are considerably less expensive than CVs and the government would not take advantage of this price difference. Considering that governments of the United States own and operate approximately 5 million light- and medium-duty vehicles, governments would surely be among the first adopters of FCVs if the vehicles naturally offered monetary incentives.

Table 18: Scenario 4 Tabular Results

Years	TCVO	CV %	FF SO	FF %	TFCVO	FCV %	H2 SO	H2 %
0	448,652	100.00%	412	100.00%	0	0.00%	0	0.00%
1	442,199	99.70%	412	100.00%	1,201	0.30%	0	0.00%
2	442,585	99.70%	412	100.00%	1,208	0.30%	0	0.00%
3	444,092	99.70%	412	100.00%	1,215	0.30%	0	0.00%
4	445,724	99.70%	412	100.00%	1,221	0.30%	0	0.00%
5	447,464	99.70%	411	99.80%	1,228	0.30%	1	0.20%
6	447,553	99.60%	411	99.80%	1,892	0.40%	1	0.20%
7	448,566	99.60%	411	99.80%	1,903	0.40%	1	0.20%
8	449,822	99.60%	411	99.80%	1,913	0.40%	1	0.20%
9	451,288	99.60%	411	99.80%	1,924	0.40%	1	0.20%
10	452,903	99.60%	411	99.80%	1,924	0.40%	1	0.20%
11	454,652	99.60%	411	99.80%	1,934	0.40%	1	0.20%
12	456,553	99.60%	411	99.80%	1,945	0.40%	1	0.20%
13	458,594	99.60%	411	99.80%	1,956	0.40%	1	0.20%
14	460,665	99.60%	411	99.80%	1,961	0.40%	1	0.20%
15	462,848	99.60%	411	99.80%	1,966	0.40%	1	0.20%
16	465,130	99.60%	411	99.80%	1,977	0.40%	1	0.20%
17	467,509	99.60%	411	99.80%	1,988	0.40%	1	0.20%
18	470,135	99.60%	411	99.80%	1,994	0.40%	1	0.20%
19	472,794	99.60%	411	99.80%	2,002	0.40%	1	0.20%
20	475,491	99.60%	411	99.80%	2,013	0.40%	1	0.20%
21	478,229	99.60%	411	99.80%	2,024	0.40%	1	0.20%
22	483,632	99.60%	411	99.80%	1,918	0.40%	1	0.20%
23	487,808	99.60%	411	99.80%	1,947	0.40%	1	0.20%
24	491,529	99.60%	411	99.80%	1,976	0.40%	1	0.20%
25	494,984	99.60%	411	99.80%	2,002	0.40%	1	0.20%
26	498,229	99.60%	411	99.80%	2,026	0.40%	1	0.20%
27	501,376	99.60%	411	99.80%	1,984	0.40%	1	0.20%
28	504,221	99.60%	411	99.80%	2,015	0.40%	1	0.20%
29	506,908	99.60%	411	99.80%	2,044	0.40%	1	0.20%
30	509,489	99.60%	411	99.80%	2,070	0.40%	1	0.20%
31	512,006	99.60%	411	99.80%	2,094	0.40%	1	0.20%
32	514,513	99.60%	411	99.80%	2,114	0.40%	1	0.20%
33	517,020	99.60%	411	99.80%	2,132	0.40%	1	0.20%
34	519,543	99.60%	411	99.80%	2,150	0.40%	1	0.20%
35	522,095	99.60%	411	99.80%	2,166	0.40%	1	0.20%
36	524,691	99.60%	411	99.80%	2,181	0.40%	1	0.20%
37	527,334	99.60%	411	99.80%	2,195	0.40%	1	0.20%
38	530,024	99.60%	411	99.80%	2,208	0.40%	1	0.20%
39	532,764	99.60%	410	99.50%	2,221	0.40%	2	0.50%
40	534,440	99.40%	410	99.50%	3,376	0.60%	2	0.50%
41	537,318	99.40%	410	99.50%	3,394	0.60%	2	0.50%
42	540,254	99.40%	410	99.50%	3,413	0.60%	2	0.50%
43	543,243	99.40%	410	99.50%	3,432	0.60%	2	0.50%
44	546,536	99.40%	409	99.30%	3,439	0.60%	3	0.70%
45	548,322	99.10%	409	99.30%	5,088	0.90%	3	0.70%
46	551,797	99.10%	409	99.30%	5,112	0.90%	3	0.70%
47	555,294	99.10%	409	99.30%	5,138	0.90%	3	0.70%
48	558,788	99.10%	408	99.00%	5,167	0.90%	4	1.00%
49	559,992	98.70%	408	99.00%	7,468	1.30%	4	1.00%

Figure 8: Scenario 4 Graphical Results
(Please note the logarithmic y-axis scale.)



10.3. Refueling Infrastructure Dynamics Scenarios

As discussed in the previous section, the Vehicle Dynamics Scenarios explored involvement and impact of government procurement and financial policies on the development of hydrogen markets. In this section, two additional scenarios are developed. Dubbed the “Refueling Infrastructure Dynamics Scenarios”, these further expand the concept of government involvement in FCV markets by incorporating the concept of government programs which undertake mass-station building – with the goal of further understanding the root dynamics of the chicken and egg phenomena and convenience costs associated with refueling station availability.

Whereas *Scenario 1* through *4* explored the concept of building 0 or 1 initial H_2 stations, *Scenarios 5* and *6* explore the possibilities that the government offer monies to build 20 initial H_2 stations in the simulation area. In *Scenario 5* and *6*, the government does not undertake procurement of FCVs. However, market conditions are manipulated to reflect favorable or non favorable hydrogen markets.

It should be noted that some non-user alterable variables have been modified directly on the *System Model Level*; these variables cannot be altered on the *User Interface Level*. Such modifications are documented to allow for future replication of scenarios. Table 19 presents a summary of the Refueling Infrastructure Dynamics Scenarios and Table 20 presents the scenario options in a user-friendly scenario grid.

Table 19: Refueling Infrastructure Dynamics Scenarios Summaries

Scenario Number	Scenario Name	Scenario Description
5	Maximum Investment	This scenario represents a situation in which there is a maximum investment inflow to hydrogen markets; the government offers monies to build 20 H_2 stations *and* offers monetary incentives on FCVs and hydrogen fuel.
6	Uncertain Markets	This scenario represents a situation in which the government offers monies to build 20 H_2 stations in an uncertain and unfavorable market. In this scenario, the government offers no monetary incentives on FCVs or hydrogen fuel.

Table 20: Refueling Infrastructure Dynamics Scenarios Grid

		Scenario Grid	
Government Station Building	20 Stations	Scenario 6: Uncertain Markets	Scenario 5: Maximum Investment
	No Stations	*See Scenario 2*	*See Scenario 4*
		Unfavorable	Favorable
		FCV Market Conditions	

10.3.a. Scenario 5: Maximum Investment

The *Maximum Investment* scenario represents a situation in which there is a maximum investment inflow to hydrogen markets. That is, in this scenario the government: (1) provides enough money for the building of 20 H_2 stations; (2) provides tax breaks on FCVs; and (3) provides subsidies on hydrogen fuel. However, unlike in previous scenarios the government *does not* procure FCVs. Instead, it is assumed that the monies otherwise used for procurement are now used to fund station building. Table 21 summarizes *Scenario 5* inputs.

As shown in Table 22 and Figure 9, the *Maximum Investment* scenario results in a complete saturation of hydrogen markets. In response to the building of 20 stations at time 0 and the offering of monetary incentives on FCVs and fuel, over 150,000 consumers who would have otherwise bought CVs adopt FCVs at time 1. As is expected, due to delays incorporated in the model, it takes two additional years for infrastructure investors to gain confidence in FCVs markets and respond to FCV adopters by building additional stations.[9] At time 3, infrastructure investors respond by building an additional 52 stations, which, in turn, are enough to allow for the reaching of

[9] The formula for the variable *Mean 3 Year FCV Pop*, which is used to determine building of new stations and incorporates the delay in station building, has been altered for *Scenario 5* and *6*. Where previously the formula would consider *Gov't FCV* as the basis for first year station building, for *Scenario 5* and *6* the formula includes the mass-building of H_2 stations at time 0 and incorporates the value into the system for determining FCV purchases at time 1.

the tipping point within the market; FCVs and H_2 stations quickly reach carrying capacity, and CV markets plummet.[10]

Table 21: Scenario 5 Inputs & Initial Values

Variable *("set" variables are not directly user-alterable)*	**Default Value**	**Scenario Value** *(alterations in **bold-italic**)*	**Units**
Area	61.4	61.4	square miles
Initial Population	564624	564624	people
Population Growth Rate	0.00568	0.00568	percent
Vehicles per Person	0.795	0.795	vehicles
Stations per 1000 Vehicles	0.92	0.92	stations
Government FCV	1885	***0***	vehicles
Utility Value at 0% Density	-30000	-30000	dollars
Utility Value at 10% Density	-3000	-3000	dollars
Elasticity	-5	-5	percent
CV Price	20000 (constant over time)	20000 (constant over time)	dollars
FCV Price	17000 (constant over time)	17000 (constant over time)	dollars
CV Fuel Cost	7.5 (constant over time)	7.5 (constant over time)	cents per mile
FCV Fuel Cost	3 (constant over time)	3 (constant over time)	cents per mile
Run Time	50 (0 to 49)	50 (0 to 49)	years
Initial FCVs (set)	1885	***0***	vehicles
Initial CVs (derived)	448876	448876	vehicles
Initial H2 Stations (set)	1	***20***	stations
Initial FF Stations (set)	412	***392***	stations

[10] There is a minor inconsistency in the markets where we see a very slight comeback in CV markets around year 30. This inconsistency is due to model structuring of long-run vehicle scrapping and should not be overly scrutinized.

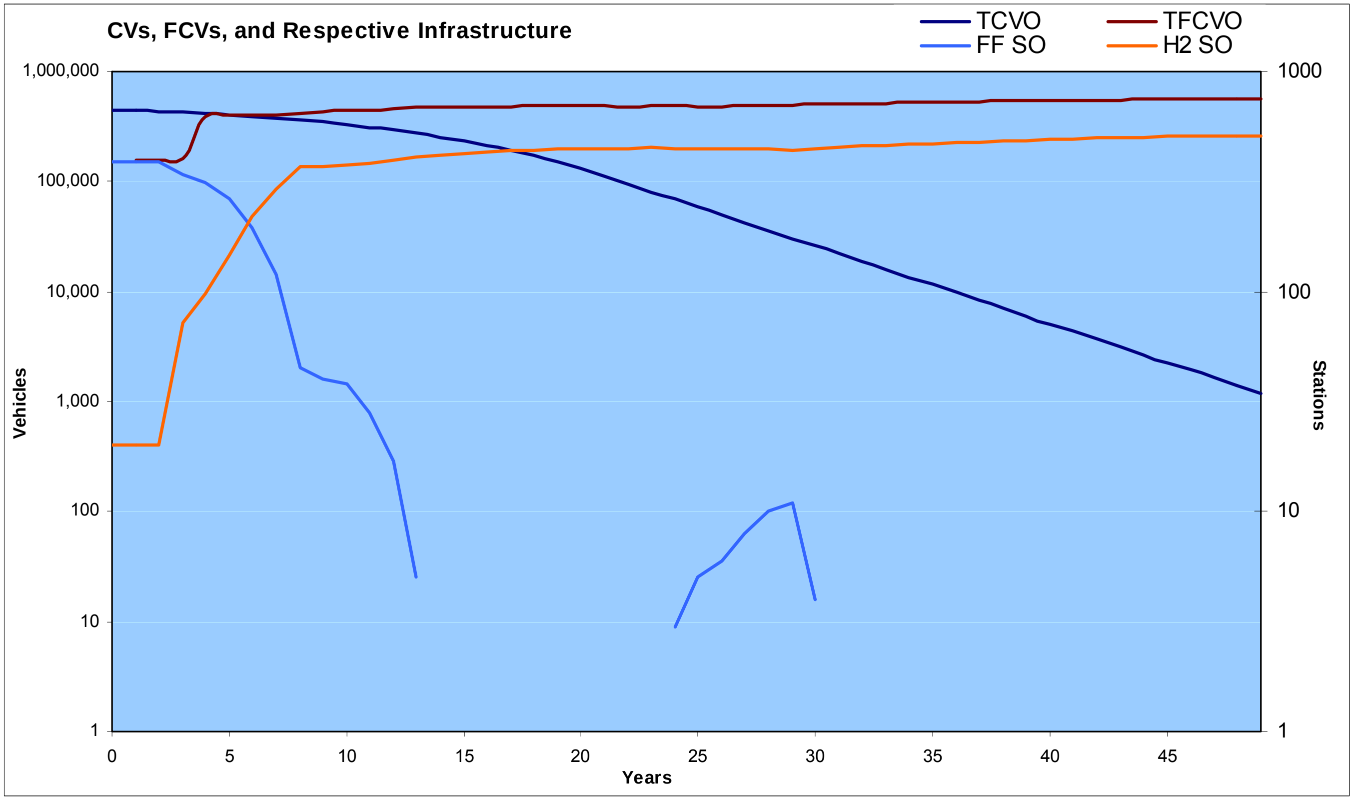
While 150,000 FCV purchases at time 1 may seem like a large jump given the adolescence of the markets, logically these purchases make sense. That is, 20 stations is more than enough in terms of station density to adequately overcome the convenience costs associated with a very limited station density. Additionally, the monetary incentives on FCVs and hydrogen fuel cause consumers to consider FCVs highly economical in comparison to CVs. Thus, in a market which exhibits almost no negative monetary penalty associated with station density, and plentiful financial benefits to adopting FCVs, one would expect such a rapid market penetration.

Of course, there are concerns associated with assuming such a financially favorable situation. *Scenario 6* discusses a situation in which mass-station building occurs in a non-favorable market – a scenario which is more in line with potential real-world situations.

Table 22: Scenario 5 Tabular Results

Years	TCVO	CV %	FF SO	FF %	TFCVO	FCV %	H2 SO	H2 %
0	448,652	100.00%	392	95.10%	0	0.00%	20	4.90%
1	442,199	73.60%	392	95.10%	158,237	26.40%	20	4.90%
2	434,566	73.20%	392	95.10%	159,136	26.80%	20	4.90%
3	425,882	72.70%	340	82.50%	160,040	27.30%	72	17.50%
4	416,259	51.40%	315	76.50%	393,589	48.60%	97	23.50%
5	405,789	50.30%	266	64.60%	401,407	49.70%	146	35.40%
6	393,467	49.30%	194	47.10%	404,949	50.70%	218	52.90%
7	379,564	48.20%	120	29.10%	407,367	51.80%	292	70.90%
8	364,315	47.00%	45	10.90%	410,157	53.00%	367	89.10%
9	347,917	44.30%	40	9.70%	436,639	55.70%	372	90.30%
10	330,507	42.70%	38	9.20%	443,348	57.30%	374	90.80%
11	312,274	41.10%	28	6.80%	448,276	58.90%	384	93.20%
12	293,383	38.80%	17	4.10%	462,914	61.20%	395	95.90%
13	273,972	36.70%	5	1.20%	472,789	63.30%	407	98.80%
14	254,067	34.70%	0	0.00%	477,528	65.30%	415	100.00%
15	233,809	32.70%	0	0.00%	480,357	67.30%	424	100.00%
16	213,321	30.60%	0	0.00%	483,070	69.40%	433	100.00%
17	192,704	28.50%	0	0.00%	484,574	71.50%	438	100.00%
18	172,210	26.20%	0	0.00%	486,323	73.80%	441	100.00%
19	151,905	23.70%	0	0.00%	489,000	76.30%	444	100.00%
20	131,846	21.10%	0	0.00%	491,719	78.90%	445	100.00%
21	112,081	18.50%	0	0.00%	493,305	81.50%	447	100.00%
22	95,279	16.60%	0	0.00%	480,326	83.40%	449	100.00%
23	80,996	14.30%	0	0.00%	485,755	85.70%	452	100.00%
24	68,854	12.30%	3	0.70%	490,820	87.70%	449	99.30%
25	58,532	11.00%	5	1.10%	472,650	89.00%	447	98.90%
26	49,758	9.40%	6	1.30%	480,358	90.60%	446	98.70%
27	42,299	8.00%	8	1.80%	487,825	92.00%	444	98.20%
28	35,958	6.80%	10	2.20%	494,575	93.20%	442	97.80%
29	30,567	5.80%	11	2.40%	500,555	94.20%	441	97.60%
30	25,985	4.90%	4	0.90%	503,752	95.10%	448	99.10%
31	22,090	4.20%	0	0.00%	509,567	95.80%	454	100.00%
32	18,778	3.50%	0	0.00%	514,507	96.50%	459	100.00%
33	15,963	3.00%	0	0.00%	518,138	97.00%	464	100.00%
34	13,570	2.50%	0	0.00%	521,979	97.50%	468	100.00%
35	11,536	2.10%	0	0.00%	525,924	97.90%	472	100.00%
36	9,807	1.80%	0	0.00%	529,839	98.20%	476	100.00%
37	8,336	1.50%	0	0.00%	533,650	98.50%	480	100.00%
38	7,087	1.30%	0	0.00%	537,362	98.70%	483	100.00%
39	6,024	1.10%	0	0.00%	540,745	98.90%	487	100.00%
40	5,121	0.90%	0	0.00%	543,899	99.10%	490	100.00%
41	4,354	0.80%	0	0.00%	547,057	99.20%	494	100.00%
42	3,701	0.70%	0	0.00%	550,223	99.30%	497	100.00%
43	3,146	0.60%	0	0.00%	553,171	99.40%	500	100.00%
44	2,674	0.50%	0	0.00%	554,601	99.50%	503	100.00%
45	2,274	0.40%	0	0.00%	556,615	99.60%	506	100.00%
46	1,933	0.30%	0	0.00%	559,087	99.70%	508	100.00%
47	1,643	0.30%	0	0.00%	559,662	99.70%	510	100.00%
48	1,397	0.20%	0	0.00%	561,213	99.80%	512	100.00%
49	1,187	0.20%	0	0.00%	563,578	99.80%	513	100.00%

Figure 9: Scenario 5 Graphical Results
(Please note the logarithmic y-axis scale.)



Note: the discontinuity in FF SO is due to the inability to graph a value of 0 when using logarithmic scale.

10.3.b. Scenario 6: Uncertain Markets

The *Uncertain Markets* scenario represents a situation similar to that in *Scenario 5.* As with the previous scenario, in this scenario the government provides enough money for the building of 20 H_2 stations. However, unlike the previous scenario, here there are unfavorable markets facing FCVs and the government provides no monetary incentives on vehicles or fuel. Specifically, *Scenario 6* assumes a FCV cost $3,000 more than CV, and FCV fuel cost 2 cents per mile more expensive than CV fuel cost. In other words, this scenario assumes that the government focuses all attention on infrastructure and none on FCV procurement or investment. Table 23 summarizes *Scenario 6* inputs.

As shown in Table 24 and Figure 10, the Uncertain Markets scenario results in a situation where the government's mass-building of stations has a ripple-effect (although minor) through the early stages of the vehicle markets. The construction of 20 stations is enough to overcome the convenience costs associated with a very limited refueling station density, but the effect is not substantial enough to create an epidemic or reach a FCV market tipping point due to the high vehicle and fuel costs. In the long run, the FCV population crashes and H_2 stations reduce to zero.

Table 23: Scenario 6 Inputs & Initial Values

Variable *("set" variables are* not *directly user-alterable)*	**Default Value**	**Scenario Value** *(alterations in **bold-italic**)*	**Units**
Area	61.4	61.4	square miles
Initial Population	564624	564624	people
Population Growth Rate	0.00568	0.00568	percent
Vehicles per Person	0.795	0.795	vehicles
Stations per 1000 Vehicles	0.92	0.92	stations
Government FCV	1885	***0***	vehicles
Utility Value at 0% Density	-30000	-30000	dollars
Utility Value at 10% Density	-3000	-3000	dollars
Elasticity	-5	-5	percent
CV Price	20000 (constant over time)	20000 (constant over time)	dollars
FCV Price	17000 (constant over time)	***23000*** (constant over time)	dollars
CV Fuel Cost	7.5 (constant over time)	***5*** (constant over time)	cents per mile
FCV Fuel Cost	3 (constant over time)	***7*** (constant over time)	cents per mile
Run Time	50 (0 to 49)	50 (0 to 49)	years
Initial FCVs (set)	1885	***0***	vehicles
Initial CVs (derived)	448876	448876	vehicles
Initial H2 Stations (set)	1	***20***	stations
Initial FF Stations (set)	412	***392***	stations

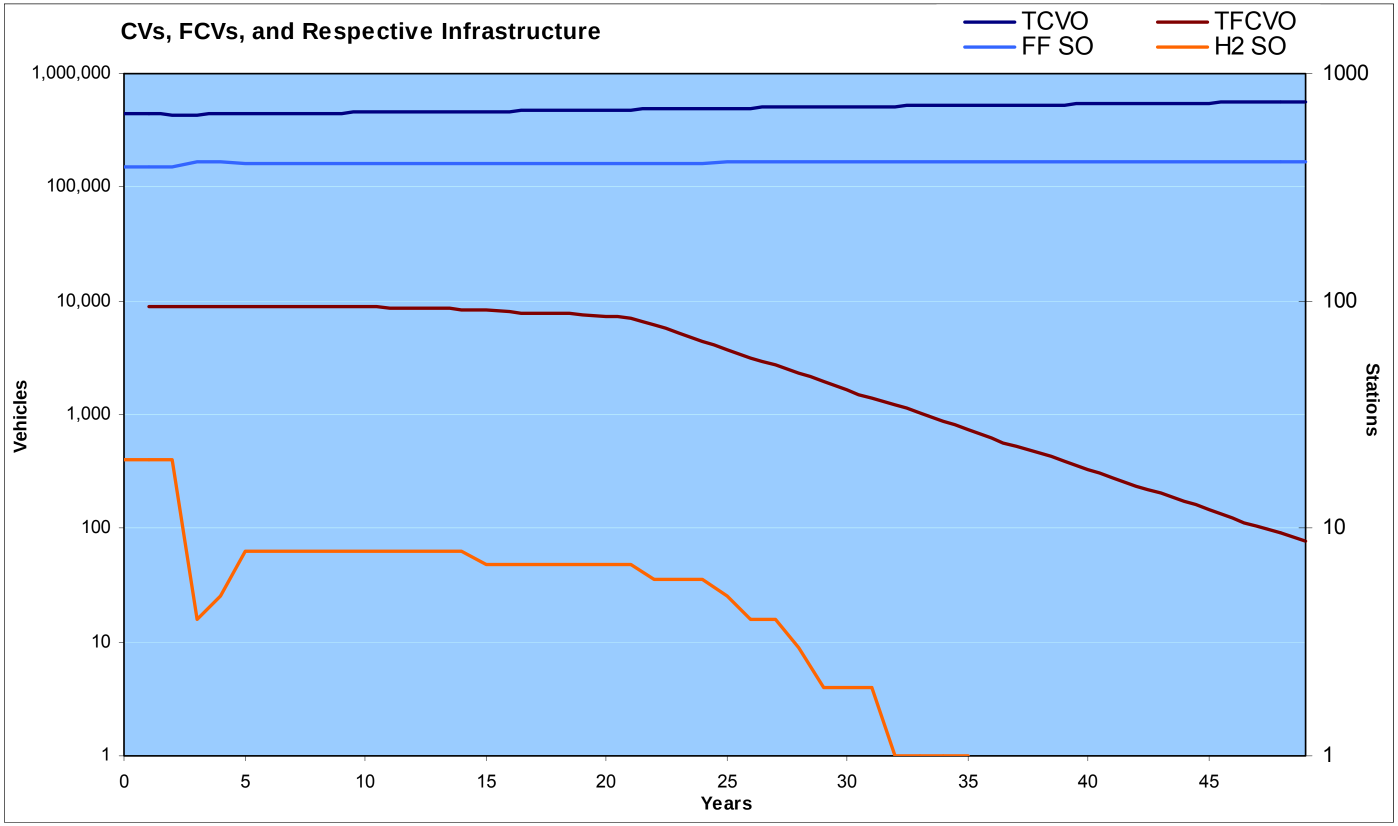
Specifically, in response to the government building of 20 stations at time 0, almost 9,000 FCVs are purchased at time 1. Purchases increase very slightly to just over 9,000 operational FCVs, but begin to decline by time 8. The 20 stations built by the government remain active until time 5 (a proper delay) – then all but four are forced to shut down accounting for the fact that there are not enough FCVs on the road. The number of stations stabilizes at 8 operational stations for a short period of time – but then declines gradually, responding to the aging and scrapping of the FCV population over time.

Although these trends are noteworthy, the bottom line is that they are nothing but a “blip” in the CV markets (with 8 H_2 stations operating, FF stations still occupy over 98 percent of market share!). The failure of the hydrogen markets in this scenario is due to the over-emphasis placed on infrastructure and the 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 consumers consider FCVs uneconomical and not worth purchasing. Here, the concept of complimentary goods reigns true – too much attention is paid to one good (infrastructure) and not enough to the complementary good (vehicles), proving highly detrimental to long-run market development.

Table 24: Scenario 6 Tabular Results

Years	TCVO	CV %	FF SO	FF %	TFCVO	FCV %	H2 SO	H2 %
0	448,652	100.00%	392	95.10%	0	0.00%	20	4.90%
1	442,199	98.00%	392	95.10%	8,928	2.00%	20	4.90%
2	434,814	98.00%	392	95.10%	8,979	2.00%	20	4.90%
3	436,277	98.00%	408	99.00%	9,030	2.00%	4	1.00%
4	446,723	98.00%	407	98.80%	9,030	2.00%	5	1.20%
5	448,378	98.00%	404	98.10%	9,030	2.00%	8	1.90%
6	448,653	98.00%	404	98.10%	9,009	2.00%	8	1.90%
7	449,692	98.00%	404	98.10%	8,987	2.00%	8	1.90%
8	450,954	98.10%	404	98.10%	8,966	1.90%	8	1.90%
9	452,405	98.10%	404	98.10%	8,944	1.90%	8	1.90%
10	454,027	98.10%	404	98.10%	8,842	1.90%	8	1.90%
11	455,852	98.10%	404	98.10%	8,740	1.90%	8	1.90%
12	457,760	98.10%	404	98.10%	8,637	1.90%	8	1.90%
13	459,728	98.20%	404	98.10%	8,534	1.80%	8	1.90%
14	461,806	98.20%	404	98.10%	8,385	1.80%	8	1.90%
15	464,034	98.30%	405	98.30%	8,236	1.70%	7	1.70%
16	466,534	98.30%	405	98.30%	8,087	1.70%	7	1.70%
17	468,875	98.30%	405	98.30%	7,938	1.70%	7	1.70%
18	471,510	98.40%	405	98.30%	7,748	1.60%	7	1.70%
19	474,211	98.40%	405	98.30%	7,558	1.60%	7	1.70%
20	476,916	98.50%	405	98.30%	7,367	1.50%	7	1.70%
21	479,622	98.50%	405	98.30%	7,177	1.50%	7	1.70%
22	485,035	98.80%	406	98.50%	6,111	1.20%	6	1.50%
23	490,152	99.00%	406	98.50%	5,200	1.00%	6	1.50%
24	493,747	99.10%	406	98.50%	4,421	0.90%	6	1.50%
25	496,227	99.20%	407	98.80%	3,758	0.80%	5	1.20%
26	499,683	99.40%	408	99.00%	3,195	0.60%	4	1.00%
27	502,971	99.50%	408	99.00%	2,716	0.50%	4	1.00%
28	505,868	99.50%	409	99.30%	2,309	0.50%	3	0.70%
29	508,682	99.60%	410	99.50%	1,963	0.40%	2	0.50%
30	511,365	99.70%	410	99.50%	1,668	0.30%	2	0.50%
31	513,918	99.70%	410	99.50%	1,418	0.30%	2	0.50%
32	516,454	99.80%	411	99.80%	1,206	0.20%	1	0.20%
33	519,044	99.80%	411	99.80%	1,025	0.20%	1	0.20%
34	521,605	99.80%	411	99.80%	871	0.20%	1	0.20%
35	524,174	99.90%	411	99.80%	741	0.10%	1	0.20%
36	526,786	99.90%	412	100.00%	630	0.10%	0	0.00%
37	529,461	99.90%	412	100.00%	535	0.10%	0	0.00%
38	532,176	99.90%	412	100.00%	455	0.10%	0	0.00%
39	534,930	99.90%	412	100.00%	387	0.10%	0	0.00%
40	537,762	99.90%	412	100.00%	329	0.10%	0	0.00%
41	540,668	99.90%	412	100.00%	280	0.10%	0	0.00%
42	543,630	100.00%	412	100.00%	238	0.00%	0	0.00%
43	546,635	100.00%	412	100.00%	202	0.00%	0	0.00%
44	549,928	100.00%	412	100.00%	172	0.00%	0	0.00%
45	553,447	100.00%	412	100.00%	146	0.00%	0	0.00%
46	557,000	100.00%	412	100.00%	124	0.00%	0	0.00%
47	560,456	100.00%	412	100.00%	105	0.00%	0	0.00%
48	563,931	100.00%	412	100.00%	90	0.00%	0	0.00%
49	567,414	100.00%	412	100.00%	76	0.00%	0	0.00%

Figure 10: Scenario 6 Graphical Results
(Please note the logarithmic y-axis scale.)



10.4. Scenario Summary and Conclusions

The six scenarios developed here explore the two stated goals of this project. *Scenario 1* through *4* primarily explore the first goal of H_2VISION: to identify the potential role of government as first-use customers in the growth of the hydrogen economy and penetration of FCVs into the mainstream consumer market. *Scenario 5* and *6* primarily explore the second goal of H_2VISION: to explore the dynamics of the chicken and egg phenomenon currently inhibiting the growth of FCVs and refueling infrastructure.

The following is a brief recap of the scenario results:

> **Scenario 1: Archetypical FCV Future.** The government made a substantial FCV procurement, built 1 refueling station, offered tax breaks on new FCVs, and subsidies on fuel. The result was a full market penetration of FCVs with primary growth occurring between year 20 and 40.

> **Scenario 2: Practical FCV Future.** The government made a small FCV procurement, did not build a refueling station, did not offer tax breaks on new FCVs, and did not subsidize fuel. The result was a stagnant, declining FCV market in which no refueling stations were ever constructed.

Scenario 3: Practical-Plus FCV Future. The government made a substantial FCV procurement, built 1 refueling station, but did not offer tax breaks on new FCVs, and did not offer subsidies on fuel. The result was a stagnant, declining FCV market in which only the initial 1 refueling station was built; no additional stations were ever constructed.

Scenario 4: Improbable FCV Future. The government made no FCV procurement, did not build a refueling station, but markets favored the development of FCVs (inexpensive vehicles and fuel). The result was a very slow growing FCV market in which the number of hydrogen stations was increasing over time – but there were still only 4 hydrogen stations existing at the end of the simulation.

Scenario 5: Maximum Investment. The government did not procure any FCVs but instead allocated money to construct 20 refueling stations. In addition, market conditions favored the development of FCVs (inexpensive vehicles and fuel). The result was an extremely rapid FCV market penetration with FCVs occupying 50 percent and 90 percent of market share by year 6 and 26, respectively.

Scenario 6: Uncertain Markets. The government did not procure any FCVs but instead allocated money to construct 20 refueling stations. Market conditions did not favor the development of FCVs (FCVs and hydrogen fuel were more expensive than CVs and conventional fuel). The result was a stagnant, declining hydrogen market; a maximum of only 9,000 FCVs were purchased and all refueling stations were forced to close by year 36.

It is important to note that in this project “successful market penetration” is determined by analyzing the final number of FCVs, CVs, H_2 stations, and FF stations in operation. That is, the value of each of the four variables at time 49. It is acknowledged that there are multiple alternative methods for determining success such as measuring the area under the population curve (the total number of CVs – and thus, fossil fuel – displaced by FCVs), the year in which a certain percentage of market penetration is reached, the year in which critical mass is reached, the year in which one population of vehicles outnumbers the other, etc. These alternative methods of determining success are not directly utilized in this project but could be calculated via H_2VISION output.

Keeping in mind the aforementioned criteria for success, a number of conclusions can be drawn from the scenario results. Consider that out of the six scenarios, only *Scenario 1* and *5* yield a successful FCV market penetration. These two scenarios have a number of factors in common: funding was provided for initial hydrogen refueling stations, tax breaks were offered on new FCVs, and subsidies were offered on hydrogen fuel. The difference between the two scenarios is that in *Scenario 1*, the government allocated the majority of resources to undertaking bulk procurement of FCVs. In *Scenario 5*, on the other hand, the government allocated the majority of resources to undertaking mass-building of refueling infrastructure.

Although both *Scenario 1* and *Scenario 5* yield a FCV market penetration, FCV growth occurred considerably faster in *Scenario 5* (in *Scenario 5*, FCVs achieved 50 percent market share by year 6; in *Scenario 1*, 50 percent market share was not achieved until year 37). The resulting time frame necessary for FCV market penetration should not be scrutinized too closely – H_2VISION is not meant to predict precise dates and timetables. However, the fact that infrastructure investment yields considerably faster market penetration results than vehicle investment allows for conclusions to be drawn concerning allocation of government funding.

Let us assume that a new FCV costs $25,000. If the government were to make a substantial purchase of 1885 FCVs, it would cost a total of about $47 million. Next, let us assume that constructing a hydrogen refueling station from scratch (as opposed to converting an existing fossil fuel station) costs $700,000. If the government were to build 20 hydrogen refueling stations, it would cost a total of about $14 million. Considering this, it would be considerably less expensive for the government to invest in infrastructure compared to vehicles – and according to the scenario analysis, would yield quicker market penetration. Even if we were to assume a FCV cost of only $15,000 (for a total bill of $28 million), it would still be twice as expensive for the government to purchase 1885 vehicles compared to building 20 stations!

However, the scenario analysis also shows that it is vitally important that investments be applied to *all aspects* of the vehicle markets. That is, *Scenarios 2, 3, 4,* and *6* were unsuccessful because in each scenario the government neglected one or more aspects of the market development. If incentives on new vehicles, subsidies on fuel, focus on infrastructure, or procurement of vehicles are ignored, the market will not succeed. Thus it is important to realize that even though it may be more efficient in terms of short-term expenditures to apply funding only to infrastructure, without also applying funding to the other aspects of market development, the funding spent on infrastructure will be wasted.

The bottom line is that the government has a great potential to play an essential role in hastening the transition to the hydrogen economy and overcoming the chicken and egg phenomena. Even in a situation where the cost of FCVs and hydrogen fuel are less expensive than CVs and fossil fuel (*Scenario 4*), the hydrogen market is still unable to reach a tipping point without the assistance of either government procurement of FCVs or funding of refueling station construction.

Thus, if mainstream market penetration of hydrogen technologies is to occur within the next half-century, it is vitally important that the federal, state, and local governments act as a first-use and innovative consumers. This conclusion is echoed by Winebrake (2002): “If hydrogen is ever to achieve significant market penetration, then coordinated, systematic market development is needed.” Governments must assist in systematic market development by supporting the deployment of hydrogen technologies, undertaking bulk procurement of fuel cell vehicles, offering subsidies for infrastructure construction or directly funding the construction of new stations, offering tax credits on civilian FCV purchase, and offering subsidies on hydrogen fuel production and delivery. The six scenarios conducted with H_2VISION show that if the government begins to aggressively financially support hydrogen markets in the immediate future, the hydrogen economy will be capable of self-sustainment in a matter of decades.

11. Project Validity

11.1. H_2VISION Validity

When validating system models it is important to discuss two areas of validity: structural and predictive. Structural validity being the validity of the underlying construction or arrangement of the system model's core design; predictive validity being the validity of predictions made using the system model through scenario or another type of analysis.

11.1.a. Structural Validity

H_2VISION is structurally validated through the previous work on which the system model was built. As explained in the *Current Hydrogen Technology and Diffusion Models* section of this paper, the Alternative Fuels and Vehicles Choice Model (AFVC) served as a vitally important building block for the structure of H_2VISION. Among other equations – identified in the aforementioned section – the AFVC model provided equations for the consumer preference variables (attractiveness coefficients, elasticity, price slope, etc.). The AFVC model has been peer reviewed and due to its strong core structure is recognized as a quality and valid system model. As mentioned in the *Diffusions Models* section of this paper, other than the AFVC, the other discussed models did not provide a structural base for H_2VISION.

Research discussed in the *Technology Diffusion and the Tipping Point* section provides significant structural validity to this project. To explain, the discussed research conducted by Griliches (1957), Bass (1969), Valente (1993), and Sterman (2000) each provide significant weight to the concept of s-shaped growth and application to the innovation of technologies. While the exact formulas derived by Griliches and Bass were not incorporated into this project, H_2VISION incorporates system feedback similar to that discussed in the work and thus lends itself to validation of the model.

Moreover, the research by Flynn (2002) discussed in the *The Natural Gas Market: Lessons Learned* section of this paper provides significant validity backing. That is, through Flynn's research, he identifies specific factors which led to the failure of natural gas vehicles to acquire significant market share. For example, Flynn identifies that the critical mass (or tipping point) within the natural gas vehicle market was not reached because the small number of vehicles made natural gas infrastructure unprofitable. Additionally, Flynn identifies that government incentives were not aggressive or widespread enough to have a significant impact on the mainstream penetration of natural gas vehicles. Comparing Flynn's research to the results achieved in H_2VISION scenario analysis allows for additional fortification of validity in that we see similar results: the tipping point is not reached without significant governmental incentives; a small number of vehicles in the markets will not foster market growth and infrastructure suppliers will be forced to exit the market.

Thus, through the system modeling work conducted by Greene, the theoretical base provided by Griliches, Bass, Valente, and Sterman, and the studying of alternative fuel vehicle markets undergone by Flynn, the work conducted under this project is structurally valid.

11.1.b. Predictive Validity

Predictive validity is typically a more complex and difficult to approach concept than its structural counterpart. In the area of alternative fuel vehicles, predictive validity is particularly difficult to guarantee. This is because never before have hydrogen fuel cells attempted to penetrate the mainstream market for application in consumer transportation. How then, is it possible to determine if the predictions of any alternative fuel vehicle futures scenario analysis are valid?

H_2VISION scenario analyses offer predictive validity in themselves. Consider *Scenario 1* in which FCVs are less expensive than CVs and hydrogen fuel is less expensive than conventional fuel. The result is full market penetration – as one would expect. That is, if all other factors are equal (remember, we assume that fuel economy, performance, etc. are equal) it is unarguable that consumers would purchase a FCV over a CV if it would save them considerable amounts of money.

Next consider *Scenario 2* in which FCVs are more expensive than CVs and hydrogen fuel is more expensive than conventional fuel. The result was minimal market penetration and a long-run stagnant market – as one would expect. Again, if all other factors are equal, it is unarguable that consumers would *not* purchase a FCV over a CV if it would cost them considerable amounts of money.

The concept of "expectation" need not be applied solely to alternative fuel vehicle innovations; it can be applied universally to almost any innovation. If a new technology is equal to but less expensive than an existing technology, the new technology will prevail in markets. Thus, H_2VISION is predictively valid in that it yields results that one would expect it to yield. However, validity concerns do exist and these concerns will be discussed in the following section.

11.2. Validity Concerns

Scenario 2 and *3* result in market situations where the population of FCVs is decreasing due to lack of consumer demand for the vehicles and scrapping of existing vehicles. As noted in previous sections, regardless of this decline, over the long-run the FCV populations never actually reach zero, but instead balance at a very small number of operational vehicles (about 50 FCVs). There are potential concerns associated with these results. That is, these 50 or so FCVs are operating in a system which does not have an active refueling station – which would lead one to question where these vehicles refuel and why, if there are no stations, there are still additional FCV purchases.

Considering the above concerns, it is acknowledged that results obtained from H_2VISION simulations may begin to "break down" when on the fringes of possible results and the zero station limit. To address this issue, the following factors should be considered:

1. Balancing at around only 50 vehicles, this population represents approximately one tenth of one percent of total vehicle population – an extremely small number of vehicles. H_2VISION is not intended to measure results to such precision and for all practical purposes, this value can be considered a non-existent FCV population.
2. On the other hand, there remains the possibility that a very small population of people *will* be enticed to purchase a FCV simply for the purpose of being

an innovative adopter and “bragging rights” associated with owning state-of-the-art technological innovations. It is not outlandish to assume that a constant 0.1% of the population will risk personal financial loss and venture to purchase a FCV although there is no reasonable method by which to refuel the vehicle.

3. In reality, the reason why H_2VISION yields a very small population of FCVs over the long-run even when there are no monetary incentives and no stations in existence is due to the incorporation of the equations from the AFVC Model. As explained previously, using consumer preference-oriented equations derived from the AFVC Model will yield that a small number of consumers are attracted to purchase FCVs even if they are considerably more expensive, the fuel is more costly, and there are no refueling stations in existence. The only way to stop this small number of innovative adopters is to associate a massive price premium with FCVs on the order of tens of thousands of dollars. Such a price premium would prove detrimental to conducting scenario analysis and gaining normal results and thus was not incorporated in the model.
4. Finally, in considering options to overcome these validity concerns, it was considered that the model be altered to *always* yield zero FCV purchases when there are zero hydrogen refueling stations in existence. This option was abandoned for two reasons: (1) due to recognized complications that would arise from implementing such a revision to the core structure of the model; and (2) due to the fact that – as explained multiple times – it is not unrealistic to assume that a small number of consumers will purchase FCVs

even when there are no stations, and these potential, although insignificant, adopters should not be outright eliminated from the model.

An additional concern arises when the population of FF stations reaches a value of zero. For example, consider the results of *Scenario 1* in which the number of FF stations rapidly falls from 198 to 91, 6, and then 0 during time 38, 39, 40, and 41 respectively. From time 41 until the end of the simulation (time 49), there are zero FF stations in operation. However, the results show the number of CVs on the road to be about 300,000 at time 41 and then decreasing steadily to about 150,000 at time 49 (the value would continue to decline if the simulation runtime was longer).

Again, this situation would lead one to wonder where these 300,000 or 150,000 CV-owners are refueling their vehicles if there are no stations in existence. In terms of H_2VISION structure, the results show a population of CV-owners when there are no stations in existence for two reasons:

1. The number of FF stations in existence is calculated by subtracting the number of H_2 stations from the total station carrying capacity – *not* by considering the number of CVs currently on the road; and
2. CVs *do not* automatically disappear when all FF stations have been forced out of the market due to the prevalence of H_2 stations. Instead, the CVs go through the model's normal vehicle-scrapping process (a certain percentage of CVs are scrapped each year based on the age of the vehicle).

Theoretically, this concept holds true; many consumers will wait for their current CV to reach a certain age or mileage before they become a FCV adopter. Still, it is recognized that the scenario results break down when dealing with zero or a very small number of refueling stations. Again, it is noted that the model is intended to provide general trends and not results precise to the single vehicle or refueling station.

There may also be concerns dealing with the upper bounds of the model. For example, can the model simulate a population of 100 million people, or a population in which consumers own on average 5 vehicles per person, or a situation in which 20 stations are required per 1000 vehicles instead of only 1 station required? Yes, the model can simulate these scenarios; H_2VISION is designed in a manner in which it will accept any value for any variable with no upper bounds (other than those set on the User Interface Level – which can be overridden if desired). Although it no limits on upper bounds exist, a user must keep in mind realistic settings. For example, although it is possible to set a population of 100 million people in an area of 5 square miles, or a population growth rate of 80%, or a government FCV purchase of 500,000 vehicles, these are not, in any way, realistic values. Thus, it is important to avoid these unrealistic settings if a user desires realistic or valid results.

12. Potential Future Work

There are multiple areas of study which are not developed in this project or within the H_2VISION modeling tool. These areas should not be considered “shortfalls” of the project, but instead should be viewed as areas of potential future work. First, as mentioned in the *Scenario Analysis* section of this paper, H_2VISION is not meant to serve as a predictive tool. That is, through scenario analysis, H_2VISION sheds light on possible future outcomes of hydrogen market growth to fortify the base of existing knowledge pertaining to hydrogen market growth. The six scenarios that were analyzed are not meant to represent the *only* possible real-world scenarios. It can almost be guaranteed that real-world hydrogen markets will not develop *exactly* as they do in any of the scenarios developed here. However, this fact does not, in any way, reduce the value of having developed a modeling tool by which users can enter specific dynamics and view potential future outcomes.

H_2VISION does not allow users to enter technical specifications of vehicles such as vehicle acceleration, top speed, multifuel capability, maintenance cost, luggage space, fuel economy, etc. It is recognized that vehicle specifications have a great influence on consumer choice and thus will be incorporated in future versions of the model. Furthermore, H_2VISION does not allow for a modeling of hydrogen market share versus other alternative fuels such as hybrid-electric, diesel, or natural gas vehicles. Some of these vehicle types – hybrid-electric particularly – have already captured a notable portion of vehicle market share and thus such competing technologies will also be include in future versions of the model.

Moreover, H_2VISION does not directly allow users to enter information regarding refueling technology advancements such as the development of efficient home-refueling systems, or the preference of distributed versus centralized refueling station technologies. H_2VISION *does* allow users to enter vehicle and fuel price fluctuations over time. Thus, a user may indirectly account for a decrease in overall vehicle or refueling price (due to technological advancements). Future versions of the model will include a direct method by which to account for technology advancements and/or compare technological alternatives.

Lastly, H_2VISION has not been applied to specific case studies or locations. A particularly applicable potential use of the model may be to integrate H_2VISION with projects outlined in the recently constructed New York Sate Hydrogen Energy Roadmap. The roadmap provides a path for hydrogen-related issues in the state of New York such as ensuring the market readiness of FCVs, determining the primary resources available and best suited to the production and delivery of hydrogen, and developing policies and incentives that will accelerate hydrogen development and use (Love, Badin et al. 2005). The current and future versions of H_2VISION would surely prove to be a valuable counterpart of work conducted under the Roadmap.

Again, the above points are not meant to be viewed as shortcomings of this project, but instead, gateways to future work. The set goal of this project *was* accomplished; a simulator tool was developed by which users can model the system dynamics fueling the emergence of hydrogen markets – capturing the concepts of complimentary goods (vehicles and infrastructure), convenience costs associated with limited refueling availability, and subsequent long-run market share of conventional and hydrogen vehicles.

13. Final Thoughts

The US Department of Energy's *National Vision of America's Transition to a Hydrogen Economy* (2002) identifies four key elements driving the development of the hydrogen future: (1) national security and the need to reduce oil imports, (2) global climate change and the need to reduce greenhouse gas emissions and pollution, (3) global population and economic growth and the need for new clean energy supplied at affordable prices; and (4) air quality and the need to reduce emissions from transportation vehicles. These needs, some of which are becoming more pressing with every passing day, have lead experts to claim that the time for the hydrogen economy is *not* the mid-21st century – rather, it is *today*, at the dawn of the 21st century that the development of the hydrogen economy is fully possible.

Through the use of systems modeling and scenario analysis, this project has analyzed the factors inhibiting the development of hydrogen markets and fundamentals of the chicken and egg phenomena. Although the scenario analysis is a vitally important aspect of this project, it should be remembered that the utmost goal of this project was to build a modeling tool by which to simulate the dynamics of hydrogen markets. This goal was successfully achieved.

Past analysis has been conducted regarding the choice of hydrogen technologies (Winebrake and Creswick 2003; Ogden, Mintz et al. 2004; EERE 2006), fuel pathway costs and benefits (Mintz 2002; Mintz, Molburg et al. 2003; NREL 2006; Yang 2006), and consumer preferences regarding alternative fuel and vehicle choice (Greene 1994). The goal of the H_2VISION project was to tackle a new area: systems analysis via simulation model usable to determine (1) the role of various government policies aimed at hydrogen market development (bulk vehicle procurement, monetary incentives, and mass-building of refueling stations); (2) the role of government as a first-use and innovative adopter of hydrogen technologies; (3) consumer preferences regarding fuel cell vehicles and convenience costs associated with refueling infrastructure; and (4) the fundamental dynamics of the chicken and egg phenomenon and long-term mainstream hydrogen technology diffusion. These goals were also successfully achieved.

The Department of Energy describes a hydrogen future as one where the nation will have a combination of central stations and distributed hydrogen networks; where every citizen in every region, state, and locality will have access to hydrogen for their vehicles; where pipelines are routed directly to high-demand areas; where hydrogen has overcome fossil fuel use; and where American consumers enjoy the economic benefits of a financially sound hydrogen energy sector and the environmental benefits of clean energy systems (DOE 2002). In the DOE's hydrogen future, hydrogen is produced domestically, cleanly, and cost-effectively, from renewable technologies such as biomass and water and fuel cell vehicles are as common as gasoline vehicles were in the late 20th century (DOE 2006).

None can argue that making DOE's hydrogen utopia a reality will not require significant resources, analysis, planning, and aggressive government and industrial policy. Indeed, as the H_2VISION scenario analyses have shown, if mainstream market penetration of hydrogen technologies is to occur within the next half-century, governments on all levels must support the hydrogen industry through direct procurement of vehicles, monetary incentives to facilitate consumer purchases, and the direct construction or funding of refueling infrastructure.

Many believe that "the future for hydrogen is now and not in 20 to 30 years" (Clark and Rifkin 2005). H_2VISION, along with previously developed models and analysis, allow policy and decision makers, business leaders, investors, and citizens to make educated decisions. Systems analysis allows for the optimal formulation of policies and decisions based on best available data and foreseeable futures. The need for a major shift in industrialized nations' energy systems is clear and present. There exists the great potential for the hydrogen economy to serve as the manifestation of the needed shift. With the help of analytic tools it may be possible to formulate and implement effective, efficient, and necessary policies to begin the constructive development of the hydrogen economy today.

A1. Appendix A: Causal Loop Diagram Structural Details

This section provides a comprehensive description of the H_2VISION Causal Loop Diagram, explaining in depth each of the reinforcing and balancing loops. Specifically, this section: (1) explains how the value of one variable in a loop can affect the value of other variables in the loop; (2) explains the nature, flow, and polarity of each loop; and (3) explains how external components can influence the flow or polarity of each loop.

A1.1. Reinforcing Loops

A1.1.a. R1: Core FCV and H2 Station Causal Loop

R1 serves as the primary causal loop which determines the number of FCVs and H2 stations operating. To determine these values, the loop incorporates two vital components: FCV market share and FCV purchasing. In this section we will describe *R1* by moving around the loop in a counterclockwise direction, beginning with *Total FCVs Operating.*

Total FCVs Operating is a function of *FCV Scrapping* (see *R3*) and *FCV Purchasing* (described later in this section)*.* In its most simple definition, *Total FCVs Operating* will increase when *FCV Purchasing* increases; *Total FCVs Operating* will decrease when *FCV Scrapping* increases. The value of *Total FCVs Operating* influences *Total Vehicles Operating*; *Total Vehicles Operating* is the sum of *Total FCVs Operating* and *Total CVs Operating* (see *R2*).

Furthermore, the value of *Total FCVs Operating* influences *FCV Purchasing* (see *R3*). Considering that there is maximum number of vehicles which will be purchased in the simulation area, the value of *Total FCVs Operating* limits the value of *FCV Purchasing*. Most importantly, however, is that *Total FCVs Operating* has a direct influence on *H2 Station Potential*, the next component of *R1*.

H2 Station Potential is determined by *Total FCVs Operating* and *Stations per 1000 Vehicles.* For example, if there were 5000 FCVs operating, and each 1000 vehicles required 1 refueling station, then *H2 Station Potential* would equal 5 stations. It is important to realize that this is a *potential*. *H2 Station Potential* influences *H2 Station Build Rate*, which is the *actual* rate at which stations are built or decommissioned. As *H2 Station Potential* increases, so too does *H2 Station Build Rate*; but *H2 Station Build Rate* is limited by *Station Carrying Capacity* (which is derived from *Total Vehicle Potential* and *Stations per 1000 Vehicles*). *H2 Station Build Rate* is also limited by *H2 Stations Operating* (see *B1*).

As *H2 Station Build Rate* increases, so too does *H2 Stations Operating*, and subsequently, *H2 Station Density.* However, consider that *H2 Station Density* will only increase if *Area* is held constant. Altering the value of *Area* will have significant effects on *H2 Station Density*; density will increase if area is decreased; density will decrease if area is increased.

H2 Station Density is the primary variable influencing *FCV Station Density Attractiveness.* The “attractiveness value” is also influenced by economic factors (such as elasticity and price slope, which are both incorporated in the H_2VISION System Model), but for the sake of simplicity, *H2 Station Density* is identified here as the primary influence.

FCV Station Density Attractiveness is one of three “attractiveness values” influencing *FCV Market Share;* the other two are *FCV Fuel Cost Attractiveness* and *FCV Vehicle Price Attractiveness*. *FCV Fuel Cost Attractiveness* is influenced by *FCV Fuel Cost*; as fuel cost decreases, attractiveness increases. *FCV Vehicle Price Attractiveness* is influenced by *FCV Price*; as vehicle price decreases, attractiveness increases. If any of the three “attractiveness values” increases, so too will *FCV Market Share.*

FCV Market Share is the primary influence on *FCV Purchasing*. For example, if *FCV Market Share* is 75 percent, then 75 percent of new vehicle purchases will be FCVs and 25 percent will be CVs. Thus, to increase *Total FCVs Operating, FCV Market Share* must be greater than 50 percent. *FCV Purchasing* is also influenced by *Total Vehicle Potential*; if *Total Vehicles Operating* is less than *Total Vehicle Potential*, then there will be new purchases until the two variables are equal. Thus, if the FCV population is already saturated (*Total FCVs Operating* is at carrying capacity), no new FCV purchases will occur (except for those that are scrapped; and then only if *FCV Market Share* is greater than 50 percent.) At the beginning of the simulation, *FCV Purchasing* is also influenced by the one-time *Government Vehicle Procurement* value. Finally, as *FCV Purchasing* increases, *Total FCVs Operating* will increase. Thus completing the positively reinforcing feedback loop.

It is also important to acknowledge that *Total Vehicle Potential* is directly influenced by *Human Population* and *Vehicles per Person.* If either *Human Population* or *Vehicles per Person* increases, *Total Vehicle Potential* will also increase.

A1.1.b. R2: Core CV and FF Station Causal Loop

R2 is essentially a mirror of *R1*. To reducing redundancy, a step-by-step description of *R2* will not be presented here. Instead, to gain an understanding of the loop, refer to the previous section, *R1: Core FCV and H2 Station Causal Loop,* and while reading the section consider “FCVs” and “H2 Stations” interchangeable with “CVs” and “FF Stations”.

The only difference in the structure of *R1* versus *R2* is that *Government Vehicle Procurement* influences *FCV Purchasing* and not *CV Purchasing*. This is because the assumed policy mandate requires that government replace a certain percentage of their current fleet with FCVs, not CVs.

A1.1.c. R3: FCV Scrapping Causal Loop

FCV Scrapping represents the population of FCVs that are scrapped per time period and is primarily influenced by *FCV Purchasing*. When an FCV is purchased, it enters the “FCV system” and ages with the passing of each year. Each year, a certain percentage of the FCVs in the system are scrapped and then the previous owner of the FCV will purchase a new FCV (or CV, depending on market share). The percentage of FCVs scrapped each year at each stage of their life is determined by *Vehicle Scrapping Rates* (although the System Model incorporates multiple scrapping rates respective to vehicle age, the Causal Loop Diagram uses one variable, *Vehicle Scrapping Rates*, to represent all scrapping rate values).

As *FCV Purchasing* increases, so too does *FCV Scrapping* (the more FCVs purchased, the more there are to scrap). As *FCV Scrapping* increases, it takes away from the total population of FCVs and thus, *Total FCVs Operating* decreases. As *Total FCVs Operating* decreases, *FCV Purchasing* then increases again. That is, *FCV Purchasing* will increase to saturate the vehicle market (considering *FCV Market Share* and *Total Vehicle Potential*). Again, as *FCV Purchasing* increases, *FCV Scrapping* will increase – thus completing the positively reinforcing feedback loop.

A1.1.d. R4: CV Scrapping Causal Loop

R4 is essentially a mirror of *R3*. To reducing redundancy, a step-by-step description of *R4* will not be presented here. Instead, to gain an understanding of the loop, refer to the previous section, *R3: FCV Scrapping Causal Loop,* and while reading the section consider “FCV” scrapping, purchasing, and operating interchangeable with “CV” scrapping, purchasing, and operating.

A1.2. Balancing Loops

A1.2.a. B1: H2 Station Building Causal Loop

B1 is a two-component loop comprising of *H2 Station Build Rate* and *H2 Stations Operating*. In its most simple form, as *H2 Station Build Rate* increases, *H2 Stations Operating* also increases. As *H2 Stations Operating* increases, *H2 Station Build Rate* then decreases, thus creating a balancing feedback loop. The reason for the balancing behavior is due to the limited station growth and total station population by *Station Carrying Capacity.* As *H2 Stations Operating* becomes closer to *Station Carrying Capacity* (based on *Stations per 1000 Vehicles* and *Total Vehicle Potential*) *H2 Station Build Rate* will become closer to zero and thus *H2 Stations Operating* will never exceed *Station Carrying Capacity*.

If *Station Carrying Capacity* increases, then there is “room” for more stations in the simulation area and thus, creating a potential for an increase in *H2 Station Build Rate*. This is only a *potential* for increase because *H2 Station Build Rate* is also influenced by *H2 Station Potential*. That is, irregardless of *Station Carrying Capacity*, if *H2 Station Potential* is not at a sufficient level, either an unsatisfactory number of H2 stations will be built or none will be built at all – thus never having the potential to reach the carrying capacity.

A1.2.b. B2: FF Station Building Causal Loop

B2 is essentially a mirror of *B1*. To reducing redundancy, a step-by-step description of *B2* will not be presented here. Instead, to gain an understanding of the loop, refer to the previous section, *B1: H2 Station Building Causal Loop,* and while reading the section consider “H2 Stations” interchangeable with “FF Stations”.

A2. Appendix B: System Model Default Scenario Variable Settings

A2.1. Vehicle Scrapping Rates

The default values for vehicle scrapping rates are based on US DOE automobile “scrappage” and “survival” rates for 1990 model years as reported in the 2004 *Transportation Energy Data Book* (Davis and Diegel 2004). To reduce redundancy it is assumed:

1. Scrapping rates are the same for FCVs and CVs;
2. Scrapping rates are based on four-year averages (for example, the scrapping rate used in the system model for vehicles aged 4 to 7 years is represented by an average of the DOE scrapping rates for vehicles aged 4, 5, 6, and 7 years old); and,
3. Vehicles aged 20 years and older adopt a constant scrapping rate based on the average scrapping rates of vehicles aged 20 to 30 years old as reported by the DOE.

Table 25 lists the default scrapping rates by vehicle age group.

Table 25: Default Vehicle Scrapping Rates

Vehicle Age	*Scrapping Rate*
0 to 3	0.00%
4 to 7	0.95%
8 to 11	4.60%
12 to 15	7.00%
16 to 19	9.60%
20 and older	15.00%

A2.2. Government FCV Procurement

In 2002, governments of the United States owned a total of 4,790,000 cars and trucks as part of fleets of 15 vehicles or more (Davis and Diegel 2004). This represents 2.1 percent of the total 228,860,000 cars and trucks in operation in the United States (FHWA estimates; (Davis and Diegel 2004)). Due to the lack of exact statistics of fleet sizes at the city-level[11], the national fleet percentage is used to assume a default government fleet size per simulation area. Since the default area is modeled after Washington, D.C. demographics, total population of government-owned vehicles in the simulation area is estimated to be 9426 vehicles. Using a default scenario which exercises a 20 percent FCV replacement purchase policy, government agencies will

[11] In personal communications with Mike Antich, editor of Government Fleet Magazine (http://www.fleet-central.com/gf/eweekly/), he explained that there is no easily accessible database of government fleets on a city basis. The problem is twofold: (1) what vehicles do you include in the database (light vs medium-duty; machines such as grass cutting equipment or construction vehicles); and (2) automobile manufacturers regard their sales information as confidential since they consider the information a customer list.

(hypothetically) purchase 1885 new FCVs at the beginning of the simulation. This value was calculated by the following four step process:

1. Find *vehicles per person national average*:

vehicles per person	= total vehicles / total population
	= 228,860,000 vehicles / 287,984,799 people[12]
	= .795 vehicles per person

2. Find *vehicles in DC*:

vehicles in DC	= DC population * vehicles per person
	= 564,624 people[13] * .795 vehicles per person
	= 448,876 vehicles in DC

3. Find *government vehicles in DC*:

gov't vehicles in DC	= vehicles in DC * percent fleet
	= 448,876 vehicles in DC * 2.1% fleet
	= 9426 government vehicles in DC

[12] Total US population based on 2002 US Census Bureau estimates USCB (2005). National and State Population Estimates. A. Annual Estimates of the Population for the United States and States, 2000 to July 1, 2005 (NST-EST2005-01), U.S. Census Bureau.

[13] Washington, D.C. population based on 2002 US Census Bureau estimates Ibid.

As previously mentioned, the default scenario exercises a 20 percent FCV procurement policy; next find the approximate number of FCVs purchased for the default scenario:

4. Find *government FCV purchases in DC*:

gov't FCV purchases	= government vehicles * policy percent
	= 9426 gov't vehicles in DC * 20% policy
	= 1885 new FCVs

A2.3. Population Variables

A2.3.a. Initial CV Population

As demonstrated above, based on Washington, D.C. demographics, the default scenario places 448,876 total vehicles operating in the simulation area. Based on vehicle population statistics regarding all vehicles operating in 2001 in the United States (Davis and Diegel 2004), the following initial CV populations are incorporated in the model:

Table 26: Default Initial CV Population

Vehicle Age	*Percentage*	*Vehicles*
0 to 3	23.90%[a]	107,281
4 to 7	24.20%[a]	108,628
8 to 11	21.60%[a]	96,957
12 to 15	18.20%[a]	81,695
16 to 19	8.05%[b]	36,135
20 and older	4.00%[b]	17,956
total pop	*100%*	*448,876*

[a] Based on US DOE values (Davis and Diegel 2004).
[b] Estimated.

A2.3.b. Initial Population

The total population of Washington, D.C. in 2002 was 564,624 people (USCB 2005).

A2.3.c. Population Growth Rate

The default net population growth rate is 0.568%, which is calculated from the national average birth and death rates as reported by the US Department of Health and Human Services (Hamilton, Martin et al. 2005).

A2.3.d. Vehicles per Person

The average number of vehicles owned per person in Washington, D.C. is based on the national average:

vehicles per person = total US vehicles / total US population
= 228,860,000 vehicles / 287,984,799 people
= *.795 vehicles per person*

A2.4. Simulation Area

The total land area of Washington. D.C. is 61.4 square miles (Wikipedia 2006).

A2.5. Refueling Station Variables

A2.5.a. Station Carrying Capacity

The default value for total refueling station carrying capacity – or maximum number of refueling stations that can operate within the simulation area – is determined by historical data on the number of refueling stations per 1000 vehicles. As shown in

Table 27, the average number of refueling stations per 1000 vehicles from 1993 to 2002 was 0.92 stations per 1000 vehicles. The data also shows that the number of stations per 1000 vehicles has decreased every year since 1993. Because of the long-term nature of the simulation, and no reliable data on the absolute minimum number of stations that can support 1000 vehicles, the model uses a constant rate of 0.92 stations per 1000 vehicles for the length of the entire simulation.

Table 27: Refueling Stations per Thousand Vehicles

Year	***Stations per 1000 Vehicles[14]***
1993	1.11
1994	1.08
1995	1.01
1996	0.96
1997	0.93
1998	0.89
1999	0.86
2000	0.82
2001	0.79
2002	0.77
average	*0.92*

[14] Source: Transportation Energy Data Book Davis, S. C. and S. W. Diegel (2004). Transportation Energy Data Book. Oak Ridge, Tennessee, Oak Ridge National Laboratory, US Department of Energy: 153.
.

A2.5.b. Initial Fossil Fuel Stations Operating

It is assumed that at time 0 the refueling station market is operating at full capacity (full capacity is determined by historical data; see *Station Carrying Capacity*). Considering this assumption, the default value for the number of fossil fuel stations operating at time 0 is 412 stations, which is station carrying capacity (413 stations) minus initial H_2 stations (1 station). Note that *Station Carrying Capacity* is derived from *Population* and *Population Growth Rate* – altering either of these values will alter the value for *Initial Fossil Fuel Stations Operating*.

A2.5.c. Initial Hydrogen Stations Operating

H_2VISION is structured in such a way that the number of initial hydrogen stations is directly derived from the number of initial FCVs operating. Thus, in the case of the default scenario in which the government purchases 1885 FCVs, the model calculates the initial number of hydrogen stations as follows:

initial H2 stations	= new gov't FCVs / 1 / stations per 1000 veh.
	= 1885 new gov't FCVs / 1 / .92 stations / 1000
	= 1.74 initial H2 stations
	≈ 1 initial H2 station (truncated)

In this case, a second H2 station will be built when the number of FCVs reaches (2 * vehicles per station), or 2196 total FCVs on the road.

Should the user alter the default values to reflect a situation in which the government makes no initial FCV purchase, *Initial Hydrogen Stations Operating* will be 0 at time 0. At time 1 and thereafter, the number of hydrogen stations operating will be calculated based on consumer preferences for vehicle type and respective refueling infrastructure.

A2.6. Economic Variables

A2.6.a. Elasticity and Price Slope Coefficient

At its most basic definition, *elasticity* is the ratio of the incremental percentage change in one variable with respect to an incremental percentage change in another variable (Case and Fair 1999). H_2VISION uses the concept of *own-price elasticity* which is a metric that determines what happens to consumer demand for FCVs when there is a change in one of the following price categories:

1. The “price” of station density;
2. The price of a FCV or CV at the dealer; and,
3. The price of fuel for a FCV or CV.

Specifically, H_2VISION incorporates the concept of own-price elasticity as used in Greene’s AFVC model (for more information on Greene’s model, see the section of this report entitled *Alternative Fuels and Vehicles Choice Model*). A particularly applicable definition of own-price elasticity is provided by Wade (2003):

> "The concept of own-price elasticity is a metric that described numerically the responsiveness of a quantity to changes in its price. It is measured simply as the percentage change in quantity divided by percentage change in price. Because price increases normally induce reduced purchases, own-price elasticities are negative quantities. A sensitive or 'elastic' response refers to percentage quantity changes larger in absolute value than the percentage price change (e.g., an elasticity of -2.0 indicates that the percentage reduction in quantity is twice the percentage increase in price)." (Wade 2003)

The H_2VISION default value for elasticity is -5, based on values in the AFVC model. It is assumed that a single value for elasticity is used to calculate demand alterations related to changes in any of the three price categories. For example, consider a scenario in which elasticity is -5.0 and the price of a FCV increases by 10 percent between time 0 and time 1. The result of this increase in FCV price would be a 50 percent reduction in the quantity of FCVs purchased during time 1 compared to the number purchased in time 0. The basic mathematically calculation is:

-5.0 elasticity
x 10 percent change in price
-50 percent change in purchases

First however, H_2VISION incorporates an additional step and uses the elasticity value, along with two additional user inputs to calculate a *price slope coefficient*[15]. Specifically, a price slope coefficient is calculated from: (1) price elasticity; (2) at a given initial market share (non-user alterable); and (3) initial vehicle price as follows:

price slope coefficient = elasticity / initial vehicle price * (1 – initial market share)

The price slope coefficient is then used to transform the dollar values of attributes into alternative-specific constants (Greene 1994), which are in turn used to calculate the attractiveness and subsequent market shares of each vehicle type and respective refueling infrastructure (for more information on attractiveness and market share variables and equations, see the section of this report entitled *System Sub-Model B: Vehicle Market Shares*).

A2.6.b. Value 1 and Value 2 (Cost Penalty at 0% and 10% Station Density)

If there is no where for a potential FCV adopter to refuel the vehicle (i.e. no hydrogen stations operating), the consumer will view this inconvenience as an economic penalty – or a *convenience cost* (for more information on the concept of convenience costs see the section of this paper entitled *Complimentary Goods*).

[15] Price slope coefficients are used for adjustments to prices to a common specification (vehicle price, fuel price) on the basis of the price determining effects of the key characteristics of an item (fuel cell vehicles) UN (1992). Handbook of the International Comparison Programme. New York, United Nations Publications.

Value 1 and *Value 2* represent the convenience cost penalty to a consumer at a limited station density of 0 percent and 10 percent, respectively. Specifically, *Value 1* represents a -$30,000 value associated with the inconvenience of having no where to refuel a FCV. Similarly, *Value 2* represents a -$3,000 value associated with the inconvenience of having only 1 in 10 stations offering hydrogen.

The Value 1-Value 2 concept serves as a fundamental component of Greene's AFVC model and has been incorporated into H_2VISION. However, the monetary values used in H_2VISION have been altered significantly from the values used in Greene's model. Compared to the AFVC model defaults, the default scenario values in H_2VISION demonstrate a significantly greater penalty for having a limited availability of fueling stations (Greene 1994; Greene, Leiby et al. 2004).

Ultimately, *Value 1* and *Value 2* are used to calculate the *Station Density Cost Attractiveness Curve* shown in Figure 11. As shown in the graph, there is a relatively large monetary penalty associated with station densities less than 10 percent, but the penalties subside quickly as station density increases. At the default scenario settings, the monetary penalty reaches $0 at 48% station density.

Altering *Value 1* or *Value 2* will have dramatic effects on the slope of the curve. For example, consider a scenario reflecting AFVC Model default values where 0 percent hydrogen stations would be perceived as only a negative $3,000 penalty and 10 percent hydrogen stations would be perceived as only a negative $1,000 penalty (Greene 1994; Greene, Leiby et al. 2004). This scenario is presented in Figure 12. As shown, there is a significantly *less* monetary penalty associated with limited station densities compared to Figure 11.

The decision to design the default scenario with a greater negative value associated with limited station densities is based on accumulated research and personal communication (Winebrake 2006).

Figure 11: Station Density Consumer Utility Curve A (H_2VISION Defaults)

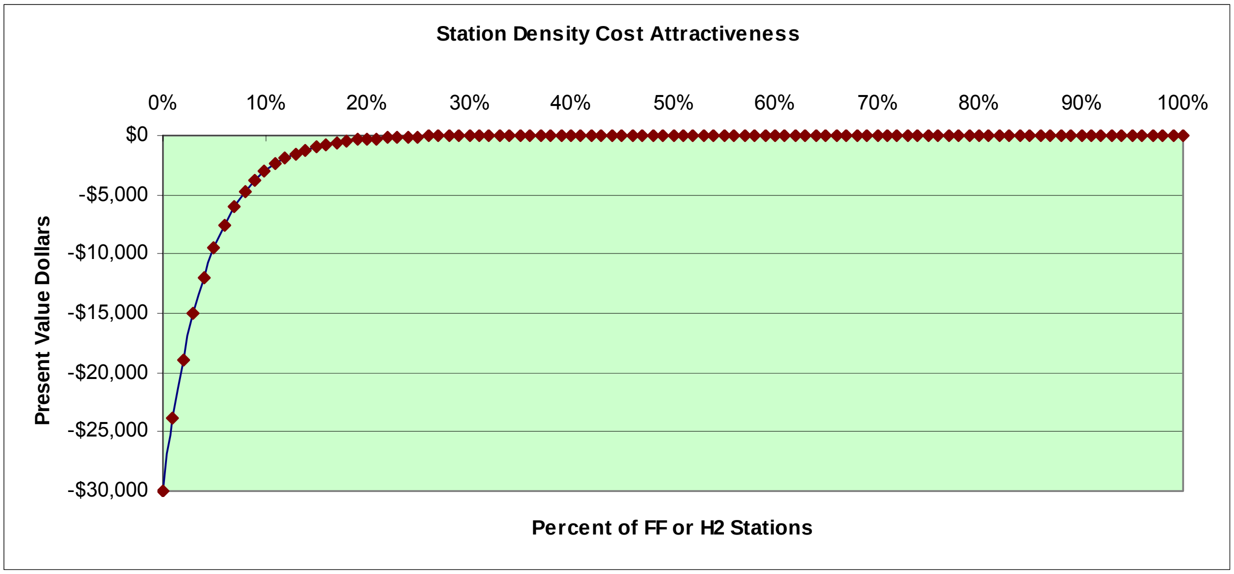
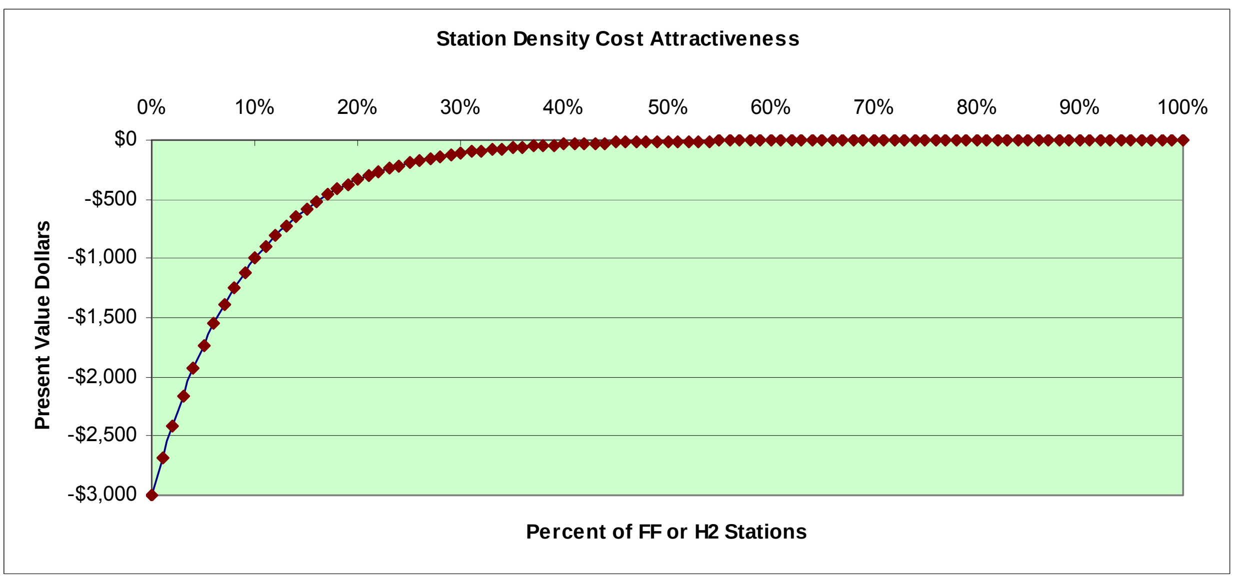


Figure 12: Station Density Consumer Utility Curve B (AFVC Model Defaults)



A2.6.c. Vehicle Price and Fuel Price

As discussed previously, the default scenario values are presented in a manner that allows a first-time run to view the model “in action.” To accomplish this, FCV price is set to $17,000 and CV price is set to $20,000. In this sense, the default scenario represents an ideal (if slightly unrealistic) situation in which FCVs are government supported with aggressive tax breaks or other monetary credits.

Similarly, the default scenario value for FCV fuel price is 3 cents per mile; 4.5 cents less than the CV fuel price default which is 7.5 cents per mile. As with *Vehicle Price*, the default scenario value for *Fuel Price* represents an ideal situation in which hydrogen fuel is government supported with an aggressive subsidy or other monetary credit.

The values for FCV and CV price, and FCV and CV fuel price are user alterable on the User Interface Level. In the *Scenarios* section of this report, these values (along with others) are altered to explore the fundamental concepts of the chicken and egg phenomenon.

A3. Appendix C: System Model Structural Details

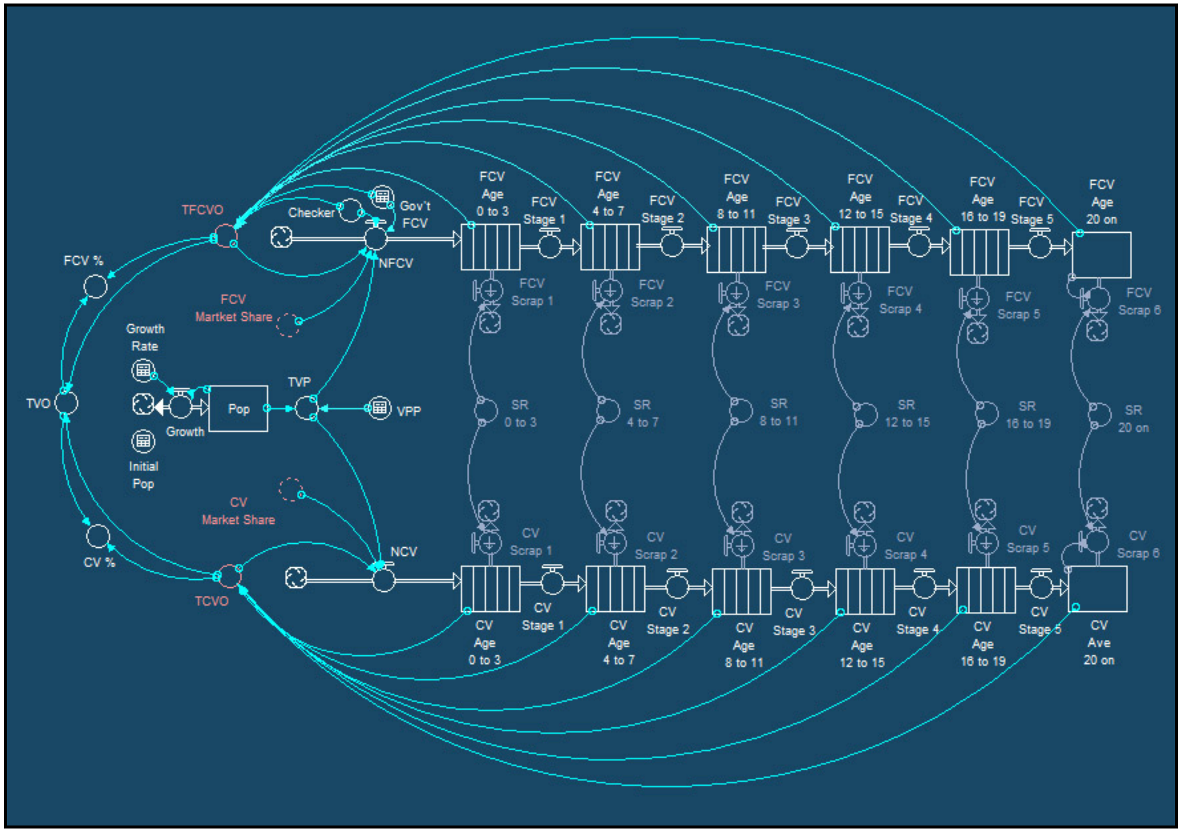
The following section discusses the three sections of the H_2VISION system model. Table 28, Table 29, and Table 30 list each of the variables in H_2VISION along with their full name, description, units, equation, and whether or not the variable is user alterable on the user interface level.

A3.1. Core H2VISION Model

The first section of H_2VISION can be considered the core or primary section of the model. The core model is a *stock-and-flow design* and captures the FCV and CV vehicle populations, vehicle aging and scrapping, human population within the simulation area, and outputs essential data regarding total vehicles operating and the portion of those vehicles that are FCVs or CVs. This modeling structure, also referred to as a *cohort model*, 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).

Figure 13 presents the *Core H_2VISION Model* as it appears in the STELLA® system modeling software. Table 28 lists details of each variable in the *Core H_2VISION Model* along with a description and vital information regarding units and equation of the variable.

Figure 13: Core H_2VISION Model



Screenshot from H_2VISION; STELLA® Research Software (Wallis, Chichakly et al. 2002)

Table 28: Core H_2VISION Model

Variable(s) in Diagram[16] *(alphabetical)*	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
Checker	Governmnet Procuremetn Time 0 Checker	This variable is a "checker" to ensure that government procurement only occurs at time 0. At time 0 the checker value is 1; at any other time the checker value is 0. The checker is multiplied by *Gov't FCV* when *Gov't FCV* is used to calculate other variables.	none	Checker = IF(TIME=0) THEN 1 ELSE 0	No
CV %	CVs as Percentage of TVO	This variable represents the percentage of the total vehicles operating that are conventional vehicles. This variable is used solely for display on in the *Simulation Results* section.	percent *(CVs)*	CV_% = TCVO/TVO*100	No

[16] "Ghosted" variables not listed.

Variable(s) in Diagram *(alphabetical)*	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
CV Age 0 to 3; CV Age 4 to 7; CV Age 8 to 11; CV Age 12 to 15; CV Age 16 to 19; CV Age 20 on	CV Scrapping Conveyor	This multi-stage conveyor holds all CVs currently operating. Each stage of the conveyor holds a population of CVs for four years and applies the appropriate scrapping rate per age. At the end of the four years, the remaining non-scrapped CVs are passed to the next stage of the conveyor. The final stage, *CV Age 20 on* holds all remaining CVs and applies a constant scrapping rate until all age 20+ CVs have been scrapped. *CV Stage 1, CV Stage 2, CV Stage 3, CV Stage 4*, and *CV Stage 5* are considered components of the *CV Scrapping Conveyor.*	units *(CVs)*	INITIAL(CV_Age_0_to_3) = 107280 INITIAL(CV_Age_4_to_7) = 108628 INITIAL(CV_Age_8_to_11) = 96957 INITIAL(CV_Age_12_to_15) = 81695 INITIAL(CV_Age_16_to_19) = 36135 INITIAL(CV_Age_20_on) = 17956 Transit Time = 4	No
CV Scrap 1; CV Scrap 2; CV Scrap 3; CV Scrap 4; CV Scrap 5; CV Scrap 6.	CV Scrapping Leakages	The *CV Scrap* leakage variables represent the number of CVs scrapped from each respective age group per year. The actual number of vehicles scrapped is determined by multiplying the respective scrapping rate by the CVs in each age group.	units *(CVs)*	Leakage Fraction = SR_0_to_3; Leakage Fraction = SR_4_to_7; Leakage Fraction = SR_8_to_11; Leakage Fraction = SR_12_to_15; Leakage Fraction = SR_16_to_19; Leakage Fraction = SR_20_on.	No
FCV %	FCVs as Percentage of TVO	This variable represents the percentage of the total vehicles operating that are fuel cell vehicles. This variable is used solely for display on in the *Simulation Results* section.	percent *(FCVs)*	FCV_% = TFCVO/TVO*100	No

Variable(s) in Diagram *(alphabetical)*	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
FCV Age 0 to 3; FCV Age 4 to 7; FCV Age 8 to 11; FCV Age 12 to 15; FCV Age 16 to 19; FCV Age 20 on	FCV Scrapping Conveyor	This multi-stage conveyor holds all FCVs currently operating. Each stage of the conveyor holds a population of FCVs for four years and applies the appropriate scrapping rate per age. At the end of the four years, the remaining non-scrapped FCVs are passed to the next stage of the conveyor. The final stage, *FCV Age 20 on* holds all remaining FCVs and applies a constant scrapping rate until all age 20+ FCVs have been scrapped. *FCV Stage 1, FCV Stage 2, FCV Stage 3, FCV Stage 4*, and *FCV Stage 5* are considered components of the *FCV Scrapping Conveyor.*	units *(FCVs)*	INITIAL = 0 Transit Time = 4	No
FCV Scrap 1; FCV Scrap 2; FCV Scrap 3; FCV Scrap 4; FCV Scrap 5; FCV Scrap 6.	FCV Scrapping Leakages	The *FCV Scrap* leakage variables represent the number of FCVs scrapped from each respective age group per year. The actual number of vehicles scrapped is determined by multiplying the respective scrapping rate by the FCVs in each age group.	units *(FCVs)*	Leakage Fraction = SR_0_to_3; Leakage Fraction = SR_4_to_7; Leakage Fraction = SR_8_to_11; Leakage Fraction = SR_12_to_15; Leakage Fraction = SR_16_to_19; Leakage Fraction = SR_20_on.	No
Gov't FCV	Initial Government Procurement of FCVs	This variable represents the number of fuel cell vehicles that the government purchases to add to their fleet at the beginning of the simulation. It is assumed that this is a one-time purchase; thus procurement will be considered only at time 0.	units *(FCVs)*	Gov't_FCV = 1885	Yes

Variable(s) in Diagram *(alphabetical)*	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
Growth	Human Population Growth	This bi-flow flow variable represents the new births or deaths in the human population. Because this is a bi-flow, it may be positive or negative, ultimately increasing *or* decreasing *Pop*. The actual rate is determined by the user-entered *Growth Rate*.	people/time	Growth = Pop*Growth_Rate	No
Growth Rate	Human Population Growth Rate	This variable represents the rate of growth of the human population in the simulation area. This value can be positive or negative to represent a growing or declining population base.	percent *(people/time)*	Growth_Rate = 0.00568	Yes
Initial Pop	Initial Human Population	This variable represents the initial population of humans (not vehicles) in the simulation area. This should be considered the population at time 0, or the base population. It will be used in the population stock and flow and the population over time will either increase or decrease depending on *Growth Rate*.	people	Initial_Pop = 564624	Yes
NCV	New Conventional Vehicle Purchases	This variable represents the rate at which CVs are purchased (purchases over time). This is a function of *CV Market Share*, *TVP*, and *TCVO*. The CVs purchased here will convey through the scrapping phases and sum in the *TCVO.*	units/time *(CVs/time)*	NFCV = (CV_Market_Share*TVP)-TCVO	No

Variable(s) in Diagram *(alphabetical)*	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
NFCV	New Fuel Cell Vehicle Purchases	This variable represents the rate at which FCVs are purchased (purchases over time). This is a function of *FCV Market Share*, *TVP*, and *TFCVO*. The government procurement of FCVs will be factored into the purchasing rate only at time 0. The FCVs purchased here will convey through the scrapping phases and sum in the *TFCVO.*	units/time *(FCVs/time)*	NFCV = ((FCV_Martket_Share*TVP)-(TFCVO-(Gov't_FCV*Checker))+(Gov't_FCV*Checker))	No
Pop	Human Population	This stock represents the human population in the simulation area. The stock is fed by a bi-flow flow variable and thus may increase or decrease based on the population *Growth Rate*.	people	INITIAL(Pop) = Initial_Pop	No
SR 0 to 3; SR 4 to 7; SR 8 to 11; SR 12 to 15; SR 16 to 19; SR 20 on	Vehicle Scrapping Rates	The *SR* (scrapping rate) variables represent the rate of vehicle scrapping for each respective age group. The *SR*s are found by taking the mean of the industry scrapping rates for the four ages held in each population. The *SR* is multiplied by the respective vehicle population and those scrapped are deducted from the population in the *Scrap* leakage variables.	percent *(Vehicles over time)*	SR_0_to_3 = MEAN(0.0,0.0,0.0,0.0) SR_4_to_7 = MEAN(0.0,0.0,0.006,0.032) SR_8_to_11 = MEAN(0.037,0.043,0.049,0.055) SR_12_to_15 = MEAN(0.061,0.067,0.073,0.079) SR_16_to_19 = MEAN(0.086,0.093,0.099,0.106) SR_20_on = MEAN(0.113,0.120,0.127,0.135,0.142,0.150,0.157,0.165,0.172,0.180,0.188)	No

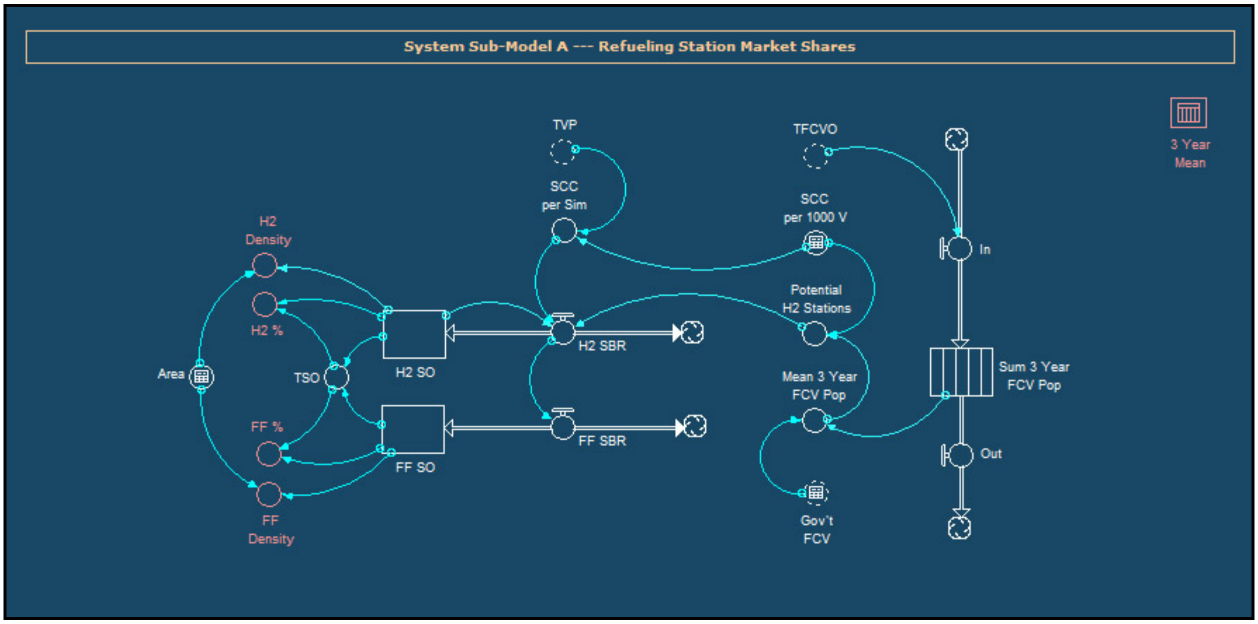
Variable(s) in Diagram *(alphabetical)*	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
TCVO	Total Conventional Vehicles Operating	This variable represents the total number of CVs currently owned and being used by civilians. This is found by summing the number of CVs operating in the *CV Scrapping Conveyor*. This variable is subsequently used to 1) determine *TVO* by adding it to *TFCVO*, and 2) determine *NCV* by subtracting from it the *CV Market Share* times *TVP*.	units *(CVs)*	TCVO = SUM(CV_Age_0_to_3,CV_Age_4_to_7,CV_Age_8_to_11, CV_Age_12_to_15,CV_Age_16_to_19,CV_Ave_20_on)	No
TFCVO	Total Fuel Cell Vehicles Operating	This variable represents the total number of FCVs currently owned and being used by civilians and the government. This is found by summing the number of FCVs operating in the *FCV Scrapping Conveyor* (and at time 0, adding *Gov't FCV)*. This variable is subsequently used to 1) determine *TVO* by adding it to *TCVO*, and 2) determine *NFCV* by subtracting from it the *FCV Market Share* times *TVP*.	units *(FCVs)*	TFCVO = FCV_Age_0_to_3+FCV_Age_4_to_7+FCV_Age_8_to_11+ FCV_Age_12_to_15+FCV_Age_16_to_19+FCV_Age_20_on+ (Gov't_FCV*Checker)	No
TVO	Total Vehicles Operating	This variable represents the total number of vehicles operating. This includes both FCVs and CVs and is found by simply summing *TFCVO* and *TCVO*.	units *(vehicles)*	TVO = TCVO+TFCVO	No

Variable(s) in Diagram *(alphabetical)*	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
TVP	Total Vehicle Potential	This variable represents the maximum number of vehicles that may operate at any given time. This is calculated by multiplying the human population by the average number of vehicles per person. *TVP* is a vital component of H2VISION; it is multiplied by the respective vehicle market shares to determine allocation of new vehicle purchases.	units *(vehicles)*	TVP = Pop*VPP	No
VPP	Vehicles per Person	This variable represents the average number of vehicles owned per person in the simulation area. The default value is based on the national average.	units *(vehicles)*	VPP = .795	Yes

A3.2. System Sub-Model A: Refueling Station Market Shares

The second section of H_2VISION can be considered a “Sub-Model” of the *Core Model*. *System Sub-Model A* captures the H2 and 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 H2s or FFs. Figure 14 presents *System Sub-Model A* as it appears in the STELLA® system modeling software. Table 29 lists details on each variable in *System Sub-Model A* along with a description and vital information on units and equation of the variable.

Figure 14: Refueling Station Market Shares Sub-Model



Screenshot from H_2VISION; STELLA® Research Software (Wallis, Chichakly et al. 2002)

Table 29: Refueling Station Market Shares Sub-Model

Variable in Diagram[17] *(alphabetical)*	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
Area	Simulation Area in Square Miles	This user-alterable variable represents the size of the simulation area measured in square miles.	miles^2	Area = 61.4	Yes
FF %	Fossil Fuel Stations as Percentage of Total Stations	This variable the percent of total stations operating that are fossil fuel stations.	percent *(stations)*	FF_% = FF_SO/TSO*100	No
FF Density	Density of FF Refueling Stations in the Simulation Area	This variable represents the density of FF stations operating at time *t* measured in stations per square mile.	units/area *(FF stations / square mile)*	FF_Density = FF_SO/Area	No
FF SBR	Fossil Fuel Station Build Rate	This value of this biflow variable is found by taking the inverse of *H2 SBR*. In other words, if a H2 station is built, a FF station is closed – and vice versa. See *H2 SBR* for more information.	units/time *(FF station / time)*	FF_SBR = -H2_SBR	

[17] "Ghosted" variables not listed.

Variable in Diagram *(alphabetical)*	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
FF SO	Fossil Fuel Stations Operating	This stock represents the total number of FF refueling stations in operation at time *t*. The flow variable *FF SBR* which feeds this stock is a biflow variable. This means that FF *SO* will increase *or* decrease depending on the number of CVs on the road. If the FCV tipping point is reached, consumers will convert to FCV consumers and thus demand for FF stations will decrease. In this case, stations go out of business or are otherwise abandoned and the *FF SO* stock decreases. The initial value for *FF SO* is equal to *SCC per Sim*. That is, we assume that the station market is operating at full and optimal capacity at time 0 (full and optimal capacity is determined by historic station density data.)	units *(FF stations)*	INITIAL(FF_SO) = INT(SCC_per_Sim)	
H2 %	Hydrogen Stations as Percentage of Total Stations	This variable the percent of total stations operating that are hydrogen stations.	percent *(stations)*	H2_% = H2_SO/TSO*100	No
H2 Density	Density of H2 Refueling Stations in the Simulation Area	This variable represents the density of H2 stations operating at time *t* measured in stations per square mile.	units/area *(H2 stations / square mile)*	H2_Density = H2_SO/Area	No

Variable in Diagram *(alphabetical)*	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
H2 SBR	Hydrogen Station Build Rate	This biflow variable represents the number of new H2 refueling stations built at time *t* based on the average number of FCVs on the road during time *t* – 1, *t* – 2, and *t* – 3, the potential H2 stations, the number of H2 stations already in operation, and whether or not the station carrying capacity has been reached. This variable makes use of IF THEN statements to account for the station carrying capacity. If the carrying capacity has been reached, no more stations will be built regardless of consumer demand for more stations. This carrying capacity is based on (1) total vehicle potential; and (2) historical data on station requirements for vehicle populations. This variable is also truncated so stations are built in increments of 1 (no partial stations are built.) The variable is biflow to account for a reduction in consumer demand for FCV stations. If the FCV tipping point is not reached and consumers return to CVs, then H2 refueling stations will go out of business, making *H2 SBR* negative.	units/time *(H2 station / time)*	H2_SBR = INT(IF(H2_SO>=SCC_per_Sim) THEN 0 ELSE(Potential_H2_Stations-H2_SO))	No

Variable in Diagram *(alphabetical)*	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
H2 SO	Hydrogen Stations Operating	This stock represents the total number of H2 refueling stations in operation at time *t*. The flow variable *H2 SBR* which feeds this stock is a bi-flow variable. This means that *H2 SO* will increase *or* decrease depending on the number of FCVs on the road. If the FCV tipping point is not reached, consumers will return to CVs and thus demand for H2 stations will decrease. In this case, stations go out of business or are otherwise abandoned and the *H2 SO* stock decreases. The initial value for *H2 SO* is based on *Gov't FCV* and stations required per 1000 vehicles. For example, if the government procures 1500 FCVs at time 0 and *SCC per 1000 V* = .92, the initial value of *H2 SO* will be 1 because 1 station is required to support 1500 FCVs. The initial value of *H2 SO* would be 2 if the government procured enough FCVs to require 2 stations, and so on. The initial *H2 SO* must be thought of as part of the government FCV procurement policy. That is, if the government enacts policy to procure 1500 FCVs, then they must include in that policy a mandate to built 1 station to support those FCVs.	units *(H2 stations)*	INITIAL(H2_SO) = INT((Gov't_FCV/(1/(SCC_per_1000_V/1000))))	No

Variable in Diagram *(alphabetical)*	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
In	Inflow of FCVs to Find Three-Year Average Number	This flow represents an inflow of *TFCVO* to the conveyor *Sum 3 Year FCV Pop.* The FCVs will be held in the conveyor for three years to find the *Mean 3 Year FCV Pop.*	units *(FCVs)*	In = TFCVO	No
Mean 3 Year FCV Pop	Three-year Rolling Average of the Number of FCVs on Road	This variable calculates a three-year rolling average of the number of FCVs on the road during time *t* – 1, *t* – 2, and *t* – 3 by taking *Sum 3 Year FCV Pop* and finding the average. This variable makes use of IF THEN statements to account for the fact that at time 0 there is only 1 year during which there were FCVs on the road; at time 1 there is only 2 years during which there were FCVs on the road; and at time > 2 there were three or more years during which there were FCVs on the road.	units *(FCVs)*	Mean_3_Year_FCV_Pop = IF(TIME=0) THEN(Gov't_FCV) ELSE(IF(TIME=1) THEN(Sum_3_Year_FCV_Pop/1) ELSE(IF(TIME=2) THEN(Sum_3_Year_FCV_Pop/2) ELSE(Sum_3_Year_FCV_Pop/3)))	No
Out	Outflow of FCVs to Find Three-Year Average Number	This flow represents a leakage (outflow) from the *Sum 3 Year FCV Pop* conveyor. The FCVs were held in the conveyor for three years and then released. The purpose is to find the *Mean 3 Year FCV Pop.*	units *(FCVs)*	Out = Transit Time = 3	No

Variable in Diagram *(alphabetical)*	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
Potential H2 Stations	Maximum Number of H2 Stations that can be Built Based on FCV Population	This variable represents the maximum number of new H2 refueling stations that can be built at time *t* based on the average number of FCVs on the road during time *t* – 1, *t* – 2, and *t* – 3. The maximum number of new stations is calculated by dividing the three-year rolling average of FCVs on the road by the number of FCVs that each new refueling station would be able to sustain.	units *(H2 stations)*	Potential_H2_Stations = Mean_3_Year_FCV_Pop/(1/(SCC_per_1000_V/1000))	No
SCC per 1000 V	Station Carrying Capacity per 1000 Vehicles	This variable represents the number of refueling stations required to support 1000 vehicles. This value is user-alterable; the default value is based on historic data.	units *(stations)*	SCC_per_1000_V = .92	Yes
SCC per Sim	Station Carrying Capacity per Simulation Area	This variable represents the total carrying capacity of all stations in the total simulation area. This includes both H2 and FF refueling stations and can be thought of as the maximum number of stations that can be sustained in the entire simulation area. This value is calculated by taking the product of the carrying capacity per vehicle and the total vehicle potential.	units *(stations)*	SCC_per_Sim = (SCC_per_1000_V/1000)*TVP	No

Variable in Diagram *(alphabetical)*	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
Sum 3 Year FCV Pop	Sum of all FCVs on the Road During the Previous Three Years	This conveyor represents the sum of all the FCVs on the road during time *t* – 1, *t* – 2, and *t* – 3. The conveyor is supplied by flow *In* and drained by leakage *Out*. *In* is the total FCVs on the road for each year. Those FCVs are held in the conveyor for 3 years, then leaked out. The resulting sum is then divided by 3 to find the *Average Number of FCVs on Road During Previous Three Years*. The purpose of a three-year rolling average is to demonstrate delays in station building. First, there is a one-year delay in considering FCVs on the road (i.e. the conveyor sums FCVs during the *previous three years*, not including the current year.) Second, *Maximum New H2 Stations Based on FCVs on Road* is calculated using the three-year average to not only demonstrate a delay in building, but also to "smooth" the creation of new stations. Station building will not occur over night – it takes time, and station builders must be certain that the FCVs are not a "fad" – and the three-year rolling average accounts for this.	units *(FCVs)*	INITIAL(Sum_3_Year_FCV_Pop) = 0	No
TSO	Total Stations Operating	This variable represents the total number of stations operating at time *t*. This is found by summing *H2 SO* and *FF SO*.	units *(stations)*	TSO = SUM(H2_SO,FF_SO)	No

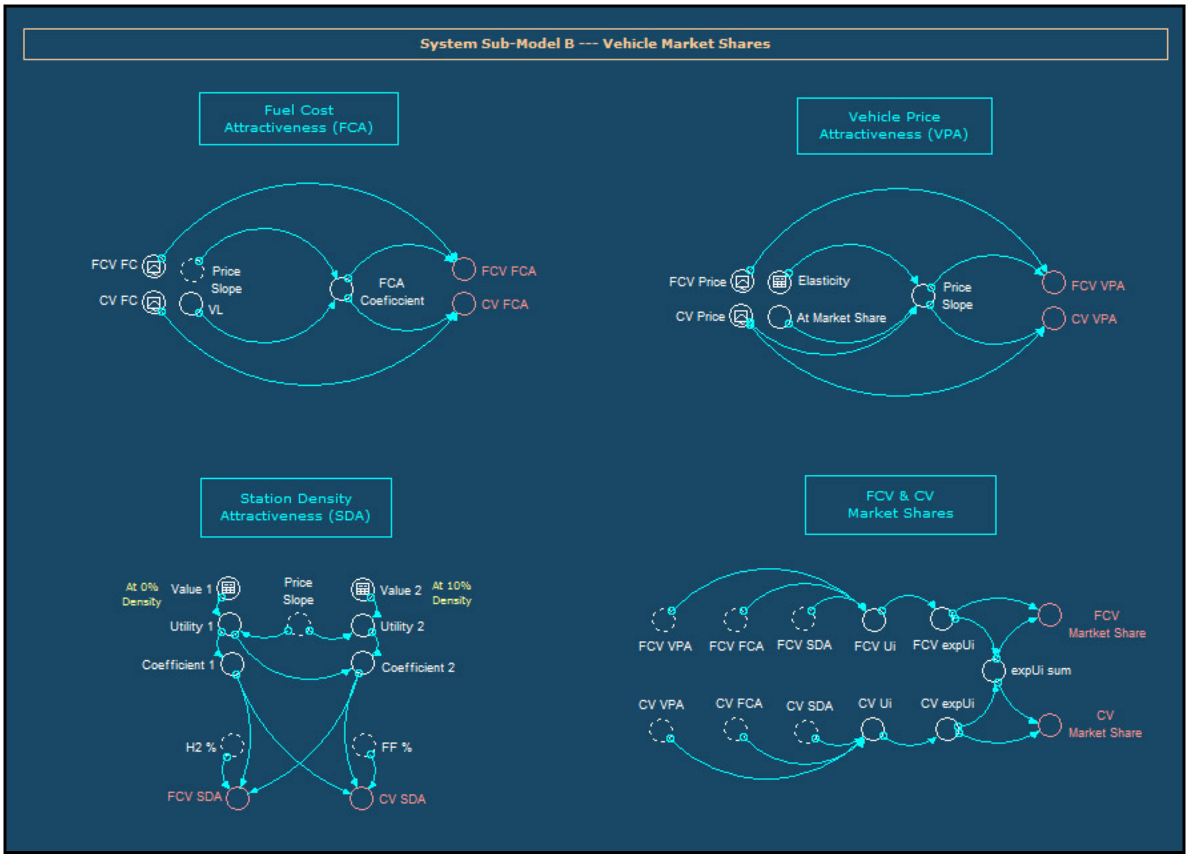
A3.3. System Sub-Model B: Vehicle Market Shares

The third section of H_2VISION can also be considered a "Sub-Model" of the *Core Model*. *System Sub-Model B* captures the market shares of FCVs and CVs. The shares are found by first calculating three "attractiveness values": Fuel Cost Attractiveness (FCA); Vehicle Price Attractiveness (VPA); and Station Density Attractiveness (SDA). The structure and equations of *System Sub-Model B* are roughly derived from the AFVC Model (Greene 1994).

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. As described previously, H_2VISION incorporates only three of these factors: vehicle price, fuel cost, and fuel availability (station density). For the purpose of H_2VISION, it is assumed that the range, top speed, acceleration, maintenance cost, luggage space, and make/model availability are equal when comparing FCVs and CVs. Furthermore, it is acknowledged that that multifuel capability and home refueling availability may, one day, be significantly important in terms of consumer preferences for FCVs compared to CVs. However, these factors have been assumed to be overall less important in comparison to price and fuel availability factors. Thus, in an aim to simplify H_2VISION analysis and isolate the fundamentals of the chicken and egg phenomenon, multifuel capability and home refueling availability have been excluded from analysis.

Figure 15 presents *System Sub-Model B* as it appears in the STELLA® system modeling software. Table 30 lists details on each variable in *System Sub-Model B* along with a description and vital information on units and equation of the variable.

Figure 15: Vehicle Market Shares Sub-Model



Screenshot from H_2VISION; STELLA® Research Software (Wallis, Chichakly et al. 2002)

Table 30: Vehicle Market Shares Sub-Model

Variable in Diagram	Full Name	Description	Units	Equation	Alterable on Interface Level?
Fuel Cost Attractiveness (FCA)					
FCV FC	Fuel Cell Vehicle Fuel Cost	This user-alterable variable represents the cost of fuel for fuel cell vehicles in cents per mile. The value should be entered in gasoline-equivalent cost. The user can enter the cents per mile fuel cost over time curve in the *Simulation Inputs* section if they anticipate a fluctuation in fuel cost.	cents per mile	FCV_FC = Graph of TIME Default value = 5 cents per mile constant over time	Yes
CV FC	Conventional Vehicle Fuel Cost	This user-alterable variable represents the cost of fuel for conventional vehicles in cents per mile. The value should be entered in gasoline-equivalent cost. The user can enter the cents per mile fuel cost over time curve in the *Simulation Inputs* section if they anticipate a fluctuation in fuel cost.	cents per mile	CV_FC = Graph of TIME Default value = 5 cents per mile constant over time	Yes
VL	Vehicle Life	This variable represents the life of a vehicle in miles traveled. It is assumed that the life of a CV and FCV are equal and thus the user should enter a value for vehicles without regard to fuel or vehicle type.	miles	VL = 100000	No

Variable in Diagram	Full Name	Description	Units	Equation	Alterable on Interface Level?
FCA Coefficient	Fuel Cost Attractiveness Coefficient	This variable uses the price slope coefficient to transform the dollar values of the fuel cost attributes into alternative-specific (CV or FCV) constants (*FCV FCA* and *CV FCA*) (Greene 1994).	cost coefficient	FCA_Coefficient = VL*Price_Slope/100	No
FCV FCA	Fuel Cell Vehicle Fuel Cost Attractiveness	This variable represents the "attractiveness value" associated with the cost of fuel for a FCV. The value is a factor of *FCA Coefficient* and *FCV FC*, which considers the *Price Slope* and vehicle life.	attractiveness value	FCV_FCA = FCV_FC*FCA_Coefficient	No
CV FCA	Conventional Vehicle Fuel Cost Attractiveness	This variable represents the "attractiveness value" associated with the cost of fuel for a CV. The value is a factor of *FCA Coefficient* and *CV FC*, which considers the *Price Slope* and vehicle life.	attractiveness value	CV_FCA = CV_FC*FCA_Coefficient	No
Vehicle Price Attractiveness (VPA)					
FCV Price	Fuel Cell Vehicle Price	This user-alterable variable represents the cost of a new FCV to the general public at a dealer. The value should be entered in current dollars. The user can enter the dollars over time curve in the *Simulation Inputs* section if they anticipate a fluctuation in vehicle price.	dollars	FCV_Price = Graph of TIME Default value = 20000 dollars constant over time	Yes

Variable in Diagram	Full Name	Description	Units	Equation	Alterable on Interface Level?
CV Price	Conventional Vehicle Price	This user-alterable variable represents the cost of a new CV to the general public at a dealer. The value should be entered in current dollars. The user can enter the dollars over time curve in the *Simulation Inputs* section if they anticipate a fluctuation in vehicle price.	dollars	CV_Price = Graph of TIME Default value = 20000 dollars constant over time	Yes
Elasticity	Consumer Elasticity	This user-alterable variable represents the price elasticity of vehicle type choice at a market share determined by *At Market Share* (Greene 1994).	price elasticity	Elasticity = -7	Yes
At Market Share	At Market Share	This variable represents the specific market share at which the user identifies *Elasticity*. The default value is 5% and thus the user should identify consumer price elasticity at a 5% market share.	percent	At_Market_Share = 0.05	No
Price Slope	Consumer Price Slope	This variable represents the coefficient of price in the consumer's indirect utility function as distinguished from the derivative of market share with respect to vehicle price. The price slope coefficient is calculated from three items of data supplied by the user: 1) a price elasticity at 2) a given market share and 3) initial vehicle price. The price slope is used to transform the dollar values of attributes into alternative-specific constants (Greene 1994).	coefficient of price	Price_Slope = Elasticity/(CV_Price*(1-At_Market_Share))	No

Variable in Diagram	Full Name	Description	Units	Equation	Alterable on Interface Level?
FCV VPA	Fuel Cell Vehicle Price Attractiveness	This variable represents the "attractiveness value" associated with the price of a FCV. The value is a factor of *Price Slope* and *FCV Price*, which considers *Elasticity* at a 5% market share.	attractiveness value	FCV_VPA = FCV_Price*Price_Slope	No
CV VPA	Conventional Vehicle Price Attractiveness	This variable represents the "attractiveness value" associated with the price of a CV. The value is a factor of *Price Slope* and *CV Price*, which considers *Elasticity* at a 5% market share.	attractiveness value	CV_VPA = CV_Price*Price_Slope	No
Station Density Attractiveness (SDA)					
Value 1	Dollar Value at Zero Percent Density	This user-alterable variable represents the monetary value associated with 0% refueling station density. In other words, in the eyes of the consumer, what would be the cost penalty of having no where to refuel their vehicle. This value, along with *Value 2*, is used to determine the cost station density cost attractiveness curve.	dollars	Value_1 = -10000	Yes

Variable in Diagram	Full Name	Description	Units	Equation	Alterable on Interface Level?
Value 2	Dollar Value at Ten Percent Density	This user-alterable variable represents the monetary value associated with 10% refueling station density. In other words, in the eyes of the consumer, what would be the cost penalty of having only 10% of the refueling stations capable of refueling their vehicle. This value, along with *Value 1*, is used to determine the cost station density cost attractiveness curve.	dollars	Value_2 = -5000	Yes
Utility 1	Consumer Utility at Zero Percent Density	This variable represents the consumer utility associated with the dollar value at 0% station density. This is calculated by multiplying the dollar value at 0% station density by *Price Slope*, which has been calculated from *Elasticity* and vehicle price.	consumer utility	Utility_1 = Value_1*Price_Slope	No
Utility 2	Consumer Utility at Ten Percent Density	This variable represents the consumer utility associated with the dollar value at 10% station density. This is calculated by multiplying the dollar value at 10% station density by *Price Slope*, which has been calculated from *Elasticity* and vehicle price.	consumer utility	Utility_2 = Value_2*Price_Slope	No

Variable in Diagram	Full Name	Description	Units	Equation	Alterable on Interface Level?
Coefficient 1	Coefficient at Zero Percent Density	This variable uses the price slope coefficient and utility values to transform the dollar values of the station density attributes into a coefficient for 0% station density. The value is then used to formulate alternative-specific (CV or FCV) constants (*FCV SDA* and *CV SDA*) (Greene 1994).	cost coefficient	Coefficient_1 = -Utility_1	No
Coefficient 2	Coefficient at Ten Percent Density	This variable uses the price slope coefficient and utility values to transform the dollar values of the station density attributes into a coefficient for 10% station density. The value is then used to formulate alternative-specific (CV or FCV) constants (*FCV SDA* and *CV SDA*) (Greene 1994).	cost coefficient	Coefficient_2 = (LOGN(Utility_2)-LOGN(Utility_1))/.1	No
FCV SDA	Fuel Cell Vehicle Station Density Attractiveness	This variable uses *Coefficient 1* (at 0%) and *Coefficient 2* (at 10%) to determine the “attractiveness value” associated with the actual H2 station density (*H2 %*) at time *t*.	attractiveness value	FCV_SDA = Coefficient_1*EXP(Coefficient_2*(H2_%/100))	No
CV SDA	Conventional Vehicle Station Density Attractiveness	This variable uses *Coefficient 1* (at 0%) and *Coefficient 2* (at 10%) to determine the “attractiveness value” associated with the actual FF station density (FF *%*) at time *t*.	attractiveness value	CV_SDA = Coefficient_1*EXP(Coefficient_2*(FF_%/100))	No

Variable in Diagram	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
FCV & CV Market Shares					
FCV Ui	Fuel Cell Vehicle Total Consumer Utility	This variable represents the sum of the three FCV “attractiveness values”. This is also the consumer’s total utility associated with all FCV attributes.	consumer utility	FCV_Ui = SUM(FCV_FCA,FCV_SDA,FCV_VPA)	No
CV Ui	Conventional Vehicle Total Consumer Utility	This variable represents the sum of the three CV “attractiveness values”. This is also the consumer’s total utility associated with all CV attributes.	consumer utility	CV_Ui = SUM(CV_FCA,CV_SDA,CV_VPA)	No
FCV expUi	Fuel Cell Vehicle Exp. Consumer Utility	This variable calculates the exp. of the sum of the three FCV “attractiveness values”.	consumer utility	FCV_expUi = EXP(FCV_Ui)	No
CV expUi	Conventional Vehicle Exp. Consumer Utility	This variable calculates the exp. of the sum of the three CV “attractiveness values”.	consumer utility	CV_expUi = EXP(CV_Ui)	No
expUi sum	Sum of All Exp. Consumer Utility	This variable calculates the sum of *FCV expUi* and *CV expUi*. This can be thought of as the total utility curve. *expUi sum* is used as a baseline by which to determine FCV and CV market shares.	consumer utility	expUi_sum = SUM(CV_expUi,FCV_expUi)	No

Variable in Diagram	**Full Name**	**Description**	**Units**	**Equation**	**Alterable on Interface Level?**
FCV Market Share	Fuel Cell Vehicle Market Share	This variable represents the total market share of FCVs. The market share is subsequently multiplied by the total vehicle potential. Then the currently operating FCVs are subtracted from the product. The final value is used in the core model to determine new FCV purchases. *FCV Market Share should be regarded as the primary determinant of FCV purchases.*	percent *(market share)*	FCV_Market_Share = FCV_expUi/expUi_sum	No
CV Market Share	Conventional Vehicle Market Share	This variable represents the total market share of CVs. The market share is subsequently multiplied by the total vehicle potential. Then the currently operating CVs are subtracted from the product. The final value is used in the core model to determine new CV purchases. *CV Market Share should be regarded as the primary determinant of CV purchases.*	percent *(market share)*	CV_Market_Share = CV_expUi/expUi_sum	No

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