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Two Hydrogen Distribution Scenarios for a City

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by

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Abstract

The development of two hydrogen production and distribution scenarios in Worcester, Massachusetts was analyzed. These scenarios, one centralized and one decentralized were analyzed with two different approaches. The first was an analysis of a fully saturated static case where every vehicle in Worcester was hydrogen powered. The second was a dynamic growth model that detailed the transition from gasoline powered vehicles to hydrogen powered vehicles. The scenarios were compared based on the information derived from both analysis approaches.

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1. Introduction

1.1 Background

A replacement for petroleum is long overdue. Despite the fact that petroleum has greatly assisted in the growth and development of the United States, its drawbacks are fast outweighing its benefits. Currently there are two major advantages to the petroleum based automotive industry, which are the price of gasoline, and the highly developed technology and distribution infrastructure. The drawbacks however, are extremely severe: greenhouse gas emissions, air and water pollution, and limits of supply.

In the United States, use of gasoline-powered automotives creates over half of the greenhouse gas emissions affecting the environment. [1] This pollution is severely damaging the air quality in highly urbanized areas, and the health of everyone living in these areas is suffering. Also, oil has had additional impacts on the environment, from running supply pipes across precious wildlife preserves, to oil tankers leaking and destroying delicate ecosystems.

The amount of petroleum is limited and one day it will run out. The projected date when this will happen is highly debated, but it is an inevitability. Most estimates discussed lie between 2010 and 2040. [2] The World Resources Institute estimates that this will occur even sooner, most likely between 2007 and 2014. [3] When half of the oil has been depleted, oil will become harder to find and at the same time demand will continue to increase as the world population and industry grow. As the past years have shown, gasoline prices are increasing rapidly, when a petroleum shortage occurs, gasoline prices can be expected to increase even faster. This price increase would negate the one true advantage of gasoline - the price.

As petroleum is a finite commodity alternative fuels for automotives need to be considered. One possible alternative is hydrogen, which is vastly abundant (it's the most abundant resource in the known universe) and when used with a fuel cell, produces only water as an emission. Hydrogen fuel is different than oil because oil has energy content in its unprocessed state whereas hydrogen must be separated from various compounds. Hydrogen is simply an energy carrier and not a form of energy as oil is. [4] Although hydrogen power is still a young technology, it is important to begin investing time and money into preparing hydrogen to supplant petroleum as the automotive fuel standard.

1.2 Problem Definition

Despite the fact that hydrogen has many advantages as an automotive fuel over petroleum, it still is a long way from being able to replace the petroleum standard. One of the main problems hindering hydrogen power is the lack of a distribution network. Currently gasoline refueling stations are readily accessible no matter where a vehicle owner is, which means they will never have to worry about finding fuel for their automotive. Hydrogen vehicle owners do not share this luxury, as there is currently not a country-wide network of refueling stations. In order for hydrogen to become a viable and popular alternative to petroleum, it needs a refueling infrastructure. This infrastructure is complex, involving the production, processing, storage, and distribution of hydrogen.

Each of these steps needs to be carefully detailed and considered in order to make this hydrogen infrastructure a reality.

1.3 Project Goals

The main goal of this project was to determine which of two hydrogen distribution infrastructures would best perform in the city of Worcester, Massachusetts. Worcester was chosen because it is representative of the average American city. The two scenarios focused on a centralized versus decentralized fuel production infrastructure. In order to answer the question of which was better, several questions had to be answered first. The most important questions to answer were how to produce the hydrogen fuel, and what the available resources in Worcester are. The specifications of Worcester and the requirements for hydrogen production needed to found qualitatively or quantitatively depending on information available. Appendix A1 includes a chart summarizing which data was presented qualitatively or quantitatively in the report. With the specifications of Worcester and the requirements for hydrogen found, it was possible to compare the two scenarios.

In determining how each scenario performed, it was important to consider how they differed from each other. There were several factors to consider in a comparison, which were as follows:

- Resource usage
- Space usage
- Reliability in fuel delivery

- Speed to adapt to consumer demand
- Cost

To determine how fast consumers would adopt hydrogen vehicles in each scenario, a system dynamics model was created. This model detailed the growth from zero hydrogen vehicles to a complete saturation of hydrogen vehicles in a city. Based on the differences in fuel cost and ability to adapt to demand, the two scenarios were compared in terms of how fast they reach a full saturation, which is until everyone in the city was driving a hydrogen vehicle.

Once everyone in the city is driving hydrogen powered vehicles, the system dynamics model is no longer useful. What becomes more important at that point is the demand for fuel created by this hydrogen vehicle saturation. This fuel demand translates into various resource demands depending on the method of hydrogen production. Since the scenarios have their own methodologies in producing hydrogen fuel, their requirements differ. Therefore each scenario's demand must be compared with the available resources the city has to offer.

2. Hydrogen Production Technologies

Despite the fact that hydrogen is the most abundant element in the universe, it is difficult to obtain in an elemental form. [5] This is because hydrogen almost never exists alone; it is always part of another compound such as water or natural gas. Therefore hydrogen must first be extracted from these compounds. In order to get hydrogen into a usable state it must first be converted to elemental form H_2. Once it is in this nearly pure form, it needs to be compressed into a liquid so it can be used as a fuel. With this said, the various methods of hydrogen production are shown in Figure 1.

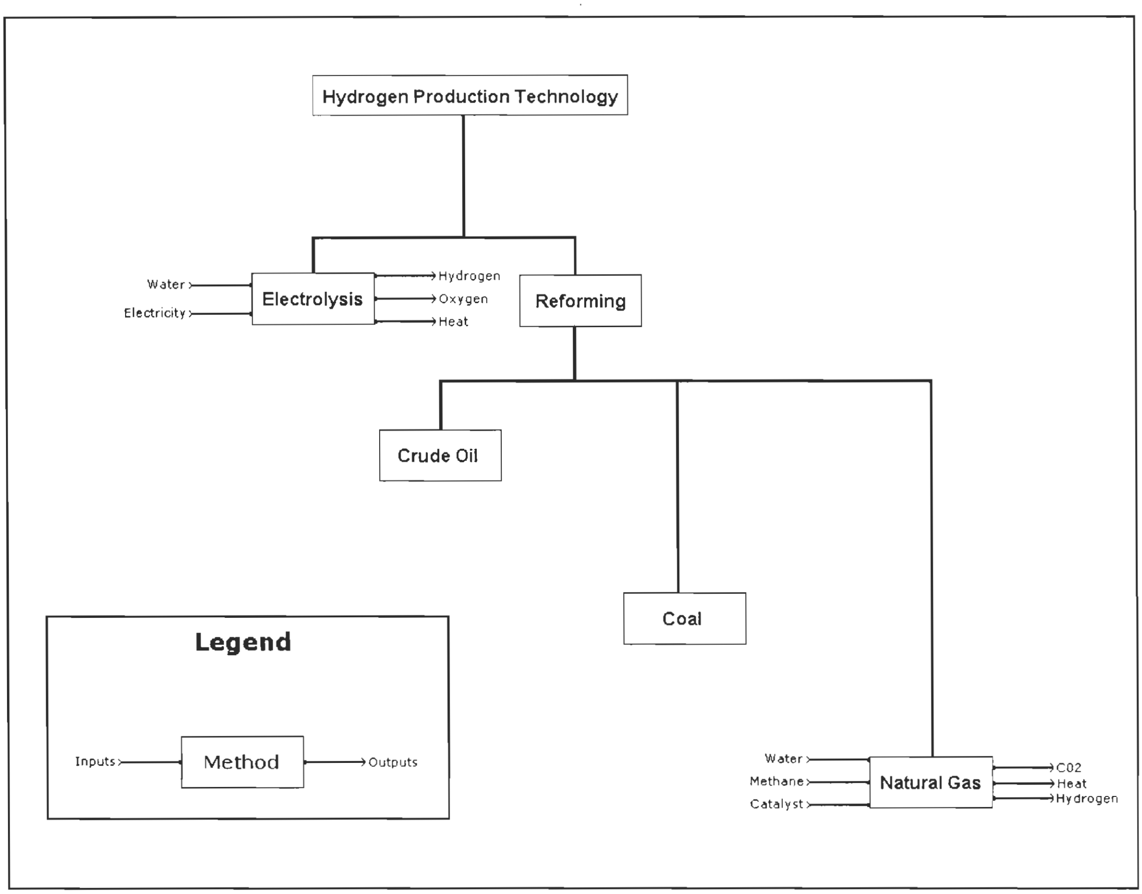

Figure 1: Hydrogen Production Methods.

Figure 1 shows the four most common methods of hydrogen production. Inputs and outputs for electrolysis and natural gas reforming are shown in the figure. For coal and crude oil reforming the processes are far more complicated and cannot easily be shown. Furthermore, coal and crude oil reforming require inputs that are mostly located regionally instead of nationwide.

Hydrogen production methods can vary on effectiveness depending on the quantity of hydrogen required. Therefore, it is important to realize how much hydrogen actually needs to be produced. This will allow for the quantity of inputs and outputs needed to produce the required amount of hydrogen. The amount of hydrogen required will be calculated in kilograms for one average car to travel an average daily distance. This amount will be determined by comparing the energy content in the gasoline used compared to the energy content for hydrogen and take into account the efficiency of automotives and fuel cells.

First, the average distance a car travels must be established. From available data no recent figure could be found but two older estimates of 11,400 [6] and 11,100 [7] miles per year were found. Also trends show that miles per year are slowly increasing and many other studies used 12,000 miles per year per car as an estimate. [8] Furthermore, common lease terms are 12,000 miles per year. From the data found, it will be assumed that the average car travels 12,000 miles per year.

To power a car for this distance of 12,000 miles, a certain amount of gasoline is required. To find how much gasoline is required to power each car, the average miles per gallon of an automobile must be determined. This number can be estimated by referring to the corporate average fuel economy (CAFE), which is 27.5 miles per gallon. This number is the average fuel economy a manufacturer's vehicles must have each model year, otherwise they have to pay large fines. [9] By dividing the average miles per year by the average miles per gallon it can be determined than on average each car uses 436.4 gallons of gasoline per year, or 1.196 gallons of gasoline per day. The Massachusetts average, found from another study, is actually 581 gallons per year, [10] however this includes gas wasted while idling in traffic. Electric motors will not require any electricity from the fuel cell while they are not moving.

The gasoline used by each car per day has a certain amount of energy. To find this energy some conversions must be done. A typical density for gasoline is 680 kilograms per cubic meter, however it should be noted that the density of gasoline could vary. [11] Using the given density, 1.196 gallons of gasoline would be 3.076 kilograms. The average energy content of gasoline is $4.59 * 10^7$ joules per kilogram. [12] Therefore, gasoline with an energy of $1.41 * 10^8$ joules is used per car per day which is about 51 gigajoules. [13] However, typical internal combustion engines are 32 percent efficient [14], which means only 32 percent of the energy content in the gasoline is used. Therefore, $4.51 * 10^7$ joules of energy is the actual energy used to mobilize each automotive per day.

With the amount of energy required to move an average car in a day estimated, the amount of hydrogen that needs to be put into a fuel cell to power an average automotive for a day can be found by doing the opposite of what was previously done. It is being assumed the mass of a fuel cell powered and gasoline-powered car are equal. The average efficiency for a fuel cell and electric motor automotive is estimated to reach about 64 percent in coming years. [15] Therefore, $7.05 * 10^7$ joules of energy are needed from hydrogen to power the automobile. The energy content of hydrogen is $1.5 * 10^8$ joules per kilogram. This means .47 kilograms of hydrogen are required per car per day.

2.1 Electrolysis

The process of electrolysis involves placing electrodes in water and running current through them. Hydrogen then bubbles to the negatively charged electrode and the oxygen byproduct collects at the positive electrode. In this extremely simple process, the only byproducts are oxygen and heat. Equation 2.1 shows the balanced reaction that occurs during electrolysis.

$$2H_2O \leftrightarrow 2H_2 + O_2 \qquad \text{[Eq 2.1]}$$

2.1.1 Water Requirement

The water required for electrolysis can be calculated using mol fractions. The molar mass of H_2 is 2.01588 grams per mole. Dividing the required amount of hydrogen, .47 kilograms per day per car, by this number it can be determined that 233.1 moles of hydrogen are required. Using equation 2.1 the amount of water required is equal to the amount of hydrogen required. The molar mass of water is 18.01528 grams per mole, therefore 4.2 kilograms of water are required per car per day.

2.1.2 Electricity Requirement

An average electrolyzer requires 4.7 kWh of electricity to produce a cubic meter of hydrogen. [16] It is known that 233.1 moles of hydrogen are needed, and one mole of an ideal gas at standard temperature and pressure is 22.4 liters, which equates to .0224 cubic meters. By multiplying the number of moles of hydrogen required by the volume of each mole, it can be determined that 5.22 cubic meters of hydrogen are required per car per day. Each cubic meter will require 4.7 kW of electricity, which means that 24.5 kW of electricity are required per car per day on average.

2.1.3 Other Requirements

On a small scale level electrolysis is relatively simple, however; when you have an electrolyzer that can convert many gallons of water to hydrogen gas at a time other problems are encountered. Hydrogen and the oxygen must be pumped away from their production point to storage tanks. Also there is heat generated during electrolysis, therefore cooling equipment is required to cool the electrolyzers. [17] Some of the heat generated is used by the electrolyzer to reduce the amount of electricity required. [18]

2.2 Crude Oil Reforming

This process involves taking crude oil and extracting as much hydrogen as possible from it. This process is cumbersome, as crude oil has a large variety of molecular formulas, so the process of extraction and yield varies depending on the source oil. This process also relies on crude oil, which is better used to make diesel and gasoline fuels, which produce better yields, and is no less polluting. The goal of hydrogen powered vehicles is to shift away from using polluting crude oil, so this method is a poor choice.

2.3 Coal Reforming

Coal reforming, also known as coke reforming, is the process of heating up coal to approximately 900 degrees Celsius where the coal turns to a gas. [19] After the coal has turned to its gaseous state, it is the mixed with steam and passed over a catalyst. This is the oldest method of producing hydrogen, and the process produces approximately 60% hydrogen and large amounts of carbon monoxide. [20] This process relies heavily on fossil fuels, and the goal of hydrogen fuel cells is a cleaner alternative to these polluting methods, so coal reforming is a poor choice. In addition, coal is only available in some regions of the country, primarily the south. The energy and cost required to move the coal from these regions to the city being examined, Worcester, will make this source of energy less competitive with natural gas reforming. Natural gas has the advantage of being available almost everywhere compared to coal.

2.4 Natural Gas Reforming

Natural Gas Reforming is a process where water in its gaseous state is reacted with methane gas. This process has two main input and output resources. The main inputs to the reaction are natural gas (CH_4) and water (H_2O), and the main outputs of the system are hydrogen (H_2) and carbon dioxide (CO_2). This method is a two stage process, the first step is shown in Equation 2.2.

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad \text{[Eq. 2.2]}$$

When a molecule of CH_4 is combined with water in its gaseous state it yields a molecule of carbon monoxide (CO) and three molecules of hydrogen (H_2). This reaction must take place in a pressure between three and twenty-five atmospheres at a temperature between 700 and 850 degrees Celsius. [21] The heat for this endothermic reaction can be produced with a variety of methods, but the most likely is simply to burn a portion of the incoming methane. In order to supply enough heat for the reaction, approximately 25% of the incoming methane would need to be burned. [22]

The second reaction of the reforming process is shown in Equation 2.3.

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \text{[Eq. 2.3]}$$

The carbon monoxide from step one is combined with gaseous water in a shift reactor to form carbon dioxide and hydrogen.

2.4.1 Natural Gas and Water Requirement

The average amount of natural gas and water required per day can be calculated using equations 2.2 and 2.3 and the number of moles of hydrogen gas required per car per day. From previous calculations, 233.1 moles of hydrogen gas are required per car per day and equations 2.2 and 2.3 indicate for every one mole of CH_4 input, and 2 moles of H_2O input 4 moles of hydrogen gas will be produced. Therefore, to produce 233.1 moles of hydrogen gas, 58.275 moles of CH_4 and 116.55 moles of H_2O are required. Using the molar mass of CH_4 which is 16.0425 grams per mole and H_2O which is 18.01528 grams per mole, it is calculated that .935 kilograms of CH_4 and 2.1 kilograms of H_2O are required per car per day. However, pure CH_4 is not available so natural gas is used, which contains about 85 percent CH_4 by volume. Therefore each automotive requires 1.1 kilograms of natural gas and 2.1 kilograms of H_2O per day. Since 25% of the natural gas must be used to heat the reaction, each automotive will need 1.47 kilograms of natural gas and 2.1 kilograms of water daily. This extra natural gas required is known as the reaction catalyst and is burned to created heat.

2.4.2 Electricity Requirement

The electricity required for natural gas reforming is extremely low. This is because there is no need for electricity in the reactions used to generate the hydrogen. This means there is no electricity used except for powering the facilities the conversion takes place in. The primary reason for this method of production is the reduced amount of electricity reforming requires relative to electrolysis.

2.4.3 Effectiveness of Natural Gas Reforming

Natural gas reforming can be effective in terms of overall cost per unit of hydrogen, but not always in emissions. The cost is primarily driven by the size of the reformer. The size of the reformer can vary, generating from .1 to one million cubic feet a day. One issue with having a smaller reactor is that the cost of the equipment is much greater. The capital cost for a small reaction that does .1 million standard cubic feet per day is $4000 per kW whereas a large one million standard cubic feet per day reactor has a capital cost of only $750 per kW. [23] Since the capital cost is lower for larger reformers, natural gas is generally more cost effective when reformed in large quantities.

Natural gas reforming produces a lot of CO_2 which can be calculated with use of equations 2.2 and 2.3. The reforming process will produce 58.275 moles of CO_2 and CH_4. The molar mass of CO_2 is 44.0095 grams per mole, thus 2.56 kilograms of CO_2 will be created by each car each day. This CO_2 could be kept out of the atmosphere by sequestering it. This is a process of storing the carbon dioxide underground, such as depleted gas fields. [24] Sequestering the carbon dioxide will also add to the over cost which will drive up prices at each refueling station. Sequestering the carbon dioxide also requires electricity, which is used to pump the carbon dioxide to the desired location.

2.5 Production Methods Summary

Each hydrogen production method requires different resources to produce hydrogen. Since each of the resources contain different amounts of hydrogen, it is important to understand the quantity of each of the resources required. In order to accomplish this, an arbitrary amount of hydrogen is produced in each method. In this case, the amount of hydrogen produced will be enough to drive a car 33 miles, the daily average in America. From this required production, the required inputs and produced outputs were calculated and shown in Figure 2. Only natural gas reforming and electrolysis methods were considered, since as discussed previously crude oil and coal reforming are poor choices for hydrogen production.

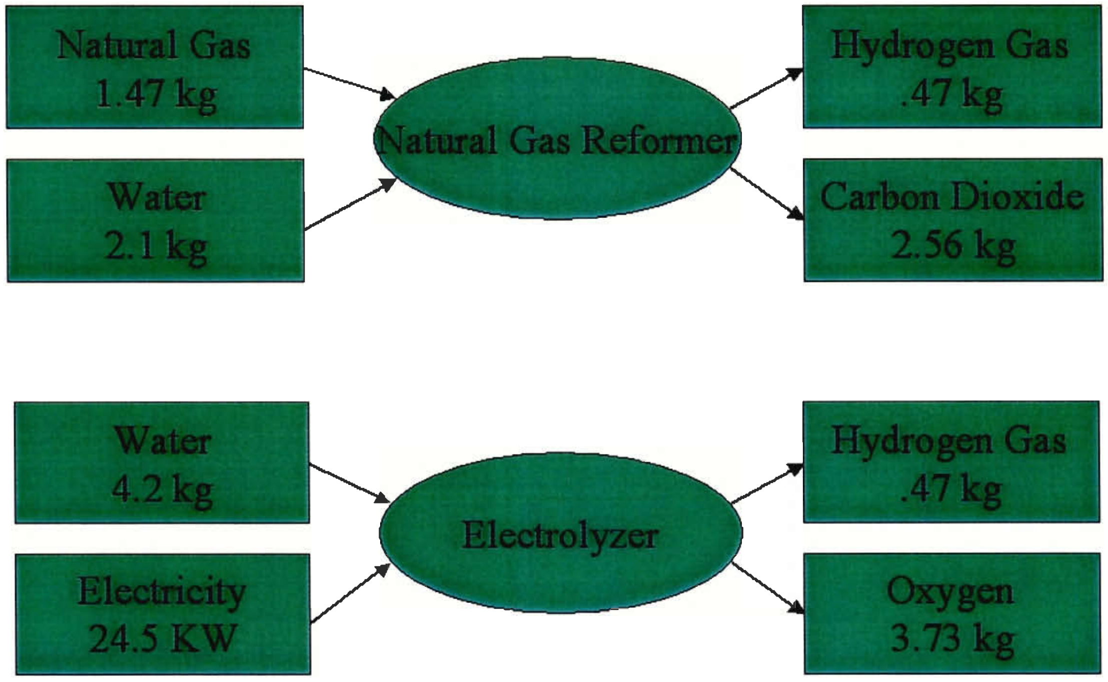

Figure 2: Input and Output Quantities for Electrolysis and Natural Gas Reforming.

2.6 Space Requirements

Space requirements for large scale production are not a concern because large scale hydrogen production facilities will be located away from the city, where land readily available in most parts of the country. However, space requirements of the hydrogen production equipment are very important if they are to be installed at former gas stations. Space required is not only for electrolyzers or natural gas reformers but also other equipment such as compressors and storage tanks. The quantitative space requirements for hydrogen production stations will be discussed in the centralized and decentralized scenarios.

3. City Specifications

3.1 Available Electricity

Since electricity is an important element in every hydrogen production method, it is crucial to know how much electricity is available for use in hydrogen production. The exact capacity for an individual city can only be estimated. [25] This is because the power grid for New England is extremely interconnected. In addition, the daily electricity production in New England is about 34,000 megawatts. The surplus for New England is about 16,000 megawatts.[26] Worcester would have access to a portion of this relative to the population of Worcester. With the population of Worcester being 172,648 people, and the New England population being 13,922,517, Worcester's share of the power would be 198 megawatts per day. [27]

3.2 Available Water

Water is used in electrolysis and natural gas reforming, the two leading methods of hydrogen production. Because of this, extensive supplies of water would be needed for either production method. Currently Worcester has a maximum water capacity of 29 million gallons of water a day. Of this maximum capacity, 24 million gallons are used each day. This means there is a surplus of 5 million gallons a day that can be used to convert resources into hydrogen fuel. [28] In order to increase the amount of water that can be delivered, the piping and pumping of the water supply must be upgraded. Currently the reservoir system is large enough to supply a much larger quantity of water, but the outflow of the reservoir system is what limits the system.

3.3 Available Natural Gas

Since natural gas reforming is a leading hydrogen production method, it is important to determine how much is available. Currently all of New England has a capacity of 3,304 Million Standard Cubic Feet (MSCF) available. The current usage of this capacity is 3,155 MSCF, which leaves a surplus of 149 MSCF. [29] Based off the population ratio of Worcester and New England, Worcester has a surplus of approximately 1,847,690 SCF of natural gas available. With Worcester's current piping networks, this translates to approximately 36,624 kg of natural gas a day.

3.4 Available Space

The available space will vary from location to location, depending on the size of the old gas station. There are currently 58 gas stations in Worcester, some of them are very small and have no room to expand, whereas some could be expanded if local property was purchased. [30] The average space available at each gas station can only be roughly estimated. The California Hydrogen Highway Network is currently planning to convert hydrogen refueling stations in a portion of California. They have estimated an average refueling station to measure 100 by 150 feet (30 by 46 meters). [31]

3.5 Population of Vehicles

The number of licensed drivers in Worcester was determined by averaging two different values. The first approximation was to take the total population of Worcester which is 172,648 people and subtract the number of people who are younger than 15 years old, which results in 138,271 people who are of age to drive in Worcester (this is slightly off because it includes 15 year olds). [32] Of this number, only 91% actually had a driver's license in 1998. [33] From this, there are 125,827 licensed drivers in the city of Worcester.

The second approximation is using the number of licensed drivers in Massachusetts, 4.39 million as of 1998 [34] and multiplying that by the ratio of the population of Worcester to the population of Massachusetts. The population of Worcester is 172,648 and the population of Massachusetts is 6,379,304. [35] This yields a value of 118,810 licensed drivers. From these two methods, the average number of drivers in the city of Worcester is 122,319. The Executive Office of Transportation states every licensed driver owns 0.86 vehicles. [36] To obtain the number of vehicles the number of drivers was multiplied by .86, which yielded 105,194 automobiles.

3.6 Summarized Specifications

Figure 3 illustrates the total available resources available in Worcester calculated in this section versus the required resources for each production method calculated in section two.

	Requirements per Day		Worcester
	Electrolysis	**Natural Gas Reforming**	**Daily Amount Available**
Natural Gas		154,635 kg	36,624 kg
Water	441,815 kg	220,907 kg	18,143,800 kg
Electricity	2,577 Megawatts		198 Megawatts

Figure 3: Production Requirements vs. Availability.

4. Scenario One: Decentralized Hydrogen Fuel Production

4.1 Definition

In this scenario, hydrogen fuel is produced on site at each refueling station. This situation has several advantages and disadvantages associated with it. The main advantage is the speed at which this infrastructure can adapt to changing consumer demand. This is because it takes a relatively small amount of time to construct new refueling stations, and each new station creates more hydrogen production. This method of production also has a major disadvantage for the same reason, as each station relies entirely on the city to provide the resources for hydrogen production.

4.2 Hydrogen Production Method

Figure 3 clearly shows Worcester does not have enough resources locally available to fully support one production method. The electricity requirement for electrolysis is so far beyond the available amount of electricity, it is completely unfeasible without the construction of a new power generation plant. Coal reforming is not possible due to the lack of a local supply of coal. Using crude oil reforming for either scenario is counterproductive, as the goal of switching to hydrogen vehicles is to discontinue the use of oil.

It is possible that Worcester could have more of each resource than shown in figure 3. This is possible because the calculations for the available electricity and natural gas where taken as a fraction of the surplus in New England by population. With this in mind, it is most likely that each station will use natural gas reforming, as the difference between the available and required is the smallest. This will still require the expansion of the piping and distribution network within Worcester to handle the increased load. If each city in New England began using natural gas reforming a natural gas shortage would occur. If this was the case, the entire New England supply and distribution network would need to be vastly expanded.

4.3 Space Usage

The space requirements within the city for this scenario are relatively large. This is because of the large area needed to house the reforming equipment, and the storage tanks needed to hold an adequate surplus of fuel. The amount of fuel each station requires is based on the total number of refueling stations and the number of vehicles in Worcester. It was calculated that each hydrogen powered car would use .47 kg of hydrogen per day. From this information it can be derived that one kilogram of hydrogen is 9.3 gallons; therefore .47 kg of hydrogen is 4.4 gallons. The average car gets 27.5 mpg and is driven 12000 miles per year. From this information it can be found that each car uses 1.2 gallons of gasoline per day. Since 4.4 gallons of hydrogen are required and only 1.2 gallons of gasoline, the storage tanks must be 3.5 times their current size.

Storing 3.5 times the volume of fuel will have to be done by putting larger tanks underground, where there is plenty of space. Still, additional space would be required for the hydrogen production equipment. If an electrolyzer is used the space required can be calculated by examining a common electrolyzer which produces .04 cubic meters of hydrogen per minute per square meter. [37] In order to be maximally efficient the electrolyzer will run 24 hours a day Therefore, in one day the electrolyzer will produce 57.6 cubic meters of hydrogen per square meter. To calculate the space required, the daily quantity of hydrogen needed per gas station must be estimated. There are 105,194 vehicles, which use .47 kg of hydrogen each, so 49,441 kilograms of hydrogen is required per day in Worcester. It will be assumed this hydrogen is distributed evenly through all 58 gas stations in Worcester, which means each gas station needs to distribute 852 kilograms of hydrogen. Since one mol of hydrogen is two grams and one mole of any gas at standard temperature and pressure is 22.4 liters, 852 kilograms of hydrogen can be converted to 9,542,400 liters, or 9,542 cubic meters. Production of this much hydrogen will require 166 square meters of space for the electrolyzers at each refueling station. As discussed before the assumed size of a refueling station is 30 by 46 meters, or 1380 square meters. Only 12% of the total space at the fueling station will be required for the hydrogen production equipment, assuming electrolysis is used.

4.4 Fuel Delivery Reliability

In terms of reliably getting fuel to the end user, the main consideration is whether or not there is an available supply of natural gas. Since the hydrogen fuel is produced at the station, if there is an adequate supply of natural gas, the consumer will be able to get fuel. If there is not enough natural gas, then the supply will either become unreliable or stations will have to resort to different production methods to make up for the deficit.

If natural gas is available, fuel delivery will be extremely reliable. If natural gas is in short supply, then fuel delivery will be unreliable unless alternative fuel production methods are used to supplement the natural gas reforming.

4.5 Cost

Small scale hydrogen production is more expensive than large scale production. As a direct result the fuel cost from a small scale production scenario would be greater. The initial capital cost for each refueling station might also be difficult for many refueling stations to afford. This high cost includes the cost of land, storage and pumping equipment, and costs for the actual construction of the facility. The cost of this would be well above that of the construction of a normal house, which generally prohibitively expensive. This would likely cause refueling stations to become fully owned by large corporations and not franchises, like they are currently.

4.6 Responsiveness to Demand

This decentralized method of hydrogen production is very flexible if there are adequate resources to supply it. It takes a relatively short amount of time to construct a new fuel station, in many cases well under half a year. If the demand for hydrogen fuel increases, the production capacity has to increase in order to provide each vehicle with fuel. Since each new station creates more production capacity, this decentralized distribution method is more able to adapt quickly to consumer demand. There is a drawback, in that this requires far more physical space within the city than the centralized production method.

5. Scenario Two: Centralized Hydrogen Fuel Production

5.1 Definition

In this scenario hydrogen fuel is produced at a regional facility and delivered to each refueling station. The primary advantage of this method is the cities are not responsible for providing the energy for the hydrogen production. Instead the facility can rely on any nearby regional power source, such as hydroelectric, nuclear, solar, or whatever else is available. This production method has an added step of delivering the fuel to the stations, which is a significant issue.

5.2 Hydrogen Production Method

With the production of hydrogen no longer relying on the energy supplied to the cities, the method used to produce the fuel becomes much more flexible. With this in mind, electrolysis would be the most effective method of hydrogen production. The vast amounts of electricity can be harvested from the regional surroundings and water can be piped in. Natural gas reforming is also viable, however not as clean as electrolysis, so if the resources are available for electrolysis, it is logical to use this method.

5.3 Space Usage

Production facilities can be located in rural areas where space is cheaper and far less limited. Therefore, the individual refueling stations will not have to have bulky hydrogen production equipment. Depending on the distribution method, large hydrogen storage tanks may or may not be necessary. If the hydrogen is piped to the refueling station a storage tank will not be necessary, however, if the hydrogen is brought to the refueling station by truck then a storage tank will be necessary. The required storage tank in this scenario may need to be larger than the storage tank required by the decentralized scenario. A hydrogen truck may only deliver hydrogen once or twice a week whereas the refueling station produces their own hydrogen. This hydrogen is produced at a steady rate and used at a fairly steady rate throughout the week. One advantage of using trucks to deliver hydrogen over a decentralized system is that the hydrogen fuel delivered to the refueling stations can easier be stored in large underground tanks. It would be much more difficult to have the hydrogen production equipment located underground due to cooling and maintenance reasons.

5.4 Fuel Delivery Reliability

Unlike the decentralized method of fuel distribution, this method has very different constraints limiting affecting the reliability of hydrogen fuel. The main issue to deal with here is the delivery mechanism used to get the fuel from the production facility to the refueling station. There are two plausible methods, developing a piping infrastructure or using tanker trucks to deliver the fuel, however, both have their own challenges.

5.4.1 Hydrogen Pipelines

Transporting the hydrogen by pipeline will require a complex hydrogen pipeline network be put in the ground. Constructing such a large network would require a huge capital cost and large amounts of time. However, once the pipelines are installed hydrogen could likely be transported quickly through the pipelines. Having a network of pipelines will also allow refueling stations to have a continuous supply of hydrogen to sell to customers. This is very different from our gasoline distribution system, where if gasoline refueling stations must plan to have enough gasoline on hand to meet demand. Besides having a continuous supply of hydrogen, refueling stations will also be safe because large amounts of combustible hydrogen will not be stored on location. Therefore, if and accident was to occur damage would by minimal to the surrounding area. This may also allow for refueling stations to be able to reach closer to residential area than if they had a large tank of hydrogen which could be hazardous.

However, the benefit of a constant supply of hydrogen would only be true if the hydrogen that was delivered was compressed to the desired 5000 psi or higher pressure. If delivered at this pressure the hydrogen would in fact be able to be directly delivered to customers' cars. However, the disadvantage of this is the whole hydrogen pipeline system must be able to handle a constant pressure of 5000 psi. This high pressured hydrogen being pumped would also have a huge safety problem if a pipe were to burst. If the hydrogen was delivered at a standard pressure the refueling stations would need to have compressing equipment on location, and would require a large storage tank for compressed hydrogen. Compressing the hydrogen as the customer buys it would likely take longer than the average person is willing to wait to refuel their car.

5.4.2 Hydrogen Trucks

Distributing hydrogen by trucks seems like the most feasible plan because this is the current distribution method of gasoline. However, gasoline tanks are generally limited by volume not weight which is unfavorable to hydrogen because it is less dense than gasoline. A typical gasoline tank tractor-trailer transports about 9500 gallons (36 cubic meters) of gasoline. Assuming this hydrogen is stored at 5000 psi each trailer will hold 1026 kg of hydrogen. This will power 2180 hydrogen cars for a day. This can be compared to the 9500 gallons of gasoline that will power 7943 cars for a day. This means that there will need to be 3.6 times more tractor-trailers to deliver hydrogen than there are now. This will result on more trucks being on the road and possibly reduce safety. Instead of needing 14 tankers in Worcester per day 50 will be required per day. This is obviously a major concern with this scenario. Another important concern with trucking the hydrogen is that additional hydrogen will be required to power the fleet of tractor-trailers that will be used to deliver the hydrogen. This will require more hydrogen to be produced and therefore use more natural gas and electricity. In addition, this fleet of trucks will increase the cost of the hydrogen. This increase in cost comes from the salaries of the truck drivers, and the fuel required transporting the cargo. The fuel cost is marginal, and would typically account for less than 1% of the total cargo. On the other hand, the average salary for a truck driver is $30,000 a year. [38] With 50 drivers that totals $1.5 million a year just for the city of Worcester, as opposed to the $420,000 there is currently. This would add over one million dollars in cost the fuel consumers in Worcester would have to pay.

There are many advantages of trucking the hydrogen to the refueling stations, however. If hydrogen is trucked to the refueling stations the infrastructure can slowly grow as the demand for hydrogen increases. The initial investment cost of the actual distribution system will be a lot lower than using a pipeline system.

5.4.3 Selected Method

For the dynamic situation trucking hydrogen to the refueling stations is the only reasonable method of distribution. The capital costs of implementing a hydrogen pipeline network would be far too great as hydrogen powered automotives are introduced. However, in the static situation, after hydrogen is clearly the dominant source of automotive fuel, hydrogen pipelines may be implemented. This does seem unlikely however because once the distribution infrastructure grows using trucks to distribute the hydrogen it would be a large capital cost to change the network over, especially when using trucks to deliver the hydrogen works. Even though it seems unlikely that there would be a switch from trucking the hydrogen to transporting it in a pipeline it is still very possible. In the future homes may be powered by hydrogen, which would mean pipelines would be crucial to cut costs of hydrogen.

Another concern is with the tanker infrastructure in place, the issue becomes making sure the tankers are able to keep on schedule, and there are enough tankers to carry the volume of fuel demanded by the consumers. Also, controlling the reliability of the fuel supply is that of the ability for the production facilities to keep up with demand. If demand grows sharply, the production facilities might not be able to keep up. If this were to happen, it would be a large undertaking to expand the facility or construct additional facilities to meet demand.

A possible outcome is a method where storage stations are constructed between the production facility and the destination cities to reduce the trucking distance. Pipelines would be constructed between the facility and these stations. Over time more storage stations might be constructed closer until a continuous pipeline existed from the facility to the city. The overall effect of this would be the initial dominance of trucking, followed by an affordable multi-stage piping network.

5.5 Cost

The cost of fuel has a large potential to be much cheaper than a decentralized production method. This is due to the fact that on a large scale, hydrogen fuel becomes cheaper to produce. The only variable that can affect this price is the cost of delivering the fuel, and the cost of keeping facilities able to produce enough fuel to keep up with demand. It is also likely that the initial capital cost for this scenario will be much higher than the decentralized scenario. This cost will be due to purchase of tanker trucks or installation of piping systems as discuss in the pervious section.

5.6 Responsiveness to Demand

This method is somewhat limited in its ability to respond to changing fuel demands. If the demand grows sharply, facilities might not have the capacity to provide adequate fuel. This would require expanding facilities or constructing new ones. This requires larges amounts of time and money, and while this construction is in process, there would be an effective fuel shortage. On the other side, if fuel demand lags, a facility might cease to be profitable. If this were to happen the parent company might choose to close the facility, effectively creating a complete shortage of available fuel.

6. Growth Analysis

The transition from gasoline fueled cars to hydrogen fueled cars will be critically dependent on the availability of hydrogen. Additional factors to consider are the cost of the vehicle and the cost of the two available fuels.

There are three basic scenarios for the success or failure of hydrogen powered vehicles being accepted by consumers:

1. Hydrogen cars will never be accepted
2. Hydrogen cars will experience acceptance for a short period of time then fall out of favor
3. Hydrogen cars will gradually become accepted and supplant gasoline cars

The goal of this analysis is to identify the conditions for which the transition will be successful and specifically to investigate the role of hydrogen supply in the transition. Before any analysis can be done with our scenarios the model must first be analyzed and tested. This is accomplished by observing the main causal loops of the model, and then analyzing the sensitivity of the overall model.

6.1 Driving Loops

The model is based on two primary feedback loops. The first of these is the cost loop. Basically as costs increase or decrease, the number of hydrogen vehicles decreases and increases respectively. The second main loop is the fuel correction loop. Depending on the shortage or surplus of fuel production, the number of hydrogen vehicles will once again fluctuate by increasing or decreasing respectively. These two loops are tied together at the junction point of hydrogen vehicles.

6.2 Completed Growth Model

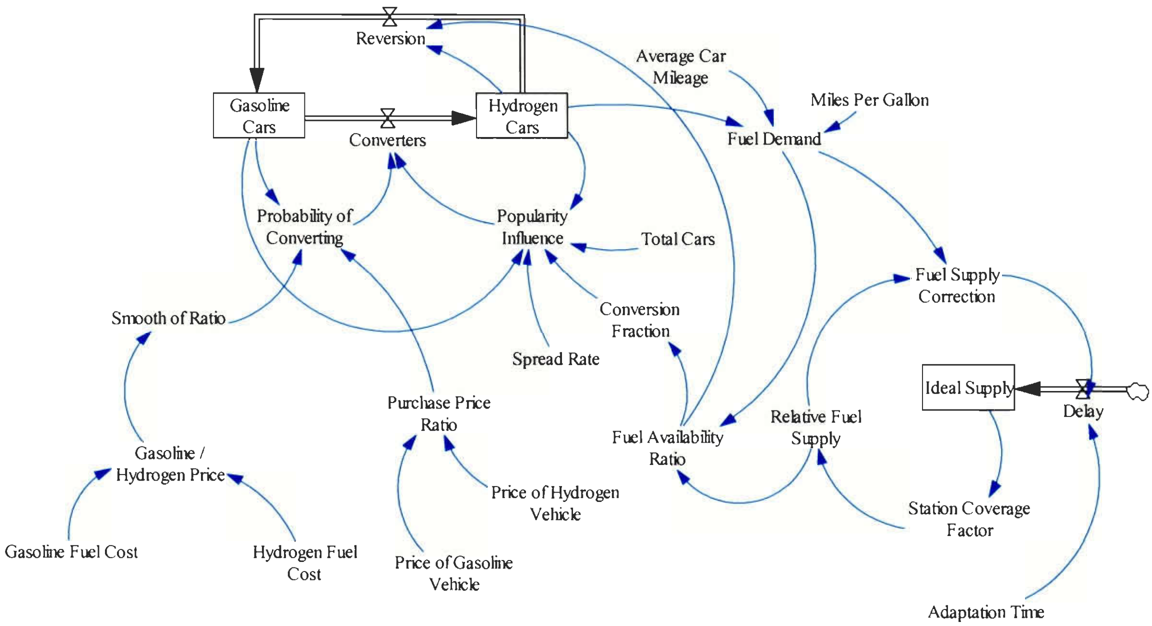

Figure 4: Completed Growth Model

The model used for simulating the growth of the hydrogen distribution infrastructure is relatively simple. This model describes how the rate of conversion from gasoline vehicles to hydrogen vehicles is affected by several key variables. There are three variables that have the most influence on this model, namely the fuel cost ratios, vehicle cost ratios, and fuel availability. Depending on the values of these variables, the conversion from gasoline to hydrogen vehicles will either be faster or slower.

6.2.1 Explanation of Stocks, Flows and Other Variables

Gasoline Fuel Cost

This is the average cost per mile of using gasoline fuel. This was calculated with a base cost of one gallon of gasoline costing $1.70. This value was approximated based on the current fuel price as of April 15, 2004 in the Worcester area. Using the average fuel efficiency of 27.5 miles per gallon, the gasoline cost was divided by fuel efficiency to arrive at a value of $0.0618 per mile.

Hydrogen Fuel Cost

The department of energy determined an accurate cost for hydrogen is $2.50 per kilogram of hydrogen. As calculated earlier a standard automotive drives 32.88 mile per day using 0.47 kg of hydrogen. The required amount of hydrogen would cost $1.18, and when this amount is divided by the miles driven per day, the cost of $0.0358 per mile.

Gasoline / Hydrogen Price

This is the Gasoline Fuel Cost divided by the Hydrogen Fuel Cost. This ratio is one of the most important aspects of the model, as it has a large impact on the adoption rate of hydrogen vehicles. If the cost of gasoline is higher than that of hydrogen fuel, than the ratio becomes larger than one and drives the adoption rate of hydrogen vehicles higher. If the price of hydrogen is higher than gasoline, the opposite happens and the adoption rate slows.

Price of Gasoline Vehicle

The average cost of a new gasoline powered vehicle is $28,000. This value does not include fuel costs or other costs of ownership.

Price of Hydrogen Vehicle

This is the average purchase cost of a new hydrogen powered vehicle. This value does not include cost of ownership or fuel costs. The cost of ownership is assumed to be the same for both hydrogen and gasoline powered vehicles. This value was assumed to be 25% higher than the price of a gasoline powered vehicle.

Purchase Price Ratio

This is the Price of a Gasoline Vehicle divided by the Price of a Hydrogen Vehicle. The behavior of this ratio is the same as that of the Gasoline/Hydrogen fuel cost ratio.

Smooth of Ratio

Currently this is just the value of the Gasoline / Hydrogen fuel cost ratio. This can be modified to add a time lag over which the price varies. This can cause instability in the rest of the model which can sometimes be of interest. In this project, however, it is not required.

Probability of Converting

This variable calculates a value based on the purchase price and fuel price ratios according to how many gasoline cars there are. This value is used along with the Popularity Influence variable to determine the conversion rate from gasoline to hydrogen powered vehicles. The higher this value, the more rapidly hydrogen vehicles will be adopted.

Spread Rate

This constant serves as a fraction of the likelihood of people adopting hydrogen vehicles from gasoline powered vehicles based on advertising – both commercial and word of mouth.

Conversion Fraction

This is a weighted version of the fuel availability ratio. The higher this value, the more rapidly hydrogen vehicles will be adopted. This is because the more available fuel is, the more willingly drivers will adopt hydrogen cars as they will know they can readily acquire fuel for their vehicle.

Total Cars

This is the total number of cars used in the simulation.

Popularity Influence

This is the combination of the impact of fuel availability, and natural converters out of the entire driving population. This variable combines with the Probability of Converting to formulate the conversion rate from gasoline powered cars to hydrogen powered cars.

Average Car Mileage

This is the average distance each car in the city of Worcester travels each day. This value was derived in section 2.

Miles Per Gallon

This is the fuel efficiency of the average American car based on CAFE. It is set to 27.5 miles per gallon as discussed in section 2.

Fuel Demand

This is a straight calculation for fuel demand. It is based on the average car mileage times the total number of hydrogen cars divided by the average miles per gallon of each car.

Fuel Availability Ratio

This is a ratio determined by the actual fuel supply divided by the demanded fuel supply. The higher this value, the more rapidly hydrogen vehicles will be adopted.

Relative Fuel Supply

This is the actual fuel supply. Because refueling stations cannot be built instantly, there is never exactly the amount of hydrogen available that is demanded until the system reaches steady state. This means that there can be more fuel than needed or less. If there is less fuel than needed, this will slow the growth of hydrogen vehicles until the fuel supply is corrected.

Fuel Supply Correction

This is simply the difference between how much fuel is needed and how much fuel there is. This value shows how much the fuel distribution network needs to grow or shrink to best meet the needs of the hydrogen vehicle drivers.

Station Coverage Factor

This currently equals the ideal supply. This is an added expansion point in case the actual distribution of hydrogen refueling stations in Worcester was to be considered. This is important if there was not an even distribution of stations throughout Worcester, and people in certain areas were not able to purchase fuel easily. This topic is beyond the scope of this project, but has been left in for future expansion.

Adaptation Time

This is a constant that determines how long it takes for the Fuel Supply Correction to be realized by the distribution network. High values in this variable result in the slower adoption of hydrogen vehicles, and low values result in faster adoption.

6.3 Sensitivity Analysis

Before the model can be used to compare the scenarios, it is important to understand how the model is affected by various changes.

6.3.1 Gasoline / Hydrogen Price Sensitivity

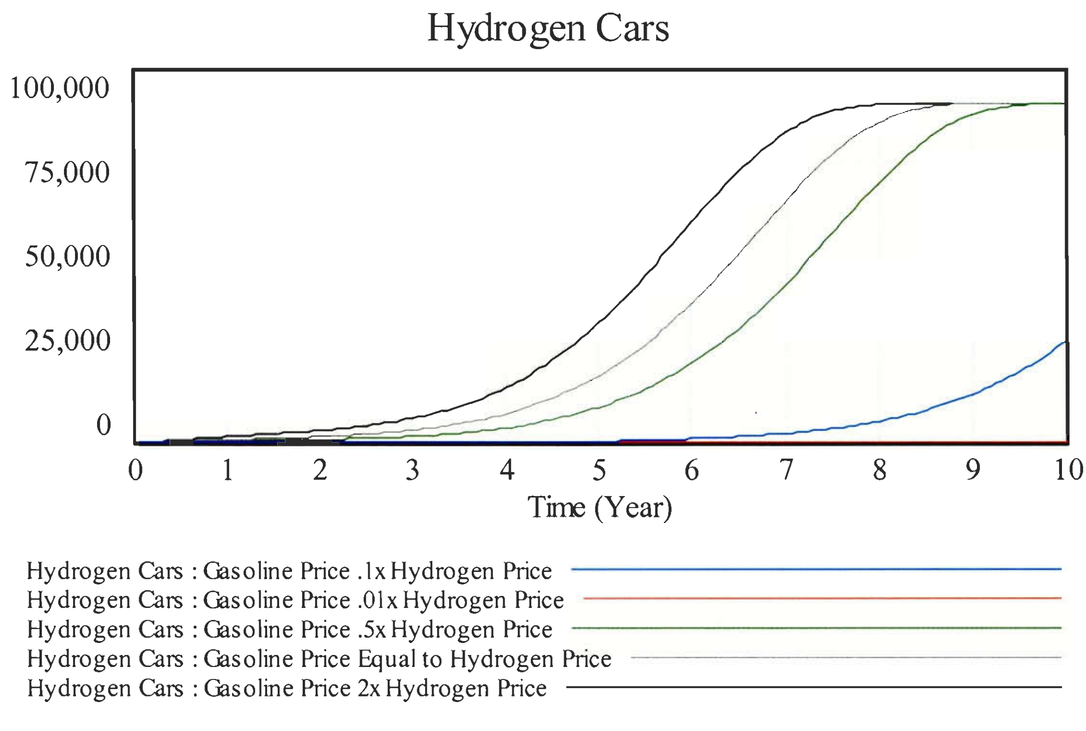

Figure 5: Sensitivity Analysis of Gasoline / Hydrogen Price

As expected, if hydrogen fuel is more expensive than gasoline, the number of hydrogen powered vehicles will grow slowly. If the price of hydrogen fuel is less than gasoline, the number of hydrogen powered vehicles will grow much faster.

6.3.2 Purchase Price Ratio Sensitivity

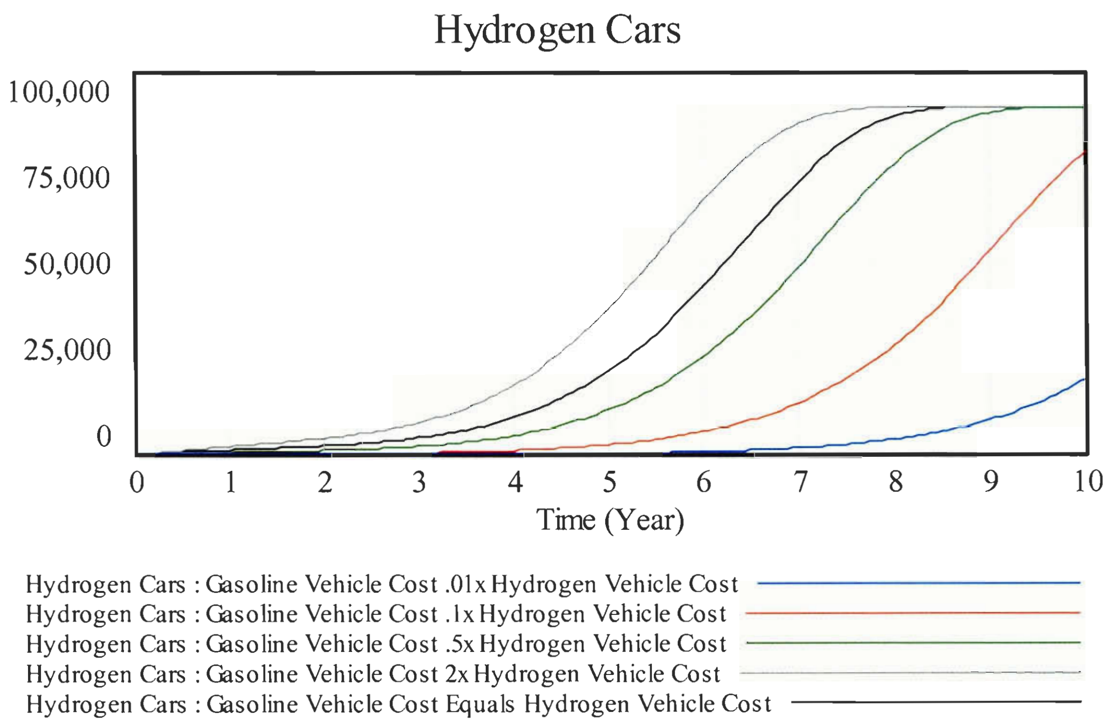

Figure 6: Sensitivity Analysis of Purchase Price Ratio

This analysis shows the adaptation rates of hydrogen powered vehicles with varying relative costs to gasoline powered vehicles. As expected as hydrogen cars become cheaper, they are adopted by consumers at a faster rate.

6.3.3 Spread Rate Sensitivity

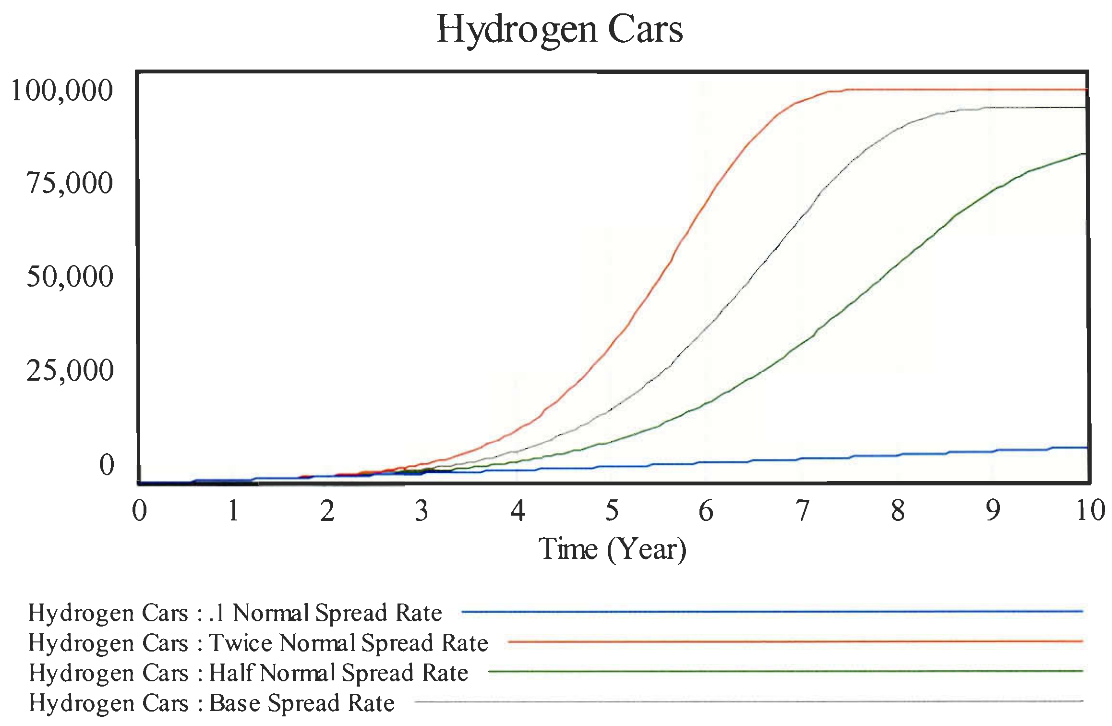

Figure 7: Sensitivity Analysis of Spread Rate

This analysis shows the affect that advertising and public opinion can have on the rate at which hydrogen cars are accepted by consumers. As expected, as this rate increases, the rates at which consumers buy hydrogen vehicles increases.

6.3.4 Adaptation Time Sensitivity

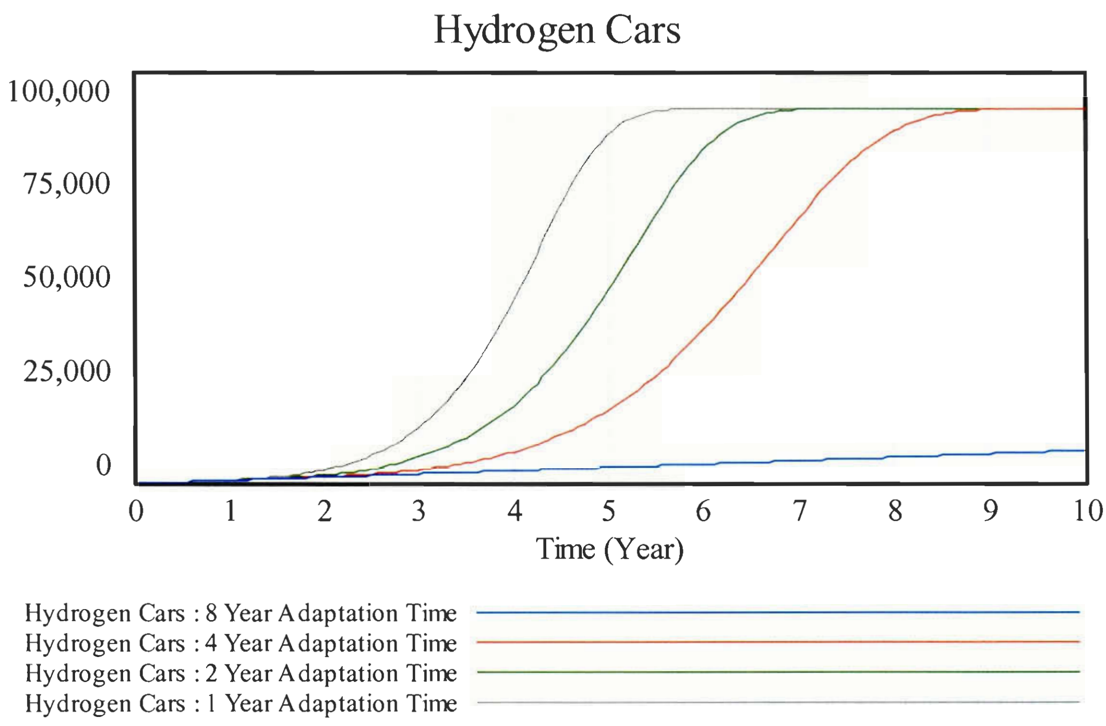

Figure 8: Sensitivity Analysis of Adaptation Time

This analysis shows how varying the amount of time it takes for people to switch from a gasoline vehicle to a hydrogen vehicle affects how long it takes for hydrogen vehicles to saturate. Once again as expected, as the time gets shorter, the time to saturation increases.

6.4 Hydrogen Cars Never Accepted

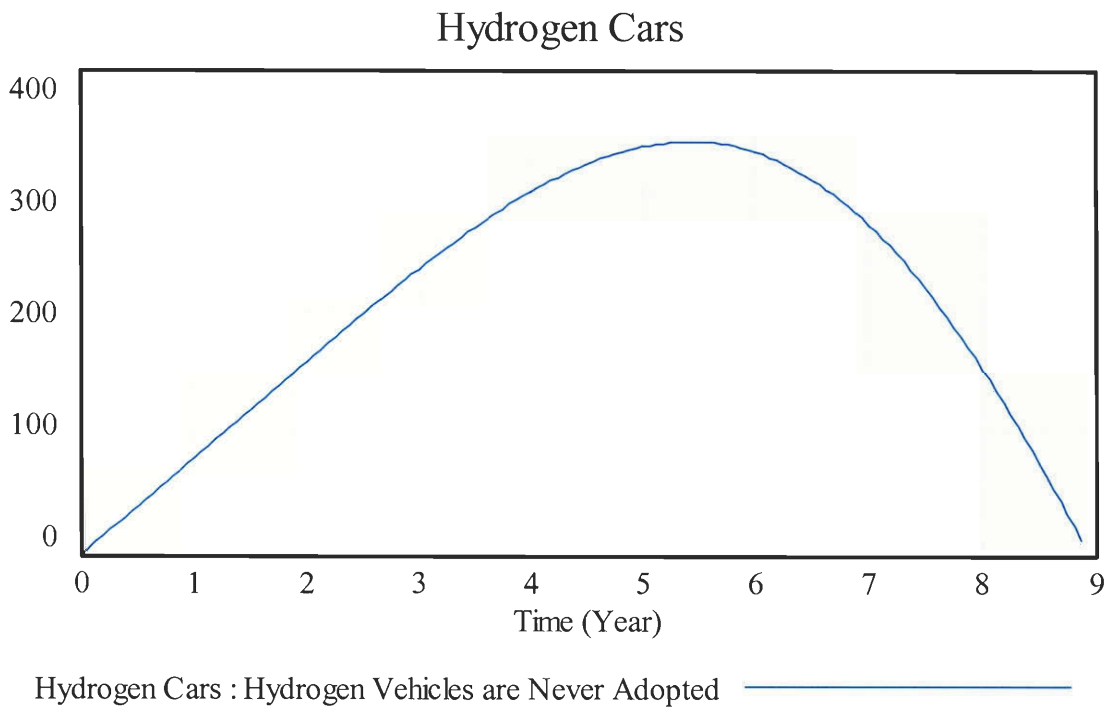

Figure 9: Hydrogen Vehicles are Never Adopted

This analysis shows the situation where hydrogen powered vehicles never become popular and fail as an alternative to gasoline powered vehicles. This occurs when the price for the hydrogen vehicles and fuel are very high, and when the responsiveness to demand is extremely slow and cannot react to any level of demand.

6.5 Hydrogen Cars Experience Acceptance for a short period of time

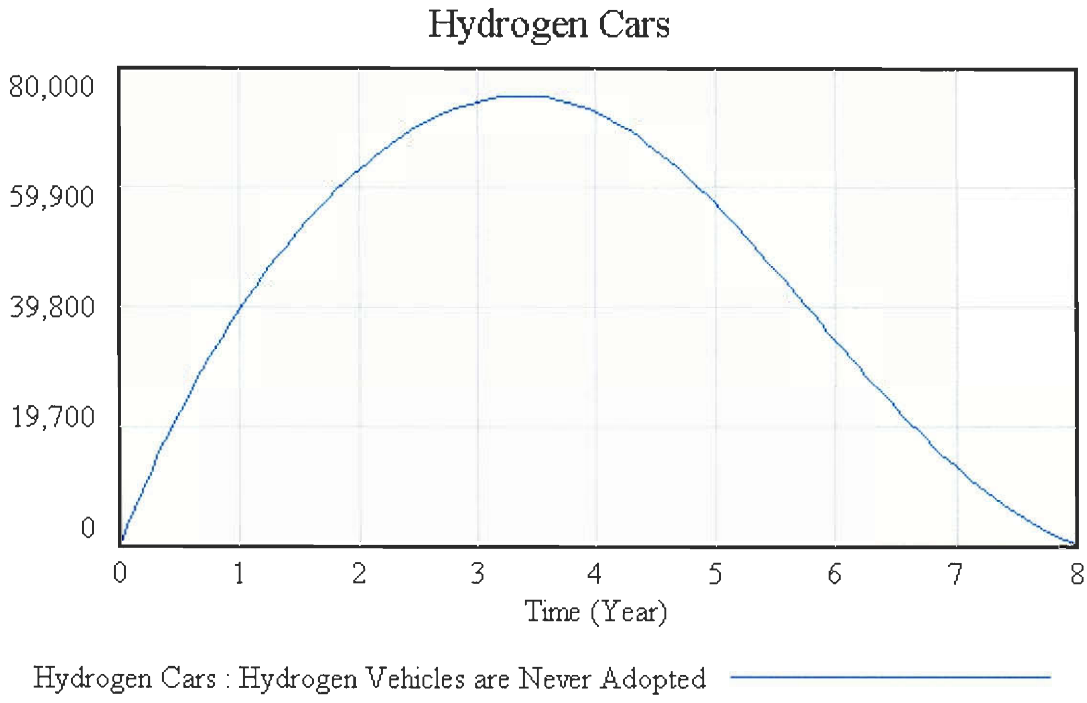

Figure 10: Hydrogen Vehicles Experience Brief Popularity

This analysis shows hydrogen cars becoming popular, and then become unfavorable. This condition is created by a slow responsiveness to fuel demand. As the growth of the hydrogen cars exceeds the distribution networks ability to provide fuel, consumers become unable to get fuel. This causes the reversion to a gasoline based fuel economy.

6.6 Hydrogen Cars Successfully Replace Gasoline Cars

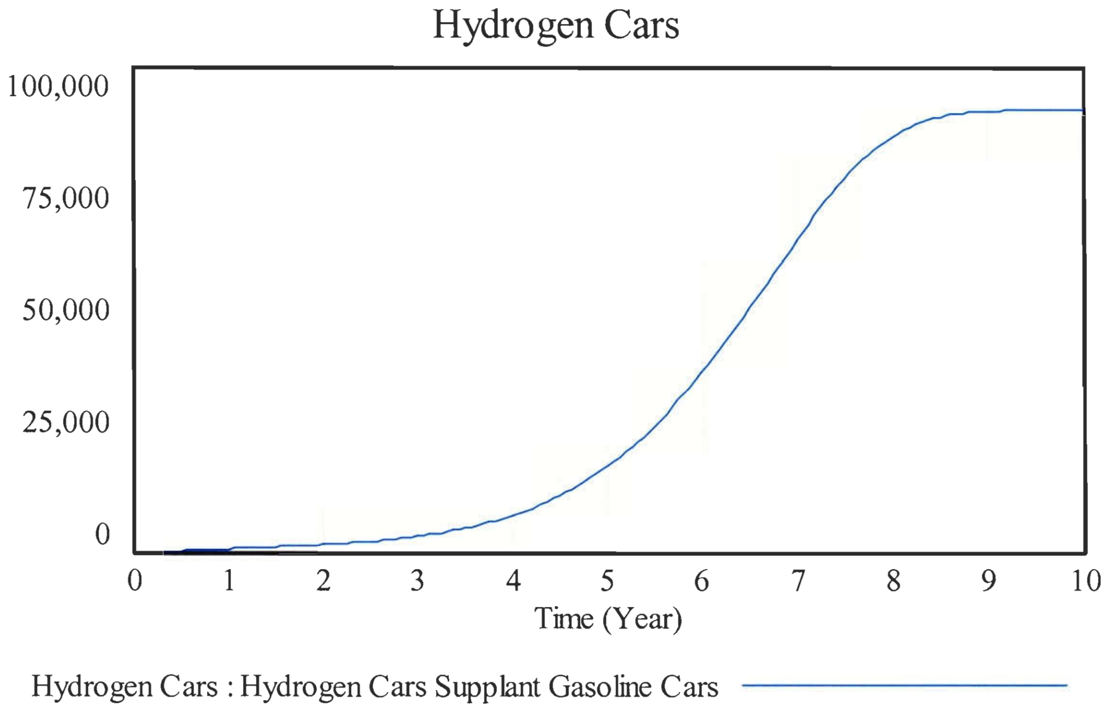

Figure 11: Hydrogen Vehicles Supplant Gasoline Vehicles Successfully

This analysis shows the ideal conversion from gasoline vehicles to hydrogen powered vehicles. This happens when hydrogen cars are cheaper, the fuel is cheaper, and the responsiveness to demand of the hydrogen distribution network is able to keep up with demand.

7. Scenario Model Comparison

With the assumption there is a demand for hydrogen vehicles; the main item of interest is which scenario reaches saturation faster. The first test is to see how much of a difference the adaptation time between the scenarios makes, each scenario was adjusted accordingly. The adaptation time was set to 3 years for Scenario Two, and 1.5 years for Scenario One. The following graph illustrates the number of hydrogen vehicles versus time where the adaptation time is the only change.

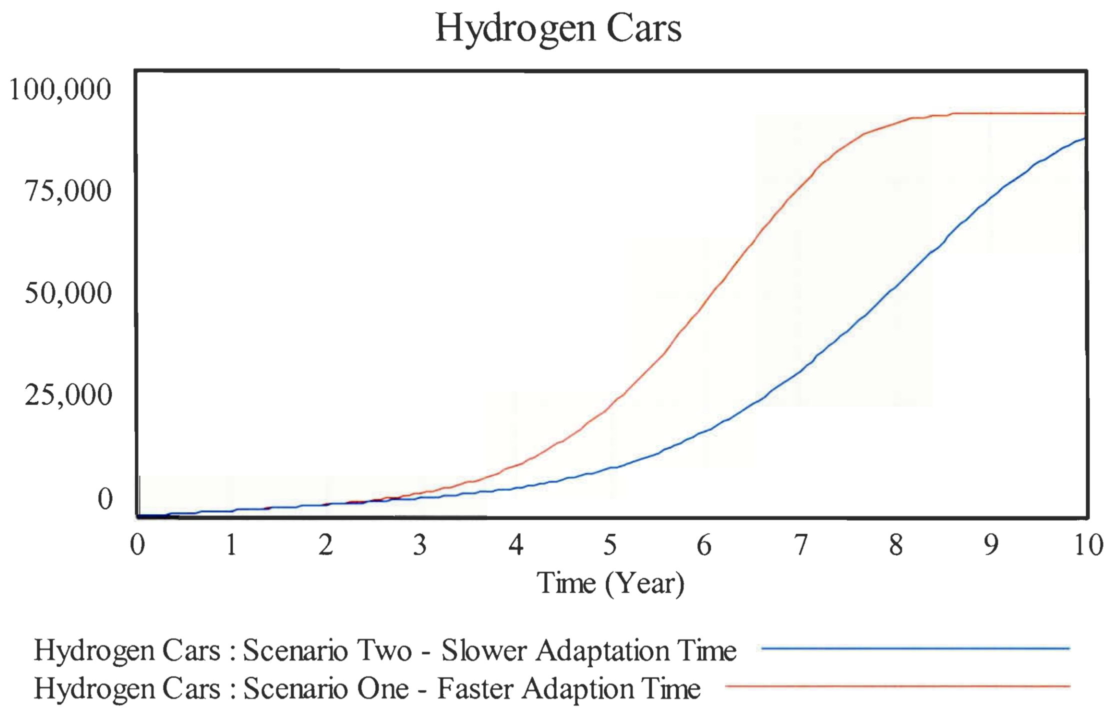

Figure 12: Adaptation Time Comparison

As the resulting graph proves Scenario One's greater flexibility and adaptation time results in Scenario One reaching hydrogen car saturation much faster than Scenario Two.

The reason behind this is because Scenario One is able to adapt to fuel demand faster, meaning there will less often be a fuel deficit.

To consider the difference in fuel cost, the adaptation time is reset so they are both equal, and the prices are adjusted. For the sake of simulation a cost of $.0618 per mile is assumed for Scenario One, and a cost of $.019 per mile is assumed for Scenario Two.

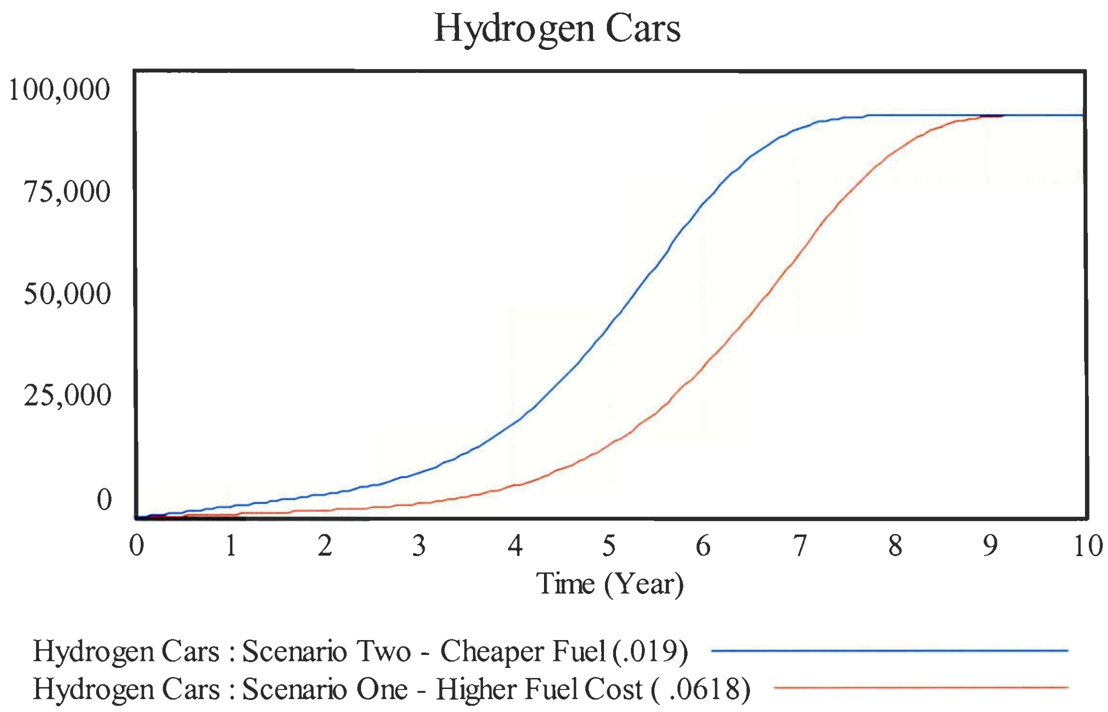

Figure 13: Fuel Cost Comparison

As expected the increased cost of hydrogen fuel production in Scenario One causes it to lag behind Scenario Two in hydrogen vehicle saturation. The next step is to set both the adaptation time and the fuel cost at the same time, to see which scenario performs best overall. Using the same adaptation times and fuel costs from the previous simulations, the following graph results.

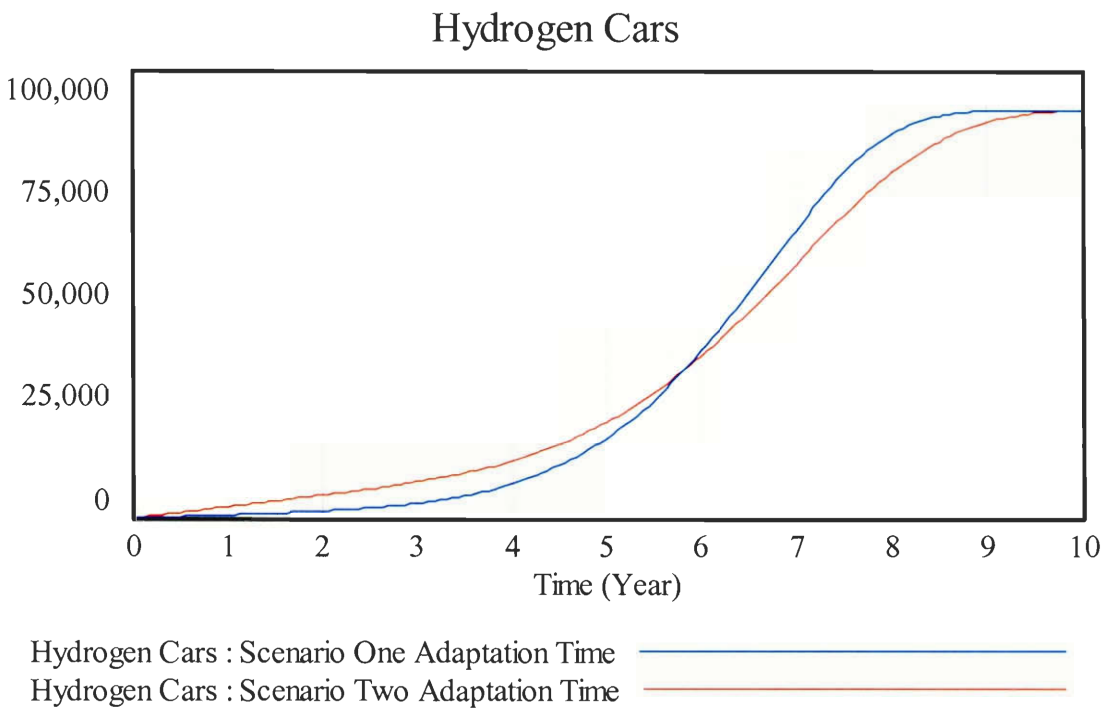

Figure 14: Combined Adaptation Time and Fuel Cost Comparison

With the major differences in each scenario accounted for, they behave very closely. In the end however, Scenario One saturates faster than Scenario Two. This result can be explained by analyzing the comparative Relative Fuel Supplies.

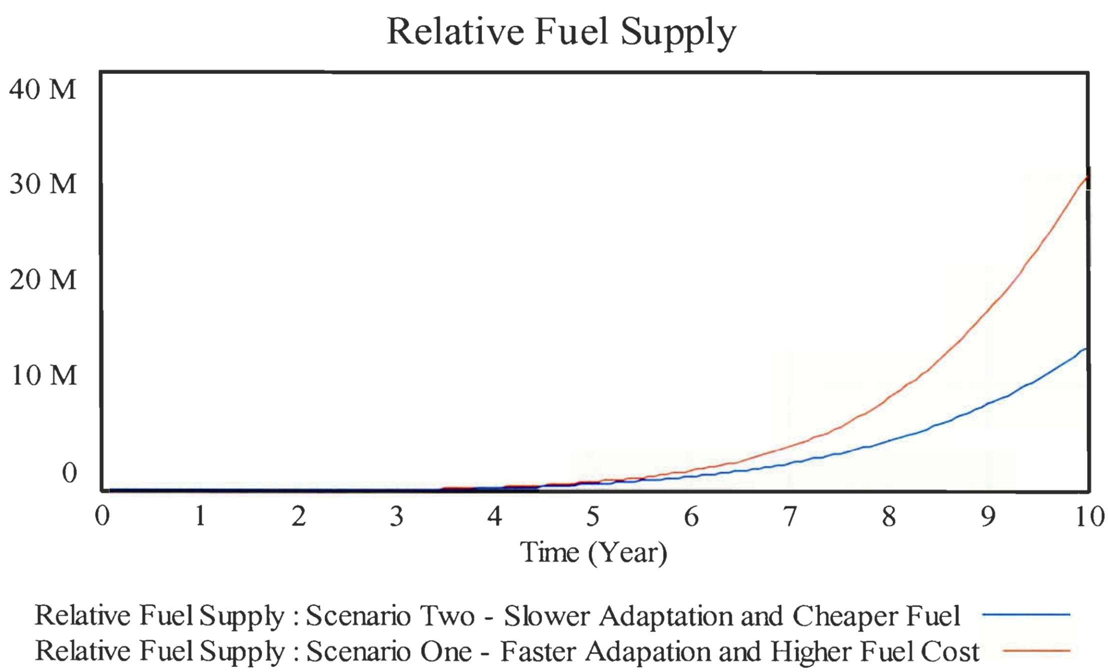

Figure 15: Relative Fuel Supply Comparison

As the graph shows, the faster adaptation of Scenario One allows the Relative Fuel Supply to closely follow the Fuel Demand. Since the fuel is more readily available, consumers are more likely to switch to a hydrogen powered vehicle, even if the fuel is somewhat more expensive. This is the expected outcome, as most consumers are not as concerned about fuel cost and efficiency as they are about convenience.

Overall the comparative system dynamics model simulated the growth of hydrogen vehicles for both scenarios very well. The model provides a realistic diffusion and growth model that exhibits realistic behavior for both of the scenarios. There are also other considerations for hydrogen growth, such as what would happen if hydrogen vehicles never caught on or if they were to fail after becoming popular. Both of these possibilities are discussed in the following section. In terms of comparing both Scenarios, the first is clearly the superior hydrogen distribution method, as its faster adaptation time allows it to better meet fuel demands. Available but expensive fuel is better than unavailable but cheap fuel.

8. Conclusions

With both of the scenarios fully defined, it becomes possible to compare them in terms of their overall ability to successfully provide end users with hydrogen fuel for their vehicles. The most important methods of a hydrogen distribution infrastructure are the cost, reliability, responsiveness to fuel demand, and the plausibility of each method. From the above research, it is clear that the centralized scenario provides the consumers with a reliable and inexpensive fuel supply. At the same time the centralized distribution method reacts slowly to consumer demand and is harder to implement, as a large factory has to be constructed all at once. On the other end of the spectrum, the decentralized distribution method would provide a more expensive and possibly less reliable fuel supply. This is because of the mixed production methods this scenario would rely on to produce the fuel. However this scenario would react quickly to consumer demand and be easy to piecewise implement. Individual refueling stations could switch to hydrogen fuel one-by-one, instead of an entire infrastructure having to be brought online at once. With the fundamentals of each scenario laid out, it is important to compare them in terms of plausibility. It is also important to note that no environmental concerns were addressed within either scenario. It is extremely difficult to estimate environmental impacts regarding hydrogen distribution infrastructures, and the inclusion of such impacts would only confuse the comparison.

In an end result, with every automotive being powered by hydrogen, the centralized distribution method would be superior. The reliability and price make it superior to a decentralized distribution method. More important than the saturation case, is the growth of the hydrogen vehicles. Centralized distribution would take a massive amount of capital and time to implement, and would be extremely risky for investors to pursue. What would be more likely is the slow growth of hydrogen refueling station by station, which is characteristic of decentralized distribution. As a result, decentralized distribution is the more realistic scenario, and would be the most likely to take place and succeed in a real world environment. Outside of the academic vacuum, the most likely scenario to take place would be a marriage of both centralized and decentralized. In other words, remote production facilities and individual refueling stations would both begin producing hydrogen for consumption.

Appendix A1

	Quantitative	Qualitative
Amount of Hydrogen required per car per day	X	
Water requirement for electrolysis	X	
Electricity requirement for electrolysis	X	
Requirements for sub processes of electrolysis		X
Water requirement for natural gas reforming	X	
Natural gas requirement for natural gas reforming	X	
Electricity requirement for natural gas reforming		X
Space requirement for electrolysis	X	
Available electricity	X	
Available water	X	
Available natural gas	X	
Available space	X	
Population of vehicles	X	
Space required for hydrogen storage	X	
Reliability for each scenario		X
Costs for each scenario		X
Space for decentralized scenario	X	
Space for centralized scenario		X
Trucking calculations	X	
Trucking costs	X	
Hydrogen pipeline network		X
Gasoline fuel cost	X	
Hydrogen fuel cost	X	
New gasoline vehicle cost	X	

Figure A1.1: Quantitative and Qualitative Measurements

End Notes

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