Cornell University

School of Civil and Environmental Engineering

Managing the Hydrogen Transition:

Project Management Issues in Development of Infrastructure and Vehicles for the Proposed Use of Hydrogen as a Transportation Fuel

Academic year 2003-2004

Executive Summary

Apart from management and technology oriented coursework, the Master of Engineering (Civil) in Engineering Management program at Cornell University requires candidates to undertake a Design Project in order to matriculate. This report is a compilation of the mode of operation, findings, results and conclusions of the *TransHydroGen Group* for our Design Project from August 20th 2003 to January 2004.

We coined the name *The TransHydroGen Group* from the fact that we were charged with the task of investigating trends of the transition to hydrogen as a fuel for passenger vehicles in the near-, mid- and long- terms. As crude oil reserves decline steadily over the years, there has been increasing concern over what future generations will rely upon to provide energy for daily operations. This issue is compounded further by the dire need to curb engine emissions that have been proven to gravely affect both the environment and human health. This report is divided into four parts that each refer to different aspects of the transition to a hydrogen economy.

The near-term issues The scope for the near-term group covered the development of a cost estimation model for the Hydrogen Fuel Cell Vehicle, calculated over the near-term period (2003 to 2004). In order to do this, we considered the major sub-systems in the vehicle that contribute to the total cost. These subsystems are Fuel Cells, Hydrogen Fuel Storage and Balance of System.

Fuel Cells - This subsystem was further broken down into components and analyzed. However, the fuel cell cost model developed was not disaggregated into component costs. The cost was found to be largely affected by amount of production and technology changes over time. Based on these two parameters, optimistic and pessimistic scenarios were used to develop linear and non-linear models for projecting cost of fuel cells from 1990 to 2020. From this, a calculator was created to predict costs for any future time period. From our model, if mass production (500,000 units) was started today, fuel cells would cost $125/ kW, $86/kW in 2010, $50/kW in 2020, and about $34/kW by 2030.

Hydrogen Fuel Storage - Both on-board reforming and on-board storage modes were studied, and on-board storage was decided upon as supported by industry trends, plus factors such as safety or weight. Based on mass production and improvement of technology over time, a model was created to estimate cost trends from 2003 through 2020. In general, a light duty FCV (Fuel Cell Vehicle) requires 5kg of hydrogen (equivalent to 19 liters; 5 gallons of gasoline) at 34.5 MPa (5,000psi) for 300 miles range, and we adopted this as our on-board tank capacity. This plays out to a cost of $595/Kg H2 today, $348/kg H2 by 2010, and about $206/kg H2 by 2020 if we went into mass production.

Balance-of-System Cost - The balance-of-system cost for the FCV is based on the cost of an ICE (Internal Combustion Engine) vehicle, where the average price of an ICE passenger vehicle is estimated at $18,000 and the cost of an 110kW ICE engine plus other engine-related accessories is approximately $8,000. Using these values, the balance-of-system cost was then calculated as $10,000 currently. A linear regression model was hence developed to estimate future balance-of-system cost as the hydrogen economy emerges. This model was developed using the Producer Price Index for passenger car bodies and inflation rates for the United States based on GDP (Gross Domestic Product) and CPI (Consumer Price Index).

Cost of a Hydrogen Fuel Cell Vehicle (HFCV Cost) - Given the three major subsystems analyzed, we developed a calculator that links all the different cost contributors to obtain an aggregated HFCV cost over time. The values obtained from this calculator are based on year x, number of mass production units started by year x, and the effective power of the fuel cells stack used (in kW). The calculator gives values from optimistic and pessimistic scenarios. On average, and assuming mass production were to begin, a standard 100kW FCV equipped with a 5kg H2 tank would cost approximately $28,880 today, $24,870 in 2010, and about $22,160 by 2020. Since we are not in mass production today, our model estimates an optimistic price tag of $220,000.

The long-term issues Secondly, the long term transition part of the report focuses on a first-pass assessment of the main variables affecting and affected by the transition from conventional passenger cars to fuel cell vehicles, from point of launch of the technology to the point where carbon-free hydrogen becomes the dominant fuel for passenger transportation. The creation of a correlation diagram (i.e. a diagram identifying main variables and their relationship to each other) was the first important step towards a more holistic understanding of the issues related to the hydrogen transition. Its analysis encouraged the creation of a model projecting variables of interest up to the end of the 21^{st} century.

This World Hydrogen Transition Model embraces the whole world and is built as a database, allowing the use of extensive resources along with rigorous data management. Its main outcomes are the projections of Gross Domestic Product (GDP), total vehicle kilometers travelled (VKT), world energy use and carbon emissions. Output from the World Hydrogen Transition Model was validated using current numbers as well as projections of energy use and carbon emissions. These include recognized scientific literature on the subject such as reports by the Intergovernmental Panel on Climate Change. The model's parameterization and user-friendly interface make it an ideal tool for scenario analysis and decision-making. Different scenarios were analyzed by the team, allowing the visualization of baseline, optimistic and pessimistic scenarios.

In addition, an extensive analysis on costs gave the team the opportunity to get a much fuller picture on issues surrounding the transition. Projections of future trends in fuel prices were calculated and the variations of these values analyzed, highlighting the fact that a successful transition will only be possible if economic, technical and environmental factors are mastered.

The Pilot Project The third part is concerned with the Los Angeles, California, pilot program: a trial introduction of hydrogen fuel cell vehicles and refueling stations. This ambitious project serves as a testbed for technology refinement, infrastructure service, cost and public support before a nationwide hydrogen rollout occurs. It is a collaboration among various levels of the government and the auto and energy industries, led and largely funded by the federal government. The program consists of a preparatory stage followed by two phases of vehicle and infrastructure introduction. Preparation begins as soon as possible and operation is planned to begin in 2010. Each operational phase concludes with a detailed objective evaluation, at which point the project can proceed to the next stage, stop entirely or continue temporarily in the current stage. The project ends no earlier than 2013 and will cost approximately $600 million, shared among all involved. 8,200 fuel cell vehicles and 43 hydrogen fuel stations will be introduced and tested in the greater Los Angeles area, involving 6,000 public participants and 10% of the downtown L.A. taxicab fleet. A software simulation is available to support the optimization of program designs.

Design of a fueling station Finally, the fourth part of this report is devoted to the first outcomes of a team that emerged in the January intersession to start the design of a hydrogen fueling station. This design is made in the context of a competition proposed by the National Hydrogen Association that requires students to work on several important aspects of such a fueling station, such as technical, economical, environmental, safety and marketing issues. It will go on after the end of the CEE 591-592 project. However, several interesting outcomes are already included in this report. First of all, the analysis on the production of the hydrogen that would be provided to the station. It was decided that one of the most economical and yet renewable way of producing it in this context would be the use of Municipal Solid Waste, processed to natural gas and hydrogen. Thereafter, a first analysis of major components is included, most notably the primary design of the fuel dispenser. Finally, an analysis of the overall process is included as a systems overview of the fuel station.

Enclosure: *All models developed as well as the simulation software are included in a CD that can be found attached to this report. An electronic version of this report is also included. A complete list of the items on this CD can be found in appendix A.*

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Contents

Part I

Introduction

Chapter 1

Introduction

1.1 The M.Eng (Civil) Management Program

The Master of Engineering (Civil) Degree is an Engineering Management-focused, intensive, one-year program offered by the School of Civil and Environmental Engineering at Cornell University. Students in the program represent an array of nationalities, and come from the various engineering disciplines offered around the world, which include computer science, operations research, industrial, civil, mechatronics, computer, chemical, mechanical, materials and electrical engineering.

The program is scheduled into 3 terms: Fall Semester, Winter Intersession, and Spring Semester. The Winter Intersession is dedicated entirely to the Design Project. To matriculate, an M.Eng candidate must complete a minimum of 8 courses plus a Design Project, comprising a total of 30 credit hours. While the Engineering Management candidate is required to take certain mandatory courses (Project Management, Engineering Management Methods, Design Project), there is generally great flexibility in options that enhance management skills. The program thus includes ". . . management science, project management, decision and risk analysis, information technology, finance and accounting and organizational behavior..." More information about this program can be found on the web (CEE, [1]).

1.2 The 2003/2004 M.Eng (Civil) Management Design Project

The design project is formatted to provide a platform for the M.Eng (Civil) degree candidates to experience first-hand real-life management in technology-based situations. This year saw an introduction of two separate projects in the M.Eng (Civil) Management design course, which are:

1. The Transition to Hydrogen Energy project,

2. The Construction Litigation project.

1.3 The TransHydroGen Group

The "TransHydroGen" name was coined from the fact that we were charged with the task of investigating trends of the transition to hydrogen as a fuel for passenger vehicles in the near- , mid- and long- terms. This report is a compilation of the mode of operation, findings, results and conclusions of the TransHydroGen Group in our project work from August 2003 to January 2004.

The United States has recently made a national commitment to research and development that would, if successful, lead to the use of hydrogen as a replacement for gasoline in light-duty passenger vehicles for the future. At the same time, the transition from current technology to the production and distribution of hydrogen, as well as the creation of a manufacturing infrastructure to support hydrogen-powered vehicles is seen by many as a formidable obstacle to the proposed transformation of our transportation system, even if all technological hurdles in the design of the vehicles themselves are overcome.

As crude oil reserves have declined steadily over the years, there has been increasing concern over what future generations will rely upon to provide energy for daily operations. This issue is compounded further by humanity's dire need to curb engine emissions that have proven to gravely affect the environment and human health. The centrality in occurrence of major oil reserves (in the Middle East), the potential for monopolistic control and the lack of self-sufficiency in other nations certainly raise concerns, one of which is national security. The ever-growing need to adopt cleaner, safer, reliable and sustainable energy has led 21st Century scientists and environmentalists to give another look at alternative energy sources.

Hydrogen is certainly one of these alternative paths, and hence our work on this project. Over the last six months, we have studied the hydrogen transition from a number of perspectives, looking at both short-term and long-term issues. Our report herein focuses on the future use of Hydrogen Fuel Cells in the Transportation Sector, primarily in passenger vehicles, from now until the year 2100.

1.4 Main Common Assumptions

Many aspects of this project involve a significant amount of uncertainty. Many different variables can be taken into account, as will be illustrated in each part of this extensive report, and all the different scenarios are influenced by strategies adopted by different stakeholders such as government, car manufacturers, environmental institutions and citizens. Some basic assumptions have been underlying the scope and the direction of our work. Here is a list of them:

1. Hurdles to fuel cell cost and storage systems will be overcome; it is only a question of when this will happen.

2. All players in the hydrogen transition (government, vehicle manufacturers, energy companies, R&D outfits, the general public) will act in good faith, without trying to distort the way the system would work ideally.

3. Only one vehicle type is being considered: light-duty passenger vehicles. This includes passenger cars and light trucks such as sport-utility vehicles and does not consider buses and freight trucks.

4. Even though hydrogen internal combustion engines (ICE) or some other technology might prove in the long run to be a superior alternative to hydrogen fuel-cells, we are limiting the project scope to FCVs, in order to keep the project scope manageable.

Chapter 2

Motivation

Why decide to work on this particular issue? What are the driving forces behind a transition to hydrogen vehicles, taking a radical turn from what has been going in the transportation industry in the past century?

1. The first answer seems quite obvious: the pressure that traditional Internal Combustion Engines (ICE) using fossil fuels is putting on the environment is affecting the Earth's climate in ways that are becoming obvious to everyone. Indeed, today 17% of CO2-emissions are due to the transportation system (Lauer, 2003, [51]). With the forecasted doubling of the number of cars by 2020, in large amount due to the explosion of the Chinese market, it is increasingly obvious that current means of transportation cannot be reproduced in developing markets without a heavy burden on the environment. A transition to carbon-free transportation systems would allow an easier implementation of production of energies in renewable ways that do not result in the production of greenhouse gases.

2. Our recent history has also shown the pressure that world oil distribution is putting on relations between countries in the international arena. A new energy system, less dependant on fossil fuels, would reduce this dependence and as a result, tensions between countries around the globe. For countries' officials, this factor may sometimes rank higher than global climate change, as illustrated by this comment by a Chinese official in the New York Times:

> [...] Zhang Jianwei, the vice president and top technical official of the Chinese agency that writes vehicle standards, said in a telephone interview on Monday that energy security was the paramount concern in drafting the new automotive fuel economy rules, and that global warming had received little attention. (Bradsher, 2003, [40])

3. In terms of health, pollution linked to transportation is said to be responsible for approximately 500,000 casualties every year, according to the World Health Organization (WHO). Transition to Fuel Cell Vehicles (FCVs) would allow the removal of these emissions from the heart of the cities, even if no permanent solution is found to produce hydrogen from renewable and non CO2-emitting sources. However, it should be noted that there is considerable effort by major manufacturers to reduce emission levels in conventional ICE vehicles.

Chapter 3

Management issues

3.1 Evolution of Team Structures

For the first half of the project, the management structure consisted of one Project Manager (PM), with one Assistant Project Manager (APM) from each team, one Systems Engineer and one Information Manager under him. The PM would be responsible for the overall execution of the project and each APM would work independent of other APMs. The Information Officer was in charge of creating a website to compile interrelated data from all three teams. The Systems Engineer would oversee all technical integration of data and resulting models from the three teams. The group members holding the above-mentioned posts were also group members of one of the three teams.

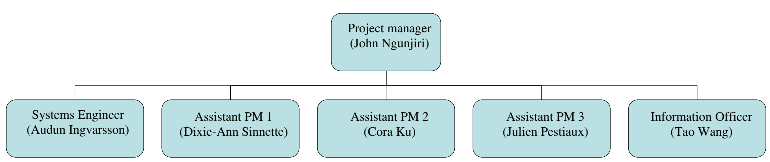


Figure 3.1: Illustration of team structures during the first half of the project

During the second half of the project, part of the group wanted to work on a hydrogen refueling station design competition. A few members of the group were enthusiastic about this new project, while their involvement implied that less of their time could be devoted to their original assignments. Our advisor encouraged us, however, to find ways to merge both projects into our January intersession, dividing our time between them.

We first finished our previous tasks. The management structure was similar to the first half of the project, but we decided the roles of Systems Engineer and Information Officer were redundant for our project. Our project did not require integration of technical data from three teams, and we used the network drive for all data exchanges between the three teams.

After the individual team tasks were completed, the group split into two teams, a competition team and a report team. In terms of management structure, it was decided that the best way to solve this issue was to create two overlaying group-structures where members would belong to their original teams as well as to either the new hydrogen competition team or another team that would take up a larger part of the compiling of our report at the end of the January intersession.

Figure 3.2 shows an illustration of these two overlaying structures, and figure 3.3 shows how each team was structured. Project manager were appointed to each new team, their tasks being to facilitate communication between the two groups as well as to oversee the work to be done and allocate work concerning the write-up of the report and the final presentation.

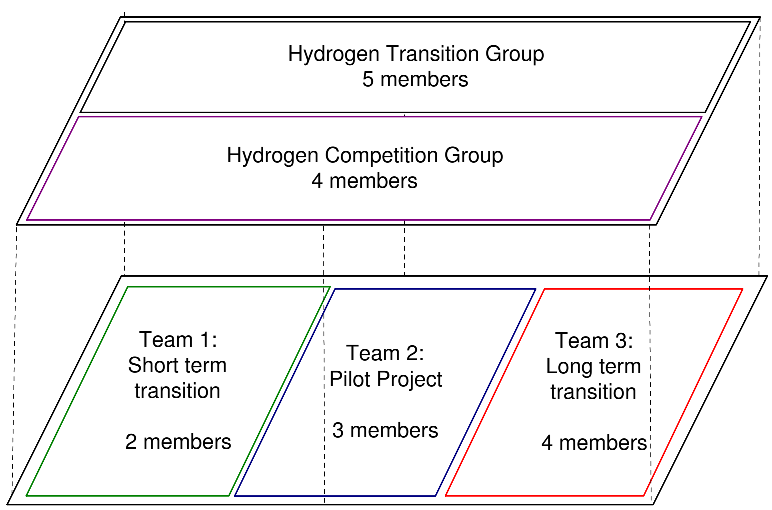


Figure 3.2: Illustration of the overlaying management structures

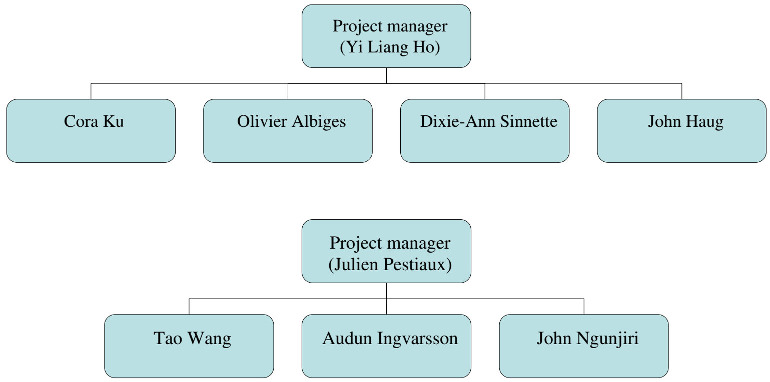


Figure 3.3: Illustration of team structures during the second half of the project

3.2 Team Timelines

This section gives an overview of the time lines of each individual team.

Time line of team 1 working on Short Term Issues	
2003	
9/1-9/15	Project initiation and readings to understand whole picture. Develop Scope Document, define variables and parameters. Compile a brief history on the alternative energy sector, focusing primarily of fuel cells and fossil fuels (for overall project).
9/16-9/30	Collect data and industry contacts for developing initial model for cost analysis of fuel cells, and storage of hydrogen. Complete review on current research on alternative energy sources and document and assess why hydrogen is the preferred choice.
10/1-10/22	Prepare overview of fuel cell manufacturers and vehicle manufacturers design. Develop initial model for cost of fuel cell vehicle over time based on mass production.
10/23	Interim presentation of findings and the overall path of project
10/24-12/4	Determine design components for project in terms of specific technologies to be used (fuel cell, reformer and vehicle). Gather costs for primary components. Create model concept for cost prediction and include timeline (from now until 2020).
12/5	Last day of classes - Group meeting and presentation
12/6-1/4	Finals and holidays.
2004	
1/5-1/13	Improve on data for hydrogen fuel cell vehicle cost model, include balance-of-system cost analysis, divide over optimistic and pessimistic scenarios, include manufacturing costs, and research on world platinum production and supply. Include information from Lomax et al report.
1/13-1/21	Transition for the hydrogen fueling station design team. Begin write-up for draft of final report and prepare presentation.
1/22	Presentation practice
1/23	Presentation
1/30	Final report

Table 3.1: Time line of team 1 working on Short term issues

Time line of team 2 working on Long Term Issues	
2003	
9/1-9/30	Start with a basic reading and understanding of the issues, variables and parameters. Build an all-including correlation chart and gather data from available literature.
10/1-10/22	Simplify the correlation chart to focus on the most important variables. Build and validate a first simple spreadsheet model focused on the USA.
10/23	Interim Presentation
10/24-12/4	Collect data and design a database to support a world model.
	Analyze the first energy simulations by comparing with oil reserves. Study and forecast fuel costs.
12/5	Last day of classes - Group meeting and presentation
12/6-1/4	Finals and holidays
2004	
1/5-1/15	Define scenarios and analyze simulations.
	Read papers by Schafer, Ogden & Nitsch.
1/15 - 1/20	Write draft report
1/21	Write presentation
1/22	Presentation practice
1/23	Presentation

Table 3.2: Time line of team 2 working on Long Term issues

Time line of team 3 working on the Pilot Project	
2003	
9/29-10/8	Make contacts to collect information on the L.A. trial project
	Gather data from available literature
10/9-10/22	Determine the amount of infrastructure (e.g. refueling points) to support population
	Determine the cost of infrastructure and the cost to government
10/23	Interim Presentation 10/25-11/2
	Determine the cost to users (fuels, vehicles, etc)
11/3-11/9	Devise strategy for transition from small trial group to entire population in the city
11/10-11/16	Research on transition from leaded to unleaded petrol
11/17-11/26	Timeline for launch of pilot project
	Length of project
11/27-11/30	Thanksgiving break
12/1-12/4	Compile data and prepare for presentation
12/5	Last day of classes - Group meeting and presentation
2004	
1/6	Read papers by Kreith & Lovin - submit summaries of key points Simulation, fleet experience
1/7	Optimistic/pessimistic scenarios
	Simulation, fleet experience
1/8	Role of industry
	Simulation, document trip breakdown data
1/9	Role of industry Simulation, document refill time
1/12	Report preliminary outline
1/13	Fuel station location (GPS) Compare 2010/2015
1/14	Gas delivery network Cash flow over time
1/15 - 1/20	Write draft report
1/21	Write presentation
1/22	Presentation practice
1/23	Presentation

Table 3.3: Time line of team 3 working on the Pilot Project

3.3 Successfully Managing the Competition

The Hydrogen Competition is a project that gathers some interesting elements of project management:

- It has a strong time constraint, with little time available and many requirements.
- Resources are complex to manage and scarce. Indeed, due to the nature of the January intersession, some members of the team were not able to join the group from the offset. Also, the group started as a team of four, a low number for a complex project.
- It implies the creation of something that has not been done before, at least at the level of the members involved. Indeed, no member of the team has an extensive background on the issue. Also, hydrogen fuel stations involve very new and little known technical skills.
- This project is also complex in that it brings together members from very different backgrounds, both in the cultural and in the technical sense: members originate from many different countries and work in field as varied as architecture, management, engineering or business.

All these factors encouraged the project managers to design a Gantt chart, a tool often used in project management and that allows them to plan their work in advance and easily visualize if the project is on schedule or not. It also make resource allocation easier. Both the Gantt chart and the resource allocation graph are included in appendix B.

Part II

Short Term Issues

Chapter 4

Introduction

4.1 Introduction

This project focuses on the use of hydrogen as an alternative energy source for light duty transportation systems. The goal is to create models that predict the transition requirements for current vehicle manufacturers. The model will consider the cost of the technology and forecast methods by which the cost can be decreased for both production of the fuel cell system, the onboard storage system and the vehicle. In the near term phase, the focus is on the feasibility of implementing hydrogen fueled vehicles based on currently available technology. The objective is to successfully manage the transition to fuel cell vehicles (FCVs) in the near-term. Specific assumptions pertaining to the near- term transition throughout the project are:

- Primary components of the FCV are the fuel cell stack and the hydrogen storage tank of light duty vehicle required 100kW fuel cell stack
- To travel 300 mile requires 5kg of hydrogen
- Component cost will decrease exponentially
- Car manufacturers will be the key player in the manufacturing transition
- The Balance-of-System (B-o-S) is $10,000 in the base year

4.2 The Fuel Cell System

History of Fuel Cells: Despite their modern high-tech aura, fuel cells have actually been known to science for more than 150 years. English lawyer turned scientist, William Robert Grove (1811 -1896), invented the "Grove cell," using a platinum electrode immersed in nitric acid and a zinc electrode in zinc sulfate to generate about 12 amps of current at about 1.8 volts. Grove realized that by combining several sets of these electrodes in a series circuit he might "effect the decomposition of water by means of its composition." He soon accomplished this feat with the device he named a "gas battery"- the first fuel cell. Others who have made significant contributions include Chemist Ludwig Mond (1839 -1909) Friedrich Wilhelm Ostwald, a founder of the field of physical chemistry (1853 -1932), William W. Jacques (1855 -1932) an electrical engineer and chemist, Emil Baur (1873 -1944) of Switzerland, and Francis Thomas Bacon (1904 -1992).

PEM technology was invented at General Electric in the early 1960s. The unit was fueled by hydrogen generated by mixing water and lithium hydride. The cell was compact and portable, but its platinum catalysts were expensive. In the late 1980s and early 1990s, Los Alamos National Lab and Texas A&M University experimented with ways to reduce the amount of platinum required for PEM cells. Recently PEM developers added the weatherproofing material Gore-Tex to their cells to strengthen the electrolyte. Researchers at the Gas Technology Institute (GTI) have verified excellent long-term performance and stability of advanced proton exchange membrane (PEM) fuel cell components. When properly designed, these components can achieve lifetime performance that meets or exceeds automotive and portable power market requirements, and possibly the continuous-duty needs of stationary power customers. In 1995, Ballard Systems tested PEM cells in buses in Vancouver and Chicago and later in experimental vehicles made by DaimlerChrysler. Early in 2000, AeroVironment selected PEM technology to provide nighttime power for its solar-powered Helios long-duration aircraft. As air quality regulations grow steadily stricter, automotive research has taken on new urgency and refreshed focus on PEM Fuel Cells and other fueling alternatives that meet these regulations.

PEM Fuel Cell Technology: The PEM fuel cells work with a polymer electrolyte in the form of a thin, permeable sheet. This membrane is small and light, and it works at low temperatures (about 80°C, or about 175°F). Typically, other electrolytes require temperatures as high as 1,000°C (Milliken, J. et al, 1998, [9]). The process is silent and is capable of converting hydrogen to electrical energy at efficiencies that are greater than two times that obtained from an internal combustion engine.

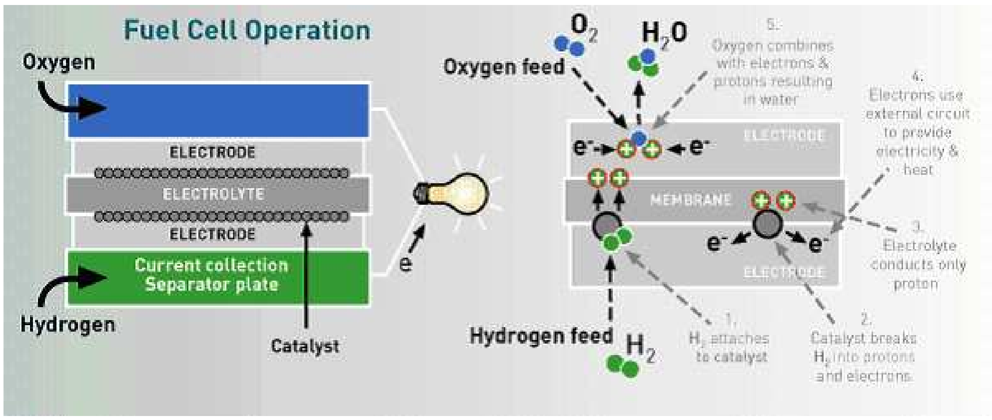


Figure 4.1: Schematic of the Fuel Cell ([**?**])

The Chemistry of a Fuel Cell: In principle, the redox reaction (reduction and oxidation reaction) occurs at the anode and cathode sites of the fuel, with the production (tailpipe exhaust) being simply- water!
Anode side:

$$2H_2 => 4H^+ + 4e^- \tag{4.1}$$

Cathode side:

$$O_2 + 4H^+ + 4e^- => 2H_2O \tag{4.2}$$

Net reaction:

$$2H_2 + O_2 => 2H_2O \tag{4.3}$$

To speed up the reaction, a platinum catalyst is used on both sides of the membrane. Hydrogen atoms are ionized at the anode, and the positively charged protons diffuse through one side of the porous membrane and migrate toward the cathode. The electrons pass from the anode to the cathode through an exterior circuit and provide electric power along the way. At the cathode, the electrons, hydrogen protons and oxygen from the air combine to form water. For this fuel cell to work, the proton exchange membrane electrolyte must allow hydrogen protons to pass through but prohibit the passage of electrons and heavier gases.

Unit Cell Voltage	0.8 Volts
Current Density	310 mA/cm^2
Power Density	250 mW/cm^2
Temperature	80 °C
Net Power	50 kW
Number of Stacks in Series	2
Current	186 Amperes
Unit Cells per Stack	188
Active Area	600 cm^2

Table 4.1: Fuel Cell Stack Statistics (Arthur D. Little Report, 2000, [24])

Chapter 5

Developing the Cost of Fuel Cell Passenger Vehicles

As an emerging technology, a general assumption of the hydrogen infrastructure project was that cost of the FCV would exponentially decrease over time as the technology matures and there are minimal returns from further development. The cost of the FCV is heavily weighted by the cost of the primary sub-systems, defined in this project as the fuel cell system and the on-board hydrogen storage tank, the remainder of the vehicle was defined as the balance of system. Consequently, the cost models developed for the primary component systems and a balance of system model were used to calculate the overall cost of a FCV. The overall methodology used in developing the FCV cost model is outlined in Figure 5.1.

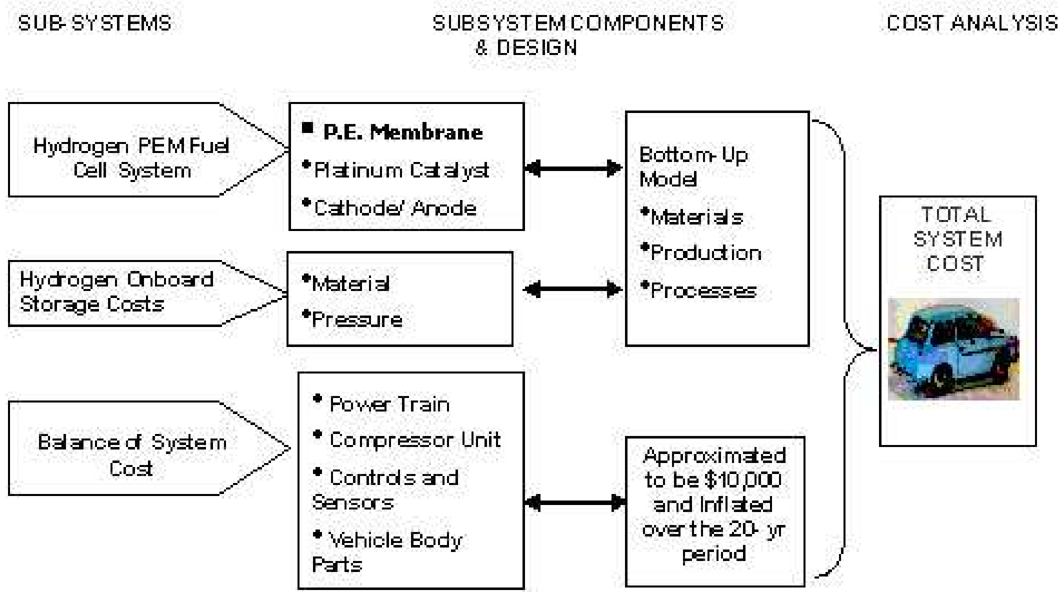


Figure 5.1: Development of FCV Cost Model

5.1 Model Methodology

Subsystem Cost-Exponential Models The fuel cell and hydrogen storage models were formulated by fitting existing or calculated information to exponential curves using Microsoft Excel software. The curve obtained gives the asymptote as the x-axis, which would inaccurately indicate that the cost of the hydrogen technology would eventually be zero. To correct this inadequacy the curves were adjusted to reflect the cost of one unit as:

$$Cost(x) = A \times exp^{-Bx} + C \tag{5.1}$$

Where: A = the current cost of the tank,
B = the exponential coefficient,
x = the numbers of years,
C = constant defining the asymptote value of minimum cost.

For each dataset two exponential curves were derived, the first curve being the unrestrained output using the software and the second curve from restraining the y-intercept to the current cost of the system. Unless otherwise supported by the literature reviewed, the difference of the y-intercepts of the two curves was defined as the asymptote value and the minimum expected cost of the system. The unrestrained equation was then adjusted to reflect the form shown in equation (5.1) using the derived asymptote value as 'C'.

Deriving optimistic and pessimistic scenarios By using the method described above, adjusted cost curves were obtained for both the storage and fuel cells systems. In each case the adjusted curves reflected costs that were higher than industry targets within a given year. Therefore, for this report to be as unbiased as possible the curves reflecting industry data were presented as the optimistic cost curves and the adjusted curves as the pessimistic cost curves. The average value of the two scenarios formed the baseline cost case.

Interpolation Methodology Costs of the primary components of the FCV were calculated for production of one unit and 500,000 units. However, realistically the production of the components or the FCV is not expected to move from prototype directly into full capacity mass production. To account for the transitional phases that will occur as the hydrogen economy emerges an interpolation methodology was developed.

Weighted (Non-Linear) Interpolation As the hydrogen transition occurs and production of FCVs approaches mass production capacity, the cost of the primary components at various production numbers will influence the overall vehicle cost. To represent bias for mass production, production at 500,000 units was assigned a weight of '1'and production at 1 unit was assigned a weight of '0'. To show the cost possibilities of production over one unit but less than mass production a logarithmic fit was used. Considering an FCV pilot project as utilizing 2200 units, the weight of mass production on the cost of 2,200 units was given as 0.1. Separate logarithmic curves were used to fit weights between 1 and 2200, and between 1 and 500000. From these two fits an overall curve was developed which gave the weight model equation as:

$$y = 0.926 \times ln(x) - 0.2649 \tag{5.2}$$

Where: y = weighted value of mass production
x = production number

The weight of the unit production was then taken as the difference $1-y$. From the overall log fit the production weights were calculated. The graph in figure 5.2 of the hydrogen storage cost model shows that increasing production results in a favorable decrease in cost that will favor the initiation of a pilot project while still reflecting that the technology is still at a costly immature phase.

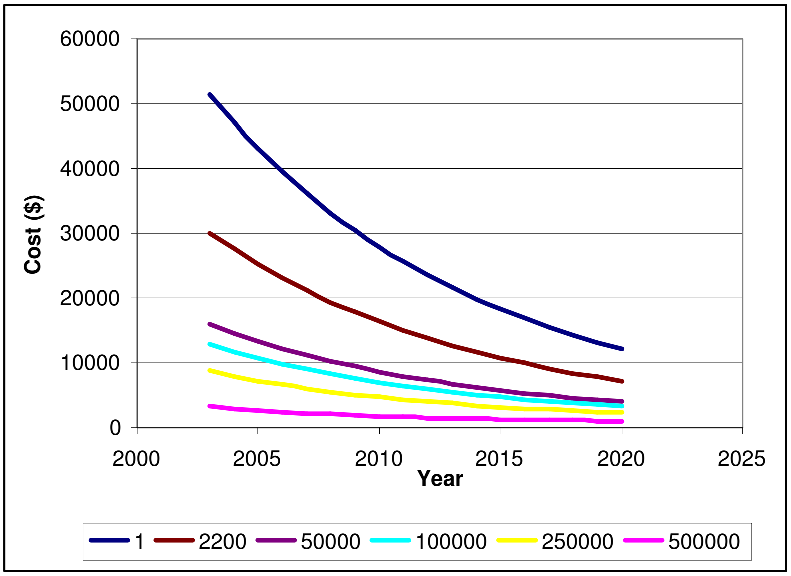


Figure 5.2: Hydrogen Storage Cost Model using Non-Linear Interpolation

Chapter 6

Fuel Cells Cost Model

In deriving the cost of fuel cells, factors such as cost of unit production, mass production and dynamics in the two production states over time were considered. Over the last 15 years there have been drastic declines in fuel cells cost, owing to factors such as government interest and support of the hydrogen energy sector, reducing the catalyst (platinum) loading per stack, proton exchange membrane and bipolar plate development, fuel processor improvements, development in the compressor units, and general awareness and extra effort by stakeholders in realizing the impact the whole phenomenon will have when it penetrates the energy sector. In our cost projections, we did not consider variables such as

- Annual Stack Efficiency Degradation (typically 0% to 1% annually)
- Fuel Cell Stack Waste Heat
- Buy-back Price

6.1 Rational for using 100kW Engine Power

In this project, the focus was on passenger vehicles, whose need for power is relatively lower as compared to commercial vehicles. From industry data and government agencies in the energy sector as shown in Table 6.1 it was deduced that 100kW was a sufficient rating for a mid-sized passenger vehicle. Similarly, most ICEs are rated at approximately 112 - 164kW.

Stationary	5 kW - 40 MW	Residential and commercial power units, combined heat and power, premium power, uninterruptible power supplies
Portable	1-50 kW	Wheel chairs, golf carts, truck and rail refrigeration units, road signs, space vehicles and satellites
Mobile	25-150 kW	Light- and medium-duty vehicles, buses, industrial trucks, naval and submarine vessels
Micro	1-500 W	Cell phones, personal digital assistants, notebook computers, some military hardware, portable electronics

Table 6.1: Applicable Fuel Cell Power Ratings ([37])

6.2 Comparison of ICEs and FCV Engine Power

Our assumption on 100kW power rating for the HFCV is further supported by comparable ICE vehicles as portrayed in Table 6.2.

	HP	kW
Dodge Neon 2004	132	98.5
FCV Model	134.1	100
Chevrolet Impala	155	115.58
Toyota Camry LE	157	117.07
Honda Accord	160	119.31
Ford Taurus	200	149.14
Isuzu Rodeo SUV	250	186.42

Table 6.2: Comparable horsepower ratings of Passenger Vehicles

6.3 Unit Production Cost

Here, ”Unit”, refers to ”custom-produced”, where no significant mass production has been done. By the year 2000, a single unit hydrogen fuel cell was priced at an average of $2000.00/kW (Business Week, 2000), compared to the $43.75/kW price for gasoline engine (priced at an industry-average cost of $3,500 for an 80kW ICE). This was definitely a high price and certainly not competitive enough to impact in the ICE-dominated world. Approximately a 40-fold+ drop (1/40) in price for the fuel cell is necessary to competitively gain a niche market share in the $200 billion a year automotive engine market (Business Week, 2000). The current trend in prices is encouraging, and extrapolation of the cost data predicts that the desired competitiveness will be achieved in the near future. The following fuel cell costs were collected from different sources as indicated in Table 6.3.

Year	Cost ($/kW)	Source
1990	5,000	Thomas & Kuhn, 1995
1997	3,000	Barbir & Gomez, 1997
2000	2,000	Business Week, 2000
2002	1,000	LexusNexis™ Academy, 2003
2010	400	Our projection
2020	390	Our projection

Table 6.3: Fuel Cell Costs Data

Other supporting data from varying sources includes:

- 1998- One company commercially offered fuel cell power plants for about $3,000 per kilowatt.
- 2000- A study by Arthur D. Little, Inc., (2000, [24]) predicted that when fuel cell costs drop below $1,500 per kilowatt by 2001, they will achieve market penetration nationwide.
- 2003- Approximately $1000 per kilowatt.

It is important to note that the expected minimum cost , 'C', referred to in equation 5.1 is the industry-projected cost of fuel cells, and is optimistically projected to be $390 per kW, and pessimistically $500 per kW in 2020 without mass production. From this data, an exponential model was derived to calculate the production cost over time resulting in equation (6.1) for a 100kW fuel cell stack.

Year	Cost ($/kW)	Source
1990	300	Ogden et al, 1999
1997	200	Industry Projected
2000	100	Arthur D Little Consultants
2002	85	Industry Projected
2010	50	Ballard Corp, GM, Ford (Projections)
2020	20/39	Lomax et al. Industry Projected

Table 6.4: Fuel Cell Mass Production Cost

$$OptimisticCost_{fuelcell/kW}(x) = A \times exp^{-0.0999x} + C \quad (6.1)$$

Where: A= Industry FC Cost in 1990, $5,000/kW
x = Number of production years
C= Lowest expected cost of a fuel cell

For the pessimistic case equation (6.1) becomes:

$$PessimisticCost_{fuelcell/kW}(x) = A \times exp^{-0.0696x} + C \quad (6.2)$$

Where: A= Industry FC Cost in 1990, $5,000/kW
x = number of production years
C= Lowest expected cost of a fuel cell

6.4 Mass Production Cost

From current industry trend, our optimal mass production was defined as 500,000 units. This is supported by the US Department of Energy's Office of Transportation Technologies fuel cell database and a recent research by Arthur D Little Consultants (MA), who approximated that an optimally-operated plant would produce 0.5M units.

The expected or industry-projected lowest cost of fuel cells optimistically will be $20 per kW (Lomax et al, 1998) and pessimistically $39 per kW at mass production. From the data presented in Table 6.4, an exponential model similar to the one developed for unit production was derived to determine the cost per kW fuel cell as shown in equation (6.3).

$$OptimisticCost_{fuelcell/kW}(x) = A \times exp^{-0.0764x} + C \tag{6.3}$$

Where: A= Industry Project FC Cost in 1990, 300/kW
x = number of production years
C= Lowest expected cost of a fuel cell, 20/kW

For the pessimistic scenario equation (6.3) then becomes

$$PessimisticCost_{fuelcell/kW}(x) = A \times exp^{-0.0764x} + C \tag{6.4}$$

Where: A= Industry FC Cost in 1990, $500/kW
x = number of production years
C = Lowest expected cost of a fuel cell

Using equations (6.1-6.4), and the non-linear interpolation methodology, the optimistic and pessimistic costs of a fuel cell manufactured at production numbers ranging from 1 unit to 500,000 units were determined. Tables 6.5 and 6.6 show selections of the forecasted costs for a 100kw fuel cell stack:

	Number of Fuel Cell Produced			
Year	1	2,200	250,000	500,000
1990	$539,000	$536,770	$285,501	$32,000
2005	$150,733	$150,120	$81,135	$11,537
2010	$106,803	$87,144	$57,656	$8,509
2015	$80,145	$65,405	$43,294	$6,442
2020	$63,968	$52,181	$34,500	$5,032
2030	$48,195	$39,238	$25,803	$3,412

Table 6.5: Selected Optimistic Projected Fuel Cell Costs

	Number of Fuel Cell Produced			
Year	1	2,200	250,000	500,000
1990	$550,000	$547,730	$291,951	$33,900
2005	$226,022	$225,087	$119,730	$13,437
2010	$174,289	$141,513	$92,349	$10,409
2015	$137,760	$111,877	$73,051	$8,342
2020	$111,967	$90,960	$59,450	$6,932
2030	$80,895	$65,779	$43,104	$5,312

Table 6.6: Selected Pessimistic Projected Fuel Cell Costs

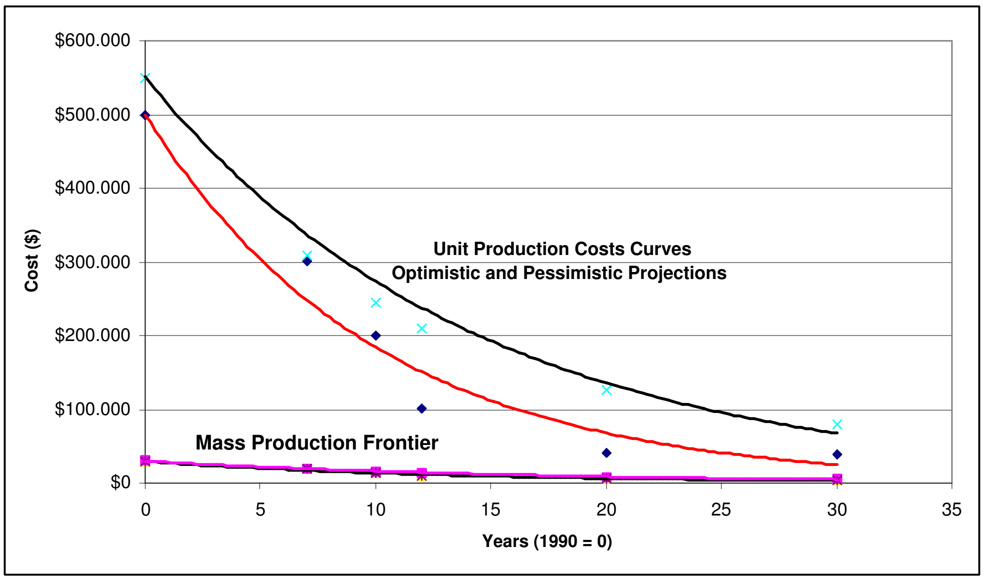


Figure 6.1: Fuel Cell Cost Model: Unit and Mass Production Showing Optimistic and Pessimistic Scenarios

In summary, the fuel cell model predicts that in 2030, fuel cells will cost $34.12 per kW (optimistically) and $53.12 per kW (pessimistically) if we entered into mass production. These figures are within industry projections of between $20.00 and $50.00 per kW in the long run. It is worth noting that the model does not consider changes in manufacturing costs such as labor and facilities, hence the slight discrepancy.

Chapter 7

Onboard Storage of Hydrogen

The introduction of FCVs in the near term is dependent on the technological maturity of the two key components: PEM fuel cells and the onboard storage of hydrogen. With respect to the storage system a major design challenge is the mass-sensitivity of the vehicle. "Each kg of energy storage on the vehicle results in a 1.3-1.7 kg increase in vehicle mass due to the additional powerplant and structure required to move and support it." The storage tanks must be lightweight to provide sufficient energy for the vehicle to achieve the target range of 300 miles. (Mitlitsky et al., 1999, [4]).

7.1 Evaluation and Choice of Onboard Storage System

The storage technology developed is expected to benefit all hydrogen powered vehicles not just FCVs. In a study conducted by Directed Technologies Inc. (DTI) and presented in 1997 the advantages and disadvantages of various systems were evaluated on the basis of weight, volume, cost, complexity, refueling impact, and development risk. Table 7.1 shows the requirements of each system.

	Compressed Hydrogen	Liquefied Hydrogen	Metal Hydride
Fuel Weight (kg)	4.7	4.7	4.7
Tank Weight (kg)	63-86	19	120
Total Weight of system (kg)	67-90	23	124
Volume(liters)	408-227	177	120
Range (km)	600	600	600

Table 7.1: On-Board Hydrogen Storage Options. (Bradley et al., 2000, [3])

Liquid hydrogen LH2, as it is often called, provides one of the lowest system volumes, along with near zero development risk, good fast fill capability, and acceptable safety characteristics. However, dormancy concerns arise due to boil-off losses that will inevitably concern the average car owner. Infrastructure impacts are three fold: first, the liquefaction process is costly, second, small-scale production of liquid hydrogen is impractical, and third, low volume distribution and dispensing of hydrogen is expensive. Consequently, liquid hydrogen will not easily support a hydrogen economy in the near term (James et al., 1997, [8]). Based on current performance, carbon adsorption systems are not competitive in terms of hydrogen mass fraction, system volume fraction, and refueling time. Carbon adsorption systems perform best at cryogenic temperatures and will only be competitive if boil off losses at room temperature decreases and a means for fast filling (<5 minutes) the system can be devised. Currently carbon adsorption systems do not achieve adequate performance for initial incorporation into FCV (James et al., 1997, [8]).

Metal hydrides These can be subdivided into two categories: low dissociation temperature hydrides and high dissociation temperature hydrides. The low temperature hydrides suffer from low H2 fraction (-2%). The high temperature hydrides require a fuel burner to generate the high temperature of dissociation (around 300°C). Both systems offer dense H2 storage and good safety characteristics. High temperature and high-energy input create the good safety characteristic of slow hydrogen release in a crash. Overall metal hydrides are either very much too heavy or the operating requirements are poorly matched to PEM vehicle systems. Without a dramatic breakthrough achieving high weight fraction, low temperature, low dissociation energy, and fast charge time, metal hydrides will not be an effective storage medium for PEM FCV (James et al., 1997, [8]).

Compressed gas Storage systems using compressed gas offer simplicity of design and use, rapid refueling capability, excellent dormancy characteristics, minimal infrastructure impact, high safety due to the inherent strength of the pressure vessel and little to no development risk. The disadvantages are system volume and use of high pressure. The many advantageous features of compressed gas storage outweigh its larger volume. Compressed gas storage is supportable by small-scale hydrogen production facilities (on-site natural gas reforming plants, partial oxidation burners, and electrolysis stations) as well as the currently available large-scale liquid hydrogen production facilities. Thus a plausible hydrogen infrastructure transition pathway exists. For these reasons, room temperature compressed gas storage is viewed as the most appropriate fuel storage system for PEM fuel cell vehicles (James et al., 1997, [8]).

Compressed gas storage is the simplest and least expensive alternative for onboard hydrogen storage (Lipman and DeLuchi, 1996, [2]). Although the energy density may be improved by increasing the storage pressure, safety issues become important. Fiber-reinforced composite (e.g., aluminum-carbon) tanks have been developed to address this issue (Lipman and DeLuchi, 1996, [2]). Thus far, tanks capable of being pressurized up to 5,000 psi are under development. In a November 2000 study for the National Renewable Energy Laboratory (NREL), the consultants of MJ Bradley and Associates found that the refilling time of compressed hydrogen tanks is similar to gasoline tanks. Also, the manufacturing technology could be similar to that used for compressed natural gas with stainless steel, aluminum or composite cylinders. Hydrogen, however, requires more volume for the same energy equivalent amount of natural gas. To increase the volume of hydrogen stored the pressure must also be increased and therefore the more expensive material is needed to construct the tanks (Bradley et al., 2000, [3]). Storage of 5kg of hydrogen (equivalent to 19 liters or 5 gallons of gasoline) is necessary for a light duty FCV to provide up to a 322-483 km range. To store 5 kg of compressed hydrogen requires a tank volume that can be packaged onto a light-duty vehicle. Therefore the tanks would need to be subjected to high pressures to ensure volume reduction. The use of insulated pressure vessels seems to be a feasible option. The insulated pressure vessel provides better on board packaging and the capacity to operate at ambient temperatures and high pressures thereby facilitating if necessary a transition from liquefied hydrogen to compressed hydrogen (Aceves and Berry, 1998, [6]). For the cost prediction model, the insulated pressure vessel was the storage system of choice using compressed hydrogen. Integral components of the insulated pressure vessel are the inner liner suitable for resisting hydrogen permeation and an exterior carbon fiber that could withstand high pressures while not significantly increasing the mass of the system. Since 1999, tanks have been designed which hold up to 3.9 kg of hydrogen with the ultimate goal being tanks with 5 kg hydrogen capacity and minimum pressure of 34.5 MPa (5,000 psi) (Mitlitsky et al., 1999, [4]).

7.2 Volume Requirements of the Hydrogen Storage System

The volume of hydrogen required contributes significantly to the mass of the storage system. Table 7.2 shows for a temperature of 20°C-100°C the volume requirements for 5kg of hydrogen at pressures in the 5,000-psi to 10,000-psi range.

The compressed hydrogen storage system for a light duty FCV requires a volume up to 60 gallons as compared to the gasoline storage system of a comparable ICE vehicle, which requires a 16-gallon storage system. The storage system in FCVs requires more space than the current ICE storage system and the system's design will have to compensate for this, ensuring that passenger space is not surrendered and safety requirements are still met.

	10,000 psi		5,000 psi	
Temperature(°C)	V(m^3)	V(gal)	V(m^3)	V(gal)
20	0.0884	23.36	0.177	46.79
25	0.0899	23.76	0.18	47.59
30	0.0915	24.16	0.183	48.39
35	0.093	24.56	0.186	49.19
40	0.0945	24.96	0.189	49.98
45	0.096	25.35	0.192	50.78
50	0.0975	25.75	0.195	51.58
55	0.099	26.15	0.198	52.38
60	0.101	26.55	0.201	53.18
65	0.102	26.95	0.204	53.97
70	0.104	27.35	0.207	54.77
75	0.105	27.74	0.21	55.57
80	0.107	28.14	0.213	56.37
85	0.108	28.54	0.216	57.17
90	0.11	28.94	0.219	57.96
95	0.111	29.34	0.222	58.76
100	0.113	29.74	0.225	59.56

Table 7.2: Volume Requirements of 5kg of H2 at varying temperatures

7.3 Hydrogen Storage Cost Model

7.3.1 Overview of Existing Economic Analysis

In determining cost of the storage system Mitlitsky and his colleagues used material and manufacturing costs as well as a 9-10% contingency markup cost. Their analysis was based on annual volume manufacturing of 500,000 units. The cost of the onboard hydrogen storage system is most strongly influenced by material cost. Preliminary economic evaluation of the hydrogen storage technology indicates the cost of various grades of carbon fiber as the major cost driver since the type of carbon fiber composites must meet or exceed the technical performance goals of the Department of Energy (DOE) at high volume production (Mitlitsky et al., 1999, [4]). The fiber cost in this analysis accounts for 60% of the overall cost. Based on the carbon fiber currently providing the highest strength-to-weight ratio and DTI's prediction of the fiber cost at $5-6/kg, the estimated cost of the pressure vessel will be $841 (2000$). This value is below DOEs targets and is based on an aggressive assumption of high volume production in 2000. Currently, the development of the storage system has yet to overcome many of material cost hindrances and the price quoted above is still unrealistic. However, from this study it is important to note the percent contributions of material and manufacturing costs as shown in table 7.3.

Cost Contributor	% Contributed
Liner	9
Fiber	60
Solenoid	8
Manufacturing	14
Cost Contingency Mark -up	9

Table 7.3: Storage Cost contributors: Taken from DTI system analysis presented by Mitlitsky et al. (1999, [4])

7.3.2 Assumptions of Cost Model

For this project the hydrogen storage cost model was based on overall estimated costs already presented in the hydrogen economy literature reviewed, the DOE's targets and engineering judgment. From the literature, the desired mass of hydrogen was set to 5 kg in a tank system capable of holding pressures up to 5,000 psi. However with continued improvements in system materials the ultimate goal are pressures of up to 10,000 psi. The model was created to predict cost of the storage system based on current dollars. As an emerging technology, the exact cost of the hydrogen storage system was not readily available. However given the cost model presented by Mitlitsky and the DOEs targets unit production and mass production costs were estimated.

7.3.3 Estimating Hydrogen Storage Cost

In the earliest phases of the FCV economy investigation the intent was to utilize an on-board gasoline reformer which converted gasoline to hydrogen on the vehicle. Gradually the focus is changing and the goal became the use of on-board storage of the hydrogen. Consequently cost estimates for a hydrogen storage system suitable for use in a light duty vehicle are not as available as estimates for the fuel cell. Therefore for this model the base year was chosen as 2003. The current cost of a hydrogen storage tank is estimated at $50,000 (Amend, 2003, [28]) and the percent contributions from Table 10 were used to validate this estimate. Based on the use of the inner liner with lowest permeability and the lightest carbon fiber, the cost of a hydrogen storage tank in 2003 was estimated. In the Mitlitsky study based on high volume production of 500,000 units, the cost is estimated for a 3.58 kg (7.9 lb) of hydrogen at 34.5 MPa (5,000 psi) stored in carbon fiber tank, with an integral solenoid and pressure relief device (PRD). The cost breakdown for the study is shown in Table 7.4.

Liner	$78
Fiber & Resin	$500
Solenoid	$69
Manufacturing	$117
10% Cost Contingency	$76
Total	$841

Table 7.4: Cost of a Hydrogen Storage Tank at high volume production: Taken from DTI system analysis by Mitlitsky et al. (1999, [4])

The exterior fiber requirements were based on the need for 100 lb of the carbon fiber to construct the 4 kg capacity storage tank. Therefore for a 5 kg capacity 125 lb of material would be necessary. The mass production cost of the fiber was given as $70/lb in the study. Estimating a three-fold increase in the prototype phase the cost of the fiber would then be $210/lb. The amount of inner liner required was estimated as 50% of the exterior fiber. The study estimated the cost of the liner as $20/lb. Again using a three-fold increase to represent unit production cost; the liner cost estimate was $60/lb. The solenoid was considered as 8% of the material cost to account for the upgrades that would be required to this technology to satisfy the current and future uses in the hydrogen storage system. The markup for manufacturing cost was also considered current, although the cost can be expected to be higher if the manufacturing area is being under utilized. For 5kg of hydrogen at the same pressure with production in the prototype phase the cost more closely matches the following numbers in table 7.5:

	Actual	Calculated
Inner liner (9% of total cost)	$4,500	$3,750
Fiber (60% of total cost)	$30,000	$26,250
Solenoid (8%)	$4,000	$2,400
Manufacturing (14%)	$7,000	$4,536
Mark up (9%)	$4,500	$3,324
Total	$50,000	$40,260

Table 7.5: Actual versus Calculated cost of a H_2 Storage System

Since the calculated and estimated values were within the $10,000 of each other the $50,000 value was used to represent the hydrogen storage system in the base year of the model. From the base year value, the cost of the system for 2005, 2010, and 2015 were predicted based on the assumption that cost would follow an exponential decay. For the 5 kg storage system the cost was as follows:

Actual Year	No. of Years	Cost ($)
2003	0	$50,000
2005	2	$40,000
2010	7	$32,500
2015	12	$15,000

Table 7.6: Cost Date for the H_2 storage system

The values were then plotted as a function of number of years to support the assumption that technological advances would account for decreasing cost over time. Using the data in Table 7.6 the exponential cost curves of the storage system shown in Figure 7.1 were obtained.

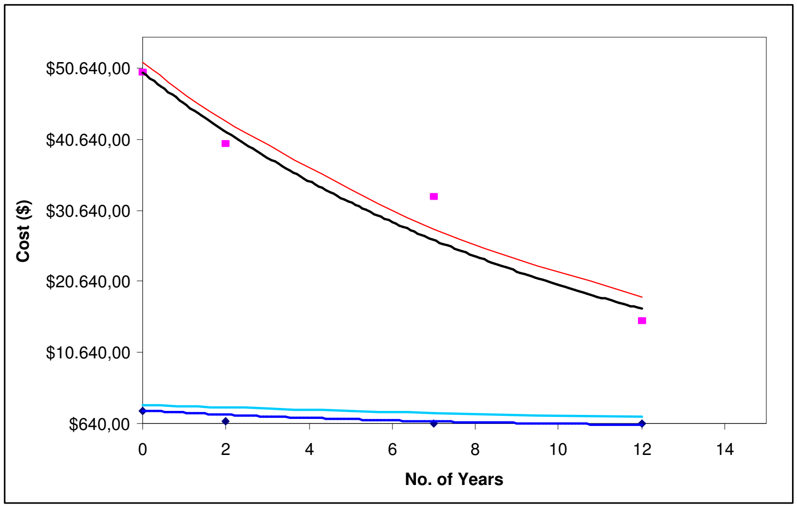


Figure 7.1: Hydrogen Storage Cost Model

The DOE's targets were used as the initial data points for the estimated cost of the storage system in high volume production. From these targets and the exponential methodology described earlier, optimistic and pessimistic scenarios were developed and show in Figure 7.1. The narrow range between the optimistic and pessimistic scenarios indicates that even in the worst case scenario the rate of decreasing cost is not expected to be drastically different from the current targets. The challenges of the hydrogen storage system are truly recognized by the stakeholders in the hydrogen economy. The cost of the specialized material needed to construct high pressure tanks that will be utilized by the general public has not been understated. Therefore the cost projection for this system captures the industry's realistic stance in addressing the challenges.

Additionally, the following equations shown in Table 7.7 were obtained to describe unit and mass production scenarios where 'x' represents the number of years.

	Mass Production	Unit Production
Pessimistic	2500e-0.0984x + 797.4	50000e-.0904x +1476
Optimistic	2500e-0.1394x +797.4	50000e-0.0909x +1476

Table 7.7: H2 Storage Cost Model Equations

At mass production a 95% decrease in the price of the hydrogen storage tank is estimated. Ultimately, the cost of the storage system in a FCV must be in the vicinity of $800 for the technology to be a competitive transportation alternative.

Chapter 8

The Balance-of-System Cost Model

The balance-of-system cost for the FCV is based on the cost of an ICE vehicle where the average price of an ICE passenger vehicle is estimated at $18,000 and the cost of a comparable 100kW ICE engine plus other engine-related accessories is approximately $8,000. Using these values, the balance-of-system cost was then calculated as $10,000 currently. The Cost for 100kW ICE Engine, plus other engine-related accessories = $8,000.

Thus: B-O-S Cost	=	$18,000
		-$8,000
Approximately	=	$10,000

For future balance-of-system cost as the hydrogen economy emerges, a linear regression model was used. The model was developed using the Producer Price Index for passenger car bodies and inflation rates for the United States based on GDP (Gross Domestic Product) and CPI (Consumer Price Index) all shown in Table 8.1.

Passenger Vehicle Bodies PPI		USA Inflation Rates	
Year	Annual PPI	CPI Based	GDP Based
1990	118.4	0.061	0.047
1991	125.1	0.031	0.034
1992	129.2	0.029	0.026
1993	133.2	0.027	0.026
1994	138	0.027	0.025
1995	139.1	0.025	0.021
1996	140.4	0.033	0.018
1997	138.7	0.017	0.017
1998	136.8	0.016	0.012
1999	137.6	0.027	0.015
2000	138.7	0.0315	0.028
2001	137.6	0.0227	0.0155
2002	134.9	0.0216	0.0142
2003	135	0.0205	0.0128

Table 8.1: Passenger Cars Body PPI, and GDP and CPI- Based Inflation Rates

From this data, the three measures were used to inflate the B-O-S cost for 1990 ($10,000) up to 2003. These inflated B-o-S costs are shown in Table 8.2. A linear curve was then fitted using Microsoft Excel for the average of these three estimates and a linear equation for Balance-of-System Cost obtained. This linear regression equation was then used to forecast inflated B-o-S values for 2004 to 2020:

$$BoS(x) = 150.8 \times x + 289585 \tag{8.1}$$

Where: x = year

From equation (8.1) all future balance-of-system costs were forecasted as shown in Figure 8.1.

Year	CPI Based	GDP Based	Passenger Car Bodies PI Based
1990	$10,000	$10,000	$10,000
1991	$10,549	$10,454	$10,273
1992	$11,004	$10,836	$10,741
1993	$11,331	$11,134	$11,199
1994	$11,647	$11,423	$11,649
1995	$11,961	$11,711	$12,184
1996	$12,270	$11,966	$12,449
1997	$12,635	$12,188	$12,603
1998	$12,931	$12,398	$12,498
1999	$13,143	$12,558	$12,268
2000	$13,440	$12,739	$12,270
2001	$13,897	$13,189	$13,184
2002	$14,230	$13,456	$13,441
2003	$14,562	$13,724	$13,697

Table 8.2: Estimated B-o-S using Inflation Rates and Passenger Car Bodies PPI

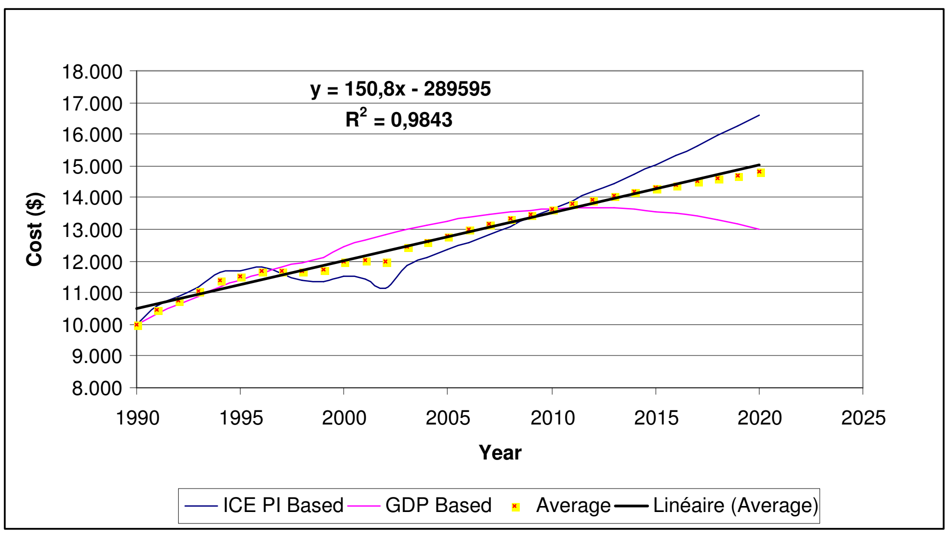


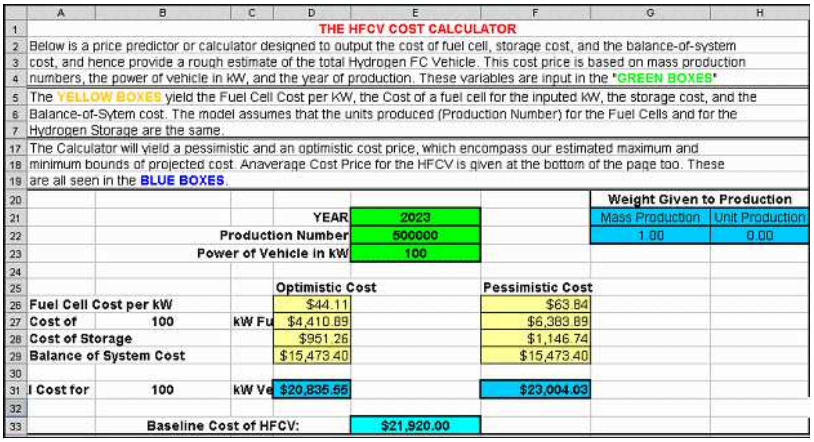
Figure 8.1: Balance of System Forecast

Chapter 9

The Fuel Cell Vehicle Price Model

9.1 The FCV Model

The price of the FCV was evaluated as the sum of the primary components namely, the fuel cell and hydrogen storage tank systems, and the balance-of-system. The exponential models for component costs and the linear regression model for balance-of-system costs determined the overall cost of the FCV as functions of production number and year. The model for determining interpolation weights was also tied to the model to ensure that the predicted cost was realistic and reflected the transition period. For the project, the FCV cost model is presented as an Excel spreadsheet calculator that allows users to input production number and year and provides a predicted cost of a vehicle indicating if the cost was weighted more by mass or unit production costs as the output. Because the exponential models predicted both optimistic and pessimistic costs of the FCVs, the calculator also gives the average of these two values as baseline cost. The output of a baseline cost is important in the pre-transition pilot phase to allow a fair estimate of cost per FCV to be represented in the roll-out budget. In the advent of a pilot, the cost of a FCV would determine the number of cars used or the margin of subsidy required from the stakeholders. A snapshot of the model is presented in Figure 9.1.



	A	B	C	D	E	F	G	H
1	THE HFCV COST CALCULATOR							
2	Below is a price predictor or calculator designed to output the cost of fuel cell, storage cost, and the balance-of-system							
3	cost, and hence provide a rough estimate of the total Hydrogen FC Vehicle. This cost price is based on mass production							
4	numbers, the power of vehicle in kW, and the year of production. These variables are input in the "GREEN BOXES"							
5	The YELLOW BOXES yield the Fuel Cell Cost per KW, the Cost of a fuel cell for the inputed KW, the storage cost, and the							
6	Balance-of-Sytem cost. The model assumes that the units produced (Production Number) for the Fuel Cells and for the							
7	Hydrogen Storage are the same.							
17	The Calculator will yield a pessimistic and an optimistic cost price, which encompass our estimated maximum and							
18	minimum bounds of projected cost. Anaverage Cost Price for the HFCV is given at the bottom of the page too. These							
19	are all seen in the BLUE BOXES.							
20							Weight Given to Production	
21				YEAR	2023		Mass Production	Unit Production
22				Production Number	500000		1.00	0.00
23				Power of Vehicle in kW	100			
24								
25				Optimistic Cost		Pessimistic Cost		
26	Fuel Cell Cost per kW			$44.11		$63.84		
27	Cost of	100	kW Fu	$4,410.89		$6,383.89		
28	Cost of Storage			$951.26		$1,146.74		
29	Balance of System Cost			$15,473.40		$15,473.40		
30								
31	l Cost for	100	kW Ve	$20,835.55		$23,004.03		
32								
33		Baseline Cost of HFCV:			$21,920.00			

Figure 9.1: Snapshot of FCV Calculator

9.2 Validation of FCV Model

For validation the estimated cost of the FCV was indexed and compared to the actual price index of other emerging technologies.

Index calculation of Emerging Technology In concept, the Producer Price Index is calculated according to a modified Laspeyres formula:

$$I_t = \frac{\sum Q_a P_t}{\sum Q_a P_0} \times 100 \tag{9.1}$$

Where: I_t = is the price index in the current period;
P_0 = is the price of a commodity in the comparison period;
P_t = is the current price of the commodity; and
Q_a = is the quantity shipped during the weight-base period.

Index calculation of FCV Using the same notation as in equation (9.1), the FCV price index was calculated as:

$$I_{FCV} = \frac{P_0 - P_t}{P_0} \times 100 \tag{9.2}$$

The weight based value Q_a was omitted since the FCV price index is based only on one product unlike the existing price index. Figure 9.2 shows the price indices for microwave ovens and colored televisions as recorded by the Bureau of Labor Statistics. Figure 9.3 shows the FCV Price Index as calculated using equation (9.2) for the scenario of 2003 being the year the technology is ramped up to mass production volumes.

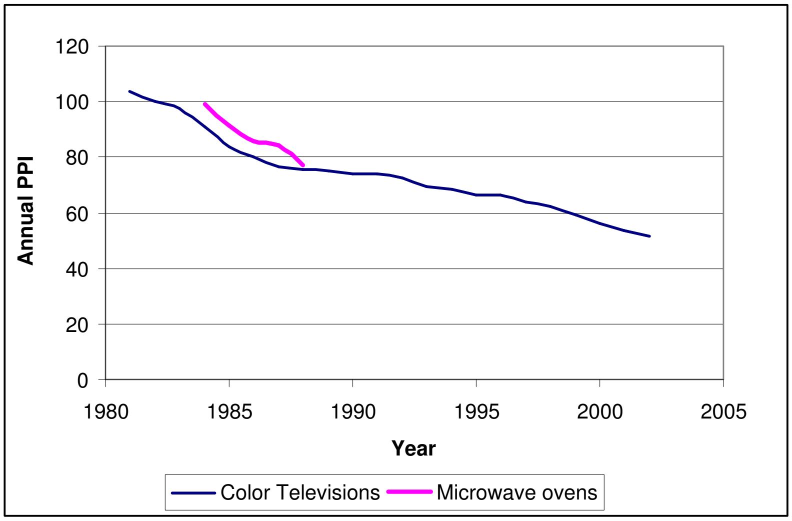


Figure 9.2: Price Index of Two Emerging Technologies

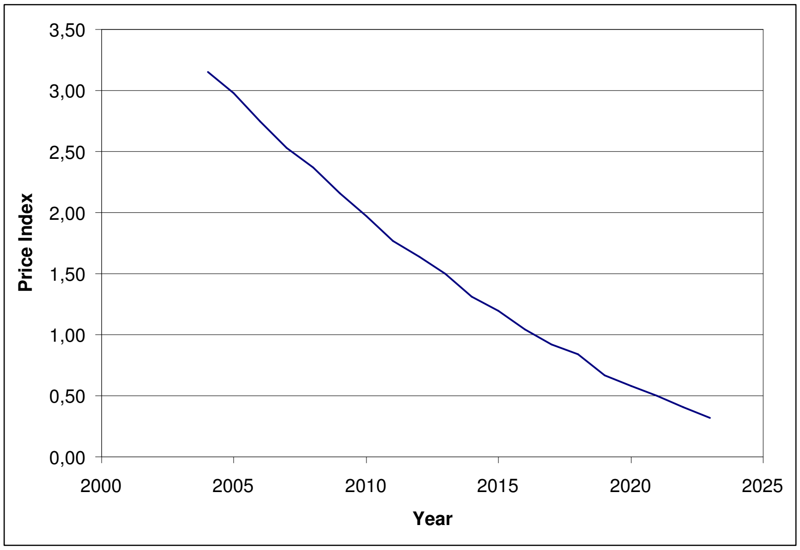


Figure 9.3: Projected Price Index of an FCV

As with other emerging technologies the price index curve of the FCV is not 'smooth' since the difference in index value is not consistent each year. In some years the price decrease is larger than in other years. The shapes of the index curves shown in figures 9.2 and 9.3 are similar with the slope of the FCV Price index curve decreasing at a faster rate. For this project, the rate of decrease of the FCV technology indicates the technology continues to improve and therefore the cost of producing the vehicles diminishes rapidly. Whereas, with the microwave or colored television the technologies are improving at a slower rate because there may not be as much incentive to improve these technologies as with the FCV economy. In fact, for most emerging consumer technologies the case maybe that they are phased out before ever transitioning to a mature technology. In this project that scenario is not foreseen for the FCV technology. The expectation of this technology is that it will eventually replace the existing ICE vehicle.

Chapter 10

Manufacturing Costs associated with the FCV Production

Although material costs are currently the largest hindrances to a hydrogen economy in the near term the manufacturing must also be considered. High volume production of the FCV and its primary components (namely the fuel cell and the on-board storage systems) will require the establishment of new production facilities or at the very least integration of new assembly lines into existing car manufacturing facilities. In the near term, based on the number of collaborative efforts between major car companies and the smaller fuel cell and on-board storage development companies, it is possible for the high volume manufacture of FCV components to occur on the same site as the vehicles, although this is not necessarily the course FCV manufacturing must take to be successful. Component manufacturing may occur at smaller facilities and transported to the FCV site with cost of component delivery then factored into the overall cost of the FCV. Consequently FCV manufacturers will need to identify which of their existing sites can accommodate the new technologies and whether component assembly will be accommodated onsite. The primary concern should be on the cost effectiveness of a restructuring an existing facility or building a completely new facility.

10.1 Fuel Cell Assembly Manufacturing Cost

Lomax and associates calculate manufacturing cost of fuel cell stacks in terms of machine rates, which include the variable costs of operating the machine such as the operator salary, energy costs, and maintenance as well as the amortized capital cost of the machine. Facilities and tooling cost are not addressed since they are expected to add only a small amount to the total cost (Lomax et al., 1998, [23]). For this project the overall assembly of a fuel cell is based on the outsourcing of the components and therefore the 22% vendor markup, as suggested by Lomax et al. was used. Also, assuming mass production coincides with the maturity of the technology; the production rate per fuel cell would be approximately 28 minutes based on a conveyor that allows simultaneous completion of two sets of stacks. Establishing the mature technologies machine rate as $4/min then the production cost per fuel cell would be $112. Additional housing for the fuel cell to ensure integration with the other components of the vehicle is estimated at $10/ fuel cell. Consequently the overall manufacturing cost of the fuel cell is best estimated at $122. Table 10.1 shows possible cost as the technology emerges. Compared to material cost, manufacturing cost at the onset of high volume production would be inconsequential but a decrease would still be recognized as the technology matures.

Technology	Assembly Line Machine Rate ($/min)	Machine Rate	Stack Cost	Outer Assembly Cost	Total Manufacturing Cost
Current (2003) Technology	6	28	168	10	178
Technology available 10 yrs	5	28	140	10	150
Technology at maturity	4	28	112	10	122

Table 10.1: Manufacturing Cost Associated with Fuel Cells (Lomax et al., 1998, [23])

10.2 On-board Storage Manufacturing Cost

For the on-board storage system the manufacturing cost is taken as 14% of the overall cost of the system at high volume manufacturing. Like the fuel cell, the majority of cost is realized by the materials (Lomax et al., 1998, [23]). Similar to the fuel cell, the 14% mark up allocated to manufacturing takes into consideration machine rates, which include the variable costs of operating the machine such as the operator salary, energy costs, and maintenance as well as the amortized capital cost of the machine.

10.3 FCV Plant Manufacturing Cost

Unlike current car manufacturing facilities the FCV plant will require additional facilities for the production of the fuel cell and storage systems. The decision to construct an entirely new facility or upgrade an existing site will be heavily weighed by the capital required and the returns manufactures expect from their investment.

10.4 Construction of a New Facility

An estimated cost of a FCV plant in the near term can be seen as having similar cost to the recently constructed Nissan plant in Canton, Mississippi. The 3.5 million ft^2 plant represents an investment of $1.4 billion, and has been designed to produce 400,000 vehicles per year at full capacity. As the most modern manufacturing plant, this Nissan site features a complex 550,000 ft^2 paint shop facility, and will employ over 5,300 people at peak production. The plant was originally to have been 2.5 million ft^2, an investment of $930 million. In June 2002 Nissan announced a $500 million expansion of the project due to strong demands for products in North America (Plant Automation Technology, 2004, [34]). Regarding these expansion cost as cost that could be allocated to the FCV manufacturing facility seems logical for this project. The paint shop facility described as the most complex and critical component of the plant requiring thorough planning and construction. In much the same way, the manufacturing facilities for the hydrogen storage system and fuel cell systems is expected to be complex yet critical components to the new plant. Therefore using Nissan's Canton venture a similar budget for the establishment of a FCV manufacturing plant at a volume production of 500,000 units was calculated and shown in Table 10.2.

Facilities	Area Required(ft^2)	Investment($)
Car Assembly	4,000,000	1.75 billion
Fuel Cell Assembly	600,000	5.00 billion
Hydrogen Storage Assembly	600,000	5.00 billion
Total	4,700,000	2.80 billion

Table 10.2: Space and Investment Required for FCV Manufacture

The area required for assembly of FCVs is not expected to increase from the current requirements of a regular car. Additional space will be necessary for the onsite assembly of the fuel cell and hydrogen storage systems. These space requirements were estimated as similar to what would be needed for specialized areas such as Nissan's modernized painting facility. Given that a plant capacity of 400,000 units required an investment of $1.4 billion, for the 500,000 units-FCV plant the investment was estimated at $1.75 billion. Although the expectation is not a linear increase in investment to account for the additional production of 100,000 units, but on the basis of the specialized needs of the FCV technology and the additional steps that may be required in the assembly line. An additional billion dollars is seen as a feasible allocation for the storage and fuel cell systems to account for possible constraints the new technology might encounter.

10.5 Restructuring an Existing Facility

Using Toyota's ability to integrate the Prius into its existing production line indicates that a complete over haul of existing plants may not be necessary thereby decreasing cost immediately. The Prius's current assembly line rolls out around one car every minute, and although it needs to pass through 11 extra stops during assembly compared with a regular car, productivity has improved by at least 15 percent for the current model (Toyota, 2003, [33]). In 1996, General Motors (GM) announced that Saturn would be building a new class of vehicles at the Wilmington, Delaware facility. Home of the Chevy

Malibu, the Wilmington Plant was a 50-plus year old, 3 million square-foot GM assembly plant on 105 acres that boasted it had built at least one car from every GM brand. To accommodate the manufacturing of this new class of vehicles, the Wilmington plant would require the investment of more than $550 million and a lot of planning and coordination to prepare for its new role (Brennan, 2003, [35]). Utilizing an existing facility provides the manufacturer with a readily available workforce and suppliers. For the FCV plant, additional material suppliers would be necessary to supply the materials for fuel cell and storage systems. Consequently, part of the decision to use an existing facility would include the possibility of additional suppliers moving into the area or the plant expanding to accommodate additional material storage facilities. In some instances, restructuring a facility can be as costly an investment as building a whole new one. In 1999 Chrysler invested $1.2 billion on a 1.1 million-square-foot, factory in Toledo that produces Jeeps, replacing an older factory and refurbishing some of the existing buildings on the site. In 2002 GM embarked on a $559 million investment to produce 130,000 luxury vehicles per year at its Lansing Grand River (LGR) assembly plant (Teresko, 2003, [36]). Based on these industry figures it would appear that refurbishing a plant will be as costly as building a new plant to accommodate production of 500,000 FCVs. Using GMs 2002 investment on the assumption that FCV production in the early years will be like luxury car production given the need for production of the primary components, the investment cost for 500,000 units will be in the vicinity of $2 billion.

10.6 Expected Returns on the Manufacturing Investment

In order the hydrogen economy to be successful, enormous capital investments are needed to meet the direct costs of manufacturing. A scenario of the returns investors can expect is presented in Table 10.3. Compared to the actual cost of the vehicle, as expected the investment returns on just manufacturing is minimal.

Initial	Investment Rate (%)	Investment Time (Yrs)	Annual Return (current $)	Cost per vehicle
Investment ($)				
New Build				
3 billion	10	20	$328,886,949	$657
	15	20	$447,332,117	$894
	20	20	$574,998,285	$1,150
	10	30	$297,021,895	$594
	15	30	$426,440,554	$852
	20	30	$562,369,103	$1,124
	10	40	$286,326,360	$572
	15	40	$421,573,838	$843
	20	40	$560,381,271	$1,120
Overhaul				
2 billion	10	20	$234,919,249	$469
	15	20	$319,522,940	$639
	20	20	$410,713,061	$821
	10	30	$212,158,496	$424
	15	30	$304,600,396	$609
	20	30	$401,692,216	$803
	10	40	$204,518,828	$409
	15	40	$301,124,170	$602
	20	40	$400,272,336	$800

Table 10.3: Manufacturing Investment Return Scenario: Plant Capacity 500,000 units for Start-up Year 2010

10.7 Transitioning to the Hydrogen Economy

As the technology associated with the FCV matures and the production number of vehicles increases the manufacturing cost is expected to decrease. In the scenario presented in the Figure 10 the decreasing cost of FCVs is attributed to increased production number and possible improvements to the manufacturing capability. By 2030 with high volume production taking place the price of a FCV can be competitively priced since its cost to manufacturers will be under $25,000.

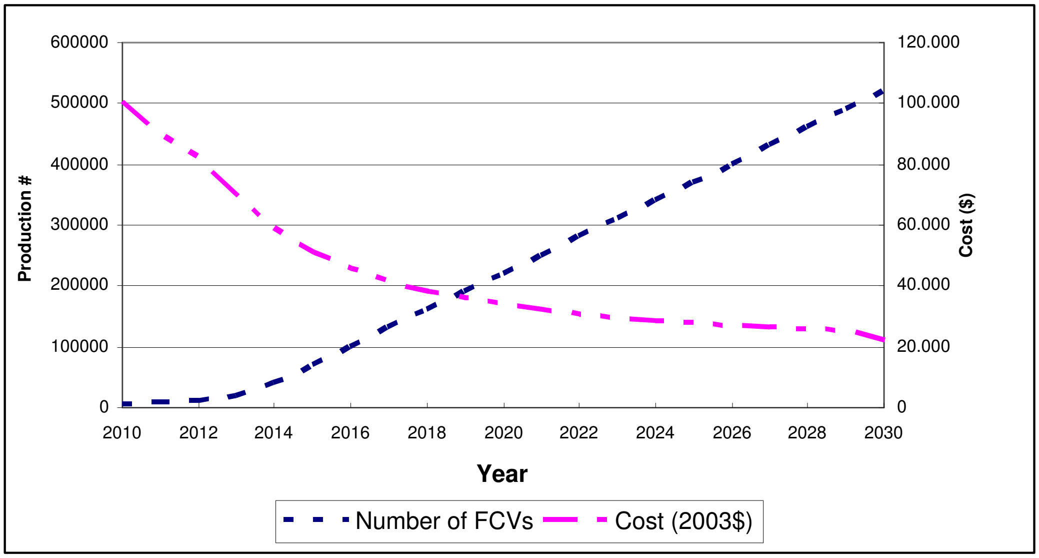


Figure 10.1: Relationship between Cost and Production

Predicting the Cost of the FCV as a Mature Technology In transitioning to the FCV, manufacturers' goal is to increase their profit margin in comparison to the current profits from the ICE technology. However, as the cost reaches values in the $20,000 to $25,000 range, indicating full capacity production and the technology is at maturity the expectation of the manufacturers would be to yield higher profits. Figure 11 shows that at its peak the FCV technology will allow manufacturers to recognize profits with the decreased cost of the vehicles. However, overtime the cost of the vehicle will begin to increase. The increasing cost may represent a need for new investment into the market to account for technology upgrades or a transition to a new more competitive technology.

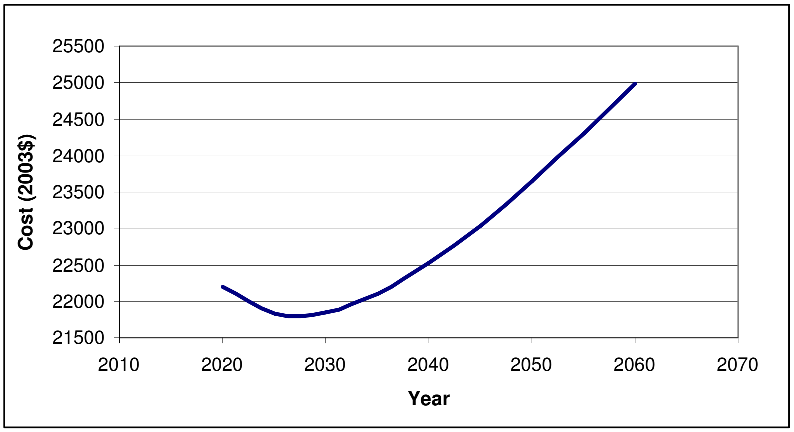


Figure 10.2: Cost of FCV as a Mature Technology

Chapter 11

The Catalyst Question: Does the World Have Enough?

One of the major concerns on sustainability of a Hydrogen-based transportation system is the fact that fuel cells rely heavily on platinum (Pt) as a reaction catalyst. The occurrence and reserves of this precious metal is thus an issue necessary to address, especially since some of the key aims of this project are to find a solution for the declining oil production, and to increase national security by reducing over-reliance on imported energy.

11.1 World Platinum Production

The Republic of South Africa is the world's largest producer of platinum, accounting for over 75% of the world supply. Other major producing countries include the former Soviet Union, the U.S.A., Canada, Chile and Zimbabwe. Minor producers include Colombia, Australia and Brazil (Blair, 2000, [21]). Table 11.1 provides a summary of annual production of platinum from1994 to 2003 (in tons):

Platinum Supply and Demand (in tonnes)											
Year		1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Supply by Region or Country											
South Africa		98.3	104.8	105.4	115.1	114.5	121.3	118.2	127.5	138.1	144.6
Russia		31.4	39.8	37.9	28	40.4	16.8	34.2	40.4	29.6	29.6
North America		6.8	7.5	7.5	7.5	8.9	8.4	8.9	11.2	11	8.9
Others		4.4	3.1	4	3.7	4.2	5	3.3	3.1	4.2	7
Total Supply		140.9	155.2	154.9	154.3	168	151.5	164.6	182.2	182.9	190.1
Demand by Application											
Autocatalyst:	gross	58.2	57.5	58.5	56.9	56	50	58.8	78.4	78.4	99
	recovery	-9	-10	-10.9	-11.5	-12.6	-13.1	-14.6	-16.5	-17.8	-20.2
Chemical		5.9	6.7	7.2	7.3	8.7	10	9.2	9	9.3	10.1
Electrical		5.8	7.5	8.6	9.5	9.3	11.5	14.2	12	12	12.3
Glass		5	7	7.9	8.2	6.8	6.2	7.9	8.9	8.1	7.6
Investment:	small	4.8	2.3	3.4	5.6	6.5	2.9	1.2	1.6	1.6	0.9
	large	7.5	8.4	4	1.9	3.3	2.8	-3.1	1.2	1.2	-0.6
Jewellery		54.1	56.3	61.9	67.2	75.6	89.6	88	80.6	86.5	76.2
Petroleum		2.8	3.7	5.8	5.3	3.9	3.6	3.4	4	4.2	4
Other		5.9	7	7.9	9.2	9.5	10.4	11.7	14.5	14.6	15.7
Total Demand		140.9	146.5	154.3	159.6	167	173.9	176.7	193.8	198.1	205

Table 11.1: Summary of Pt Production from 94-03 (John Matthey Ltd, 1999, [26])

11.2 World Platinum Reserves

The majority of platinum reserves worldwide are found in a deposit known as the Merensky Reef, located in the Bushveld complex of South Africa. Estimated reserves for the Merensky Reef are 10,357.46 tons (Anstett, 1982, [17]), with an average grade of 7.09g per ton. A similar geologic occurrence can be found in the Great Dyke of Zimbabwe, with estimated reserves of 3,940.6 tons of platinum at an average grade of 2.835g per ton. Estimated Russian reserves within the Noril'sk deposit are 1417.48 tons (Blair, 2000, [21]). The primary platinum producing area in the U.S. is the Stillwater complex in Montana, with an estimated reserve base of 198.45 tons at a grade of 17.01g per ton. Minor U.S. platinum deposits can be found along the Salmon River in western Alaska as well as in the Duluth Gabbro of northeastern Minnesota. An important Canadian platinum deposit at Lac de Iles, Ontario contains an estimated 85.05 tons at a grade of 3.544g per ton. Canadian byproduct platinum is produced in Sudbury, Ontario. Several

Chilean copper deposits also produce byproduct platinum. The estimated worldwide platinum reserves total 14,543.31 tons (Anstett, 1982, [17]).

Recycling: The primary source of scrap platinum is spent auto-catalysts. A secondary source is recycled jewelry. Johnson Matthey Ltd. estimated that 12.19 tons were recovered from auto-catalysts in 1999, around 8 percent of the annual market. Auto-catalyst recycling exhibits a lagged supply behavior, reflecting the amount consumed in the year of automobile production combined with the average service lifetime of the automobile (Christian, 1997, [18]).

11.3 Platinum Demand Projections

Autocatalyst (catalytic converters) consumption is currently on the rise, projected at 5% annual growth (Christian, 1999, [19]), and has significant potential for long-term growth as developing nations adopt emissions standards similar to the U.S. and Europe. South African reserves are expected to last 300 years (Dhliwayo, 1999, [20]), indicating a substantial amount of platinum supply. In fact, some of the world's largest platinum mines are currently undergoing expansions in mine production (Dhliwayo, 1999, [20] and Christian, 1999, [19]). There is also strong evidence from other metals that a reduction in overall mining costs is likely in the future as well (Blair, 2000, [21]). In other words, platinum prices are expected to continue dropping and mine output is expected to be able to keep up with demand well into the future. Calculating Platinum Loading in a PEM Fuel Cell: A study by Arthur D. Little produced in March 2000 shows that the combined anode and cathode platinum loading for a 50kW PEM Fuel Cell is 0.8 mg/cm2. However, with more recent technology in reducing catalyst amounts per effective area, a research study by Directed Technologies Inc. for the Ford Motor Company used a platinum loading of 0.25 mg/cm2 (Lomax et al, 1998, [23]). Further research conducted at Los Alamos Laboratories, proved that as little as 0.13 mg/cm2 may be satisfactory in the future (Gottesfeld, 2004, [22]). Other related statistics are shown in the Table 11.2. For this analysis the average Pt required was estimated at 0.2 mg/cm2.

Net Power	100 kWe
Active Area	600 cm^2/cell
Unit Cells per Stack	188 cells
Number of Stacks in Series	4

Table 11.2: Fuel Cell Statistics

Given the above statistics, the total amount of platinum required per kW is found to be:
= (4 stacks x 188 cell x 600 cm^2 /100 kWe) x 0.2 mg/cm^2
= 902.4 mg Pt/kWe
= 0.9024 g Pt/kWe

This translates to approximately 90.24 grams Pt for a 100kWe (effective kW) engine. Currently, Platinum (Pt) costs about $30.00 per gram (London Stock Exchange, Jan 9th 2004), hence our cost would be:
= 90.24 g per vehicle x $30.00 per g = $2707.20 per vehicle.

Quantitatively, if mass production began today (500,000 vehicles), we would require approximately 45.12 metric tons of platinum for fuel cell application only. There are about 5.0 million passenger cars produced and sold annually, which is a ten-fold increase from our 500K projection. This would thus require abut 450 Tons Pt/year. With 15,000 Tons in reserve, there will be sufficient Pt to last for 35 years, assuming no recovery of used Pt, and assuming all reserves are dedicated to FCV production henceforth. This also assumes that technology will not improve on Pt loading per effective area, and that all other factors are constant. Assuming a total world production of passenger vehicles of 30 million per year, the total platinum required annually would be 2707.2 Tons. With an annual recovery of the platinum at 10%, FCV lifecycle of 10 years, and assuming current Pt loading will not change, there would probably be sufficient Pt for 15 to 20 years. This raises the issue of sustainability of a hydrogen economy. Continued over-reliance on platinum at current loading levels will have to change.

Reducing Fuel Cells Demand for Platinum: Researchers recognized years ago that the platinum content of PEMFC electrodes could be reduced by dispersing nanoscale platinum particles on a porous, electronically conductive media (Vulcan carbon) and adding a proton conducting media -a perfluorosulfonic membrane, Nafion® (Ugarte et al., 2002, [15]). When surrounded by Vulcan carbon and Nafion, platinum serves more effectively as an electrocatalyst for hydrogen oxidation and oxygen reduction because there are ample transport paths for protons and electrons. Whereas the catalytic activity of platinum is critical, the electrode reactions are mediated by the rate of the transport of the gases, protons, electrons and water to and from the platinum surfaces (Swider-Lyons et al., 2003,[16]). Our proposed future actions to mitigate this unfavorable trend include:

1. Decrease need for Pt as the sole PEMs' MEA catalyst
2. Increase efficiency of recovery and recycling of Pt
3. Improve technology to reduce the loading amount of Pt
4. Seek to develop alternatives such as alloys. USDOE already proposes: Platinum-lead oxides, Platinum- Nickel oxides and Platinum-Tin oxides.

Part III

Long Term Transition

Chapter 12

Introduction: Goals and Scope

The objective of this section of the project is a first pass assessment of the general outcomes of the transition from conventional vehicles to fuel cell vehicles, from point of launch of the technology to the point where carbon-free hydrogen becomes the dominant fuel for passenger transportation. The analysis will focus on three main areas of expertise:

1. **Projection of the different variables included in our analysis:** An important outcome of our analysis will be our ability to project the evolution of several important variables up to the end of the 21st century. These projections are based on models built through the use of spreadsheets, databases and sofwares such as Matlab. Such projections include the use of energy in the future, the production of CO2 due to passenger vehicle transportation, the amount of total vehicle kilometers travelled throughout the world and Gross Domestic Product.

2. **Ability to build and study various scenarios:** Our models are meant to be highly parameterized to allow possible users to interact with the application and see the kind of impact each variable has on the system. It also allows users to use numbers that seem to be more accurate to them, or policies that seem more appropriate.

   An example of technical numbers would be the evolution in the efficiencies of traditional ICEs (Internal Combustion Engines). Indeed, a high increase in this efficiency could make ICEs more interesting than FCVs for a longer period of time. An example of policy would be the amount of taxation set on pollution throughout the world. Indeed, this highly fluctuating parameter can have a huge influence on consumption patterns and could possibly trigger the transition to FCVs.

3. **Projection of cost parameters:** To get an idea of the passenger vehicle cost through the 21st century, we need to project the retailed price of gasoline, natural gas and hydrogen.

Chapter 13

Energy Cost Analysis

13.1 Introduction

Fuel costs are one of the important criteria that shape the decision in selecting energy resources and carriers in transportation. Because fuel costs are visible and selective, consumer may consider a wide range of alternatives that is suitable for them in the future. Fuel costs do not stand-alone; they are closely related to vehicle cost most users are concerned about. Whether to choose gasoline, natural gas or hydrogen becomes a hard and wide topic either for short term or long term. Ideally in the long run, the hydrogen transition from fossil fuel to renewable energy is inevitable. Our analysis illustrates that the cost of hydrogen shows good trends compared to other energy sources or carriers. In the light of our analysis, it seems that the global demand of hydrogen transition in the long run will increase steadily and eventually hydrogen would become an important energy carrier for most transportation applications. Before we go further on fuel analysis, it is better to have a good understanding on how fuel cost and efficiency relate to vehicle cost.

13.2 Definition of Vehicle Cost

Vehicle cost is a general term that includes driving cost, the cost of owning and operation on automobiles ([66]). The amounts of ongoing expenses are monthly payment, sales tax, interest, insurance, maintenance, repairs and costs of fuel. Prices can be a very contributing factor to the costs of ownership. The fixed costs include insurance, license, registration, taxes, depreciation, and finance charges. These costs are affected by different factors that are hard for us to manage. So we only consider the variable costs, which include the costs of fuel, maintenance and tires. For our project, we believe that by improving the fuel costs, the driving costs will eventually be reduced in the future as we predicted. To make our forecasting reasonable, we made some assumptions below that set our works under more realistic and rational scope (1994, [93]).

Assumptions

1. Although at a particular point in time the fixed costs increase with inflation, in the long term the fixed costs remain at a constant level that has little affects on the trend of reducing driving cost in the future.

2. In variable costs, the maintenance and tires can be improved in the future, but do not have strong impact on reducing the driving cost.

3. Our data is based on 15,000 vehicle-miles per year. (Fact: The U.S. Department of Transportation reports that most new vehicles are driven 15,000 miles per year, while the average used car is driven 13,500 miles.)

4. Since fuel costs are highly visible to consumers, they dominate the alternative transportation cost.

Figure 13.1 shows sample curves of fuel cost for different types of vehicles in $/gallon based on 1998$/mile (Maples, 2000, [54]). From the chart, the fuel cost of driving vehicle dropped rapidly from 1980 to 1988, which is highly due to the falling price and improving fuel efficiency. The resulting increase in fuel consumption was offset by low fuel prices, keeping cost per mile low at about 6 cents. Rising gasoline prices in 2000 will likely interrupt this trend temporarily, as they did in 1990 (Ludwig, 2002, [94] and Litman, 2002, [53]). The fuel cost is actually the formula of Fuel Price and Fuel Efficiency. Accordingly, decreasing the fuel price and improving the fuel efficiency will likely reduce the vehicle cost, which becomes our of project major target. We know that different energy resources have distinct production line and reservation so that consumer prices are diverse. Therefore, by focusing on

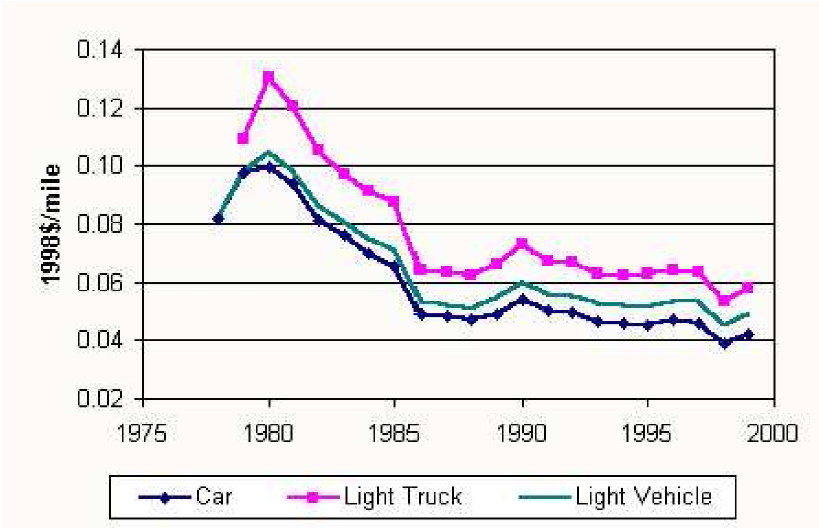


Figure 13.1: Fuel costs

various types of energy resources, we are able to recognize the best alternative energy that not only costs less but also produces energy effectively with sufficient amount of reservation.

Here is the list of energy resource and carriers we are interest in:

- Gasoline
- Natural Gas
- Hydrogen
- Fossil Fuel in the broad sense
- Renewable energy

Before we go into detail, we would like to show a chart to illustrate how we go from the vehicle-model to the energy-model. Vehicle cost will be our major output, comprised of fixed cost and variable costs. All components in the fixed costs are likely to be constant, while the variable costs are comprised of maintenance, tire and fuel costs. The fuel cost will be one of the major targets of our project, and can be divided into two separate important models, the fuel price and the fuel efficiency ([95]). Both of them extend to different type of energy sources that eventually provide us with a strong indication that hydrogen not only is the cheapest but also the most efficient energy carrier of the future.

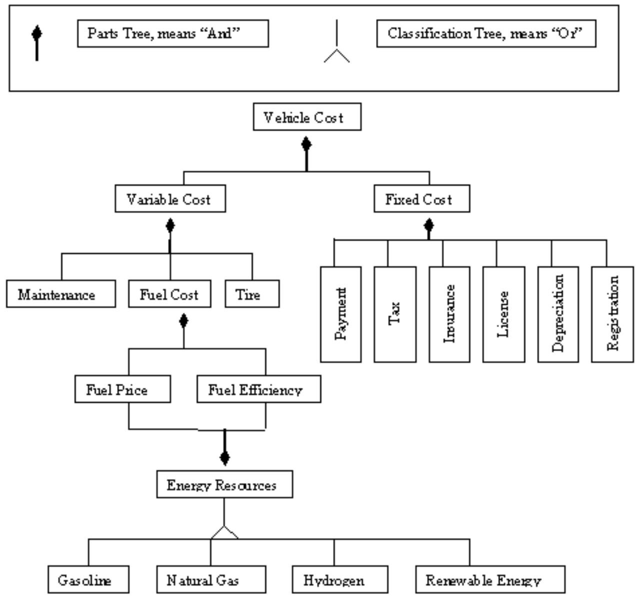


Figure 13.2: Chart of the relationship between Vehicle Cost and Fuel Cost ([96], [97] and [98])

13.3 Retail Price of Gasoline

The retail price of gasoline is the most visible energy statistic that most American consumers consider. However, most of them probably only have a general understanding that the gasoline prices are related to those of crude oil. Like other goods, gasoline is priced at many different levels in the marketing chain and that rises and falls due to various factors. The retail level is the one we are primarily interested in because it is the one that is visible to the consumer, at the service station, convenience store, or other retail outlet. The components of the retail price of gasoline include marketing and distribution costs, refinery costs and profits, federal and state taxes and the cost of crude oil. Figure 13.3 below shows the relationship of those components and the changing percentage reset in different years in the United States (EIA, [99], Parry et al., 2002, [59] and Bartlett, 2000, [67]).

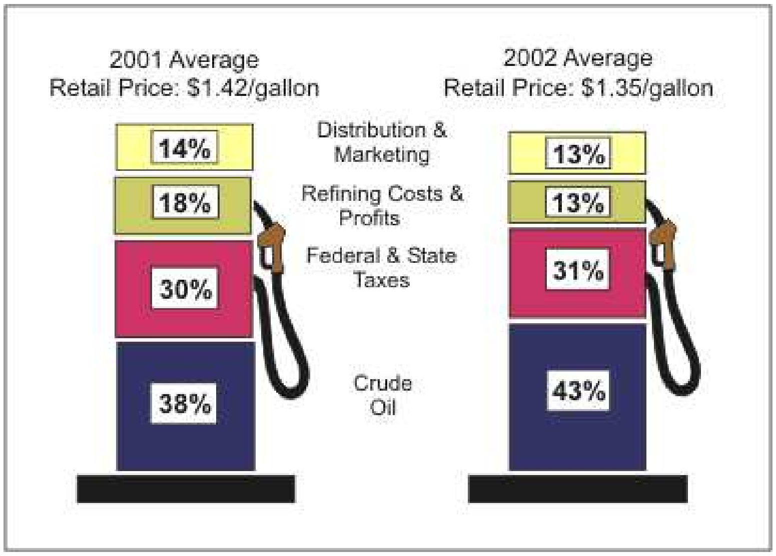


Figure 13.3: Components of retail price of gasoline

The price of crude oil accounted for 43% of the cost of a gallon of regular gasoline in 2002. This part of shares varies over time and among regions that are highly affected by the economic theory of demand and supply so that we could have little control and ability to predict future trend. The Federal and State taxes are another large component of retailed price of gasoline. Different countries have different tax proportion, we will discuss the world tax rate later.

In the USA in 2002, taxation counts for 31% of the retailed price, and was significantly controlled by federal government and local offices. The Energy Information Administration provided data saying that: "Within this national average, Federal excise taxes are 18.4 cents per gallon and State excise taxes average about 20 cents per gallon". So adjustment on taxes can have significant impact on the price of gasoline. Another 13% shares of retailed gasoline price for 2002 were the refining costs and profits. The different formulation requirement in different parts of the country determines the percentage of this share. The way gasoline is conducted and delivered to individual stations, and how purchasers operate and resale to the general public makes up the distribution and market share of the retail price of gasoline. It reflects market conditions and factors like location and marketing strategy. The crude oil price oscillated very much due to different outside factors such as the Persian Gulf War that resulted in high increases on crude oil prices. Although the retailed gasoline price increased along with crude oil price, with the control of federal taxes the rate of increase is smaller than the rate for crude oil. Figure 13.4 shows the gasoline index differential based on 1990 price which the Persian Gulf War started at the end of that year (EIA, 2002, [68], EIA, [69], EIA, 2004, [70], EIA, 2003, [71] and Platt, 1974, [72].

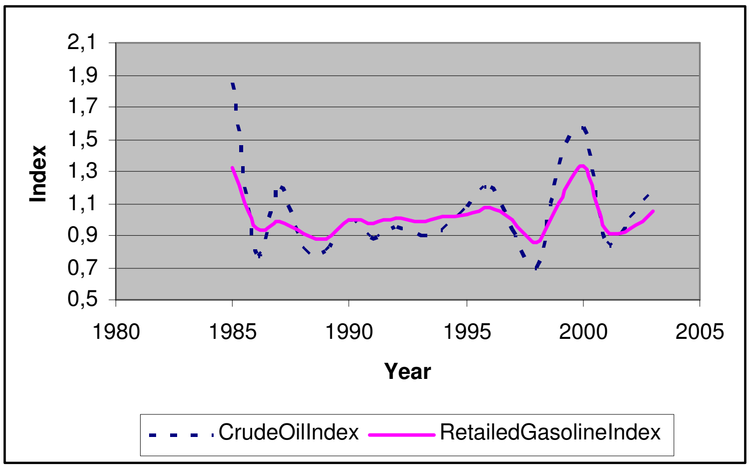


Figure 13.4: Gasoline index differential based on 1990 price

Based on 1990 price, the crude oil price dropped by 12% whereas the retail price only decreased by 2% in 1991. In 1994, the crude oil price dropped by 7% whereas the retailed price increased by 1%. In 1999, the crude oil price increased largely by about 34%, however, the retail price increased much less by only about 10%. From figure 13.4, we see that the line of retail gasoline index differential was smoother than the crude oil index. The year 2000 saw the greatest increase in gasoline price for both crude oil and retailed gasoline. However the retail price increased 33% in contrast to the 57% increase of crude oil. The retailed price index did not increase more or decrease faster than the crude oil. Therefore, we can conclude that the retail gasoline prices cushion the effect of crude oil cost swings. Since the federal taxes are a large portion of the retail price, it is reasonable that controlling the tax could alleviate the unexpected cost swings of crude oil. However, the world gasoline prices in different country are significantly different mainly because each country has very different tax rate ([99], [59], [67], EU, [73], IEA, 2000, [74]).

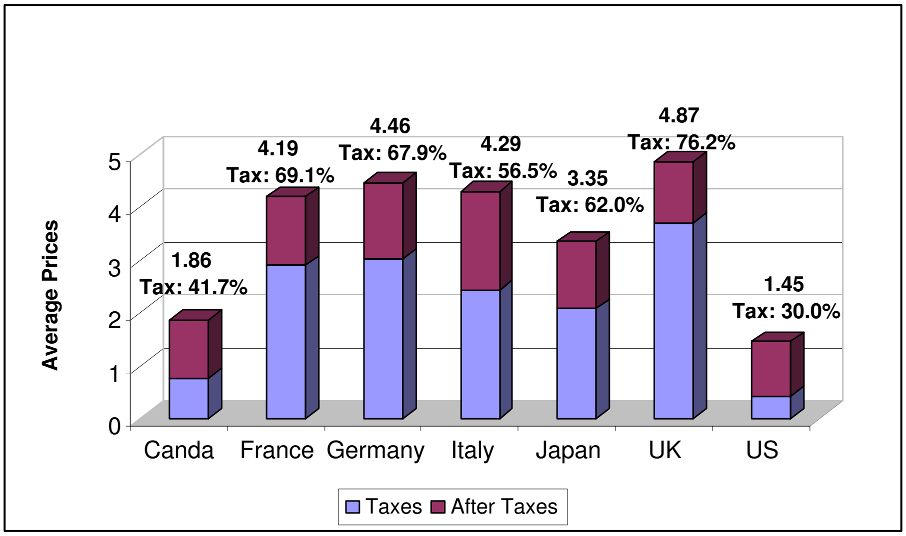


Figure 13.5: World Gasoline Average Prices vs Tax Rate 2003 ($/gallon)

In 2003, the US gasoline price was lower than other countries in the world mainly because it had a tax rate lower by 30%. United Kingdom had the highest gasoline price from its devastating 76.2% taxes among those samples. Notwithstanding, most reports and articles showed the British government's unwillingness and unlikely to drop its tax rate.

Even with crude oil prices at fluctuating stage, the retailed prices can be moderated from fast rise and rapid fall due to tax control. However, they are still changeable from many factors such as local retail station competition and seasonal driving growth, which typically increase in summer and falls in winter. Good weather and vacations cause U.S. summer gasoline demand to average about 6% higher than during the rest of the year, so that price would increase 5-6 cents during summer time with crude oil unchanged. We know that if demand rises quickly and supply declines unexpectedly, the price will increase rapidly. So the supply, demand and distribution significantly affect the curve of real data and even for our forecasting of trend of gasoline price. The retailed price along with different components cushions the effect of crude energy cost swings as much as possible. It made our forecasting of retailed price reasonable by limiting the effect of possible world event on crude oil such as Persian Gulf War or other factors ([68], [69], [70], [71], [72], [75] and [76]).

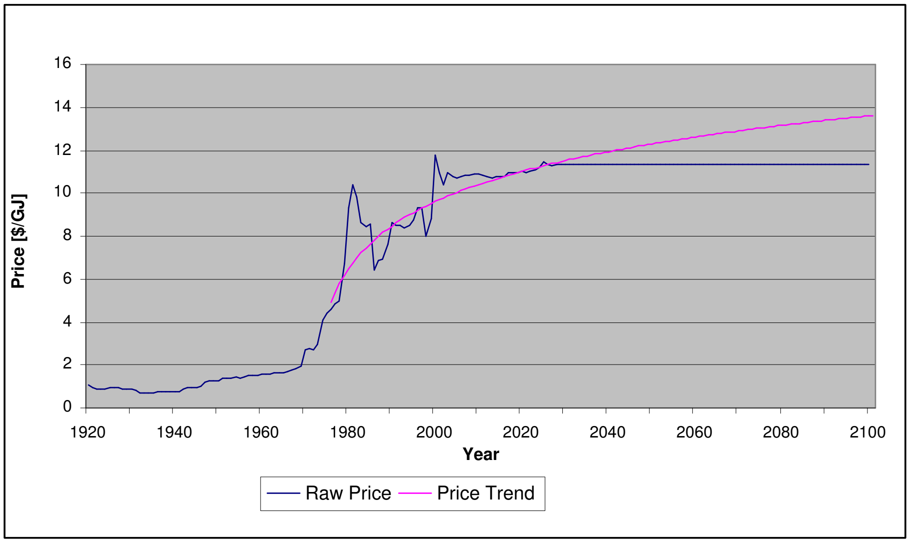


Figure 13.6: Retail price of gasoline in the United States

The chart shows the example of U.S retail gasoline price from past data to future trends. We currently have the raw real data from 1970 to 2000, and use consumer price index to interpret them to early years to 1920. We can see that from 1970 to 2000 the retailed price of gasoline increased rapidly but fluctuated largely from year to year, which probably depended on the higher demand of gasoline but few supply of crude oil and the war in the oil countries. After 2000, the oil product settled at some level, but the demand still increased, so we could make it as assumption in future. Based on the regression of those current possible data, we forecasted the trend of gasoline price and came with an logarithmic trend line. We used the average weight method to extend the gasoline price prediction from the EIA at level $11.33

per GJ[1].

Even if there exists some affecting factors, the price will probably not fall below this level, but rather increase along with our expected trend line. So in the year 2100, the price will probably be at $13.62 per GJ; it may be less but most likely not less than the level of $11.33 per GJ. However, several assumptions are made out to ensure our forecasting feasible and reasonable. The cost of gasoline components may change differently, but the overall resulting price still increases. Also, the supply of crude oil may level at some constant or may decline due to world oil reservation, but the demand of consumption will remain still and not allowing the high marketing value decrease at all. There still exists a lot of uncertainties. For example: we know the oil scarcity in the future, but if hydrogen transition does not succeed and consumers have to depend on oil still, the price of hydrogen will increase exponentially. On the contrary, if most fuel consumers switch to other alternative fuel, consuming of oil is no longer necessary, the price will probably decrease in future. The source data we used are based on EIA reports and forecasting until 2020. Beyond that year, we use our best judgment and more conservative calculation to roughly estimate what the future price of gasoline look like.

Table 13.1 shows some sample gasoline prices of U.S. in 50 years gap:

Years	Price ($/GJ)
1950	1.27
2000	9.61
2050	11.33-12.30
2100	11.33-13.62

Table 13.1: Sample Gasoline Price

It can be seen easily that in the first 50 years the gasoline price at 1950 was about 1/8 times of the price at year 2000; but the next 50 years the price increased very slowly. At the end of 20th century, people developed a lot of new energy resources and carriers so that gasoline would not be the only one determinant energy for consumption. There are some interesting alter-

[1]Giga Joules = 10^9 Joules

natives ways to consume energy nowadays, though still currently expensive. However, it is projected that the price will decline to comparable values in the future, especially the one we are most concerned with in this report - hydrogen.

13.4 Consumer Price Estimate for Natural Gas

During the past 50 years, the consumption of natural gas grew very fast, however, its price continuously changed and was volatile. Residential, commercial, industrial and electric utility customers are the primarily consumes of natural gas. The data we collected was average consumer price. It is hard to only focus on any particular fields, because the residential and small commercial customers use gas in relatively small quantities. They are likely not to be interrupted during service and have a tendency toward higher prices. Industrial and electric utility consumers generally use gas in larger volumes. They are likely to contract on shorter-term and interruptible with even lower prices. However, many of them could switch to other fuels if natural gas became scarce or too expensive. The raw annual data we collected was from 1980 to 2000 from the Energy International Agency (EIA) database. The consumer price of natural gas is composed of three major components which are:

1. Transmission costs - for moving the gas by pipeline from its source to the customer's local area
2. Distribution costs - for bringing the gas from within the local area to the user's facility
3. The cost of the gas itself

As crude oil price, the raw natural gas price fluctuates unexpectedly. It is hard to predict future trend of natural gas price based only on the gas itself. However, we could integrate all factors together that balanced the consumer price and estimated the future. The natural gas index differential from 1980 to 2003 showed that the retailed price actually alleviated the unstable rise and fall of raw natural gas price more or less (EIA, 2000, [77], EIA, 2003,

[78], EIA, 2000, [79], EIA, 1997, [80], EIA, 1973, [81], EIA, 1974-76, [82], EIA, 1977-96, [83], EIA, 1997, [84] and EIA, 2003, [85]).

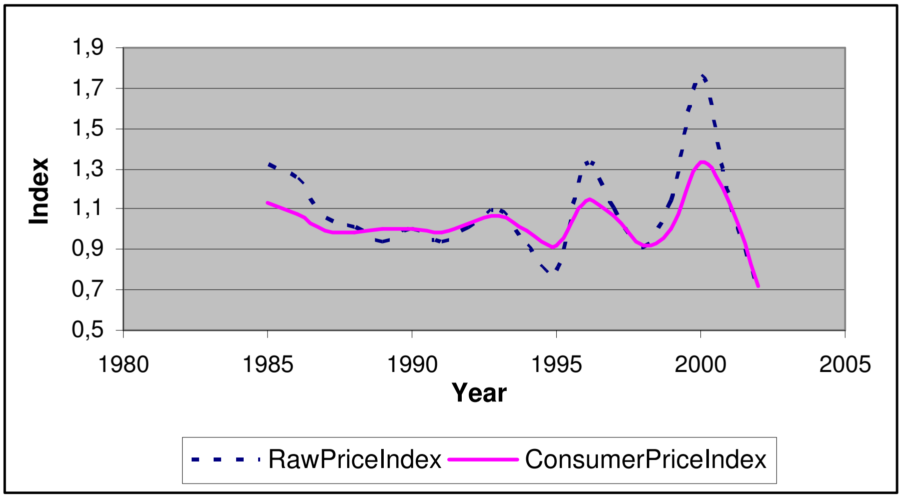


Figure 13.7: Natural Gas Index Differential based on 1990 price

The data is based on 1990 price, the change was not significant until after year 1995. In 1996, the raw price of natural gas increased 32%, whereas consumer price increased 14%. In 2000, the price of natural gas increased suddenly with 76% during the year; however, the consumer price did not follow such large gap and increased reasonably of about 33%. The price started to fall in 2002, the raw price dropped 29%, and the consumer price dropped about the same of 28%. Except 2002 where there was a large decrease in price, most years beyond 1990 had prices increasing or slightly falling. From the index comparison from previous years we could make a reasonable forecast trend for the price of consumer natural gas. Below is a chart of estimates of consumer price of natural gas with possible forecasting ([77], [78], [79], [80], [81], [82], [83], [84] and [85]):

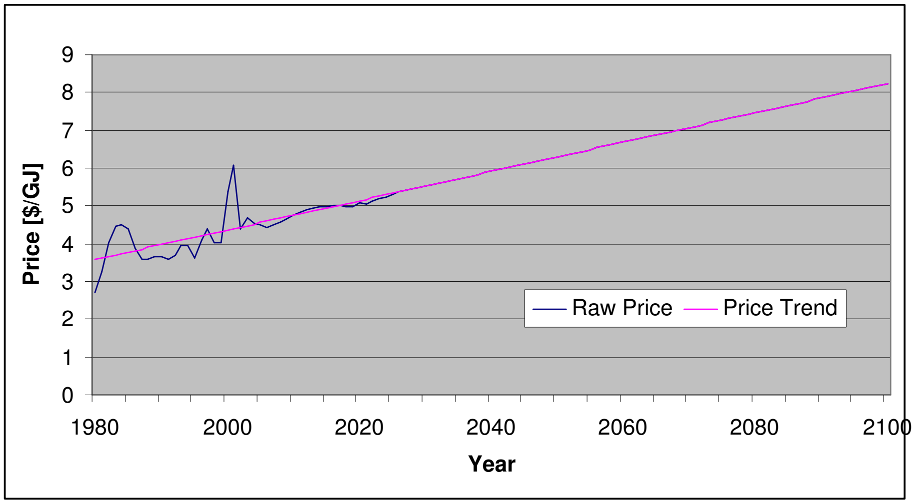


Figure 13.8: Consumer Price Estimate for Natural Gas (U.S.)

The curve line of raw data from 1980 to 2000 on the chart shows that natural gas prices fluctuate very much. In 1999, the price was at $4.04 per GJ. It jumped to $6.07 per GJ in 2001 and fell down $4.68 per GJ in 2003. The natural gas price fluctuation in great parts can be explained by the swing of natural gas supply and demand throughout the year. For example: during the summer, domestic gas production and imported gas can more than satisfy customer demand, and excess supplies are placed into storage facilities. In the winter, demand for gas generally exceeds production and import capabilities, so withdrawals from storage are used to provide the extra gas needed to meet customer requirements. Seasonal changes in the cost components also can lead to unusual outcomes. It is therefore interesting to look at some of the reasons for natural gas prices to temporarily rise:

- Prolonged or severe winter season might rise the demand of higher consumption.
- A lot of constraints exist in the pipeline delivery system.
- Depressed volumes of natural gas in storage that can make operators cautious about removing gas from their diminishing inventory especially in the early months of the heating season.

- Supplies to customers sometimes are restricted by operational difficulties.

From the above reasons, we should neglect them in the longer term forecasting. From a regression of raw real data from 1980 to 2000, a linear trend line was calculated that extends our price prediction to 2100. Compared with previous trends of gasoline prices, we can see that at year 2100, gasoline price will likely be around $13.62 per GJ even with a slow increase, whereas natural gas will probably be $8.24 per GJ. The price might be changing drastically in the period of 2020 to 2100 with few real forecasting source data to support it. This uncertainty exists because we do not know how the future demand of natural gas will look like. The main consideration is that the demand for natural gas will still be high; however, it is possible that the reserves of natural gas will face scarcity for the last 70 years. On the basis of current data, it is clear that projections are difficult. Simply based on the price comparison, we can assume natural gas will more likely be the future world energy resource than gasoline. However, it is biased to make our conclusion only from prices observations; a lot of other factors such as energy reservation, consumption, pollution issues might effect the future price. We will go further into these issues below. Also, both gasoline and natural gas prices are very volatile; we need another energy that not only steadies in seasonal effect but that is also cheaper in the future. In the following section, we will analyze the trend of hydrogen price that could help to draw the possible transition scenario of world energy demand to hydrogen.

13.5 Unit Cost of Hydrogen

Hydrogen prices are determined based on estimated equipment costs, energy costs, and additional conventional economic assumptions. Below is a very brief relationship model (Simbeck, 2002, [62]):

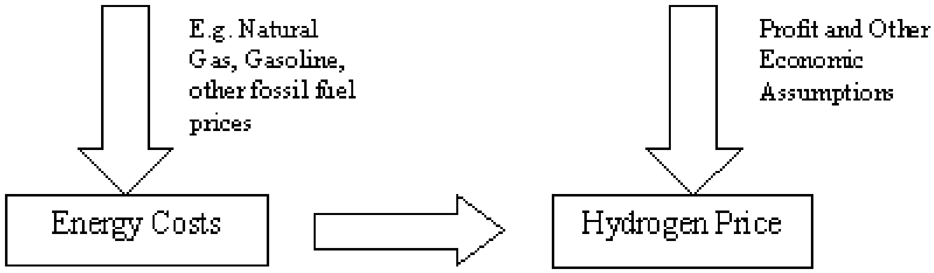


Figure 13.9: Relationship model for the price of hydrogen

We know hydrogen does not exist in pure form, so that it is produced either through reforming fossil fuel or separating water into its two basic compounds, hydrogen and oxygen through electrolysis requiring the production of electricity. Therefore, prices of primary energy sources will determine the price of hydrogen. For central production plants, there are several intermediate steps before the hydrogen could be dispensed into fuel cell vehicles. The purified hydrogen has to be either liquefied or compressed before it can be transported through pipelines, cryogenic trucks, or tube trailers. The unit cost of hydrogen is the cost modules for producing, handling, distributing, and dispensing hydrogen from central plant and fuel station to fuel cell vehicle applications and end users. Therefore, the unit cost is the average cost of hydrogen in liquid storage, pipeline, and tube trailer after the process of producing, delivering and fueling. The following table gives an idea of the proportion of each of these steps in the total price of hydrogen. (Lasher, [50])

Electrolysis Based Hydrogen ($/kg)	Liquid H2	Pipeline	Tube Trailer
H2 production	6.17	5.13	5.30
H2 delivery	0.18	2.94	2.09
H2 fueling	1.27	1.07	1.00
Total	7.62	9.14	8.39

Table 13.2: Proportion of different costs in the total cost of hydrogen

The $8.38 cost of electrolysis hydrogen in 2003 will be the average of $7.62,

$9.14 and $8.14 per kilogram. From the Asilomar 2003 conference and the SFA Inc. report, we get an idea of the current hydrogen prices based on different types of energy sources. In 2003, the price of natural gas based hydrogen was $37.89 per GJ; the price of electrolysis hydrogen was $84.85 per GJ; whereas the price of petroleum based hydrogen was $41.01 per GJ. We notice that the unit cost is primarily based on raw price of by-product energy resources and operation cost, but the most expensive part in current year is the process to generate hydrogen. As an assumption, with the improvement of the operating process through years, the price of hydrogen will drop rapidly until the value of its price match the comparable value of raw price of using energy resources. Our prediction is that in the year 2020, the price of petroleum based, natural gas based, and electrolysis hydrogen will target to $8.76, $11.48, and $19.13 per GJ. The inverse of a logarithmic trend line shows that by using various ways of producing hydrogen, the prices of hydrogen drop rapidly to lower level. If hydrogen prices follow these trends, the price of petroleum based hydrogen will be lower than the price of gasoline by the end of 2020, and we hope that some time around the year 2100 the average unit cost of hydrogen will reach a lower limit around $5.00 per GJ and be more or less steady on such a level in the future. Figure 13.10 shows the projected curves of hydrogen prices based on natural gas, petroleum and electrolysis ([50], Morgan, 1993, [56], Asilomar, 2003, [86], NREL, [87] and [88]):

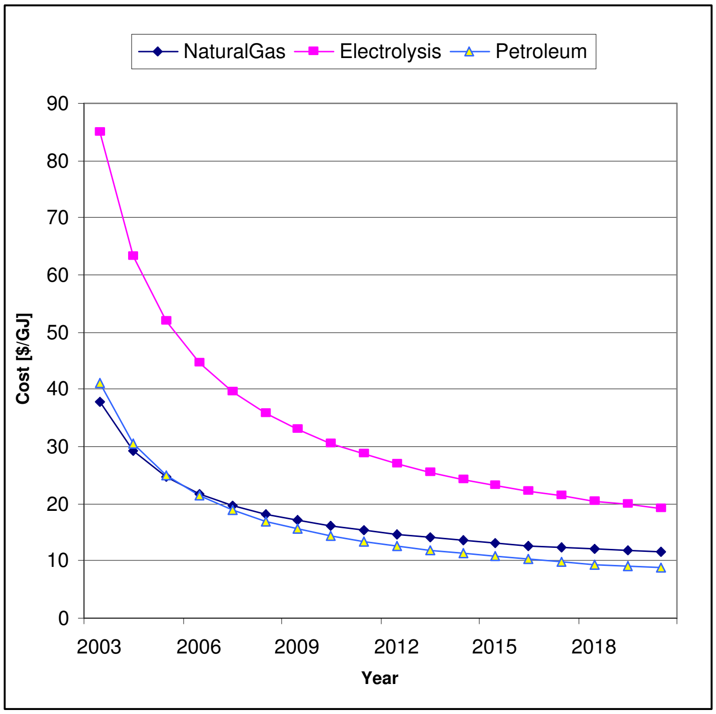


Figure 13.10: Unit cost of hydrogen based on different types of methods

These curves tell us that even though currently electrolysis hydrogen is far more expensive than petroleum and natural gas based hydrogen, it should be decreasing rapidly. The reason is that electrolysis needs cheap water and electricity, and the most expensive part is the difficulty of the generating process. By improving that through technology, the price of electrolysis hydrogen could decrease significantly in the future and eventually reach the level of natural gas based hydrogen. On the contrary, the natural gas and petroleum based hydrogen price decrease slower and are hard to improve in the long run mainly because of the scarcity of such resources in the future and their sensitive fluctuation. The procedure of generating hydrogen from natural gas and petroleum will not dominate the price with well-developed technology, because of the overbearing importance of the scarcity of these energy resource. Therefore, in the long term, electrolysis will be a good technology and clean procedure to generate hydrogen. To attend for the uncertainty in the projection in the cost of electrolysis based hydrogen, we derived optimistic and pessimistic scenarios compared to our baseline based on different reports and articles (sources: [50], [56], [86], [87] and [88]):

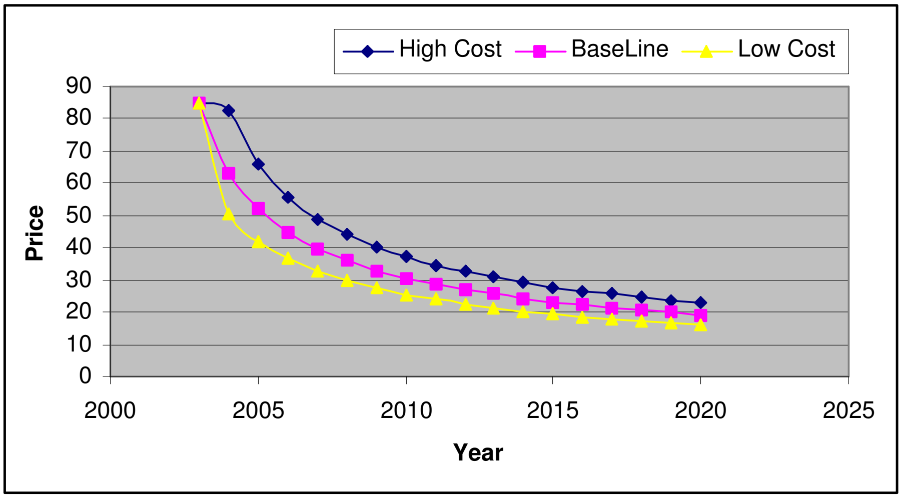


Figure 13.11: Electrolysis Hydrogen [$/GJ]

The data in figure 13.11 is roughly estimated since few real data could be provided from outside resources, so that we had to use our best imagination and own derived formula to predict the possible trend. As should be noted, the price of electrolysis-based hydrogen could drop very fast and reach a much lower level before slowing down. This could happen if there is a strong breakthrough implying a sudden price drop for the electrolysis. On the contrary, the top curve shows how hydrogen prices would evolve if the price of electrolysis stays at high levels and drops relative slowly, but decreases at a constant rate. We expect that hydrogen prices will fall in between these high and low values.

Using Renewable energy to produce hydrogen Renewable energy can be used to produce electricity ultimately used for the electrolysis process. As will be mentioned in other parts of this report, such technologies exist today but are still in their early stage of development for most of them. The resulting price of hydrogen is very difficult to predict at this time since manufacturers are competing but far from being settled on clear standards, techniques and prices. Rolf Hug pointed out that "the production costs of solar hydrogen can only be roughly estimated: if it is obtained through large PV systems (300 MW electrolysis), a cubic meter will cost, in the least expensive case, about $1.69, which corresponds to a kilowatt price of about $0.49 for electricity from fuel cells". (Rolf, 2000, [89]) This is the optimal cost and is used as part of the unit cost of hydrogen. Renewable energy is highly appreciated in the future, but the cost of renewable energy utilities will have to be taken into account into the cost of hydrogen on market. For example, the cost of solar panel far exceeds that of wind power. Additionally, few data show the cost of renewable energy based hydrogen; we could hardly predict well what the cost future of renewable hydrogen world will like to be. Nevertheless, solar hydrogen is an option that will have to be analyzed further and which has great potential (Brown, 2001, [41]).

13.6 Conclusion

Comparisons of the trends of fuel costs dominate many discussions on new transportation fuels; however, fuel costs are only a small fraction in vehicle costs, and very distinctly so in different countries. For example, the fuel cost in US is likely to be one eighth of the total cost of owning and operation a car, whereas it can be quite different in other countries. Hydrogen energy is more favorable than other energy carriers because it has inherent qualities and is projected to become relatively cheap. Currently however, the price of hydrogen is still ten times or more than the price of gasoline due to complex generating process. Ideal projections see the procedure improving rapidly with fast increase of technology, so that at particular point in the long run the hydrogen price will drop lower than comparable gasoline or natural gas prices. The direct comparison of hydrogen and gasoline costs might be less meaningful because of their difference in energy quality, however. Therefore, comparison among gasoline based, natural gas based and electrolysis hydrogen prices becomes very important. As long as the hydrogen is generated from fossil fuels, their prices will have a direct influence on the price of hydrogen. It is thought by many that hydrogen will provide perfect support for an economy based on carbon-free sources of energy and that the cost of hydrogen will not be a big barrier once technology will have improved and the cost of solar structure reduced.

Chapter 14

Model Building

Throughout this project, building a comprehensive model on the main issues related to the hydrogen transition has been one of our primary goals. We started by focusing on building a flexible spreadsheet model concentrated on the United States which included the major variables of the transition to fuel-cell vehicles. This allowed us to experiment and develop our modelling tools and make sure that our methodology was effective. Building up first a simpler spreadsheet model also allowed us to understand better the complexity of our task. The final version of this first model gave us interesting information on how to build a stronger framework and encouraged us to use a database for our second version. This ultimately allowed us to expand the span of our work to the entire world without compromising on the rigor of our effort.

This chapter will describe these tools that were built throughout the project. We will start by explaining our variables and how they are linked to one another. Thereafter we will describe the two versions of our models, and finally, in chapter 15 we will analyze the results of our second database model and include an interpretation of these figures in the light of other numbers we have been confronted to in the literature.

14.1 Variables and Parameters

Our first task in the modelling part of our work included a general analysis of the issues at hand. We built an extensive, though obviously not all-encompassing, general correlation diagram including major variables and concepts linked to the Hydrogen transition, allowing a holistic overview of the issues. This chart concentrates on variables directly linked to passenger car vehicles and hydrogen. Five areas were highlighted:

1. **Energy:** This area includes major energy issues, mainly linked to sources and uses of fossil fuels and other types of energies.

2. **Demographics:** This area covers major variables of population and economics data, such as Gross National Product (GNP).

3. **Cars:** This theme includes variables linked to cars and manufacturing.

4. **Hydrogen:** Another important area including variables more directly related to the use of Hydrogen as a fuel, one of the assumptions of this project being that such a transition will happen in the future.

5. **CO2:** This is another major variable in our chart, as it is one of the main drivers of the transition to cleaner forms of transportation, through the increasing risk of climate change. The graph below in figure 14.1 shows that Fuel-Cell Vehicles have the potential to produce much less carbon emissions than other energy carriers, but only if being part of a clean energy-chain.

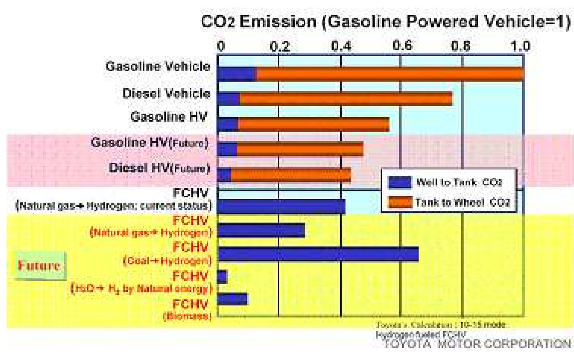


Figure 14.1: CO2 emissions of projected vehicles types. We notice that producing hydrogen from coal has the potential to be much more harmful than conventional combustion engines. On the contrary, hydrogen produced from natural energies seems to be very promising.

We put together a correlation diagram that includes each of these areas and gives a graphical representation of which variables are interacting. A general view of this diagram can be found in figure 14.3 below.

Narrowing down the system We also needed to clearly define what the scope of our project was in the light of this correlation diagram. This project is restricted to the analysis of passenger transportation in personal vehicles. Let us define those terms clearly:

1. *Personal vehicles* are personal cars, sport utility vehicles (SUV), and light trucks.

2. *Passenger vehicles* are all vehicles carrying passengers such as personal vehicles, buses, trains and airplanes.

This boundary can be hard to define and numbers in our study, which we found from different sources must be taken with care. For example, light trucks are often cited as being included in passenger vehicles because they are often used for personal transportation and not for commercial purposes. This is especially true in the case of sport-utility vehicles (SUVs) in the United States, very popular at the moment and mostly used for pure personal transportation. This difficulty in the clarity of the boundaries of our system occurs again in the case of Vehicle Kilometers Travelled (VKT) for passenger vehicle, a measure that is very hard to dissociate from other kilometers travelled. Figure 14.2 clarifies the scope of our project.

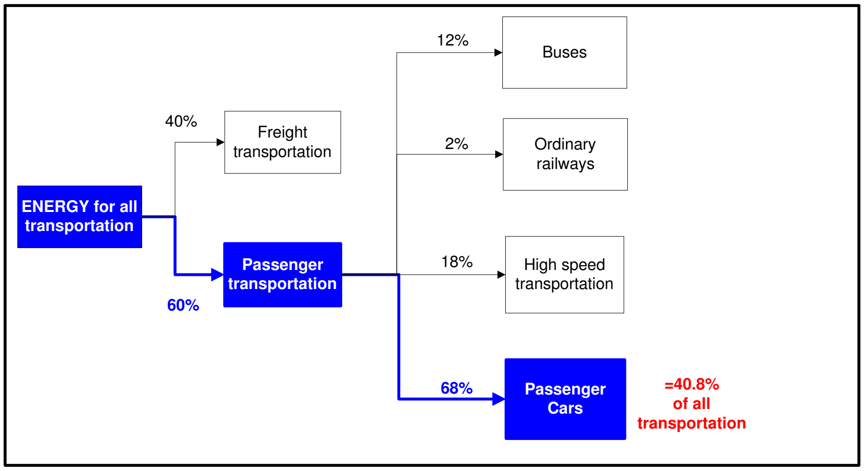


Figure 14.2: World transportation classification based on the percentage of the total amount of energy used by transportation. This project concentrates on the issues of passenger cars, considered to extend up to light duty vehicles, such as SUVs. (Classification based on numbers found in a paper by Schafer, 1998, [61])

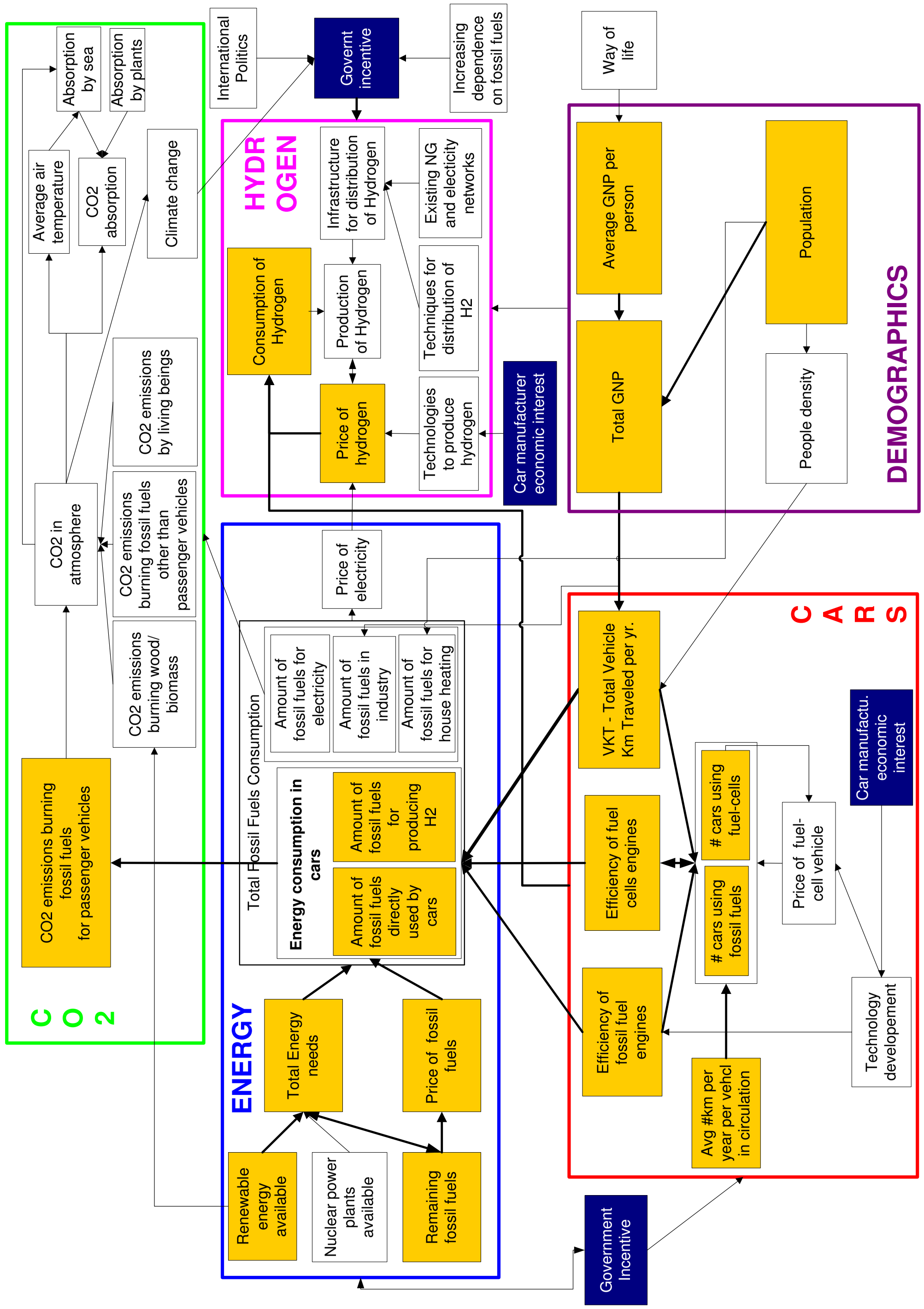


Figure 14.3: The correlation diagram: Our models are mainly focusing on variables highlighted in orange. They are linked by bolder arrows. Variables highlighted in blue reflect an influence that some particular entities (government and car manufacturers in this diagram) can have on the transition: they are discussed in following sections.

Defining transitions and energetic opportunities As clarified in section 14.2.1, we have introduced two kinds of transitions: the FCV and the Renewable transition. They are supposed to occur either consecutively or simultaneously in the course of the 21st century:

1. The Fuel Cell Vehicle (FCV) transition concerns the progressive replacing of Internal Combustion Engine (ICE) passenger vehicles by FCVs.

2. The Renewable transition is concerned with the increasing use of renewable energy for passenger vehicles, to stand in for the polluting fossil fuels.

The main difficulty with fossil fuels is that they all produce CO2. Techniques are being researched to sequester the CO2 but the predicted cost, both in money and in the energy expended in pumping the CO2 from where it is produced to where it will be stored is a heavy barrier to this solution. As an alternative, the fission process does not emit any CO2, and from the standpoint of global warming, nuclear energy provides an ideal source. But the public has very real fears of it, and few nuclear power plants have been built worldwide in recent years.

The most obvious alternative energy source is the sun. As stated Dresselhaus and Thomas in Nature, "to take the United States as an example, the total amount of solar energy falling on the continental 48 states is about $4.67 \cdot 10^4$ quads per year well in excess of the 98.6 quads that the United States consumes annually" (Dresselhaus et al., 2001, [45]). The principal disadvantages of solar energy are that at present the conversion efficiency of sunlight to electric power is not high, and sunlight varies with time of day, weather conditions and season. But the work published by Muneer et al. shows that "it is estimated that a single solar photovoltaic station of 250x250 km^2 area, or 12 decentralized stations each 72x72 km^2 area would be sufficient to meet the year 2020 world electricity demand". (Muneer et al., 2001, [57])

The use of wind for electricity generation has been expanding rapidly in recent years, due largely to technological improvements, industry maturation and an increasing concern with the emissions associated with burning fossil fuels. A detailed analysis by the Department of Energy's Pacific Northwest Laboratory in 1991 estimated the energy potential of the U.S. wind resource at 10.8 trillion kilowatt-hours (kWh) annually, or more than three times total current U.S. electricity consumption. (Elliott et al., 2001, [46])

Hydrogen can be produced from a variety of widely available renewable resources, using technologies such as electrolysis of water (powered by wind, solar or hydro electricity), or gasification of renewably grown biomass. (Ogden et al., 1993, [58])

14.2 Model 1: U.S. Hydrogen Transition Model

14.2.1 Description

This section describes our first model on the hydrogen transition which concentrates on the United States of America and assesses the impact of two major transitions. The first of these two transitions is the transition from traditional internal combustion engines (ICE) vehicles to fuel-cell vehicles (FCV), while the second one is the transition from sources of energy heavily based on fossil fuels to carbon free renewable energy sources. This would allow our society to move to sustainable sources of energy to fuel their economic prosperity.

Illustration Building upon the correlation chart that we created, main variables were highlighted and we studied what the exact nature of their relationship was. We then analyzed how this relationship could be translated in mathematical terms and finally implemented these links into a spreadsheet model. Figure 14.4 shows our variables once taken out of our correlation chart. It also features a symbol that represents both transitions mentioned above. The mathematical aspects of these transition distributions are covered in section 14.2.2.

Description of variables The following list describes all variables included in the model and their origin.

1. **Average GNP per capita(t)**[1] [$/(capita*year]: Historical and projected average Gross National Product per capita.

[1]where mentioned, *(t)* refers to time and means that variables are not just studied in some specific years but through time, up to 2100.

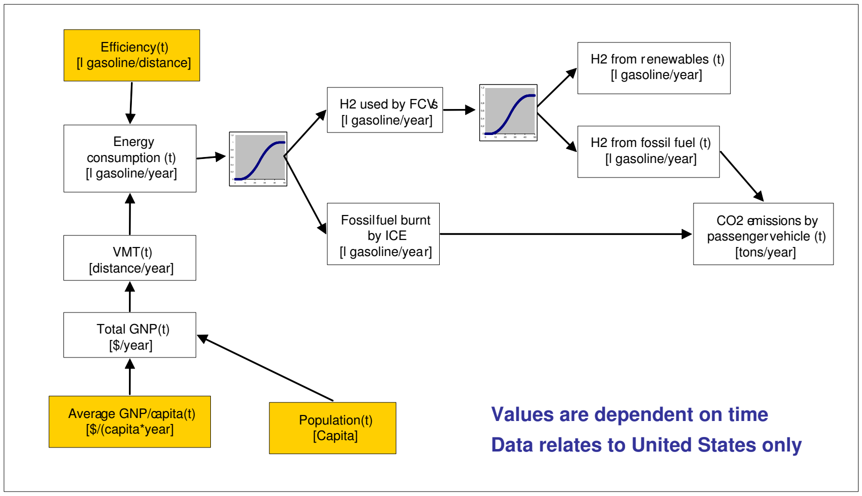


Figure 14.4: Representation of our first U.S. Hydrogen Transition Model, built in a spreadsheet. Variables highlighted in orange are input variables of our model which are derived from other variables (even though some require historical data to allow projections in the future, e.g.: Vehicle Miles Travelled).

Origin: World Bank Indicators Data (2002) for data from 1960 till 2000. Linear Regression 2000-2100.

2. **Population(t)** [capita]: Historical and projected population of the United States.
Origin: United States US Census Bureau data (2002, [107]).

3. **Total GNP(t)** [$/year]: Total Gross National Product of the USA.
Origin: Calculated multiplying Average GNP per capita and Population.

4. **VMT(t)** [miles/year]: Total distance travelled by vehicles per year.
Origin: 1960 to 2000 data from the Bureau of Transportation Statistics (2004, [110]); and 2000-2100 data projected by linear regression based on Total GNP.

5. **Efficiency** [liters gasoline/distance]: Efficiency of ICE vehicles, meaning the amount of gasoline used to cover a certain distance.
Origin: 1995 data is real data from the World Energy Council (1998,

[104]). 1960, 2020, 2050 and 2100 are parameters of our model entered by the user. The default values were 15, 11, 8 and 4 [liters/100km] respectively.

6. **Energy consumption** [liters gasoline/year]: Consumption of energy by passenger vehicles in terms of gasoline.
   Origin: Calculated multiplying VMT by Efficiency.

7. **H2 used by FCVs** [liters gasoline/year]: Amount of Hydrogen Fuel used by Fuel Cell Vehicles over the years if the transition is started.
   Origin: Computed through the use of a triangle distribution that assumes the pattern of the transition (see appendix C).

8. **Fossil fuel burnt by ICE** [liters gasoline/year]: Amount of fossil fuels (primarily gasoline) used by traditional vehicle over the transition years.
   Origin: Computed in parallel with H2 used by FCV.

9. **H2 from renewables** [liters gasoline/year]: Amount of the Hydrogen Fuel used by FCVs that is produced by renewable energy sources.
   Origin: Computed through the use of a triangle distribution, with different parameters but identical shape.

10. **H2 from fossil fuels** [liters gasoline/year]: Amount of the Hydrogen Fuel used by FCVs that is produced by non-renewable sources.
    Origin: Computed in parallel with H2 from renewables.

11. **CO2 emissions by passenger vehicles** [tons CO2/year]: Amount of CO2 produced by burning fossil fuels for passenger vehicle transportation.
    Origin: Calculated using a constant of 2.5 [kg/liter] that relates the burning of gasoline to amount of CO2 produced.

14.2.2 Graphical Outcomes of Projections

Important remark In the following section we show some graphical outcomes of the projections of our variables in more details. It is important to highlight the fact that projections are made quite far into the future, up to the end of the 21st century, and these projections are based on trends shown over only the last 40 years in the case of most variables. This obviously implies a strong element of uncertainty. However, it is very hard to reduce that uncertainty. What can be done is to bind this uncertainty, analyzing this data in a statistical way through a sensitivity analysis and recognizing the limits of the projections. A simple sensitivity analysis is carried out in our second model. We have decided, in the light of past data, to use certain linear regressions which seemed to reflect actual trends very well. There are many other ways of modelling these future trends, but it is not clear that they would prove to be better. Only future will tell.

1. Population was directly projected by the US Census Bureau which gave projections until 2100. This is illustrated in figure 14.5.

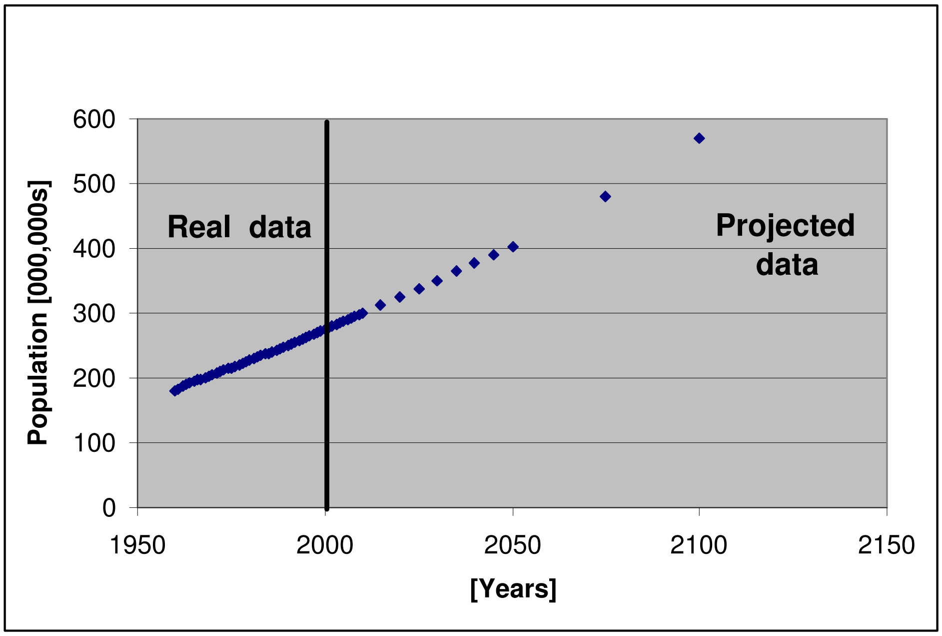


Figure 14.5: Projection of the population of the USA: data collected by the Census Bureau (2002, [107]). Real data was collected up to the year 2000, and projected up to the year 2100.

2. We assume the GNP per capita to be a linear function dependent on time. Indeed, past data from 1960 till 2000 show a pattern that can be assimilated to a linear one as a first approximation, neglecting fluctuations (see figure 14.6). We used the regression line indicated on the graph with real data to project data into the future.

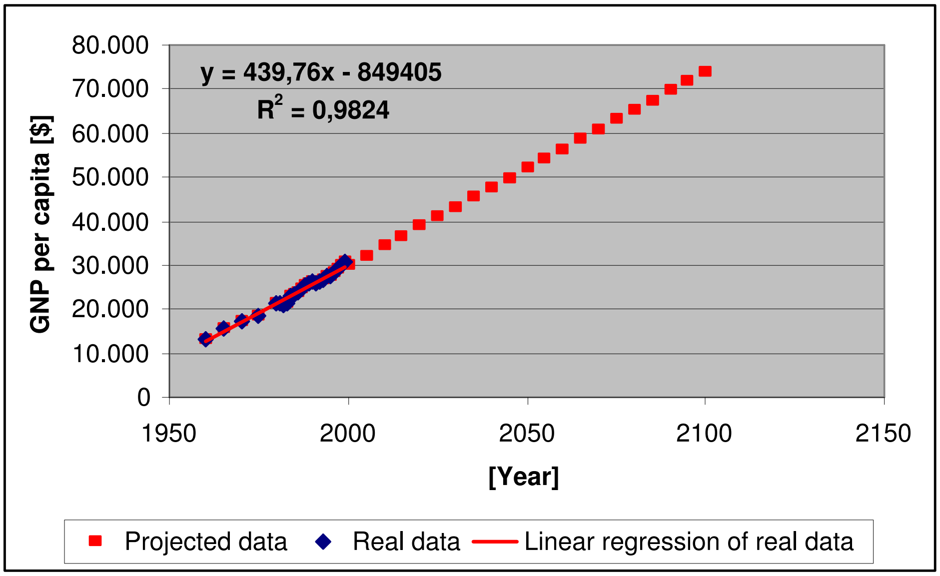


Figure 14.6: Projection of the GNP of the USA: data was projected using the linear regression shown on the graph

3. From there, total GDP was calculated multiplying GDP per capita by population. The forecast of total GDP of a country can be approached in at least two different ways. Either the total GDP is forecasted directly by using past GDP data; or the GDP per capita is first forecasted and multiplied by the estimated population to give the total GDP. We chose to use the latter method based on the following reasons:

    - We believe that even though the importance of direct physical labor is declining, each person has the potential to increase the income of its country. At least, under normal circumstances, consumption of the country will increase as population grows and in the long run the income must support the consumption.
    - A lot of effort has been put into population forecast by the World Bank. We believe that by using their results and just forecasting the GDP per capita linearly would give a somewhat more realistic forecast than forecasting total GDP linearly. For some of the developed countries the population is predicted to saturate and even

decline in future. By basing our total GDP forecast on population this is taken into account.

This is illustrated in figure 14.7.

As we are multiplying two values that are rising linearly with time, we are getting a quadratic curve. Some argue that population will saturate in a nearer future, instead of linearly increasing like projected by the U.S. Census Bureau (notice again that this projection is not ours). A strong argument in favor of this linear increase is the important component of immigration in the population trends in the United States.

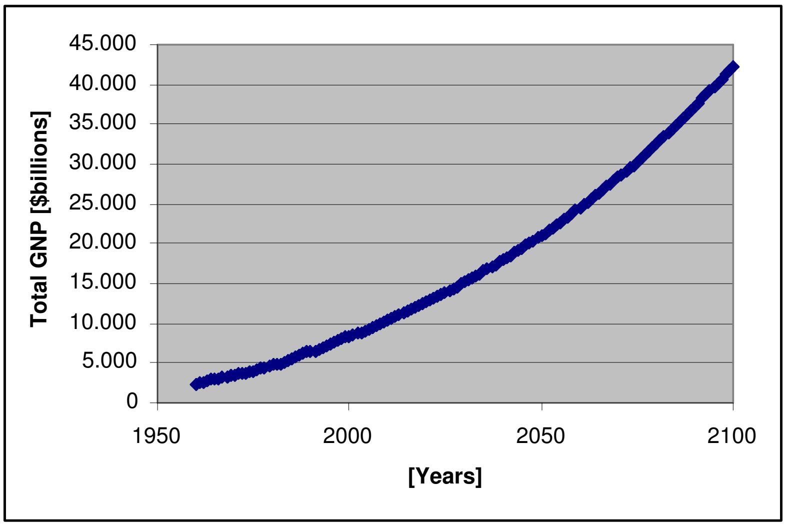


Figure 14.7: Calculations of Total GNP of the USA: population multiplied by GNP per capita.

4. As far as projecting the total Vehicle Miles Travelled (VMT), we assumed the amount of travel to be a linear function of Total GNP levels. If we bring it down to per capita levels, this translates into the fact that a person's amount of travelling is a linear function of how much money that person makes. This can be seen as a strong assumption, but was verified through available data for the United States for the years 1960 till 2000. Also, this method was actually mentioned in a paper by

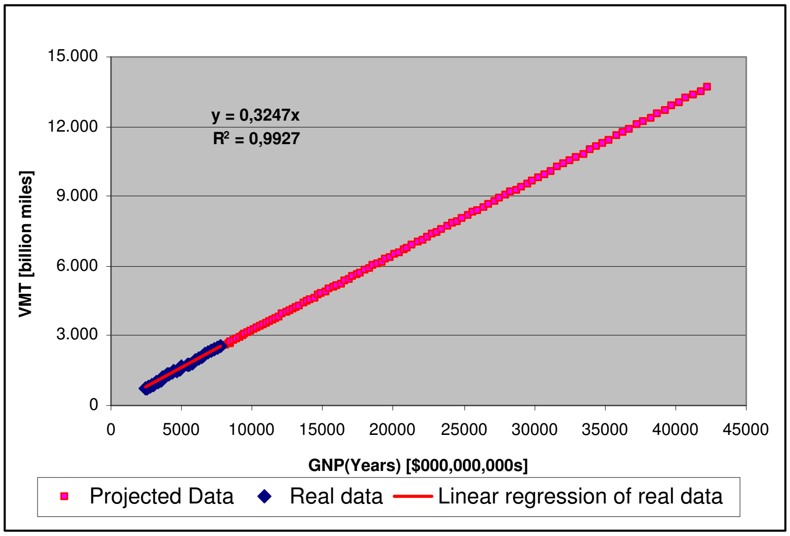


Figure 14.8: Projection of the total Vehicle Miles Travelled in the USA

Schafer on the global demand for motorized mobility (Schafer, 1998, [61]). We thus built a linear regression on the basis of such data. This regression is shown in figure 14.8. As was mentioned in the introduction to this section, the proportion of projected data to historical data seems relatively large, a logical implication of projecting relatively far into the future.

5. We decided that efficiencies for Internal Combustion Engines (ICE) should be a parameter entered by the user, apart from values of 1995 from the World Energy Council (1998, [104]) . Indeed, we have seen such a range of projected numbers that it seems difficult to pinpoint one scenario more than the other. These values will also reflect very strongly the strategies and policies adopted by governments in that respect. The scenario analysis in section 15 will show a few examples of such choices.

6. We assume both transitions used (from ICEs to FCVs and from fossil fuel energy sources to renewable ones) to occur following a triangular distribution. This function has been built to integrate to 1 and to have a linearly accelerating rate of transition until half the transition is over,

and to decelerate linearly thereafter until the end. More information on this issue can be found in appendix C.

14.2.3 Results of the U.S. Hydrogen Transition Model

This section will mention some of the basic comparison made to validate our first model before we moved on to our World Hydrogen Transition Model. The analysis is relatively short, seen that we will look further into our more complete model.

The following two graphs in figure 14.9 show the comparison in projection on the use of petroleum till 2040 in millions of barrels. The first graph is an output of our model and the second from a presentation by David Garman (Assistant secretary, US Department Of Energy) at the Hydrogen Transition Conference held in Asilomar in the summer 2003 ([86]).

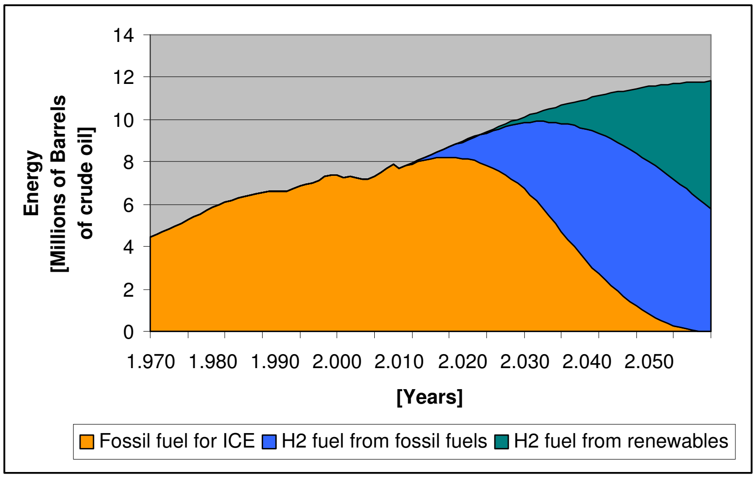
It is encouraging to see that both shapes and values are similar. In 1970, both models indicate about 5 million barrels of crude oil were needed to fuel the passenger fleet, and the peak of this consumption is predicted at about 10 million barrels of crude oil around 2025. These results are based on setting both transitions in our model to particular starting dates and duration: the FCV transition was set to start in 2005 and last for 45 years, while the transition toward non-fossil fuel sources of energy was projected to start in 2000 and last for a 100 years.

14.3 Model 2: World Hydrogen Transition Model

14.3.1 Description of the World Hydrogen Transition Model

New variables and sources

Our next goal was to extend our model to the entire world. We found that the most effective way to do this was to use a database that included all data available on countries around the world. Different sources gave us access to data on a wide range of countries. First and foremost, World Bank



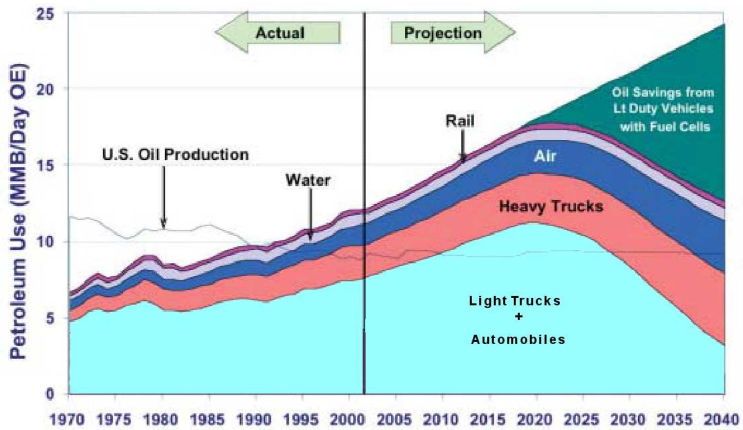


Figure 14.9: Those 2 figures allow us to compare the results of our model to results originating from the Asilomar conference (2003), in a talk by Mr. Garman (Assistant secretary, US Department Of Energy). Our results need to be compared to the green area including automobiles and light trucks, as both of these types are included in our scope. The green area in the graph resulting from our work represents energy that is not originating from the burning of fossil fuels.

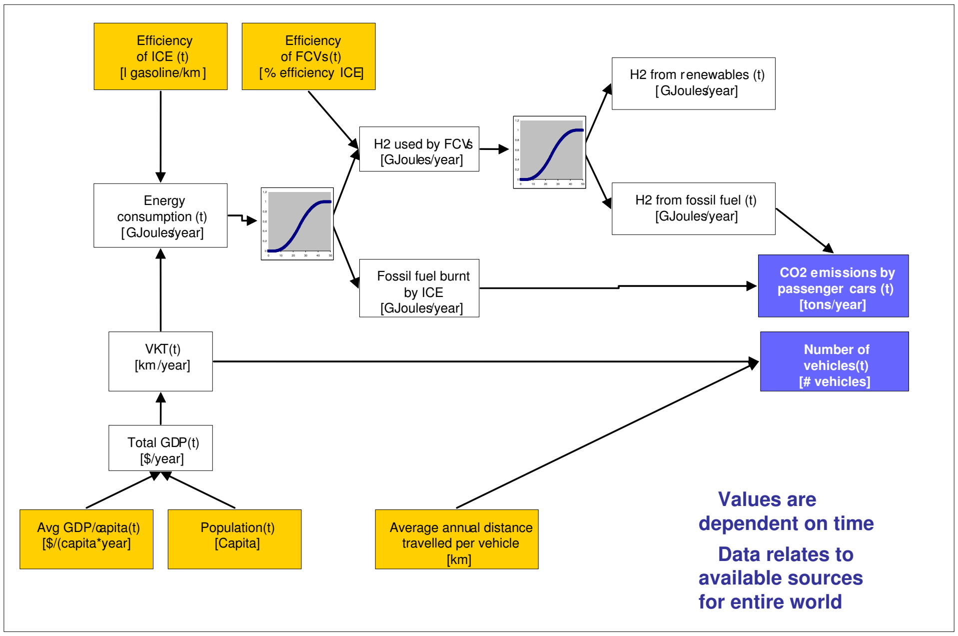


Figure 14.10: Overview of our second model. Variables highlighted in orange are input variables of our model, while other variables are results used for further calculations in some cases. Historical data was needed to compute the coefficients of the regression.

Indicators included Population and GDP data. VKT were gathered from the International Road Federation (IRF). All this data was organized in a single database where the same relationships were created between variables as in our first model confined to the United States. New variables have been included in this second model, most notably, we calculate the number of vehicles based on the average annual travelled distance per vehicle. Figure 14.10 gives a representation of the variables and their links.

Discussion on new sources

1. **GDP per capita:** Our main source for past GDP per capita was the World Bank Indicators (WBI), a database containing time series of various information for 207 countries of the world. We choose to use values for GDP per capita in fixed USD 1995 to eliminate the effects of price index changes in our model. All our monetary outputs

are therefore corresponding to USD 1995 values. The WBI seams to be a good source for the GDP per capita around the world. It is in accordance with other sources and few data where missing.

2. **Population** The past and forecasted world population was obtained from WBI. The time series include population data per country per year from 1960 to 2000, and a forecasted population per country every five years to 2090. All our sources agreed on population figures when compared for the past, but forecasted world population varied significantly between different sources. For example the forecasted world population by the Population Reference Bureau (PBR) is 9.2 billions in 2050 while 8.8 billions in WBI projection. Thus the world population forecasted 2050 by WBI is 96% percentage of the PBR forecast. Projected population of USA 2050 by PBR is 422 millions, by WBI 358 millions and 404 millions by the USA Census Bureau. Thus the WBI forecast of USA population in 2050 is only about 85% of the PBR forecast. The population of USA is highly affecting our overall results as we project it to present around 40% of the total VKT of the world at 2050.

3. **VKT** The main data source for the past VKT for countries around the world was the International Road Federation (IRF). It was the only one source found containing data for countries all a round the world. Although the IRF numbers on VKT seems to be rather low compared to other sources such as the Bureau of Transportation Statistics (2004, , [110]), a decision was made not to mix VKT number from different sources as they use different or unclear classification on passenger vehicles. Therefore in our World Hydrogen Transition Model we only used VKT data from IRF, either from their hardcopy reports or a spreadsheet published on World Bank website containing data for the period 1960-1983.

4. **Fuel efficiency** Fuel efficiency figures for a base case where obtained from the World Energy Council (WEC). As pointed in their report, their estimates are very sensitive to the underlying assumptions (which where not stated in their report). Three fuel efficiencies are therefore defined for each efficiency class in our model corresponding to pes-

simistic, base and optimistic values of fuel efficiency.

Description of the database

Implications of the use of a database The World Hydrogen Transition Model has been built using Microsoft Access XP. The use of a database implies positive and negative consequences.

Negative consequences:

- Some useful functions and tools in MS Excel are not available in MS Access, such as distribution functions and Solver.
- Excel is more flexible when constructing small models.
- All calculations must be coded manually.

Positive consequences:

- It is easier to combine data series from multiple origin into one data set.
- Data is organized in a rigid way and cannot be changed by accidentally shifting cells.
- Data can be filtered and managed very easily, allowing to observe and work on different groups of data more easily. Countries can be organized by continents, levels of development, regions (sub-categories in continents).
- Data can be visualized, filtered, classified and generated in graphical interface.
- Any change in the overall model structure are applied to all the data at once.

The use of the Open Database Connectivity (ODBC) allows us to perform more complex calculations in Matlab, such as the linear regression for all the countries, both for Gross Domestic Product and Vehicle Kilometers Traveled,

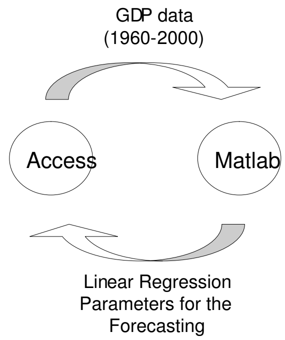


Figure 14.11: Illustration of the use of Open Database Connectivity (ODBC)

which is not supported by Access. The ODBC is a standard method of transfering data between databases and programs. ODBC drivers use the standard Structured Query Language (SQL) to gain access to external data. The combined data management power of Access and flexible calculation tools of Matlab we found to be a quite powerful mixture. Figure 14.11 gives a graphical illustration of this tool, using GDP data as an example.

Structure of the database The database structure was designed to allow flexible graphical analysis. The main data table contains approximately 29.000 records of different indicators for different countries on a yearly basis spanning the period of 1961-2001 for past values and 1961-2100 for forecasted values. Table 14.1 gives an overview of the indicators used in our study while a full list of indicators can be found in appendix D.

Classification by efficiencies Three classes (H, M, L) of vehicle efficiencies where defined in the data structure. Each group can take pessimistic, base and optimistic values which can be changed by user through graphical interface for five instinct years. Calculations of energy consumption are based on the efficiency matrix. The input values in the matrix are linearly interpolated to get continuous efficiency values in time.

Classification of countries into regions and continents To allow flexible aggregation, filtering and classification, countries were identified by continent, region in continent, development status and vehicle efficiency. While

Name	Description
CountryName	Country name
CountryCode	Country code
Year	Year
VKT	Vehicle Kilometers Traveled past data
ForPop	Past and forecasted population data from WB
ForGdpCap	Forecasted GDP per capita
ForGdp	Forecasted GDP
ForVkt	Forecasted VKT
NY.GDP.PCAP.KD	GDP per capita (constant 1995 US$)

Table 14.1: Indicators used in our study

EffClass	EffClassName	Scenario	1960	2003	2020	2050	2100
H	High Efficiency	Opt	11	7.5	5.5	4.5	3.5
H	High Efficiency	Bas	12	8	6.5	6	5.5
H	High Efficiency	Pes	13	8.5	7.5	7.5	7.5
M	Medium Efficiency	Opt	14	9.5	7	5	4
M	Medium Efficiency	Bas	15	10	8	6.5	6
M	Medium Efficiency	Pes	16	10.5	9	8	8
L	Low Efficiency	Opt	16	11.5	9	6.5	5.5
L	Low Efficiency	Bas	17	12	10	8	7.5
L	Low Efficiency	Pes	18	12.5	11	9.5	9.5

Table 14.2: Default setup of efficiency matrix

Development Status	GDP per Cap min [2000 USD]	GDP per Cap max [2000 USD]
VLD	0	3,000-
LD	3,000	10,000-
MD	10,000	20,000-
HD	20,000	+

Table 14.3: Classification of each country's development status according to GDP per capita

the first three identifiers are fixed in the database structure, the efficiency class of each country can be changed by the user through graphical interface. An overview of continents and regions can be found in appendix D. Each country's development status was decided based on per capita income in the year 2000. The classification bins are as described in table 14.3.

The general table relationships of the database are as shown in figure 14.12. Parametric queries were used to dynamically calculate results based on user input, and feed them to the graphical interface.

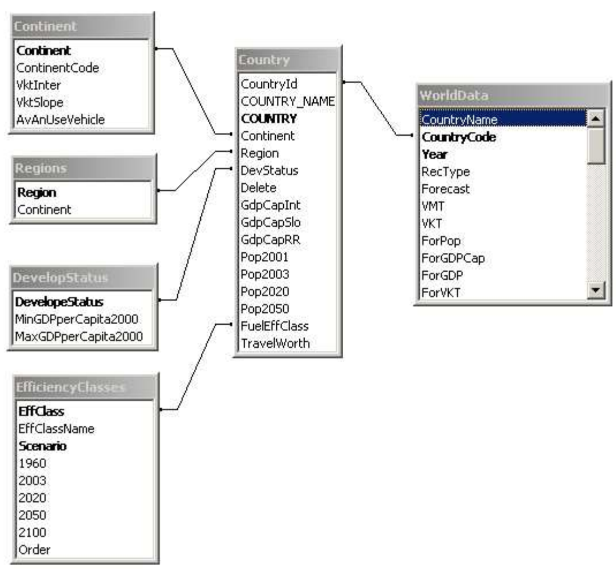


Figure 14.12: Table relationships in the database

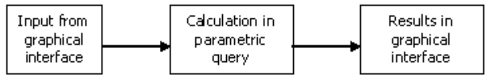


Figure 14.13: Calculation process in the database

The graphical interface A graphical interface was designed to make it easy for users to access the model, change parameters and variables, run simulation and to analyze various inputs and outputs. The database application of the World Hydrogen Transition Model starts up with the following window wherefrom all the main features can be accessed.

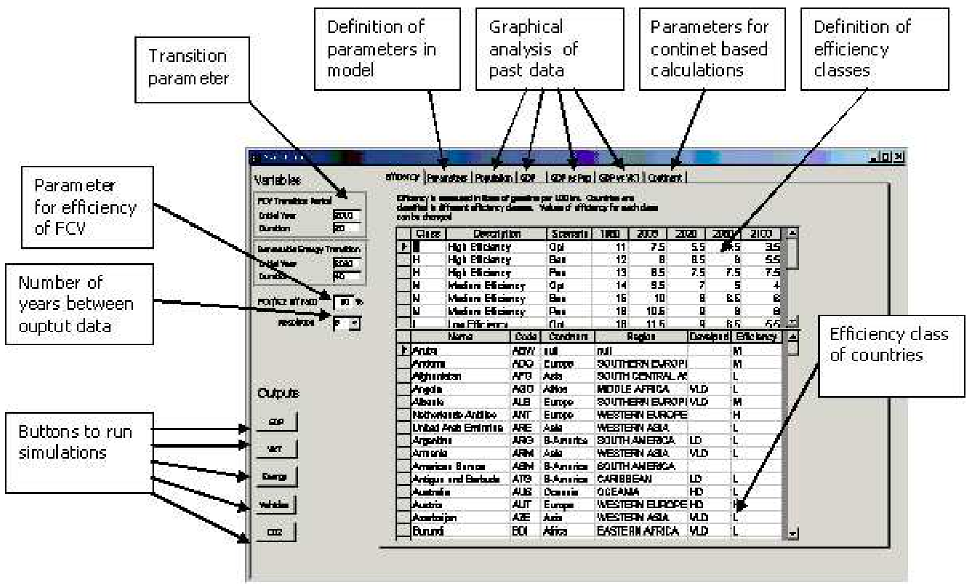


Figure 14.14: Illustration of the graphical interface and the use of each of the features: startup window of World Hydrogen Transition Model

The use of pivot tables and graphs allows the user to analyze the large amount of data used in the model dynamically, by drags and drops on the screen. To be able to use effectively the pivot features of MS-Access in the interface design, the data structure and the query process had to be organized as described earlier. All of the models input and output data can be aggregated, classified and filtered by:

- Develop status based on GDP per capita
- Continent of the world
- Region such as Western Europe
- Country name

Following are few examples showing the function and appearance of the dynamic graphical interface of pivot charts.

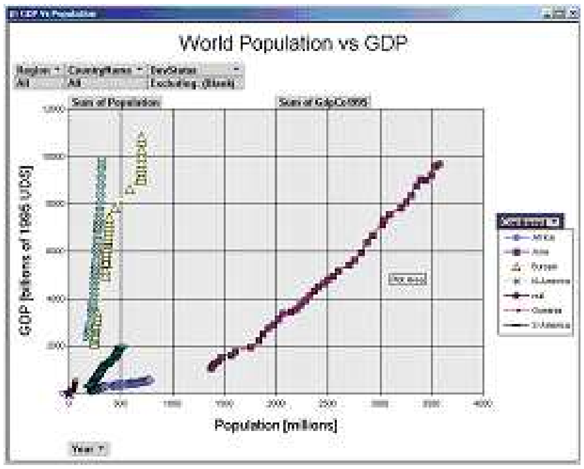


Figure 14.15: Graphical interface: GDP vs population in all continents

Figure 14.15: Aggregation and classification shows how the graphical interface can be used to compare how trends of *GDP vs Population* for different continents have developed during the period 1961-2001. There are two shift in the path of population in Europe, which are due to missing data in the World Bank time series of population. Firstly, population data were not available for Germany before 1971 and secondly the east block of Europe was not included in the population data until 1989. The same kind of analysis can be performed for any country, region, continent and for set of countries of different develop status.

Analysis of a case: Not all the world countries have the same constantly growing capita and GDP. As a result of civil war the population and GDP of Rwanda decreased during the period 1992-1994 but have been recovering since then.

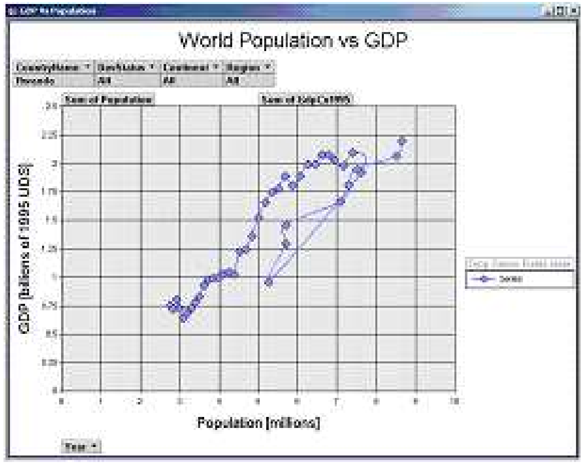


Figure 14.16: Graphical interface: The past development of GDP vs Population in Rwanda trough the period 1960-2000

Evaluation of transition: Figure 14.17 shows a representation of one of how number and type of vehicles evolve during the vehicle transition. The user simply has to press on the *Vehicles* button to visualize the output.

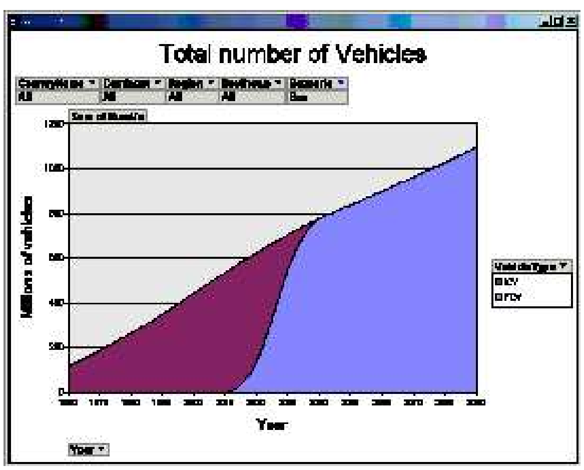


Figure 14.17: Number and type of vehicles in the world transition from ICE to FCV in the years 2010-2040

In the MS-Access XP version the graphics generated by pivot graphs are not exportable as they are directly linked to the underlying data. Therefore all the pivot graphs had to be copied as bitmaps from the application to be usable in the text of the report.

Forecasting Vehicle Kilometers Travelled: As said previously, the GDP of each country is forecasted using its individual data from the past 40 years. We assume that the GDP per capita will follow the same linear pattern, and multiplying by the predicted population (as given by the World Bank Indicators), we forecast the GDP of each country for the 90 following years. This is the same method as used in the spread sheet model for the United States, applied for each of the 207 countries included in our database.

The way of forecasting VKT is a bit different, as the IRF data on past VKT was not as complete as for the GDP, preventing us from doing an individual linear regression analysis for each country. But we still wanted to make forecasts as specific as possible, as we noticed that even wealthy countries had different VKT/GDP ratios, as shown in the following graph. USA is clearly more passenger vehicles intensive than Norway and Japan.

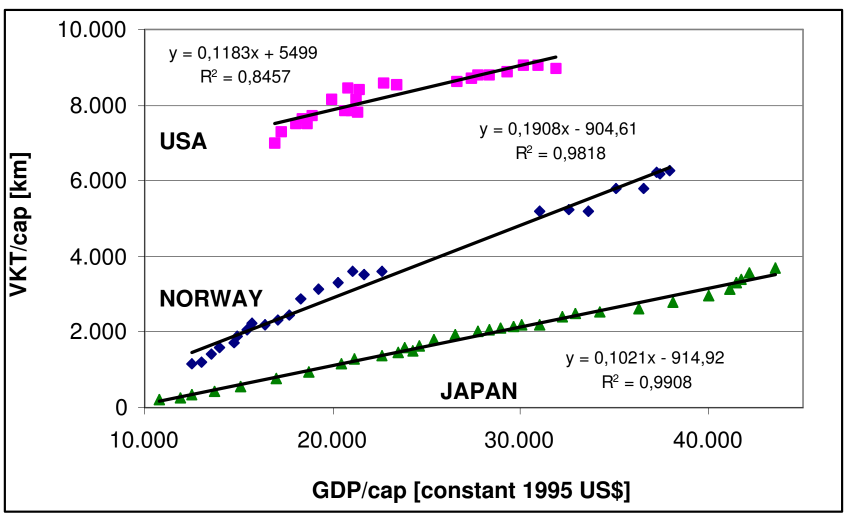


Figure 14.18: Illustration of some results on the linear regression VKT/cap vs. GDP/cap for USA, Norway and Japan during the last 30 years

We grouped countries by continent (Africa, Asia, Europe, North America, Oceania and South America), and noticed that over the past 40 years, total VKT could fairly well be modeled as a linear function of total GDP, with various slopes and intercepts for different continents, as shown in the following graph.

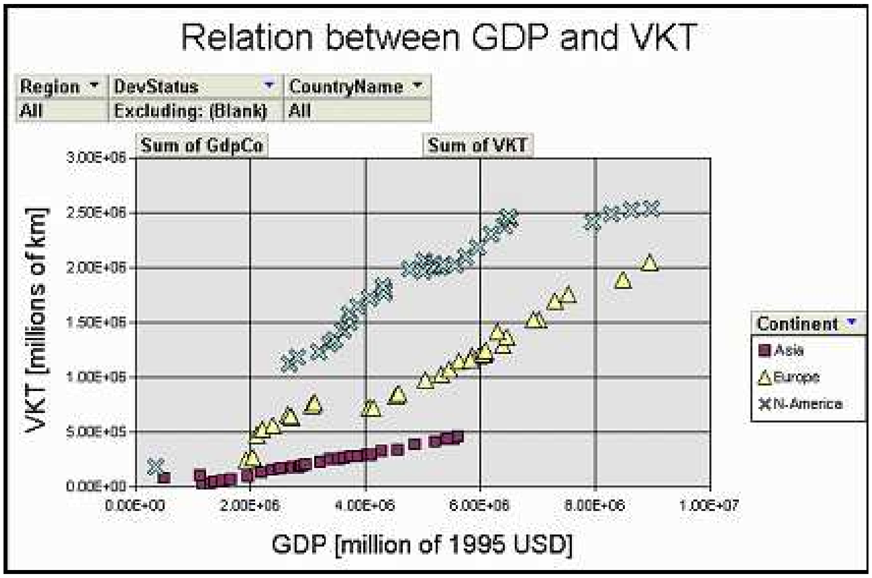


Figure 14.19: VKT vs. GDP for Asia, Europe and North America over the last 40 years

As a result, for a given continent, we assumed that VKT is a linear function of GDP:

$$VKT_{continent} = a_{continent} \times GDP_{continent} + b_{continent} \tag{14.1}$$

The values of the linear intercept a and the slope b for each continent are given in the table 14.4 below.

Continent	VktInter (millions of 1995 US$)	VktSlope (km/$)
Africa	1,973.20	0.29
Asia	-182,588.00	0.14
Europe	-335,493.00	0.26
N-America	564,176.00	0.26
Oceania	916.00	0.38
S-America	-2,794.60	0.20

Table 14.4: Slope and intercept for each continent

Link between GDP and VKT At the beginning of this study we where encourage by our advisor to start our own model building, when estimating the effect of future hydrogen transition. We where hinted that total VKT for USA seemed to be a fairly linear function of GDP. After construction our model based on this correlation, we recognized the similarity of our work and the studies of Schafer (Schafer 1998, [61]) where he introduces the relationship between the per capita mobility and per capita income as

$$\frac{pkm}{capita} = b \times \left(\frac{GDP}{capita}\right)^{m} \tag{14.2}$$

where pkm is motorized mobility by all transportation modes in the region, $capita$ is the total capita of the region, GDP is the Gross Domestic Product of the region, b is a constant and m is a constant.

The calculation of the constants b and m in equation 14.2 is not carried out in Schafer's paper but he mentions that in its simplest form the model can be expressed as:

$$\frac{pkm}{capita} = b \times \frac{GDP}{capita} + C \tag{14.3}$$

where C is a constant and it has been assumed that $m = 1$. This is very similar to our approach except that we limit our scope on the use of personal vehicles instead of motorized mobility (pkm) and we work on the basis of total GDP and total VKT (where VKT is the total vehicle kilometers travelled in a region) instead of per capita basis. In equation:

$$VKT = b \times GDP + C \tag{14.4}$$

As said before, we had available VKT data for only half of the countries included in our database. And there was even no country for which we had VKT data for every year from 1961 to 2001. In order to build the linear regression at the continent level, we added up for each year the available VKT data (which gave $VKT_{continent}(t)$), and the corresponding GDP (which gave $GDP_{continent}(t)$) of the countries of a given continent. As a result, for a given year (from 1961 to 2001) and a given continent, $GDP_{continent}(t)$ does not correspond to the sum of the GDP of each country of the continent, but rather the sum of the GDP of countries that contribute to $VKT_{continent}(t)$.

Having calculated the slope and intercept for each continent, we were able to forecast the total VKT of each continent from 1961 to 2090 using the linear functions. For a given continent and a given year, we were now adding the forecasted GDP of each and every country so that the forecasted VKT of the continent corresponds to the contribution of every country.

The main difficulty was to find a way to go from a continent level to the countries level in term of forecasted VKT. Since we believed that there should be a relationship between the GDP of a country and its VKT, we decided to attribute to each country the same part of $VKT_{continent}(t)$ as it represents in $GDP_{continent}(t)$. As a result, the forecasted VKT of a specific country is given by the following equation:

$$\begin{aligned} VKT_{country} &= \frac{GDP_{country}}{GDP_{continent}} \times VKT_{continent} \\ &= \frac{GDP_{country}}{GDP_{continent}} \times (a_{continent} \times GDP_{continent} + b_{continent}) \end{aligned} \tag{14.5}$$

14.3.2 Validation of World Hydrogen Transition Model

The output of the World Hydrogen Transition Model of hydrogen transition was validated in a number of ways. The results from the model were compared with figures from external resources such as articles and published reports.

Validation of the model through the back-casting of VKT Following up on our discussion on the forecasting of VKT, we can also use the same equation to estimate the VKT of each country in the past (1961 to 2001). This is also a way to validate our method, by comparing the estimated VKT with the real data available. France was the country for which we had the largest number of VKT data (38 years out of 41 years), and as a result, it was one of the most interesting country to estimate the performance of our method. Besides, France is only a small part of Europe in term of GDP. The following graphs shows that the estimated VKT match quite well the real data.

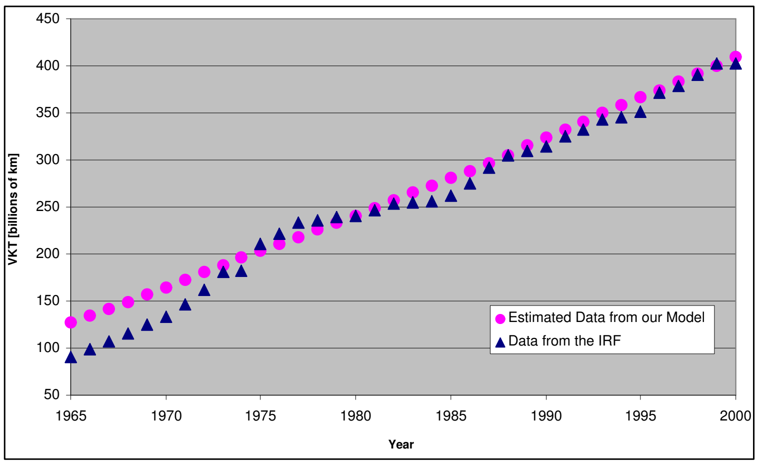


Figure 14.20: Estimated VKT and real data for France

Other validation data Energy consumption of USA transportation is 25 EJ[1] in 1997, according to Björklund et al. (Björklund et al., 2001, [39]). The proportion of energy used for all passenger vehicles is assumed by Schafer to be about 60% of the total energy used in transportation or 16 EJ in this case. The resulting energy consumption of personal transport vehicles in USA 1997 from our model is 11 EJ or about 69% of the total energy used in passenger transportation compared to 78% from Schafer for the year 1991 decreasing. (Schafer, 1998, [61])

[1]Exajoules = 10^{18} Joules

Energy consumption of the world passenger transport was 37 EJ in 1990 by all modes and the energy use of the car mode was 68% or 25 EJ at that time. From our model we calculate this number to be 23 EJ.

Grubler and Nakicenovic (1991) forecasted the world automobile fleet to saturate around 2010 at about 500 million vehicles and Walsh (1993) expects the number to be 700 millions and increasing. (Schafer, 1998, [61]) Burns comes up with a different number for 2020, "[b]ased on present growth rates, as many as 15 percent of the people living on the planet could have a vehicle by 2020. (. . .) The total number of vehicles could increase from about 700 million [today] to more than 1.1 billion." (Burns, 2001, [42]) From our model we forecast this number to be currently 535 millions and increasing. Evolution and trends could be studied in greater details in another study.

Chapter 15

Results and Analysis

We now have reached an interesting point in our work as several tasks have been accomplished: a thorough analysis on variables and issues of concern has been made and two models have been created on the basis of this analysis, one consolidating the work of the first. These models will now be used to forecast several scenarios and will be compared to other forecasts of similar variables. To do so, we have implemented three scenarios in our model by changing the different parameters that we have, namely: values for different efficiency classes, start and duration of transition toward Fuel-Cell Vehicles, start and duration of transition toward Renewable Energy Sources. The outcomes of our different variables are directly linked to these parameters.

1. Baseline/Expected scenario: the most likely scenario using values for the different parameters that we believe to be the most likely ones.

2. Optimistic scenario: scenario related to setting the parameters to optimistic values.

3. Pessimistic scenario: scenario related to setting the parameters to pessimistic values.

Remark: optimism (pessimism) refers to less (more) CO2 emissions, which is not to be confounded to higher (lower) GDP values.

We have analyzed them using the following framework:

	Pessimistic start duration of both transitions	**Expected start duration of both transitions**	**Optimistic start duration of both transitions**
Optimistic efficiencies	Great improvements in efficiencies slow down the motivation for transition	Efficiencies are good but transitions are still started in time	Efficiencies are very good but there is a clear motivation for transition. Actors realize the importance of gaining efficiency and early transitions
Expected efficiencies	Efficiencies improve as expected but transition is not encouraged. Greater risk of late start and thus of climate change	This is the baseline scenario, efficiencies are as expected and transition starts as we believe should be planned, improving CO2 emissions early	There is a clear realization that both transitions are needed for the good of future societies, even though efficiencies are good
Pessimistic efficiencies	Efficiencies are not improving well; climate change is of greater concern and the use of oil very high	Efficiencies are clearly not improving well, but transitions are started as planned, hopefully soon enough	Actors respond early to the clear drive for fueling the transitions as efficiencies are not improving

15.1 Analysis of World Oil Production

Bartlett presents three scenarios of yearly world crude oil production based on three ultimate recoveries: 2,000, 3,000 and 4,000 billion barrels. (Bartlett, 2000, [38])

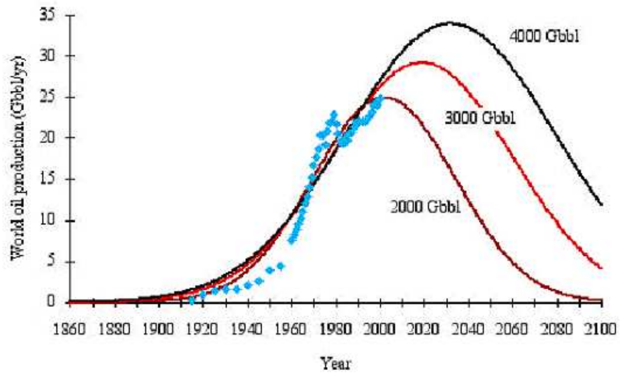


Figure 15.1: World oil production based on Hubert style curve (Bartlett, 2000, [38])

The generally accepted ultimate recovery is more or less around 3,000 billion barrels, as pointed by Riva in his article for the Congressional Research Service, *World Oil Production After Year 2000: Business As Usual or Crisis?* (Riva, 2000, [109]). As a result, our reference will be the estimated yearly world oil production based on an ultimate recovery of 3,000 billion barrels, where the peak production occurs around 2020. This kind of trend is clearly validated by Greene (Greene, 2003, [47]).

In order to be able to compare this reference with the passenger vehicles needs in oil as simulated by our model, we need to convert the figures into a common energy unit: Giga Joules (GJ). We know that 1 barrel of oil corresponds approximately to 6.1 GJ. Besides, Chevron's website states that on average, two barrels of crude oil are needed to produce one barrel of gasoline. (Chevron, 2004, [111])

Baseline Scenario: FCV transition: 2020 - 2050 Renewable transition: 2020 - 2050 We made three different simulations (baseline, optimistic and pessimistic) based on our estimation of the efficiencies. The passenger vehicles energy demands are shown in the following graph, where three categories appear: fossil fuel (gasoline) needs for ICVs, fossil fuel needs to produce hydrogen and renewable energy to produce hydrogen.

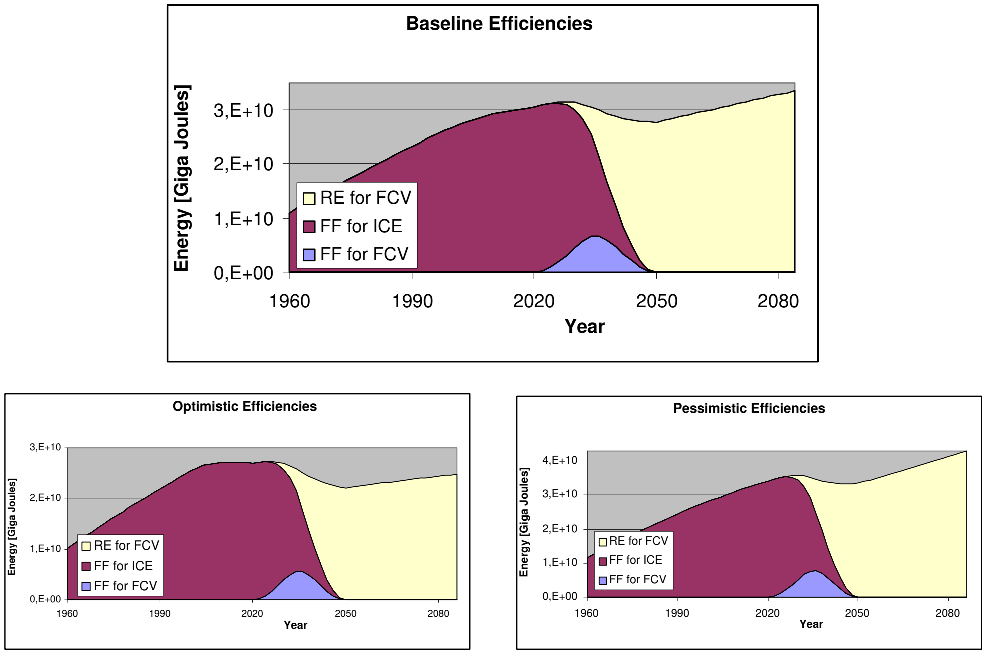


Figure 15.2: Passenger vehicles energy needs, baseline scenario

We can see that the total energy needs is planned to decrease between the years 2020 and 2050, due to the improvements in vehicle efficiency. Comparing the needs in oil with the world oil production, figure 15.3 shows that in no case, the passenger fleet will require more than 36 % of the total production.

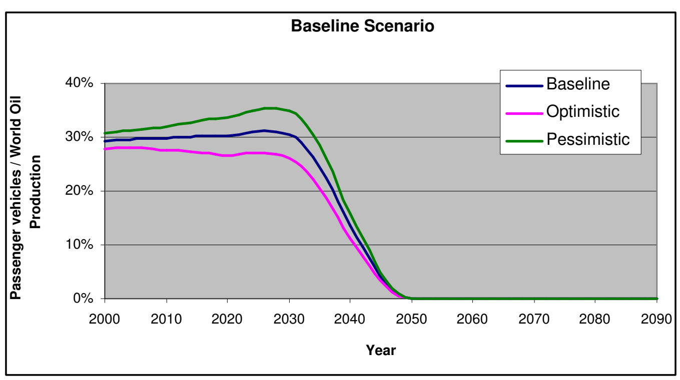


Figure 15.3: Passenger vehicles oil demand compared to the projected world oil production

Optimistic Scenario: FCV transition: 2010 - 2030 Renewable transition: 2010 - 2040 This scenario is not very far from our baseline, and passenger vehicles do not require more than 42 billion GJ per year (figure 15.4). In terms of the world oil production, it is no more than 33 %, which is encouraging (figure 15.5).

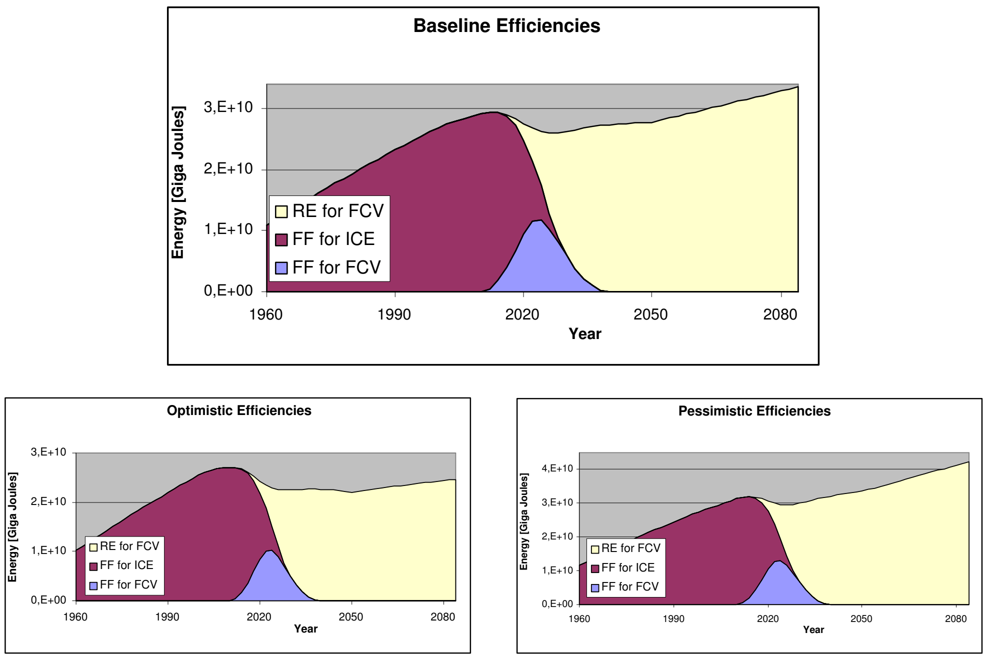


Figure 15.4: Passenger vehicles energy demands in the optimistic scenario

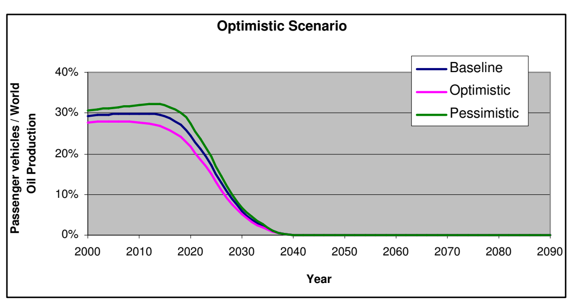


Figure 15.5: Passenger vehicles oil demand compared to the projected world oil production

Pessimistic Scenario: FCV transition: 2030 - 2070 Renewable transition: 2060 - 2100 In this case, both transitions start pretty late and last 40 years (figure 15.6).

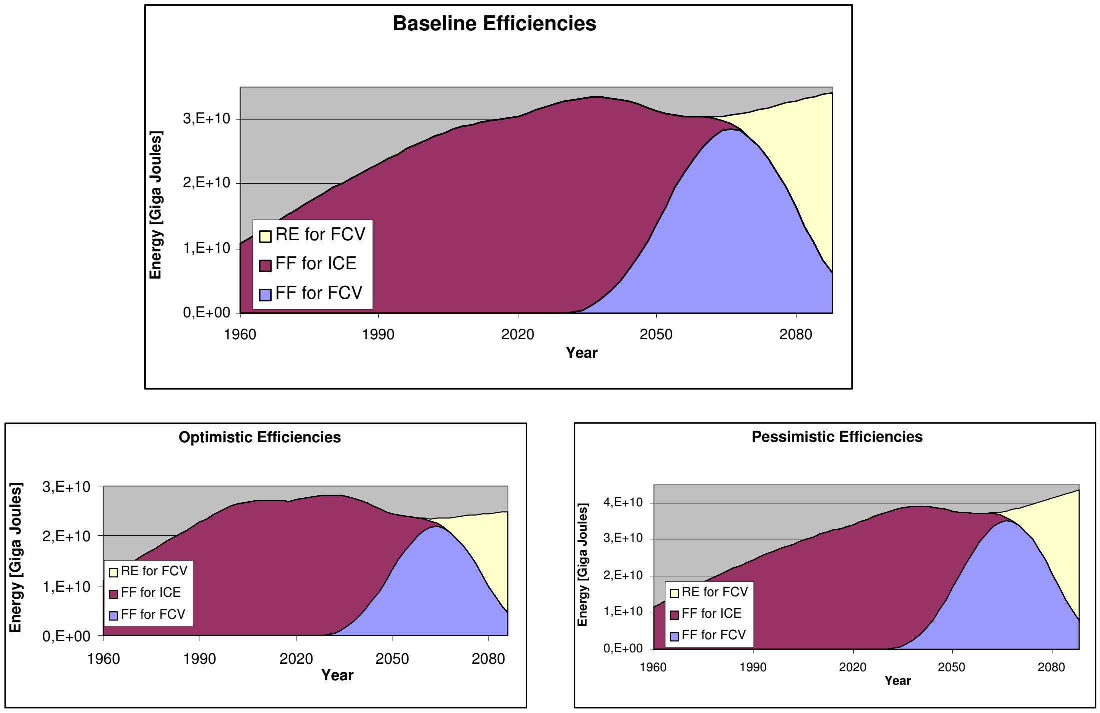


Figure 15.6: Passenger vehicles energy demands in the pessimistic scenario

Due to the improvement in efficiencies, the needs in fossil fuels will peak around 2030, and decrease to zero while the renewable transition is processed. Compared to the world oil production, the peak in 2030 represents less than 40%, but the decrease in passenger vehicles needs that follows is not as quick as the projected global decrease in oil production. As a result, as shown in the following graph, it will represent a great part during the period 2060-2080.

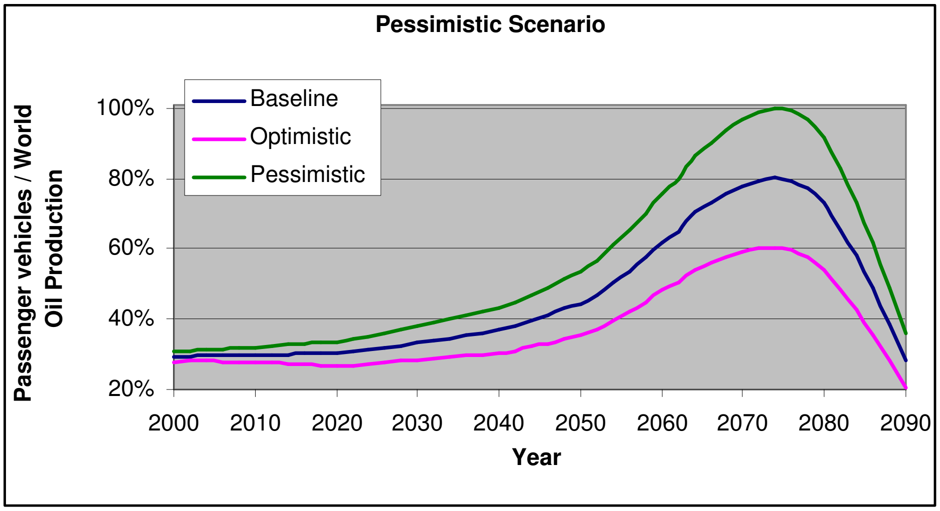


Figure 15.7: Passenger cars oil demand compared to projected world production

This perspective is clearly not reasonable, as we cannot imagine that personal vehicles will squeeze out all other uses of petroleum. An important oil crisis might appear even before 2050, when passenger cars would require half of the world crude oil production. Other fossil fuels like coal or natural gas could be considered to substitute for oil. (Greene et al., 2003, [47]) point out that unconventional oil resources such as oil sands, heavy oil or shale oil can prove to be an attracting resource and substitute for conventional oil beyond 2020. In any case these alternatives will help deal with pollution issues, which is why our study considers scenarios where renewable energy sources fully replace fossil fuels within the 21st century.

15.2 Analysis of Carbon Emissions

This section analyzes our results on carbon emissions. To do so, we will first introduce what proportion of anthropogenic sources our report is concerned with, before moving on to comparing our results to figures by the Intergovernmental Panel on Climate Change (IPCC).

15.2.1 Anthropogenic Sources of Carbon Emissions

Human sources of carbon emissions can be broken up in three categories: the ones originating from the burning of fossil fuels, from the production of cement and from changes in land-uses. We go on describing exactly what portion of human-caused carbon emissions our report is concerned with. It is often referred to the report on climate change from the Intergovernmental Panel on Climate Change (IPCC, 2001 , [64]).

Description of the 3 main anthropogenic sources of emissions

Current anthropogenic emissions of CO2 are primarily the result of the consumption of energy from fossil fuels. Figure 15.8 summarizes emissions over the period from 1959 to 1999 (Keeling and Whorf, 2000 , [64]). Estimates of annual global emissions from fossil fuel burning and cement production reach a maximum in 1997 of 6.6 PgC/yr (0.2 PgC/yr of this was from cement production).

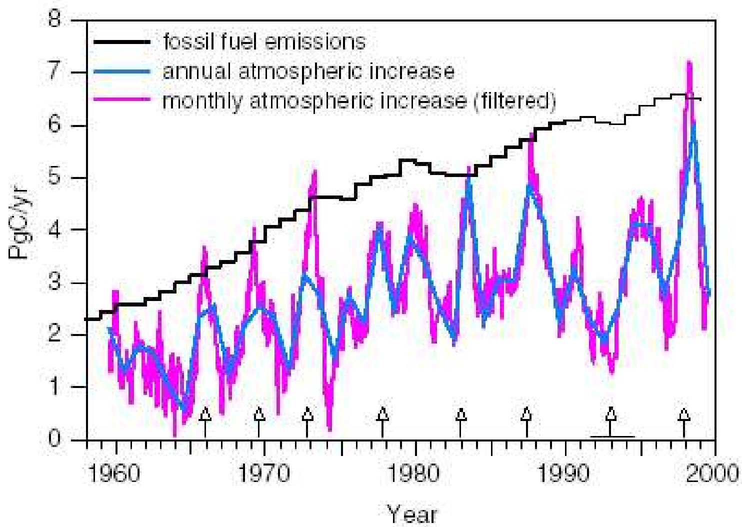


Figure 15.8: Estimates of annual global emissions from fossil fuel burning (Prentice et al., 2001, [64])

About 10 to 30% of the current total anthropogenic emissions of CO2 are estimated to be caused by land-use conversion. Such estimates rely on land cover data sets which are highly variable, and estimates of average carbon density of vegetation types, which are also highly variable with stand age and local conditions. Hence they cannot be specified as accurately as is possible for fossil fuel emissions. The calculations of this source of GHGs is based on the concept of net land-use flux, comprising the balance of positive terms due to deforestation and negative terms due to regrowth on abandoned agricultural land (Houghton, 1999 , [64]).

Proportion of each of these emissions

It is very difficult to find accurate measures of what each source is actually contributing to carbon emissions, however, different literary sources allow us to get an idea of how much passenger vehicles contribute to these. Figure 15.9 summarizes what carbon emissions are made of and goes further in showing what portion of the burning of fossil fuels we are concerned with in this report, namely the burning of fossil fuels in personal vehicles.

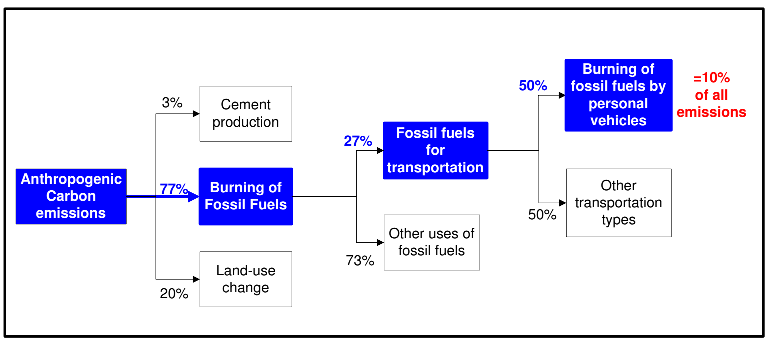


Figure 15.9: Worldwide approximate proportions of carbon emissions, narrowing down to the percentage due to passenger vehicle transportation.

Considering carbon emissions from this specific category implies two ratios that we have tried to estimate using available data:

1. The amount of CO2 for vehicles is considered to be 27% of global CO2 emissions for the USA (source: EPA, see calculations in Appendix E.1)

2. The amount of CO2 produced by passenger vehicles is considered to be about 50% of all emissions by vehicles in the Czech Republic (source:

Czech Republic Transport Yearbook, 1998, [105], see calculations in Appendix E.2). Considering how hard it is to find worldwide data on this subject we decided to use this figure as a first approximation. It seems that an eastern European figure is probably closer to the average world figure than an American figure due to its average economic status.

This implies current values for passenger vehicles emissions' ratio to global emissions of about 10%. Another source concerning the European Union this time gives us a value of 12% (EU, [100]).

15.2.2 Comparison of our Results to Other Sources

We have tried to compare our results concerning carbon emissions to other relevant sources. However, we have found no other work concentrating on the same type of transitions as the ones we are describing through our World Hydrogen Transition Model. We have thus decided to compare our work to models of the IPCC which gives us results for several different scenarios of global carbon dioxide emissions from all sources. We will compare our results in 2 ways:

1. We will look qualitatively at the shape of our curves for future trends of CO2 emissions up to 2100. This includes elements such as when those curves peak at their highest values, how fast they decrease thereafter and when they reach much lower levels.

2. Secondly we will look quantitatively at how much our projected passenger vehicle emissions contribute compared to global IPCC values in the future by computing the ratio of one against the other.

Our results Figure 15.10 illustrates our results for CO2 emissions for the 9 scenarios we analyzed. They are summarized in 3 graphs, each of them representing one of the 3 scenarios for the start and duration of the transition and including 3 curves that refer to the 3 different efficiency scenarios.

We notice, as expected, that pessimistic values for future efficiencies during the 21st century imply higher carbon emissions: those curves are represented by the green curves. Also, more pessimistic projections about the start of both transitions (towards FCVs and towards renewable energy sources) imply later decrease in CO2 emissions.

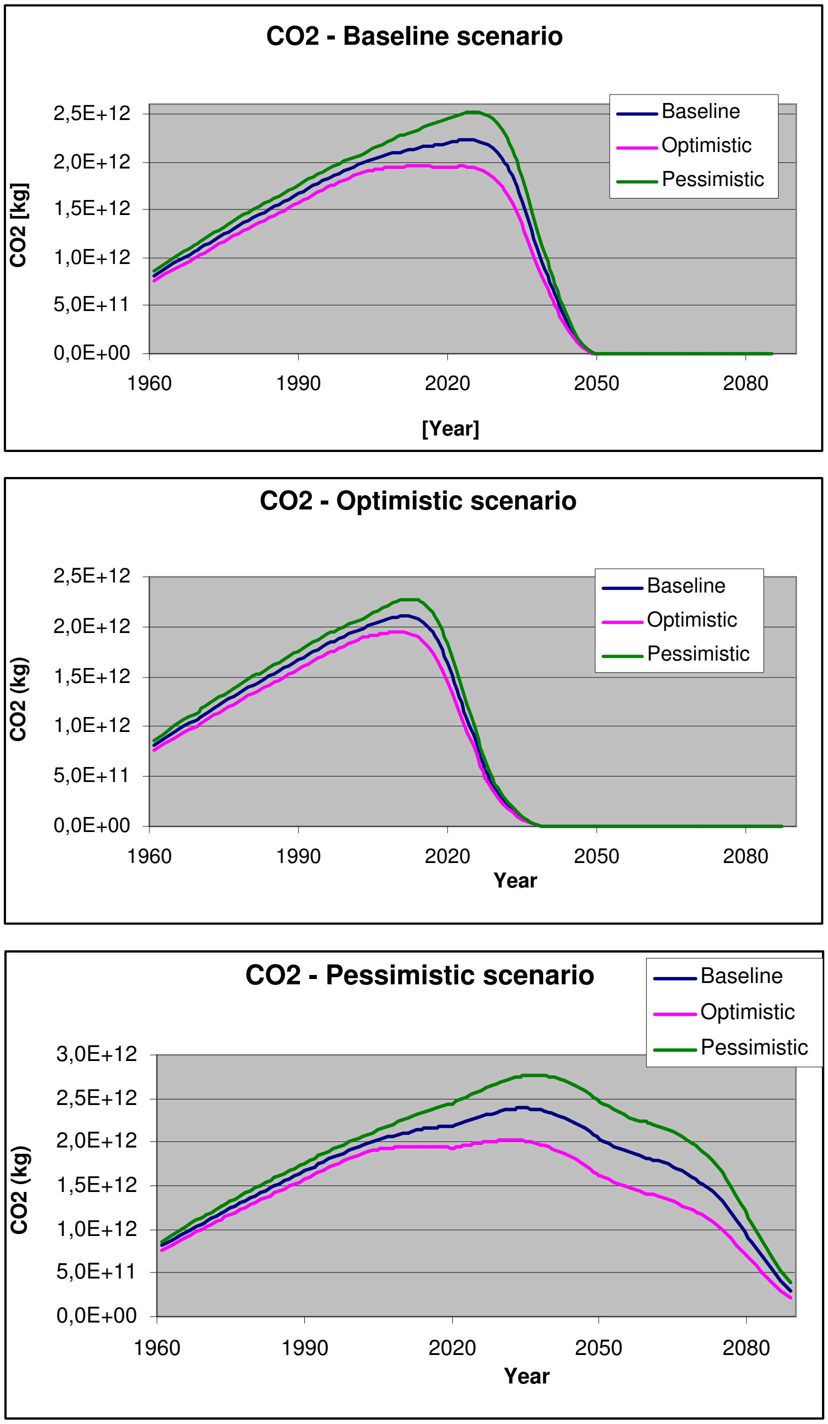


Figure 15.10: Figures represent carbon dioxide emissions from passenger vehicles as projected by our model for each type of scenario for transition types and include the 3 different efficiency scenarios

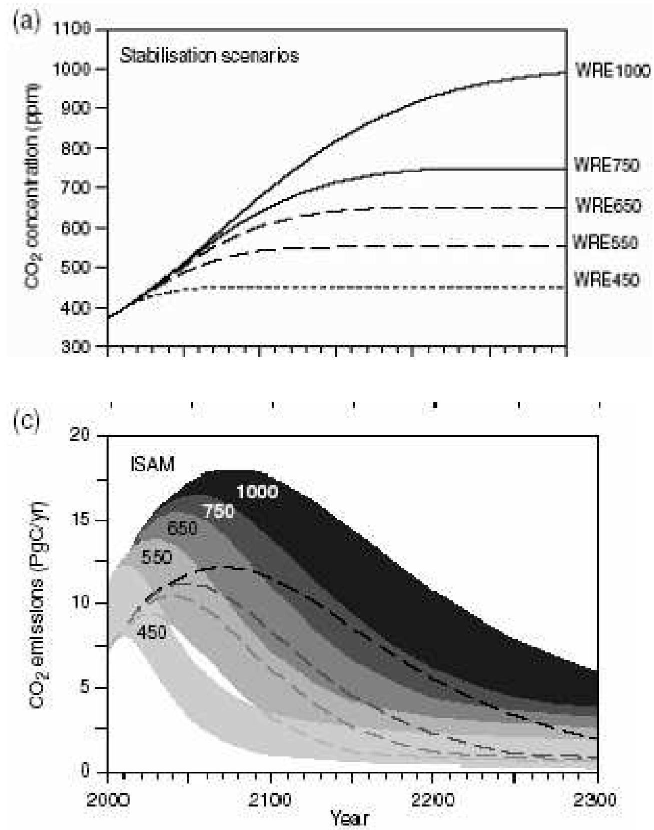


Figure 15.11: Results by the IPCC. Picture (a) represents concentration scenarios, picture (c) the outcomes of the ISAM models

Comparisons to IPCC results Figure 15.11 shows results from the IPCC models. Figure (a) represents the concentrations of carbon dioxide that several different scenarios are projected to lead to. The 550ppm scenario is the one that is most often used in literature (seemingly because it is often mentioned in the political arena - IPCC, 2003, [65]). All these scenarios are called mitigation scenarios, meaning that they imply some interventions by government offices to encourage change. Figure (c) shows results of a model that extrapolates projected values of CO2 considering each of the different scenarios of stabilized concentrations mentioned above.

1. Qualitative comparisons

   We notice that the 550 ppm scenario of the ISAM model peaks at around 2030, similar to both the peaks of the baseline and the pessimistic scenarios. Decrease is relatively slow for the IPCC projections, unlike the shape of our results.

Remark: As far as their values around 2100, our values are much more optimistic, but our results only include passenger vehicles and the decrease in emissions is due to both better efficiencies of Fuel-Cell vehicles and of the necessary transition to non-CO2-emissions ways of producing hydrogen. This is quite different from the results of the IPCC model which are not directly studying those transitions but likely values. In short, we base our work on the assumption that those transitions will happen and we show how carbon emissions will be reduced as a result of those transitions: this is thus an optimistic scenario from the start. The main object of our study is the effect of extending these transitions to future times.

2. Quantitative comparisons

   As far as quantitative comparisons are concerned, the following graphs in figure 15.12 show percentage ratios of carbon emissions as projected through our model compared to the ones projected by the IPCC model. It is obvious that these values drop sharply very quickly for scenarios projecting very fast transitions. Of more interest, however, are the relative percentages of our results compared to the IPCC ones. We are floating around approximately 6 %. These values are quite different from the one mentioned in our previous section highlighting that passenger vehicles emissions' ratio to global emissions are said to be about 10%. We believe, however, that these numbers are very different in different parts of the world and that our values correspond quite well to current data available on production of C02 by personal vehicles.

   It is also interesting to look at how long these ratios need to drop to much lower values in each of the different scenarios. It is clear that the pessimistic scenario implies staying at current values of emissions much longer into the future.

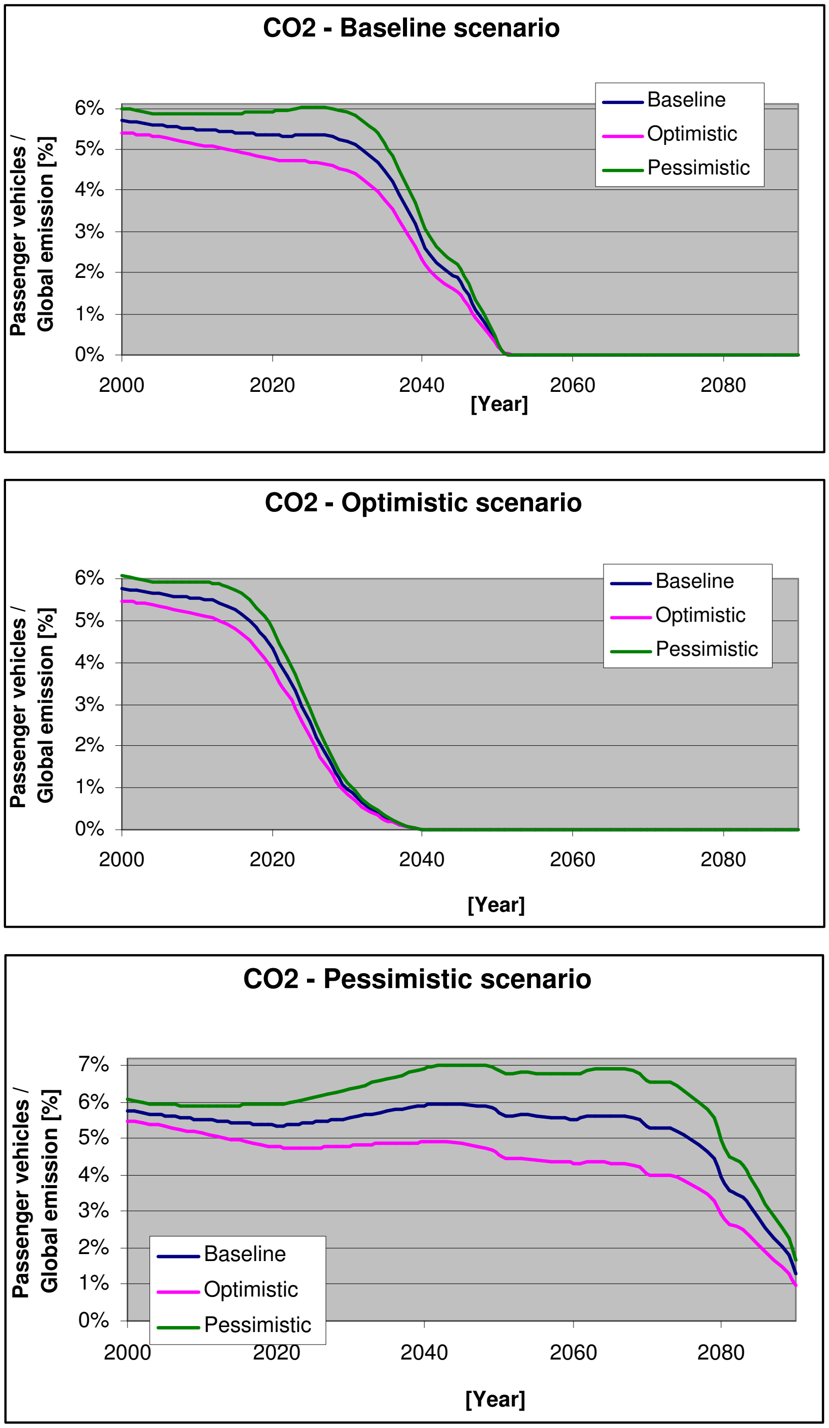


Figure 15.12: Figures represent the ratios of carbon dioxide emissions from passenger vehicles as projected by our model to results for global emissions from the IPCC (for each type of scenario for transition types and include the 3 different efficiency scenarios)

15.3 Scheduling

15.3.1 The Renewable Transition

We now consider both the optimistic and baseline scenarios for the FCV transition, and try to predict the allowable duration of the renewable transition. As we have seen in the previous section, an important constraint is the world oil reserves, and we will work in the worst case, where the ultimate recovery of oil is only 2,000 billion barrels (see figure 15.1 above). We can see that we should have used half of the world ultimate recovery before the year 2020, even 2004 according to the most pessimistic scenario.

We built the curves of cumulative production by summing the yearly world crude oil production for both scenarios. The remaining reserves are then deducted by taking the difference between the ultimate recovery and the cumulative production (figure 15.13).

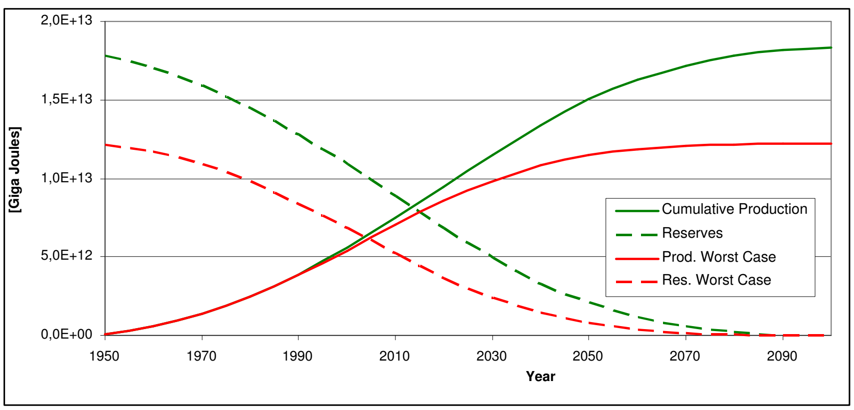


Figure 15.13: Estimated World Oil Cumulative Production & Reserves

We know that today, approximately 30 % of the crude oil production is used to produce gasoline for passenger vehicles (World Resources Institute, 2004, [112]). Assuming that this ratio will remain the same in the future, we can compare the yearly fossil fuel energy consumed by passenger vehicles with the remaining reserves, and predict if the transition simulated would be feasible. This gives us an idea of the maximum duration of the renewable energy transition, for various starting years.

As said previously, this analysis is based on the pessimistic scenario for the world oil reserves (ultimate recovery of 2,000 billion barrels). The following graph gives an idea of our reasoning. Starting the transition in 2060, and making it last 40 years, we can see that in the years 2070 and after, there will not be enough reserves to sustain the needs. A renewable energy transition starting in 2060 cannot last longer than 30 years.

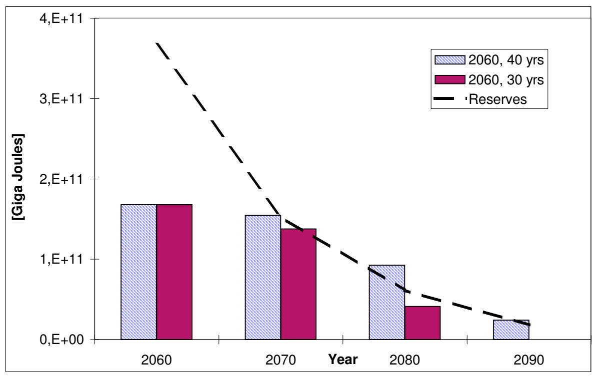


Figure 15.14: Feasibility of a simulation of the transition as modelled

We repeated our simulations for two FCV transitions (optimistic scenario: 2010-2030 and baseline scenario: 2020-2050) and various characteristics of the renewable transition. The following graph shows the result of our analysis. It shows that if we start the renewable transition early (2020), we can allow it to last quite a long time (80 years), while if we start it pretty late (2060), it has to last less than 30 years.

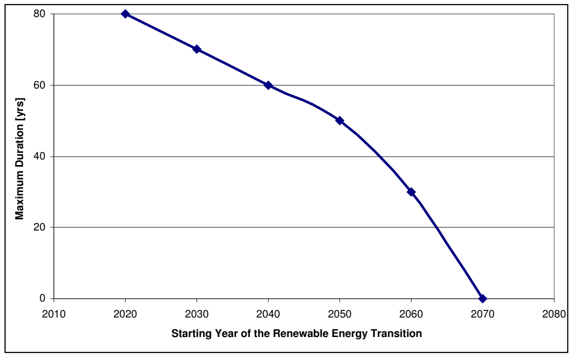


Figure 15.15: Possible Duration of Transition as projected by our model

15.4 Cost and Timing while using Solar Hydrogen

If we consider the baseline scenario for both transitions (2020-2050) and the baseline efficiencies values, what will be the requirements in term of renewable energy, and how can we provide such quantities?

As mentioned in the section 14.1, zero-emitting energy sources alternatives are quite numerous and can all prove to be attractive in the future. Among other challenges, if the technology to sequester the CO2 is developed, if nuclear energy is better understood by the public or if the cost of wind electricity decreases, we could imagine to support the renewable energy transition with various sources. For the purpose of our study we chose to consider a simple case where all the hydrogen used for FCVs comes from solar energy.

The following graph shows the repartition of hydrogen needs from renewable energy for passenger vehicles by continent.

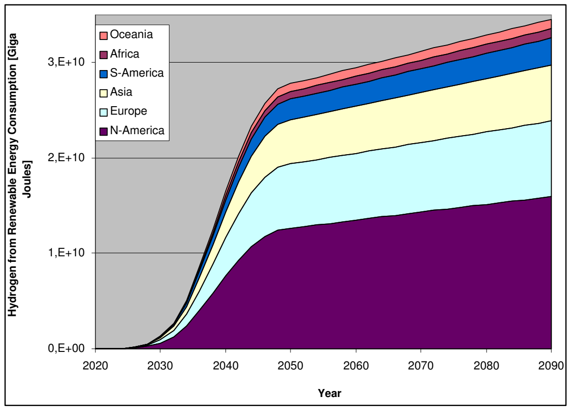


Figure 15.16: Hydrogen from renewable energy required for passenger vehicles in the baseline scenario

Ogden and Nitsch ((1993, [58]) indicate that sufficient photovoltaic hydrogen to meet the world's foreseeable energy needs could be produced on a few percent of the earth's desert area, given that less than 2,500 km^2 of land area can produce 1 exajoule of hydrogen per year. If we assume that each continent needs will be supplied by solar photovoltaic stations installed within or close to the continent, the land requirements are shown in the following graph.

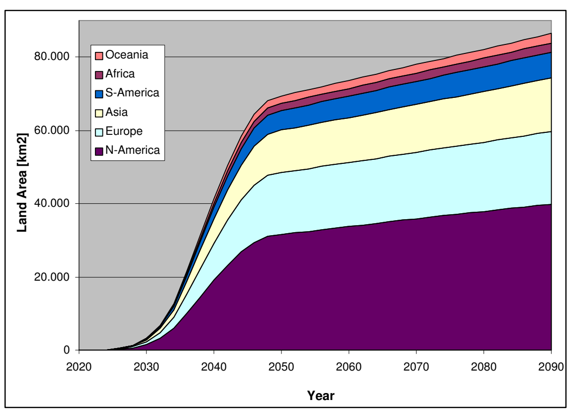


Figure 15.17: Land area required to produce photovoltaic hydrogen for passenger vehicles

The requirements for North America in 2090 (40,000 km^2) correspond to less than 5% of the U.S. desert area. Southern Spain has more than 20,000 km^2 of unused arid zones, which is sufficient to provide the hydrogen needed for the whole Europe. North Africa can also prove to be a potential producer of hydrogen for Europe, given that being located at a lower latitude, it is has smaller variations in the solar reception throughout the year. The other four continents have easily enough desert areas to meet the demand in hydrogen for passenger vehicles.

We have seen in the Energy Cost Analysis chapter that electrolysis based hydrogen will cost less than $20 per GJ in 2020, and no more than $10 per GJ at the end of the 21st century (average cost of hydrogen after producing, handling, distributing and dispensing). Assuming a linear decrease, the cost of producing hydrogen for passenger vehicles is shown in the following graph. We can see that the cost will peak around 2050. For North America, it represents $ 200 billion, which is less than 0.7 % of the current GDP of this continent.

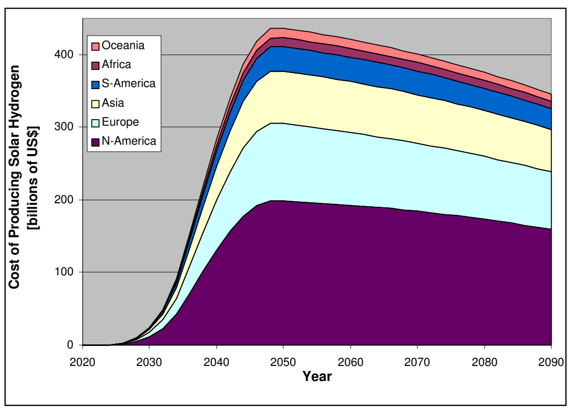


Figure 15.18: Cost of solar hydrogen for passenger vehicles

Ogden and Nitsch (1993, [58]) give the investment cost for solar hydrogen production systems: around $300 for a hydrogen production of 1 GJ per year. We assume that this cost will be $200 in 2020, decreasing to $100 at the end of the 21st century. The following graph shows the yearly investment expenditures for solar hydrogen systems.

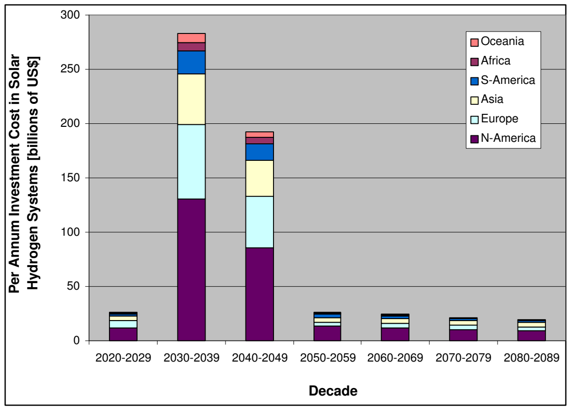


Figure 15.19: Yearly investment cost in solar hydrogen systems for passenger vehicles

In order to pay for the renewable transition, cash outflows will be large from 2030 to 2050. During the 2030's, $130 billion will have to be spent each year to build the systems supporting North America, which represents less than 33 % of the current annual U.S. military budget.

15.5 Actors and Strategies

As mentioned in the introduction of our scenarios, several entities have the power to have a great influence in the transitions that we believe to be on their way. Governments certainly have the opportunity to encourage or discourage these transitions through their actions in fields such as fuel taxes, or through subsidies for research and development in related issues, as well as in international conventions. Car manufacturers and oil companies also have an important role to play, directing their strategic plans toward an inclusion of hydrogen and its future applications, working in the light of *eco-efficiency*, instead of the traditional *money-efficiency*.

15.5.1 Main Actors: the Industry

The industry obviously has an important role to play, as they will be the driver of these transitions by actually producing the necessary goods. This includes players such as major oil companies, car manufacturers, fuel station operators, etc. In the larger picture, let us look at eco-efficiency, a concept now often referred to by many authors. Wastes, noise, hot fumes, lack of insulation, transportation of goods; all reflect direct losses of efficiency, which in turn are directly related to MONEY. Eco-efficiency encourages an improvement in society's practices at all stages in the life cycle of a product, "from cradle to grave": extraction, transformation, retail, use and post-use. During each of these five different stages eco-efficiency encourages a more appropriate use of our Natural Capital by redesign, reduction in transportation, intelligent use and finally recycling.

> As subsequent chapters will show, the unexpectedly large improvements to be gained by resource productivity offer an entirely new terrain for business invention, growth, and development. Its advantages can also dispel the long-held belief that core business values and environmental responsibility are incompatible or at odds. (Hawken et al., 1999, [48])

Importantly, these practices are seen as "win-win" scenarios, where environmental gains are backed up by economical ones: an "uncoupling [of] economic growth from increasing environmental stress" (Young, [63]). Indeed, efficiency is money, is the underlying rhetoric in Hawken, Lovins and Lovins' *Natural Capitalism* (Hawken et al., 1999, [48]). Their work focuses on giving its readers an impressive array of applications of this principle. The argument even goes that companies that do not invest in these new kinds of processes right now will be left behind in future years. A clear objection to that however, is the emphasis on short term results that is stressed in our economy. As soon as there is economical uncertainty, companies tend to invest in short term activities that will not involve important risks. The lumber industry is one of many examples of this tendency for short term investments. Clear-cutting is a cheap way to get lumber quickly, while destroying an entire eco-system that will take years to recover, if ever.

15.5.2 Main Actors: Governments

Along with companies' continuing efforts towards increased efficiency, however, it is clear that government and organizations have an important role to play in giving direction to this mental turnover. Indeed, both are interdependent and can trigger positive change. As Young puts it, "ecological modernization is about a broader approach to economic and industrial policy-making." (Young, [63]) New tools that are developed often have true cost as an underlying concept. "As long as that damage goes unaccounted for, as long as virgin resource prices are maintained at artificially low levels, it makes sense to continue to use virgin materials rather than reuse resources discarded from previous products." (Hawken et al., 1999, [48])

Governments have several avenues toward encouraging citizens to be more environmentally friendly and consider the impact of their actions through right consumerism. Some of these options are summarized below:

1. One way governments can encourage future developments is by raising taxes on some particular goods. Taxes, along with subsidies, are some of the most powerful market-based institutions that could foster change across the entire economy. Being systemic makes them potentially extremely powerful. Detractors however underline the fact that taxes and subsidies are so interconnected to election that they end up being used for purposes that are undermining the environment. A clear example is gasoline prices in the United States.

   > Even with the recent increase in prices at the pump, gasoline in the US is still cheaper than bottled water, thanks to myriad subsidies. What economists call the "full social cost" of gasoline - including traffic congestion, road accidents and pollution - is estimated to be at least $5 per gallon. Moreover, gasoline subsidies create an energy policy by default that is the opposite of the government's priorities: prolonging dependence on foreign oil and discouraging investments in cleaner technologies. Traffic-congestion delays cost at least $100 billion per year. Pollution levies health and other costs that may well run as high as $150 billion per year. (The Christian Science Publish. Soc., 2000, [102])

2. Subsidies are another way to allocate government spending that can encourage very different kind of practices. A good example is the U.S. heavy investment in R&D in the field of hydrogen through programs

such as the "Hydrogen, Fuel Cells & Infrastructure Technologies Program", a multi-year research, development and demonstration plan by the DOE [1] (DOE, 2003, [103]).

However, subsidies harm sustainable development if they reduce capital stocks (as in over-fishing, deforestation or air and water pollution), and also harm it if they inhibit technological change encouraging resource-inefficient processes. "But indirect linkages are just as important and very much neglected in the literature. Among these: Is population growth encouraged? Is poverty encouraged such that poverty in turn encourages environmental losses? Are environmentally-induced health damages induced? (. . .) Protectionism also inhibits technological change which could bring gains in natural resource productivity, e.g. by lowering energy-output and materials-output ratios." (Pearce, [60])

3. Governments also have the power to set standards for the industry. By setting standards for vehicle emissions for example, governments encourage car manufacturers to invest more into cleaner cars and fuels. Such standards have probably been one of the drivers for Hybrid vehicles, cars that use batteries and electrical engines to increase their efficiency by recouping energy when braking.

4. Issues such as carbon emissions cross international borders by the simple nature of gases and the atmosphere. This implies that policies also need a strong international component. Advances such as the Kyoto protocol would be extremely welcome to encourage all countries to act as one in the fields of Green House Gases (GHG). In this case the U.S. has been extremely un-cooperative. Their withdrawal from the protocol has put off the activation of the treaty: indeed, ratification requires "the signatures of 55 industrialized nations accounting for at least 55% of the global greenhouse gas emissions from industrialized countries in 1990. (2004, [101])" Seen that Russia also decided not to ratify the protocol, it is clear that international cooperation is an extremely complex issue that hopefully will improve in future years. Many of the issues mentioned in this report depend on it.

[1] Department Of Energy

Part IV

Pilot Project

Chapter 16

Introduction

16.1 Summary

The pilot program is a trial rollout of hydrogen passenger vehicles and their supporting fuel infrastructure in and around Los Angeles. It is an ambitious project that involves the collaboration of all levels of government, automotive and energy industry partners and the general public. The government spearheads the effort, most likely through the Department of Energy, and provides public funds to finance the project. Auto and energy companies provide vehicles and maintenance, fuel stations and hydrogen generation and delivery. The pilot is composed of distinct phases, each of which has specific funding and technology needs, goals, timeframes and criteria for success. Custom software simulates the activities of the pilot program during operation for use in optimizing a particular design.

16.2 Motivation

The pilot program is ambitious and expensive and its execution must be justified. Individual automakers have tried introducing alternative fuel vehicles in the past, but none have deeply penetrated the auto market. DaimlerChrysler has sold more than one million flexible fuel vehicles, which run on either standard gasoline or corn derivatives (DaimlerChrysler, 2003, [128]). It is safe to assume that few of those vehicles are using anything other than gasoline since there is no obstacle to the status quo. Daimler's experience introducing E-85 flexible fuel vehicles met with muted success. The number of E-85 refueling stations in Minnesota grew from 35 to 77 between 1998 and 2003, representing only 5% of all fuel stations in the state (Robertson, 2003). As further assurance that individual alternative fuel efforts are making less large-scale progress than is desired, DaimlerChrysler also states that it is hoping to have fewer than one hundred fuel cell vehicles, including buses, on the road by 2004.

The pilot program is an attempt to collect the individual expertise of automakers, energy companies and the government under the umbrella of a focused project. Though ambitious in the scope of both its technical challenges and the management challenges that will result from having many commercial and public entities collaborate, it represents the first well-funded effort with such a wide base of support. The Department of Energy is pushing for a decision on an alternative to fossil fuels by 2015. The success of the pilot program is not necessarily contingent on acceptance of hydrogen as a future transportation fuel, however. If the program can answer the remaining questions about the viability of hydrogen and put to rest ongoing debate, then it will have served its purpose. There also exists a vehicle-infrastructure "chicken and egg" problem wherein auto manufacturers are unwilling to mass produce fuel cell vehicles because the supporting fuel infrastructure does not exist and energy companies are unwilling to build alternative fuel stations because there is no critical mass of client vehicles. The pilot program is designed to directly address this problem by mandating the simultaneous introduction of a significant number of hydrogen fuel stations and fuel cell vehicles.

The pilot project will be targeting participants who plan to use the hydrogen FCVs as their only vehicle or as their secondary vehicle. For the former, we will be providing a facility for them to exchange their vehicles if they wish to make trips out of the area covered by the pilot project. The latter will be encouraged to use their secondary hydrogen FCVs as much as possible through incentive schemes like hydrogen fuel rebates. If the pilot proves the viability of a larger rollout of hydrogen infrastructure, the participants may keep and continue using their fuel cell vehicles. If participants do not wish to keep their FCVs, or if it is decided not to begin a larger hydrogen introduction, they may trade them in to the automakers for a conventional gasoline vehicle.

Recent increased national security concerns add weight to the environmental and depleting-resources arguments in favor of finding alternatives to fossil fuel. The federal government therefore has motivation to test and roll out a new transportation fuel and its leadership role in the pilot program will keep it on track. The industrial partners will gain various incentives for supporting the program and will be in a better position to begin a national hydrogen infrastructure rollout.

16.3 Marketing Concerns

Silicon Valley marketing expert Geoff Moore describes general issues to consider when marketing disruptive technologies (Moore, 1991, [118]). He makes a distinction between continuous and discontinuous innovation. Discontinuous innovations require users to change their behavior with respect to the new technology or the technology it is intended to replace. Often, the introduction of discontinuous innovations requires modification of other existing technology. The hydrogen infrastructure pilot program represents a set of strongly discontinuous innovations. The vehicles people use will require different maintenance, will likely have different interiors including new dashboard gauges for the new powertrain components and will have a different fueling interface. The supporting hydrogen fuel station infrastructure requires entirely new stations and a new fuel delivery network. At its least disruptive, the stations will require localized extensions to the existing natural gas delivery network.

According to Moore, an innovation may pass through five categories of customers throughout its lifespan. The number of categories it successfully wins over define the success of the technology in its product or service form. Moore describes this through the Technology Adoption Life Cycle (Moore, 1995, [119]). Each category of customers represents a personal affinity with or aversion to innovation. The first groups a new technology must win over are the innovators and early adopters. Innovators actively seek out new technology, with no practical requirements on its utility. Innovators are important cheerleaders but represent a very small proportion of the population. Early adopters are the first people to recognize the potential use of a new technology. Success with this group is a first indicator that a technology may succeed in the larger market. Early adopters also represent a small segment of the population, so innovations fail commercially if they are not adopted beyond this group. The early majority is the first large segment of the population; Moore estimates it to be one-third of the total potential market. The early majority requires practical arguments for both the technology's inherent utility and why it should replace an existing solution. Success with the early adopters sets an innovation up for widespread use and commercial viability. Long-term profitability typically follows since the transition from early majority to the late majority is generally far less risky than the transition from early adopters to the early majority. The other groups, the late majority and laggards, are of less interest to the pilot program since they become relevant only after a technology is mature.

The early adopters and early majority are the main groups of interest to the pilot program. Innovators include mainly those people and companies developing alternative fuel vehicles. The relatively few people using natural gas buses or vegetable oil or electric powered passenger cars represent the current crop of early adopters. The pilot program must expand that set of early adopters to include larger segments of the population and industry. The program and its participants must serve as an example to the pragmatic early majority, who are content to wait for gasoline-powered cars to be replaced by any technology that proves it will be a viable long-term choice.

The problem, according to Moore, is that there exists what he calls a chasm between the early adopters and the early majority. There are gaps between each successive pair of customer groups, but these are often easier to cross. For example, innovators initially began investigating the potential of hydrogen-powered vehicles but early adopters did not get involved until the first commercial products became available. The chasm is difficult to cross because the product being marketed to the two groups on either side is largely the same but each group evaluates it from a different perspective. The early adopters are willing to take some risk and be leaders in the adoption of a new technology, which they hope will provide some preemptive personal or commercial competitive advantage. The early majority must be sold on the product derived from the technology as a low-risk evolutionary improvement in productivity.

Technical advances in hydrogen fuel cell vehicles have pushed the technology beyond the laboratory and into the hands of a small segment of car buyers. It now must be pulled into general use. The pilot program is intended to use a large, concentrated set of early adopters to demonstrate to other early adopters, including the general public and commercial and government entities, that hydrogen fuel cell vehicles and their supporting fuel infrastructure can be successfully introduced to a large metropolitan environment. This is the first step in winning over the minds of the early majority. It is unexpected that the pilot program will serve to cross the chasm to the car buying public since there will be no supporting infrastructure. If the pilot is successful, the auto and energy industries in the early adopter group will expand the hydrogen vehicle infrastructure nationwide. Government impetus, contingent on the success of the pilot, will contribute to this expansion. At some point, the infrastructure will be widespread enough that the early majority will begin to purchase hydrogen-powered vehicles in commercially-significant numbers. So, the intent of the pilot program with respect to Moore's marketing philosophy is to create a large base of early adopters using and expanding a nationwide hydrogen vehicle infrastructure. It will create a solid foundation for making the leap across the chasm.

Chapter 17

Planning Phase

17.1 Government and Industry

The pilot program is designed around phases with assessment points that must be satisfied before proceeding both to ensure the program remains on track and successful and to hedge bets against the vagaries of government funding. The planning phase extends from the government's decision to operate the pilot to the proposed start date of the program. The earliest tasks in this planning phase will, of necessity, concern specification of how industry and government will coordinate on the program. The government must build political momentum for the project on both the federal and regional levels and secure funding. Doubtless, the government will not clear funding for all phases of the pilot, so early funding must cover at least the costs associated with hashing out specific roles and deliverables for all entities involved. These partners will then determine the specific needs for the rest of the planning phase, which include marketing, education, securing participants and construction of the initial infrastructure. If the remainder of the planning phase is funded, it is logical to require that the first phase of the program be funded as well, since it is useless to build hydrogen fueling stations if the vehicle commitment is in doubt.

17.2 Marketing and Education

17.2.1 Public Relations

The marketing and education parts of the planning phase are closely linked. This effort must engender public support for the program and its overall goal of initiating a national hydrogen vehicle rollout. People must be educated about the state of fossil fuel consumption and reserves. A simplified breakdown of the benefits of hydrogen as a fuel must be conveyed. The unjustified safety fears many people still have about hydrogen must also be confronted early to dispel myths that could prevent the program from ever gaining serious momentum.

The other aim of the marketing effort concerns simple public awareness and soliciting potential participants to sign up. As with any advertising strategy, we need to have a small number of focal points and be clear about them when we market the pilot project to potential users. The emphasis will be on environmental benefits and the depleting level of current fuel sources. Most people will be concerned about the practicality of their hydrogen vehicles beyond the pilot project. We will therefore need to convince users that this concept of a hydrogen vehicle is not a flash in the pan, but a project that will eventually lead to a national rollout. Some other issues we will need to highlight are safety concerns with storing and using hydrogen, availability of refueling stations and maintenance facilities.

The following four points (Kobliski, 2000, [132]) are considered in planning our strategy:

1. Demographics - We must know what segments of the population comprise our customer base and be able to define them according to the standard age and gender groups. For the initial phase of the pilot project, we will be targeting families with middle to high income. The second phase will extend the pilot to areas covering high to lower income levels.

2. Location - We will only use advertising media that can deliver our message to the right demographic groups. Each media source defines the primary audience it reaches and money will only be spent on those that match the demographic groups we have identified as potential

users. The concentrated locations of service defined in the program also help narrow down the potential advertising channels.

3. Message - The most effective advertisements sell their story in the shortest time possible. We need to hire creative writers and editors for this. The selection of advertising medium is also important.

4. Frequency - We need enough visibility that our customers will see or hear our message. Advertising venues require detailed scheduling. It is more effective to place a substantial schedule on one station or in one publication than to spread our resources out and not achieve effective frequency anywhere.

17.2.2 Advertising Media

Internet The Internet can be used to provide more information about the pilot project. While it may not reach out to the public as effectively as other forms of media, we can direct potential users to a website where they can gain more detailed and specific information on the project.

Television Television is king when it comes to direct response advertising. According to the Television Bureau of Advertising, more than half of all consumers say they are most likely to learn about products or brands they would like to buy from television commercials.

Radio Advertising through the radio has its advantages in making an impact on our target audience. According to Josef Albers, a scientist of the eye, "The visual memory is very poor in comparison with our auditory memory." (Williams, 2002, [139]) Many advertising strategies involve advertising aggressively on the radio and using the Internet to provide the customer with extra details or visual aids.

Newspapers Newspapers are usually read more completely by the over-50 segment of the population than by younger people who prefer to get their news from radio and television. This target group is relatively more affluent and, hopefully, willing to spend extra money on acquiring a new car.

Advertising in the local newspaper of our designated pilot project area will be more effective than in a large metropolitan newspaper.

Celebrity Endorsement Using celebrities or field experts to promote the pilot can more effectively advertise the project. "Creating a marketing program using an outside endorser draws attention to your message and confers credibility." (Gordon, 2002, [131])

Special Events A very effective method of advertising would be to organize an exhibition or road show in local malls or at a conference such as the National Hydrogen Association annual conference. This reaches a wide yet targeted audience and allows the potential users to interact with the project representatives to obtain information first-hand. They would also have the opportunity to sign up for the project on the spot.

Public Transportation Given that the pilot will take place in a metropolitan area, inexpensive ads on buses and taxis may prove effective. Also, once the pilot program begins, we can use our fleet of hydrogen-powered taxis to advertise the project.

Due to time restrictions, we have not explored the details of the cost of advertising and educating the public. We will set aside a budget of $3 million to aggressively promote the pilot project.

17.3 Construction

The planning phase also involves construction of the initial infrastructure for Phase I of the pilot program. The details of station geographical layout, cost and time to build are covered in later sections. The timeline is designed to ensure that the needed stations are in place before the first phase of operation can begin. Extra time is allocated since this project is the first known rollout of such a large number of identical stations.

Chapter 18

Phase I

18.1 Public Participants - San Fernando Valley

One of our underlying assumptions is that we will be implementing our pilot project in Los Angeles, California. In selecting an ideal place for the pilot project, California provides several advantages:

- California is the most technologically advanced state in the USA. It is an ideal springboard for hydrogen-based technology,
- California has the greatest traffic pollution problem in the USA. Its goal is to reduce fuel consumption by 15% by 2020 (US Department Of Energy, 2003, [123])
- The South Coast Air Quality Management District currently has 21 hydrogen refueling station projects spread throughout California.

We selected the San Fernando Valley for the following reasons:

- It is a residential area. We will be targeting homemakers because they have more time to give feedback on the project as opposed to city dwellers. We also want minimal disruption to the commercial sector,
- It is a strong middle-class area, with a median household income of $40,138. More affluent people will be more willing to and financially capable of buying a new car,

- It is very near Hollywood and Beverly Hills. We will be able to get celebrity support to promote the project.

San Fernando Valley is located northwest of downtown Los Angeles. It has a population of 1.6m people and has a land area of 345 square miles (Economic Alliance of the San Fernando Valley, 2003, [129]). There are an estimated one million cars in the San Fernando Valley area.

The project will begin in 2010 with 2,000 heavily subsidized passenger cars purchased by program participants. A hydrogen refueling network, described below, will support these vehicles traveling in and around the San Fernando Valley and downtown Los Angeles. The daily use put on these vehicles will, if the program is successful, vindicate the utility of hydrogen fuel cell vehicles for most daily travel needs. It will also serve as an example of the costs involved in constructing the new fuel infrastructure needed to support them.

We decided to request that participants purchase the fuel cell vehicles because the expectation is that the hydrogen fuel infrastructure introduced during the pilot program will be only the leading edge of a wider southern California investment in hydrogen stations. Designing the program such that all stakeholders involved assume some risk increases the pressure to succeed and should help remove obstacles that sometimes derail experimental efforts. It also helps to slightly offset the costs and risk assumed by government and industry. Participants will purchase their own fuel, which is predicted to cost less than the equivalent amount of gasoline, as demonstrated in a later section. Vehicle use and instances where trips would not be possible due to vehicle or fuel infrastructure limitations will be tracked. To support the inevitable need for maintenance, the program's industry partners will have available either a qualified repair facility or a small pool of unused vehicles for which a participant can swap their car while repairs are made. It is likely that we will have participants who will not have access to a gasoline-powered car for extraregional travel. Because participants will have purchased their hydrogen cars, we feel it is right to make available gasoline cars when necessary. This stand is justified by recent travel statistics which indicate that the average American drives 21% of their annual miles outside their home region (U.S. Department of Transportation, 2002, [142]). Given that the program must have strong involvement by automakers, making available a moderate standard car will not be a problem and will represent a very small part of the overall cost and organizational challenge inherent in the pilot.

18.2 Fleet

We will also study the use of fleet vehicles in the project. It will focus on taxis because they:

- Are easy to implement, control and study because they usually travel within a confined area,
- Serve the public and so hydrogen technology can reach out to more people.

However there are also some problems with fleets. One of them is the difficulty of transferring the experience of fleet managers to the general public. Thus, over 90% of the program's vehicles will be used by individuals. Others include lack of maintenance facilities, expensive repairs and hard-to-get parts (Kilmer, 2004, [114]). The project will ensure that the fleet will get the necessary support to maintain the vehicles. The program calls for introducing 200 hydrogen-powered taxis in the downtown area.

18.3 Refueling Stations

San Fernando Valley - There are 6,133,216 registered vehicles in the Los Angeles County. These vehicles traveled 76,973 million miles in 1998. (Metropolitan Transportation Authority, 2004, [124]) Since the hydrogen fuel efficiency for our model car is 65 miles per kilogram, each car needs 193 kg of hydrogen per year, or 16 kg per month. With an onboard capacity of 4-5 kg, each car needs approximately 5 refills per month, so 2,000 cars need a total of 333 refills per day. Since each mid-size station has a capacity of 50 refills per day (Energy Independence Now, 2003, [130]), 7 refueling stations is the minimum needed to support 2,000 cars. By spreading the 7 stations equally around the San Fernando Valley, a driver will not be more than 6 miles away from a refueling station.

Fleet - There are currently about 2,300 taxis in downtown Los Angeles (Los Angeles Downtown Visitors Guide, 2003, [133]). We will introduce hydrogen technology in 200 cars, or almost 10% of the taxi population. We assume that each taxi uses 3 times as much fuel as the average car. This requires about 100 refills per day. We will need 2 stations to cope with this demand. Taking into account the users from San Fernando who travel to downtown Los Angeles every day for work or daily activities, we will construct a total of 3 refueling stations in downtown Los Angeles.

Hydrogen will be produced mainly via onsite electrolysis at the refueling stations. Onsite production is preferred over centralized production because it minimizes the need for expensive new pipelines and delivery network before the introduction of a sufficient number of users to provide adequate return on investment. (Lovins, 1999, [115]) Although onsite natural gas reformation is generally a cheaper option on a large scale, to supply the fuel to a small number of fuel-cell vehicles, it would be cheaper to use off-peak retail electricity to split water than to locally reform natural gas. (Thomas et al, 1998, [120]) However, in order to gain experience and to experiment with the various production channels, natural gas, will be used to produce hydrogen at a small number of stations.

18.4 Locating Fuel Stations

The Global Positioning System (GPS) was first developed by the U.S. military to act as a military navigation system. It is a constellation of 27 satellites that orbit the Earth. Many cars are now equipped with GPS receivers. The receivers locate four or more of these satellites to pinpoint its location. The onboard computer contains a pre-loaded map of the area and the coordinates of all possible destinations. The user selects a destination before the journey and the navigation system guides the driver to the designated location.

Our vehicles could be installed with such a device with the coordinates of the refueling stations pre-programmed into the onboard computer. Connected to the fuel indicator, when the car is low on hydrogen, the computer will use the GPS receiver to navigate the driver to the nearest hydrogen refueling station. Warnings can alert the driver as the car travels out of range of any stations that can be reached with the remaining fuel. Further, the system will communicate with other GPS receivers in the region to provide information such as current usage and expected waiting time at the selected station.

Although many domestic cars already have relatively inexpensive GPS receivers and adding them to our program vehicles should not be a problem, more inexpensive solutions exist. Including GPS receivers not networked to the fuel system, as in current cars, will allow the driver to manually locate a fuel station and obtain directions. The simplest alternative is distributing to participants a detailed map indicating the locations of all available hydrogen stations. The more robust first option presented is certainly, however, the safest as it is very important to remain within reach of a fuel station (Kilmer, 2004, [114]), something most drivers take for granted today.

18.5 Gas Delivery Network

For the pilot project, the hydrogen fuel will be produced mainly by on-site electrolysis. However, in order to gain experience on other production channels, hydrogen will be produced by reformation of natural gas at some selected refueling stations. A well-developed natural gas delivery network is therefore essential. In California, there are extensive long-range, high volume transportation pipelines - the ”backbone” transmission system - that move natural gas across the state. Several natural gas providers, such as Pacific Gas and Electric Company, have distribution infrastructure to move gas from the high-volume pipelines to end-use customers. Composed of more than 35,000 miles of distribution pipelines, this local transmission and distribution system delivers the gas to homes and businesses all across California (Pacific Gas and Electric Company, 2004, [135] and California Public Utilities Commission, 2001, [126]). Through the network, natural gas is readily available in areas where hydrogen stations will be located. Once the stations are connected to the distribution system, natural gas can be used to produce hydrogen.

Chapter 19

Phase II

If the pilot program is successful among downtown and San Fernando Valley users, it will be expanded to include regions further away from Los Angeles. The first phase is subject to evaluation criteria that are discussed in a later section. The expansion areas identified are (NationMaster.com, 2004, [134]):

- Ventura County - Simi Valley, Moorpark & Thousand Oaks Population: 160,000 Median income per household: $74,609 Area: 114 mi^2 45 miles from downtown L.A.
- Orange County - Irvine Population: 165,000 Median income per household: $72,057 Area: 49 mi^2 42 miles from downtown L.A.
- Riverside & San Bernardino - Riverside and San Bernardino Population: 1.5m Median income per household: $36,393 Area: 220 mi^2 45 miles from downtown L.A.

These areas were selected because of their proximity to Los Angeles. They allow the pilot program to expand around the core area from Phase I, building off the existing infrastructure and expanding the supported region that all participants can use. Irvine, in particular, has a long history of affiliation with environmental programs and we expect strong support for the hydrogen pilot (About Irvine - the City of Irvine, 2003, [125]). The expansion regions also include areas less affluent than the San Fernando Valley, reflecting our belief that the pilot must demonstrate the utility of hydrogen vehicles for the average American. Riverside and San Bernardino are home to many people who work in Los Angeles but live further away from the city to take advantage of lower living expenses.

The expansion regions will each be of the same scale as the San Fernando Valley project. Each region will be allocated 2,000 FCVs and contain 7 hydrogen refueling stations. Stations will be within 2 to 5 miles of each other. There will also be 3 stations along each highway, one every 10 miles, connecting downtown Los Angeles to the expansion regions. A total of 12 highway stations will be built, connecting Los Angeles to Irvine via I-5, to Simi Valley via CA 101, to San Bernardino along I-10 or I-210 and to Riverside via CA 91, which connects with I-5 northwest of Irvine. This comes to a total of 33 new fuel stations for Phase II.

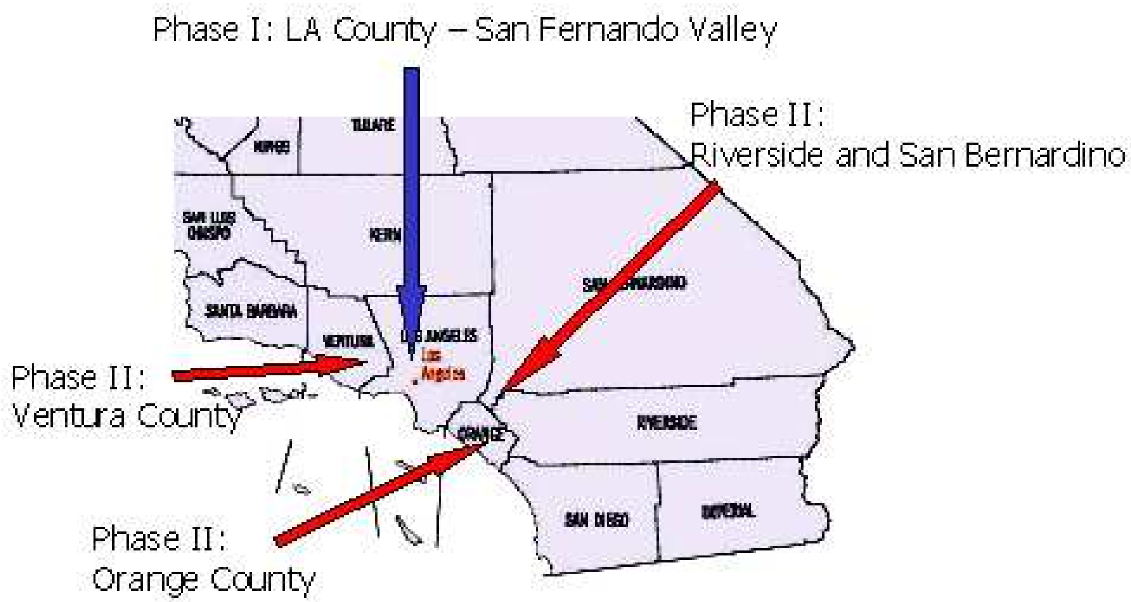


Figure 19.1: Map of Los Angeles and neighboring counties

Chapter 20

Costs

20.1 Cost of Fuel

As the technology used for hydrogen fuel production matures, the cost of hydrogen is expected to fall in the future. However, there is no guarantee that the price of hydrogen will fall below that of gasoline. To overcome this potential cost barrier, during the pilot project, any difference between the price of hydrogen and gasoline will be paid for by the government. The subsidization ensures that hydrogen will be cost-competitive with gasoline and participants will only have to spend as much as they would otherwise spend on gasoline.

	2010	2011	2012	2013	2014	2015
H2 cost (per kg)	$4.01	$3.75	$3.53	$3.34	$3.18	$3.04
Equivalent kg of Gasoline cost	$4.01	$3.97	$3.97	$3.94	$3.95	$3.94

Table 20.1: Expected costs of hydrogen and gasoline from 2010-2015

The expected costs of hydrogen and gasoline are listed in Table 20.1. Since the cost of hydrogen is expected to be equal to or below that of gasoline in 2010-2015, the period when the pilot project will run, the fuel cost can be paid by the participants in full and a subsidy will not be needed.

Assuming that an average passenger car in California consumes 193 kg of hydrogen, each participant will spend an annual sum of $774 on fuel in 2010, when the pilot project starts. This is exactly the same as what participants will have to spend if they are using a car that runs on gasoline. With the downward trend in hydrogen price and the high efficiency of hydrogen fuel cell vehicles, hydrogen will become cheaper than gasoline in 2011, making it a more economical fuel than gasoline.

20.2 Cost of Cars

A total of 8200 hydrogen fuel cell vehicles will be operating throughout the life of the pilot project. This is a relatively small number of cars to be manufactured. Because the pilot cannot take advantage of economy of scale, the per-vehicle cost is expected to remain high during the course of the pilot project. The estimated production costs of hydrogen vehicles for the period 2010-2015 are listed in Table 20.2.

	2010	2011	2012	2013	2014	2015
Unit vehicle cost	\$112,351	\$106,838	\$101,785	\$97,152	\$92,906	\$89,014

Table 20.2: Expected unit cost of hydrogen fuel cell vehicle in 2010-2015

The high costs associated with these alternative vehicles will make them less acceptable to the public. It is unlikely that participants will willingly spend over a hundred thousand dollars to experiment with new technology and participate in the pilot project. To overcome this financial obstacle, a subsidy from the government is needed. Each participant will contribute \$20,000 toward the purchase of a hydrogen vehicle, with the option to purchase outright, finance or lease. The remaining cost absorbed by the program partners. This guarantees that the hydrogen vehicles will be affordable to the public with respect to similar gasoline cars on the market.

Planning to start Phase I of the pilot project in 2010, the government will have to spend \$203,173,058 on subsidizing the 2,200 cars in the San Fernando Valley and Los Angeles. Another \$521,030,760 will be incurred when an additional 6,000 hydrogen vehicles start operating in Phase II in 2011, bringing the total cost of the vehicle subsidy to \$724 million. This raw cost is very high and potentially a serious obstacle to the proposed pilot program. Alternatives for reducing the government's cost are discussed under the role of industry players, in a later section.

20.3 Cost of Stations

The cost of building a hydrogen station that can support 50 refills per day is estimated to be $1.35 million (Weinert, 2003, [122]). For Phase I of the pilot project, a total of 10 hydrogen stations will be built to service the 2,200 cars. $13.5 million will be incurred for the construction of these refueling facilities. For Phase II of the project, 33 additional stations will be built in the neighboring counties and along major highways, adding $44.55 million to the cost of stations. The total cost of constructing hydrogen stations is $58.05 million.

20.4 Cash Flow

The cash flows associated with the pilot project if it proceeds according to the expected time scale are outlined below. The total cost to government will be $784 million.

Year	Description	Cost
2009 3rd quarter	Building stations for Phase I	$13,500,000
2010 1st quarter	Fuel subsidy for Phase I	$ -
2010 1st quarter	Vehicle subsidy for Phase I	$203,173,058
2011 2nd quarter	Building stations for Phase II	$44,550,000
2011 4th quarter	Fuel subsidy for Phase II	$ -
2011 4th quarter	Vehicle subsidy for Phase II	$521,030,760

Table 20.3: Cash flow over time

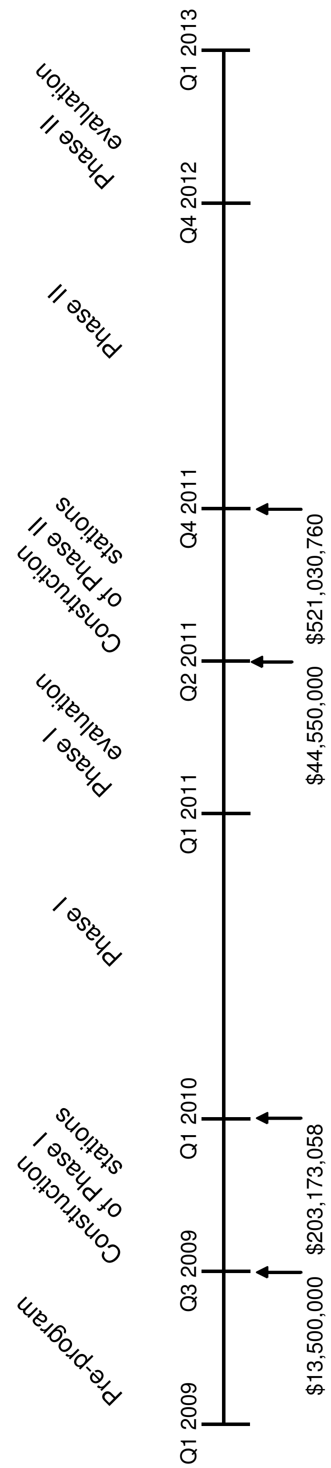


Figure 20.1: Cash flow diagram

Chapter 21

Timeline

21.1 Start Date

We have defined the 2010 program start date as feasible given the preparatory work that must be done to unify the efforts of government and different industry players. Approximately one year before the pilot program is slated to start, we must begin educating the target population as well as the general public about the hydrogen project in order to build support for the effort and to dispel any negative impressions about hydrogen. Safety education will be a key component of this pre-program stage. We must also market the pilot program to the target areas so the initial round of participants can be identified and secured.

Construction of the supporting facilities, such as refueling stations, will start before Phase I so the infrastructure network is in place before the program officially begins. It is also important that reliable fuel cell vehicles be ready for production well before the project begins. Since automakers have claimed that a marketable FCV prototype is not yet available, we believe 2010 is the earliest time to start the project, as it allows enough time for the development and production of the vehicles. The two main phases of the program focus on maintaining the infrastructure and vehicles and measuring the performance and acceptance of the system. Phases I and II are each slated to last for one to two years, depending on funding and satisfaction of success criteria. We may only move beyond a phase when the success criteria for that phase are met. If the program as a whole succeeds, the government may begin making legislative moves to prod industry to begin a wider national rollout of hydrogen vehicles. This proposed timeline fits well with the Department of Energy's stated aim of choosing a future commercialized energy source by 2015 and having hydrogen fuel cell vehicles and infrastructure available by 2020 (Chalk, 2003, [127]).

21.2 Duration

There are two operational phases to the pilot project. We plan to launch the pre-program phase one year before the start date of the actual project, with construction of hydrogen stations starting 6 months into the pre-program phase. Phase I can start as soon as all the preparatory work and construction of facilities are completed and it will last for one year, followed by a 3-month evaluation period. If all the success criteria are satisfied, construction of hydrogen stations needed for Phase II will begin and the second phase of the project will be launched. Otherwise, Phase I will be extended for a year with specific improvements made to meet the success criteria. Similar to the first phase, the one-year Phase II will be followed by an evaluation phase. Upon satisfaction of all success criteria, the pilot project will end and the government may take measures to trigger a national rollout of hydrogen vehicles.

The duration of each of the phase elements is summarized in Table 21.1. In the optimistic case, the total length of the pilot project is 4 years. In the worst case, where an extension period is required at the end of both Phases I and II, the length of the project is extended to 6.5 years.

	Optimistic duration	Pessimistic duration
Pre-program	6 months	6 months
Construction of Phase I stations	6 months	6 months
Phase I	12 months	12 months
Phase I evaluation	3 months	3 months
Phase I extension	—	12 months
Phase I extension evaluation	—	3 months
Construction of Phase II stations	6 months	6 months
Phase II	12 months	12 months
Phase II evaluation	3 months	3 months
Phase II extension	—	12 months
Phase II extension evaluation	—	3 months

Table 21.1: Duration of the different phases in the pilot project

21.3 2010 versus 2015

Considering the amount of preparatory work that must be done, we have decided that 2010 is earliest date that the project can start. Starting the project in 2010 allows the government and industry players to gain valuable real world experience earlier on. Conversely, starting the project at a later date brings down the total cost of the project. Hydrogen technology is currently in a developmental stage and the associated costs are constantly decreasing over time. We have examined and compared the total project cost for two different start dates, 2010 and 2015. The cost breakdowns for these two start dates are shown in Table 21.2 and Table 21.3. With the optimistic timescale, the total cost for starting in 2010 and 2015 are $746 million and $686 million, respectively.

	Optimistic timescale	Pessimistic timescale
Phase I stations	$13,500,000	$13,500,000
Phase I vehicles subsidy	$203,173,058	$203,173,058
Phase I fuel subsidy	$ -	$ -
Phase I (evaluation) fuel subsidy	$ -	$ -
Phase II stations	$44,550,000	$44,550,000
Phase II vehicles subsidy	$521,030,760	$462,914,340
Phase II fuel subsidy	$ -	$ -
Phase II (evaluation) fuel subsidy	$ -	$ -
TOTAL	$782,253,818	$724,137,398

Table 21.2: Cost breakdown if project starts in 2010

	Optimistic timescale	Pessimistic timescale
Phase I stations	$13,500,000	$13,500,000
Phase I vehicles subsidy	$272,228,000	$272,228,000
Phase I fuel subsidy	$ -	$ -
Phase I (evaluation) fuel subsidy	$ -	$ -
Phase II stations	$44,550,000	$44,550,000
Phase II vehicles subsidy	$392,683,530	$355,101,450
Phase II fuel subsidy	$ -	$ -
Phase II (evaluation) fuel subsidy	$ -	$ -
TOTAL	$722,961,530	$685,379,450

Table 21.3: Cost breakdown if project starts in 2015

21.4 Success Criteria

A set of success criteria was established to judge if the pilot project is making satisfactory progress. These criteria will be used to determine whether to move from the first phase of the pilot program to the second and whether to consider the program a success and move toward national rollout. These success criteria target four main areas - users' experience, costs, technology issues and public perception and acceptance. This setup is flexible enough that each phase can end after evaluation in terms of the success criteria rather than according to a strict schedule.

1. Vehicle performance and related technology issues

   It is expected that the functionality of hydrogen fuel cell vehicles will continue to improve during the course of the pilot project. By the end of Phase I, the vehicle performance should be comparable to an inexpensive gasoline car. By the end of Phase II, it should be comparable to at least a medium gasoline car to ensure that these alternative vehicles are marketable to the general public.

2. Station availability

   Using data on the average vehicle miles driven, a model was developed to determine the number of stations required in the pilot project region. During the project, feedback from participants and data on the daily use of the hydrogen stations will be collected to check if there are enough refueling stations to service all the hydrogen cars or if stations are underutilized. The existing model will be adjusted to increase or decrease station density as necessary. The model will be used to set benchmark station density levels for national implementation.

3. Fuel availability

   During both phases of the project, it is necessary to ensure that onsite electrolysis and reforming will produce enough hydrogen fuel to support the high loads imposed by the participating vehicles. Feedstock delivery and hydrogen generation capacity will be compared to peak station use.

4. Station use - refueling time, difficulty

   Ultimately, we expect that the refueling time at hydrogen stations will be comparable with that of gasoline stations and it will not take longer to refuel a hydrogen car than a gasoline car. By the end of Phase I, we will check to see if the refueling time can be further shortened and if the downward trend on refueling time is sufficient to reach the ultimate goal. It is also important to ensure that the hydrogen refueling systems are easy to use and are not causing inconvenience or difficulty to users.

5. Costs

   By the end of Phase I, the actual costs will be compared to the predicted costs to validate the various models used. These models will be adjusted if necessary so that more accurate cost estimates can be made. During the Phase II evaluation period, we will check to see if the costs have reached a publicly acceptable level. If so, the pilot project will close successfully.

6. Efficiency

   Actual and predicted values on fuel efficiency will be compared to validate the model. The pilot project will continue if the efficiency has not reached a publicly acceptable level.

7. Safety issues

   Prior to the pilot project, both the hydrogen fuel vehicles and refueling stations will be tested to ensure they are safe for daily use. Their safety will be monitored constantly throughout the program.

8. Public perception Public acceptance is an important factor to determine success of the pilot project. A negative public perception would definitely hinder the hydrogen transition process. We aim to achieve a minimum of 60% acceptance among the pilot group by the end of Phase I. By the end of Phase II, we expect the acceptance among the pilot group to rise to 70%. A 60% acceptance among the general public is also anticipated.

   These public perception acceptance numbers are not rigidly determined. They are simply an attempt to create an objective criterion for subjective personal opinions. We wish the acceptance rate to be high enough to sustain the next phase of the program but not so high that we cannot reach the stated goal. The target for the completion of the second phase is higher than that for the first phase. We recognize that participants in the first phase will likely experience a few problems during the program since we are introducing new technology and supporting infrastructure. The higher target for Phase II reflects our requirement that these issues be largely resolved before moving beyond Phase I.

Further, the people whose opinions we are measuring are different at each stage. For the first phase, our participants are leading edge innovators and early adopters of new technology. These people are more likely to accept minor problems in the new technology because they recognize the potential benefits it brings. Acceptance rates are likely to be higher among this population. However, we must also consider whether our infrastructure and vehicle utility will satisfy the needs of a larger class of consumers. We must poll general public attitudes to determine how the program is progressing to satisfy the so-called early majority. These consumers represent the bulk of the mainstream population who are expected to purchase a hydrogen-powered vehicle. If this group does not find a practical use for hydrogen vehicles versus gasoline vehicles or does not consider hydrogen power to be the next evolution of transportation energy, a national rollout of hydrogen power will probably fail. The pilot's commercial participants must feel that a national rollout will be economically viable or they will have little motivation to go beyond the bounds of the pilot.

Chapter 22

Optimistic and Pessimistic Predictions

We presented the expected total cost and cash flows for the pilot program above. In addition, we have studied the costs in optimistic and pessimistic scenarios. Two different variables were examined - time and cost. The optimistic timescale is identical to the expected one used earlier. It represents smooth execution of the pilot project where no extension phases are required. Conversely, the pessimistic timescale corresponds to the time required to carry out the pilot project if success criteria are not fully satisfied the first time and both Phases I and II need to be extended.

Using the spreadsheet model (Cost Calculator - 2010.xls), the total costs and cash flows under four different scenarios are calculated and listed below.

Year	Description	Cash flow
2009 3rd quarter	Building stations for Phase I	$ 11,000,000
2010 1st quarter	Fuel subsidy for Phase I	$ -
2010 1st quarter	Vehicle subsidy for Phase I	$ 160,718,316
2011 1st quarter	Fuel subsidy for Phase I evaluation	$ -
2011 2nd quarter	Building stations for Phase II	$ 36,300,000
2011 4th quarter	Fuel subsidy for Phase II	$ -
2011 4th quarter	Vehicle subsidy for Phase II	$ 408,421,260
2012 4th quarter	Fuel subsidy for Phase II evaluation	$ -

Table 22.1: Scenario 1 - Optimistic cost, optimistic timescale. Total cost of project is $616,439,576.

Year	Description	Cash flow
2009 3rd quarter	Building stations for Phase I	$ 16,000,000
2010 1st quarter	Fuel subsidy for Phase I	$ 197,410
2010 1st quarter	Vehicle subsidy for Phase I	$ 245,627,800
2011 1st quarter	Fuel subsidy for Phase I evaluation	$ 78071
2011 2nd quarter	Building stations for Phase II	$ 52,800,000
2011 4th quarter	Fuel subsidy for Phase II	$ 387,988
2011 4th quarter	Vehicle subsidy for Phase II	$ 633,640,260
2012 4th quarter	Fuel subsidy for Phase II evaluation	$ 6,071

Table 22.2: Scenario 2 - Pessimistic cost, optimistic timescale. Total cost of project is $948,737,600

Year	Description	Cash flow
2009 3rd quarter	Building stations for Phase I	$ 11,000,000
2010 1st quarter	Fuel subsidy for Phase I	$ -
2010 1st quarter	Vehicle subsidy for Phase I	$ 160,718,316
2011 1st quarter	Fuel subsidy for Phase I evaluation	$ -
2011 2nd quarter	Fuel subsidy for Phase I extension	$ -
2012 2nd quarter	Fuel subsidy for Phase I ext evaluation	$ -
2012 3rd quarter	Building stations for Phase II	$ 36,300,000
2013 1st quarter	Fuel subsidy for Phase II	$ -
2013 1st quarter	Vehicle subsidy for Phase II	$ 359,903,520
2014 1st quarter	Fuel subsidy for Phase II evaluation	$ -
2014 2nd quarter	Fuel subsidy for Phase II extension	$ -
2015 2nd quarter	Fuel subsidy for Phase II ext evaluation	$ -

Table 22.3: Scenario 3 - Optimistic cost, pessimistic timescale. Total cost of project is $564,921,836

Year	Description	Cash flow
2009 3rd quarter	Building stations for Phase I	$ 16,000,000
2010 1st quarter	Fuel subsidy for Phase I	$ 197,410
2010 1st quarter	Vehicle subsidy for Phase I	$ 245,627,800
2011 1st quarter	Fuel subsidy for Phase I evaluation	$ 26,024
2011 2nd quarter	Fuel subsidy for Phase I extension	$ 104,094
2012 2nd quarter	Fuel subsidy for Phase I ext evaluation	$ 4,887
2012 3rd quarter	Building stations for Phase II	$ 52,800,000
2013 1st quarter	Fuel subsidy for Phase II	$ -
2013 1st quarter	Vehicle subsidy for Phase II	$ 568,925,160
2014 1st quarter	Fuel subsidy for Phase II evaluation	$ -
2014 2nd quarter	Fuel subsidy for Phase II extension	$ -
2015 2nd quarter	Fuel subsidy for Phase II ext evaluation	$ -

Table 22.4: Scenario 4 - Pessimistic cost, pessimistic timescale. Total cost of project is $883,685,375

From these results, we can see that the total cost of the project is lower under the pessimistic timescale. With the extension phases, some of the costs are incurred at later points than in the optimistic timescale. Since the costs of vehicle and fuel are anticipated to decline with time, we would expect a lower total cost with the extensions. Although extending the project timeline can lower the costs, we would still aim to finish the pilot project by 2013 because the ultimate goal of the pilot program is to gain early real world experience to ensure success of a national hydrogen transportation transition.

Chapter 23

Role of Industry

23.1 Natural Capitalism

Natural capital refers to the Earth's natural resources and the ecological systems that support life on Earth. These systems are literally priceless because they have no known substitutes. For example, in 1991-92, the $200-million Biosphere II project in Arizona was unable to sustain breathable air for eight people. Few business practices or public policies take into account the value of natural capitalism.

The Rocky Mountain Institute (RMI) claims that firms typically enjoy increased profit and distinct competitive advantages by doing business if natural capital are properly valued. Their natural capitalism business model consists of four major elements:

1. Basic changes in production design and technology allow organizations to stretch natural resources up to 100 times further. This results in reduced operation costs, capital and time needs and initial capital investments.

2. Natural capitalism promotes closed-loop systems that return environmentally harmless products to the environment or as inputs for other processes. This reduces dependence on non-renewable resources, eliminates waste and increases production efficiency.

3. Natural capitalism focuses on providing services rather than selling products. This allows the provider to market his services cheaper and

more efficiently, reducing overhead and the impact of economic fluctuations.

4. Companies should reinvest in what RMI calls natural and human capital - natural resources and people. Businesses can cost-efficiently expand natural capital required for operations.

> Innovative organizations are already prospering from these four principles. Their leaders and employees are also feeling better about what they do: eliminating unproductive tons, gallons, and kilowatt-hours makes it possible to invest in human capital-the people who foster the innovation that drives future success. (Rocky Mountain Institute, 2004, [137])

23.2 Mass Hydrogen Production at the Wellhead

Throughout the project, the energy industry will examine the potential for large-scale hydrogen generation to supply the needs of regional hydrogen-based transportation systems. We examined two possibilities for mass producing hydrogen: reforming natural gas and electrolysis. By reforming natural gas, hydrogen producers can obtain profits in three areas. First is the profit from shipped hydrogen. Second, carbon dioxide, a by-product of the reforming process, can be pumped into the gasfields to recover more natural gas. Gasfields can hold about twice as much carbon in the form of CO2 as originally held in the form of natural gas. Third, under Kyoto Protocol trading or other similar environmental arrangements, producers can earn profit from the sequestering of carbon. (Lovins, 1999, [115])

For mass hydrogen production using electrolysis, intermittent sources such as solar cells and windfarms or renewable sources such as hydroelectric dams can increase their economic value by providing energy to split water instead of selling electricity to a saturated bulk market. This is because, if current technical advances continue at their current pace, fuel cell cars will use hydrogen 2.5-3 times more efficiently than current cars use gasoline. Hydrogen could therefore fetch a higher price based on its higher energy content. "In fact, that value is equivalent to selling the electricity used to make hydrogen at a price about 5-7 times higher than Pacific Northwest dams can actually get for their electricity today." (Lovins, 1999, [115])

23.3 Refueling Stations

There are several potential stakeholders that might be interested in building and operating refueling stations.

Fuel providers could improve their current technology and design for eventual commercialization, gain practical experience in operating these stations, evaluate their performance standards, gain future contracts from the government and obtain feedback from their customers. Automakers might want to use these stations to test their new vehicles, analyze and acquire data, demonstrate vehicle capabilities and prepare their vehicles for commercial delivery. Colleges and universities would explore education and research opportunities. In addition, they could get grants from the government and provide consulting services to the industry. (Weinert, 2003, [122])

23.4 Automakers

From our cost model, the projected cost sof FCVs are as high as 6 times the cost of current gasoline vehicles. In addition to government subsidies for the consumer, automakers should further subsidize these costs to make fuel cell vehicles more appealing during the pilot project. General Motors is spending about $1 billion on FCVs (Perry, 2004, [136]). We can convince them to use part of that money to subsidize the burden on consumers. This will hopefully allow the hydrogen transition to gain further momentum.

Automakers that take part in the pilot project would be allowed to develop their own cars, as opposed to working with each other to produce a single design. This allows them to develop their own resources to produce differentiated products and provide alternative technology in the FCVs. It also provides choice to the program participants.

By participating in the pilot project, automakers can gain practical experience on real use and operation of hydrogen FCVs. They can fix any problems that the current models have and make improvements accordingly. This gives them a competitive advantage over automakers without the experience. It also allows them to establish a customer network. It will help them build credibility within the industry and gain public confidence. Any automaker that succeeds in a program as visible as this pilot will be widely acknowledged as a trusted commercial leader in alternative fuel vehicles. Working with the government on the pilot project increases the chances of their obtaining research funding and tax concessions from the government to speed up the design and production process.

23.5 On-site Hydrogen Supply

While it may be possible, and highly likely, that there will be an eventual large-scale production of hydrogen at a plant, there are several benefits to small-scale, on-site hydrogen production facilities. Having hydrogen produced at large central plants may take advantage of economies of scale, but losses in the production plants and the distribution network can be significant. In addition, distributed fuel generators do not require large fuel markets and do not require large-scale fuel businesses. Even though distributed generators such as small-scale steam reformers and electrolyzers are still produced in low volume and are thus expensive, they have advantages of lower risk, more flexibility, simpler security and better environmental quality. These points should convince small-scale hydrogen equipment producers that there is a market for their products in the hydrogen economy. (Lovins, 2002, [116])

This argument is based on a parallel discussion about the national electrical distribution system where Lovins argues that power generation is migrating from remote plants to decentralized locations such as customers' backyards, basements, rooftops and driveways.

Companies such as Stuart Energy (Stuart Energy, 2004, [138]) specialize in manufacturing electrolyzers for the production of hydrogen. They have developed mature technology that can be used in the pilot program. These companies can gather practical data through the daily operation of many small-scale hydrogen production units and improve their offerings to better position themselves for the transition to a hydrogen economy. Their close collaboration with the government can significantly increase their chances of being awarded future contracts.

Chapter 24

Lessons from the Leaded Gasoline Transition

In the 1970s, the EPA announced a phase-out of lead in gasoline because of increasing knowledge about health concerns associated with lead exposure. While the motivation for the transition to hydrogen is not centered on health threats as during the 1970s, there are several lessons we can adopt from the unleaded gasoline transition.

The government should recognize that industry has a key role to play in such a potentially huge project. To ensure the successful transition to a hydrogen-powered transportation system, tight cooperation between all interest groups - e.g., automakers, consumers, government, fuel companies - is a must. Even though this transition may eventually prove profitable to industry players, the government has to recognize that many companies may incur huge losses during the initial transition phase. The government can use tax incentives or other benefits to encourage automakers and consumers to partake in the initial transition. (Megnin, 2001, [117])

There are also several steps the government can take to initiate the transition. Restrictions on automakers, such as a limit on the number of gasoline internal combustion engines produced and gasoline credits (U.S. Environmental Protection Agency, 1998, [144]) producers can trade, will inevitably shift the focus to environmentally benign vehicles. This assumes that hydrogen FCV technology is mature enough to displace internal combustion gasoline vehicles. An artificial price differential can be created between gasoline and hydrogen through taxation to make hydrogen more economically attractive. There must also be strict emissions standards and an eventual ban on gasoline powered vehicles should occur.

Public perception is very important. Many people, especially in Asia, did not want to make the transition to unleaded gasoline because they felt that unleaded gasoline was inferior and affected the performance of their vehicles. In Malaysia, people only accepted unleaded gasoline after the government introduced a ”super” unleaded gasoline. (Megnin, 2001, [117]). The government also needs to educate the public on health and environment issues resulting from gasoline use and the rapidly depleting amount of fossil resources available.

Chapter 25

Pilot Program Simulation Software

A first iteration has been built of a software simulation tool designed to aid in the optimization of a pilot program setup. It is useful for testing whether a given infrastructure is sufficient to support a given user load, if the infrastructure topology is efficient and how sensitive it is to variations in user driving habits. Given a number of users in a defined region, destinations for their vehicle trips, statistical averages for characteristics of various regional trips, locations of refueling stations and basic vehicle performance metrics, the system simulates daily trips made by each user and builds vehicle and refueling station usage statistics. These figures can demonstrate the utility of a given pilot program configuration and help to optimize the final setup given user driving habits.

25.1 Summary

The system considers its world to be a coordinate grid, within each space of which live simulation entities. Simulation entities are currently either a fuel station or a vehicle belonging to a program participant. This first version of the system does not have a concept of continuous time and does not simulate the concurrent activities of simulation entities. Rather, it operates discretely - each step in the simulation, assumed to be one day, executes each of the simulation entities independently and sequentially. This precludes handling some issues of concern to a pilot program designer, such as estimating queue length at fuel stations, but allows for a much simpler system to be designed in a brief time. An overview of the simulation is as follows:

Initialize: Time (day of week)
Participants (assign to locations) and driving habit profiles
Vehicles (assign to participants) and performance specifications
Fuel stations (assign to locations)

Loop: For each participant:
Determine day's trips
Execute trips
Increment day

End: Collect usage statistics from fuel stations and vehicles

25.2 System Components

The system is initialized to a specific day of the week, which is relevant to trip profiles. The system tracks days by date, but simulation always begins on January 1, 2000. It does not know about holidays, though the component that handles system time could be expanded to handle special days and be initialized to a specific date. Participants, called drivers in the system, are constructed and assigned a driving habit profile, or trip profile. Trip profiles can be any module that provides an interface for a driver to obtain a set of trips to be made in a day. Currently, a trip profile based on National Household Travel Survey (NHTS) data is used. The NHTS is a survey of local and long-distance travel habits within the United States made periodically by the Department of Transportation. NHTS data relevant to the pilot simulation include the number of local trips Americans make on average each day of the week, the distribution of types of trips made and their associated average distances. Vehicles have performance characteristics such as fuel efficiency, fuel capacity and a low fuel threshold and one is assigned to each participant. Vehicles track the number of miles they travel, the number of times they refuel and how much fuel they use. Fuel stations track each refuel by identifying the vehicle, time of refuel and amount of fuel dispensed. Fuel stations could be expanded to track time spent refueling and average queue length given a number of vehicles that can be served simultaneously. Currently, fuel stations always have a refueling nozzle available. The individual vehicle and station usage data can be aggregated to calculate any related statistic of interest, such as daily vehicle use or weekly amount of fuel needed at each station.

25.3 Simulation

For each day the system simulates, each driver generates and executes a set of trips for the day. The driver first queries its trip profile to determine how many trips it is to make. The NHTS profile considers the average number of trips American drivers make in a day and scales that by the distribution of trips across days of the week. For each trip, it queries the trip profile to determine the destination and whether it is a round trip. The trip profile can return any destination to the driver and this is the main way different profiles can differentiate themselves. The NHTS profile determines an NHTS-defined type of trip based on the probability of occurrence of each type. NHTS-defined types of trips are treated as either destination-specific (targeted) or distance-specific (random). Targeted trips, such as work trips, are always made to a given location. Random trips, such as shopping trips, are made in random directions but have an average distance. Both types of trips can be one-way or return.

For each trip, the driver determines whether the vehicle has enough fuel to make the trip without dropping into the fuel reserve. If so, the vehicle and driver move to the new location, miles are accumulated, fuel is consumed and, unless a return leg must be made, the trip is complete. If the vehicle does not have enough fuel, the driver determines the nearest fuel station, travels there, refuels and attempts to make the original trip. When the day's set of trips is exhausted, the driver makes one final trip home.

25.4 Limitations/Expansion

There are some known limitations to this first version of the simulation. The system treats time discretely and simulates each driver sequentially. Thus, there is no way to simulate usage conflicts at a fuel station. As mentioned above, the system's concept of time can be easily expanded, though adding time step granularity smaller than one day would require more work. Trips are all assumed to be made at constant fuel efficiency and with no regard to duration or time of day. It also does not measure fuel wasted due to traffic delays, which is a concern given that the pilot program is intended to operate in Los Angeles. The system's concept of spatial location is currently that of a uniform grid. The only link to real-world distances is a simple miles-per-gridspace parameter. A modified system using latitude and longitude measures would be more accurate and flexible and could be added with few changes to the logic that relies on the grid concept. A full geographic information system implementation would be the ultimate expression of realism but the drastic increase in complexity accompanying knowledge of the road system would be prohibitive and produce few additional gains in output information.

The implementation of vehicle travel does not handle out-of-fuel events in a realistic manner. If a vehicle runs out of fuel during travel, it magically completes the trip and refuels itself, akin to calling AAA for help. If the vehicle runs out of fuel heading to a station, it will require no fuel at the station and refuel 0 kg. More advanced functionality could determine if there was a path to the destination via one or more other fuel stations and reject the trip if no path is found. This could be used to track regional or long-distance trips that the proposed fuel infrastructure cannot handle. The current implementation is used because well-formed data, including appropriate distances between home and work and relatively short daily trips, should preclude out-of-fuel events from occurring. Out-of-fuel events are tracked in the statistics generated per vehicle. Out-of-fuel events could also be avoided by expanding the travel decision logic to determine whether a trip would leave the vehicle outside the range to a fuel station. Currently, trips are made only if the destination is within reach.

The code is structured such that more advanced implementations of the basic functionality can be made relatively painlessly through changes to as few areas of the code as possible. For example, the general vehicle class can be subclassed to simulate specific types of vehicles with particular characteristics. In full detail, if a new type of trip profile is desired, the developer must create a superclass that provides a client interface to concrete classes of the trip profile abstract type, build the new trip profile class as a subclass of the abstract profile class, modify the public interface of the NHTS profile class and change only the driver code that interacts with trip profiles. The initialization code can then be extended to construct the two types of trip profiles and assign either specific one to a given driver. This is merely a basic use of well-modularized polymorphism.

The most useful improvement to system usability would be the addition of a better interface. Currently, the system is driven by a set of text files. Generating these text files by hand is, at best, tedious and, for large simulations or repeated use on different test cases, impractical. A graphical interface presenting a map and overlying grid with user-resolvable size would allow the user to click on grid spaces to assign fuel stations and participants. It may allow the user to highlight an area and assign a given number of participants to the region using some distribution. It could also provide a way to create a set of vehicles and assign them to participants. For cases where the user is less interested in detailed, manual control of simulation parameters and more interested in running sets of different data to establish trends, a simple text-based script could generate the system input files. This could be useful if the user wishes to hold some of the simulation parameters constant and modify others, such as determining how a given fuel infrastructure responds to different numbers or distributions of participants. For initial testing of the simulation code with pilot program variables, a python script was built to generate the input text files.

One additional statistic that might be of interest is tracking the number of miles ”wasted” diverting to fuel stations. If a trip is to be made between two points but the vehicle must refuel before reaching the destination, the difference in miles actually traveled and miles between origin and destination could be logged as wasted or extraneous.

25.5 Details

The UML-style diagram below depicts the relationships between the major classes in the simulation. In our notation, the prefix A on a class name indicates an abstract base class while C indicates a concrete class. Note that there are other supporting class files, such as those which encapsulate the notion of the units miles or kilograms.

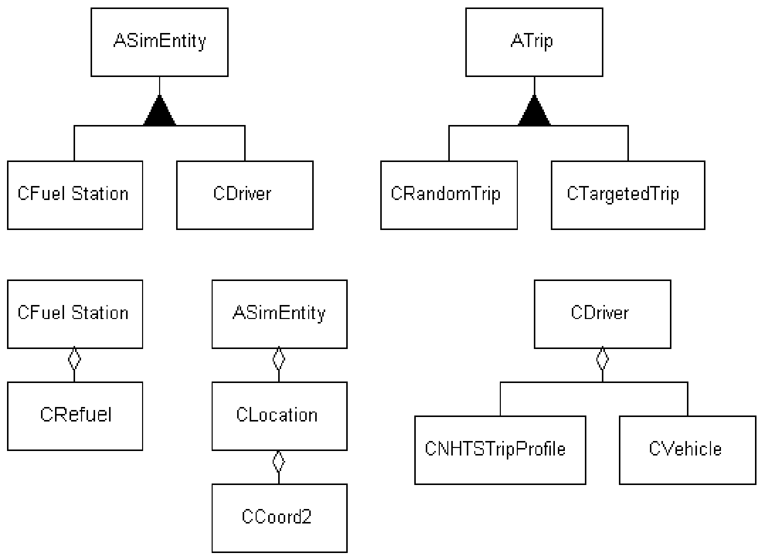


Figure 25.1: UML diagram of major simulation components

The electronic version of this report contains the source files, including project and workspace files for building within Microsoft Visual Studio. Browsable code-level documentation is provided as generated by the third-party program *doxygen*. The electronic submission contains readme files which describes it's the contents of the various directories.

Third-party code is used to perform tokenization of the input data files. Compiling this code occasionally causes an internal compiler error with Visual C++ 6.0. Removing any object files generated (cleaning the project or deleting the .obj file) and recompiling solves the problem. The third-party code is contained to one compilation unit within the simulation code - *tokenization.cpp*.

Running the simulation application, *pilot.exe*, from the command line with no arguments or the arguments `"-h"` or `"--help"` will give a brief usage description. The `"--longstats"` option, which generates detailed statistics output, can take a long time to execute if many days or vehicles are simulated. As a benchmark, a 550MHz Pentium III with PC-133 RAM simulating 2,000 vehicles and 7 fuel stations over 365 days generated over 300,000 lines of statistical output and ran for 5.5 hours. The time spent simulating vehicle travel was brief; aggregating the statistics afterward took the majority of the time. One potential point for future work would be to run a small case within a performance profiling application, such as Rational's PurifyPlus or gprof under UNIX, and determine how to speed up the gathering of statistical information.

Once a simulation run is complete, the output can be imported into a spreadsheet for analysis. To import data into Microsoft Excel, start Excel and open the output file. In the text import wizard, import the file as delimited by tabs and commas.

Further details about the installation, compilation and execution of the pilot simulation can be found in the readme file in the electronic report submission, which contains all data files associated with this project. 1.6. Results Simulations were performed to reproduce the conditions of Phase I of the pilot program. A rectangular area approximating the size of the San Fernando Valley was defined and 2,000 participants and vehicles randomly distributed therein. Each vehicle was identical, with attributes as used in the pilot program spreadsheet analyses - 4.5 kg tank, 0.75 kg refuel threshold and 65 miles per kilogram efficiency. 2001 NHTS data formed each driver's trip profile. Each work destination was set to downtown L.A. and work trips were made no more than once per weekday. Seven fuel stations were added to the region to equalize coverage to all areas as best as possible. Three additional fuel stations were added equidistant around the point approximating the center of downtown Los Angeles. The distribution of stations and drivers is illustrated below. Stations appear as red asterisks, numbered 0 through 9 left to right, top to bottom. The blue dots represent the home locations of drivers. For this simulation, the grid point [0,0] corresponds to the northwestern corner of the San Fernando area, which extends to [225,-100]. Los Angeles center was approximated at [240,-166]. This assumes 0.1 miles per grid space.

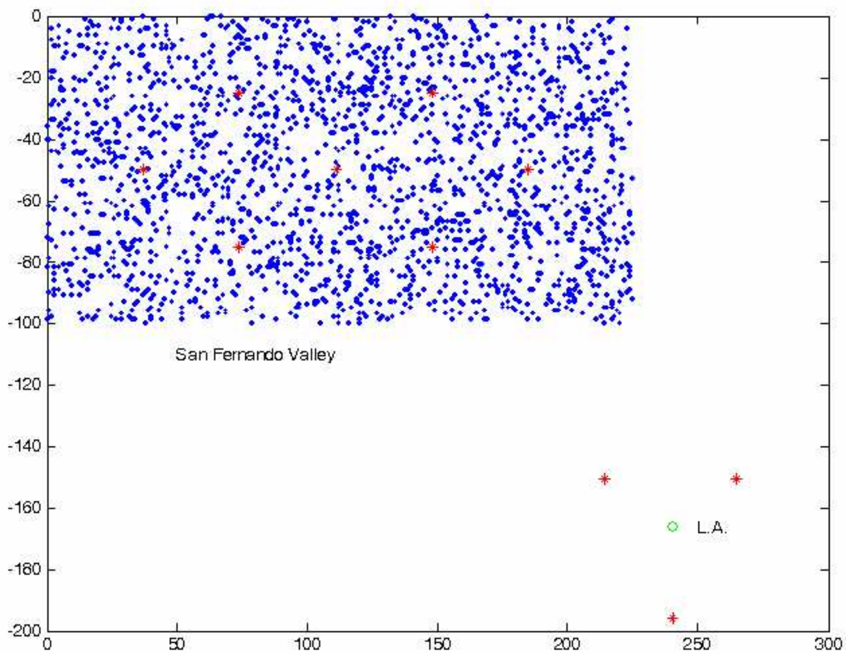


Figure 25.2: Setup for Phase I simulation run

Initial simulations over 365 days with the 2001 NHTS average 4.5 trips per person per day resulted in at least twice the expected annual mileage. Trips were adjusted to never be return trips, since each driver returns home at the end of each day, and the number of trips per day was reduced to 3.1. This resulted in approximately 12,000 miles per person per year for regional travel. Data derived from the final simulation's output is presented in the tables below.

	Max Daily Refuels	Avg Refuels per Day	Avg kg/refuel
Station 0 [74;-25]	76	30.99	3.74
Station 1 [148;-25]	89	30.57	3.75
Station 2 [37;-50]	113	46.58	3.75
Station 3 [111;-50]	33	11.17	3.7
Station 4 [185;-50]	97	36.03	3.75
Station 5 [74;-75]	68	27.88	3.74
Station 6 [148;-75]	53	18.91	3.72
Station 7 [214;-151]	38	14.24	3.74
Station 8 [265;-151]	107	40.7	3.69
Station 9 [240;-196]	35	13.09	3.68

Table 25.1: Fuel station statistics from Phase I simulation run

Avg miles per vehicle	12082.14
Avg miles per day	33.1
Avg ”fuel station” miles	191.57
Avg # refuels	49.3
Avg ”fuel station” miles per refuel	3.89
Avg ”fuel station” miles per day	0.52
Total empties	0
Avg miles per refuel	245.06
Avg miles per kg	65
Avg kg per refuel	3.77
Avg kg used	185.88
Avg kg used per day	0.51

Table 25.2: Vehicle statistics from Phase I simulation

The data shows that the average refueling load per station is within the predicted bounds. However, there are significant spikes in usage that could potentially cause backups at stations. Based on the average amount of fuel dispensed per refuel, the vehicles appear to be refueling very close to their refuel threshold. Given this low variance, we may be able to lower the suggested refuel threshold and somewhat reduce station demand. However, without the additional trip logic suggested above, the system occasionally created out-of-fuel situations when the refuel threshold was set to 0.5 kg.

The miles spent diverting to fuel stations beyond planned trip distances was less than 200 miles on average annual driving of over 12,000 miles. In terms of refuels, less than 4 miles were spent given an average of 245 miles between refuels. This 1.6% of miles spent diverting to stations appears to be reasonable and partially justifies the selected station density.

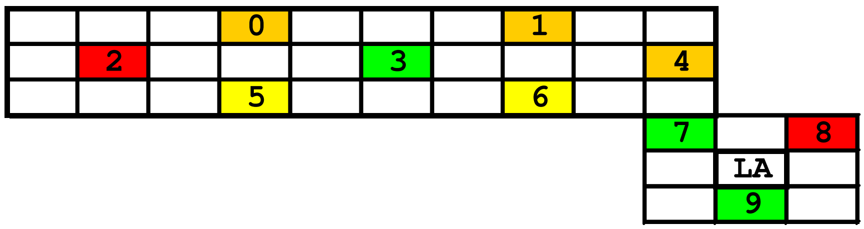


Figure 25.3: Fuel station distribution and station loadings from Phase I simulation run

Station loading is most easily viewed graphically, as above. The particular topology of the stations could be improved to relieve the burden on the most used stations. As expected, the stations on the periphery of the served region saw higher use than those on the interior, where drivers have more potential station choices. Surprisingly, however, station 9 had very low use yet it served all potential trips south of Los Angeles. Given that station 4 is relatively close to station 8, station 8's load was expected to be lower.

Chapter 26

Driver Travel Habits

Data from the 2001 National Household Travel Survey (U.S. Department of Transportation, 2002, [142]; U.S. Department of Transportation, 2003, [143] and U.S. Department of Commerce, 2002, [140]) were filtered for relevance to the pilot program. Some of the derived information guided assumptions built into the pilot and other was used as input to the simulation. The relevant raw data and derived tables are included in the appendix and summarized here.

The average American makes 4.5 local trips per day, totaling 11,933 miles per year and 81% of all personal vehicle trips made, local and long-distance. The average American averages 8.45 long-distance trips per year, representing 0.65% of all trips, 2,774 miles and 19% of total annual mileage.

Note that these percentages differ slightly from some of the derived data in the appendix of NHTS data due to difficulties correlating per-vehicle and per-person trips. Rounding errors are also present since total mileage is reported to the nearest million or billion for data representing the travel habits of the entire American population in a year. Local trips are distributed by trip purpose as shown in table 26.1:

Trip Purpose	As % of all local trips	As % of all local miles
Work	14.8%	19%
Work-related	2.9%	3.7%
Family/personal business	44.6%	33.6%
School/church	9.8%	9.7%
Social/recreational	27.1%	33.2%
Other	0.8%	0.8%

Table 26.1: Local Trips Distributed By Trip Purpose

More local trips are made later in the week than earlier, distributed as shown in table 26.2:

Day of Week	Percent
Sunday	12.9%
Monday	13.8%
Tuesday	14.0%
Wednesday	14.7%
Thursday	14.6%
Friday	15.6%
Saturday	14.5%

Table 26.2: Local Trips Distributed By Days

The average distances of local trips (in miles) are (table 26.3):

Trip Purpose	Miles
Average vehicle trip length	9.06
Home to work	11.8
Shopping	5.64
Other family or personal business	6.93
Social and recreational	11.24

Table 26.3: Average Distances of Local Trips

Long-distance trips by personal vehicle are distributed by purpose as shown in table 26.4:

Trip Purpose	As % of all LD trips
Commute	12.2%
Business	12.6%
Pleasure	50.2%
Personal Business	11.3%
Other	3.3%
Total	89.6%

Table 26.4: Local Trips Distributed By Purpose

Part V

Hydrogen Fueling Station Design

Chapter 27

Introduction

During the second semester, four members of the TransHydroGen entered the Hydrogen Refueling Station Design Competition organized by the National Hydrogen Association (NHA). This entailed a transition of these members from the main design project into this new venture. The competition guidelines were sent to us by NHA and our work so far has been done within these measures. The Hydrogen Competition Team was set up as a branch of the TransHydroGen Group, with the spring semester overall Group Project Manager doubling up as the Assistant Project Manager in-charge of the competition team. With the Competition Team members' duties reduced for the main project, we were able to pay more attention to the competition. To complete the team and meet competition requirements, we increased our knowledge base with help in architecture, marketing, and cost analysis.

Our main conceptual guidelines Whereas the design process of a conventional refueling station is a challenge that is continuously being improved by key players in the gasoline industry, the challenge is even more daunting when dealing with highly compressed hydrogen gas. As such, our research into safety issues, sound technical designs, hydrogen fuel sourcing, storage and dispensing issues, and user education for the future, all compound to make the challenge interesting and worthwhile. First and foremost, the team felt the need to create a solid framework within which the hydrogen fueling station could be designed. We felt that the only way to reach an interesting output was to built it around powerful concepts related to this emerging technology. Five main ones emerged from our discussions.

1. **The Transition Concept** The fact that hydrogen is in such an uncertain transition phase has many implications that we felt should be reflected in our design. Growing customers, increasing fueling needs, development of hydrogen production technologies, many factors encouraged us to work towards a specific design. We want it to be: a modular design so we can easily add new dispensers if required by growing needs; a highly standardized fuel station, to ease the reproduction of the station in other similar contexts.

2. **Sustainable development Concept** A hydrogen economy has interesting aspects for many different reasons. We wanted our design to reflect strongly the environmental aspect of those motivations. And this means in our context that hydrogen needs to be directly linked to renewable forms of energy sources. If not, we feel that it loses an important dimension.

3. **The Safety Concept** Introducing a new technology always implies overcoming new hurdles. In the case of hydrogen, one of them is the need to have public opinion backing up such a transition. To us, this implies the need to design the fueling station in a way that allows customers to feel inherently safe about the fueling process. This would fuel the transition more than any kind of marketing campaigns.

4. **The Teaching Concept** The teaching concept merges both the safety and the transition concepts into a requirement for our fueling station: customers need to understand what is happening around them, they need to realize the potential advantages such a transition can have and how our design allows them to feel entirely safe. This can be emphasized in the beginning of the operation of the station and put through with things such as panels, interactive expositions, handling of hydrogen, allowing customers to drink water produced by its combustion, etc.

5. **The Customer-friendly Concept** Another factor that will influence the design and the transition is how customer-friendly our station is. Short fueling times and easy to use interactive panels would be some possible implications of this concept.

To put all these into perspective, the NHA required us work within the following competition rules and guidelines that can be found at

<http://www.hydrogenconference.org/H2contestRules.pdf>

Competition Schedule and Duties The competition organizers, NHA, gave us the following time schedule for entry to the competition:

Early announcement to alert universities	Sep 30, 2003
Draft Guidelines and Rules released to interested universities	Oct. 15, 2003
Open meeting to review Draft Guidelines and Rules	Nov 5, 2003
Final contest rules and guidelines released	Nov 15, 2003
DUE: Team registration and design statement	Dec 15, 2003
DUE: All final entries at NHA offices	Mar 3, 2004
Selection of winning teams	Mar 3-Mar 23 2004
Winners announced	Mar 26, 2004
DUE: Winning Team submits presentation to NHA	Apr 16, 2004
Awards ceremony, plenary and poster presentations	Apr 28-30, 2004

Table 27.1: Overall schedule for the competition

In the beginning, a project schedule was set up to ensure we addressed all key areas as required by the competition guidelines. Below is a list of the major areas of expertise required to complete the competition:

1. Technical design: Hydrogen Sources Major components Fuel process Control system Anticipated energy use A1-site plot A2-3D drawing

2. Safety analysis Define failure modes Analysis of 3 failure mode

3. Economic analysis Capital cost Operating costs Hydrogen cost Resources costs Maintenance costs Selling price of H2 Comparison $/mile H2-ICE

4. Environmental analysis Energy balance- Well-to-tank Well-to-wheel analysis

5. Advertising/Marketing Slogan Poster

Chapter 28

Technical Design

28.1 Production of Hydrogen

Our first task was to investigate the various methods of obtaining hydrogen gas for our fuel station. Several different options were studied and the following section gives a summary of some of the findings we made during our research. We decided to select the most economically feasible yet sustainable source, which outrightly entailed our research into the cost analysis of various methods, their pros and cons to the environment, and their reliability in future.

Hydrogen production/sourcing options We looked at various source of Hydrogen to be used in our designed fueling station, and these were classified into conventional and renewable sources:

- Conventional Sources

  1. Electrolysis - Convert water to hydrogen and oxygen
  2. Natural Gas - Reformed to provide hydrogen

- Renewable Sources

  1. Solar Energy - Provide electricity
  2. Wind Turbines - Provide electricity
  3. Municipal Solid Wastes (MSW) and Sewage - Provide methane gas or hydrogen gas

Figure 28.1 shows the different avenues explored by our team to decide on the production of hydrogen for the fuel station.

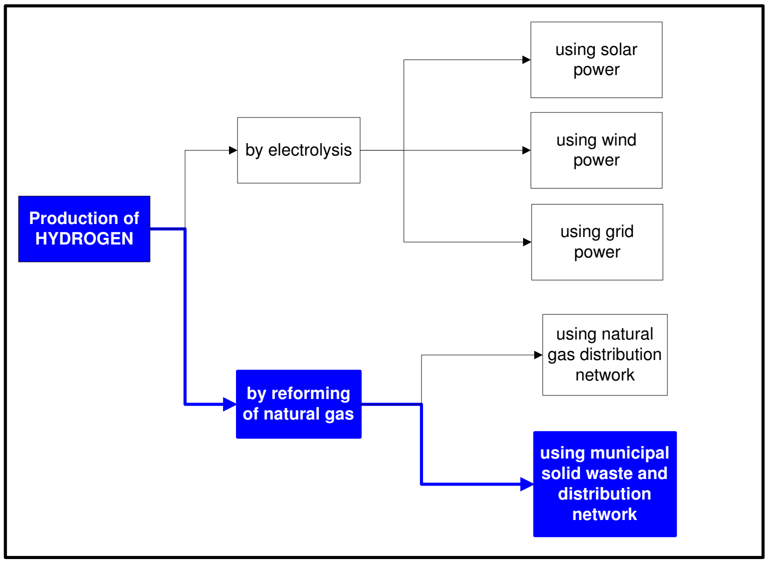


Figure 28.1: Classification of the different ways of producing hydrogen that we analyzed roughly to make an educated decision on the source of hydrogen.

28.1.1 Production by Electrolysis

Production based on solar energy

Photovoltaics The potential for solar energy is huge but hasn't been harnessed technologically yet. Photovoltaics have the advantage over other renewable sources of energy of being less land intensive, about 1/30th of those for biomass. For example, southern Spain has more than 20,000 km2 of unused arid zones, which could produce 8 exajoules of hydrogen per year, about one-third of the estimated potential use in Western Europe. "And in the United States, an amount of hydrogen equivalent in energy to current oil consumption (34 exajoules) could be produced on 0.7 percent of the U.S. land area (or 9 percent of the U.S. desert area)." (Ogden and Nitsch, 1993, [58]).

One of the issues with using renewable sources of energy such as solar or wind is their intermittent nature which makes their use in the global energy market more complicated. Hydrogen has the potential to be a great energy carrier in this context, bridging the gap between those technologies and the user of motorized transportation. It is a very capital intensive mode of producing electricity, however, and costs have not been brought down sufficiently to make it a attractive option in our context where production of hydrogen by electrolysis is still much more expensive than by reforming natural gas. Preliminary calculations show that the capital cost of solar panels to fuel a fleet of about a thousand vehicles would be higher than $30 millions, a much higher number than for other types of hydrogen production.

Remark: Photoelectrolysis Another process using solar energy but that does not require electrolysis is being studied. It would break up water directly into hydrogen and oxygen. This process, known as *photoelectrolysis* combines the photovoltaic cell with a catalyst, which acts as an electrolyzer (Kruse et al., 2002, [49]). This could reduce prices and improve efficiency in the future.

Production based on wind power

Few would argue against the fact that wind power is the type of renewable energy that has reached the highest level of commercial viability. Its efficiency has risen to much higher levels in the last few years, mostly through the shift towards bigger wind turbines and higher towers. This logically went hand in hand with reductions in prices: "the cost of electricity from utility-scale wind systems has dropped by more than 80% over the last 20 years." (AWEA, [91])

As is often the case with renewable types of energies, the production site plays a major role in its efficiency. Wind speeds of $5\frac{m}{s}$ are said to be required for the economics of wind power to be favorable. Various locations in the United States have been recognized as having a huge potential as wind energy providers. Most notably, North Dakota is known as "the Saudi Arabia" of wind, having enough wind potential "to supply a third of the electricity consumption of the lower 48 states." (Liu, 2003, [92]). Various alternatives have been studied to link the production of wind power to the one of hydrogen, allowing this energy to be used through a very flexible energy carrier. Both the building of a power transmission lines infrastructure or hydrogen pipelines network imply costs that still scare away investors from such projects. A study by General Motors estimates the resulting cost of hydrogen from such power generation to be around $9/kg, a number still far exceeding the $2 target the DEO is going after. The major cost factors highlighted in this study are the cost of electricity, the electrolyzer cost and the cost of the efficiency associated with it (Liu, 2003, [92]).

28.1.2 Production Based on Reforming Natural Gas

Production based on Municipal Solid Waste (MSW)

At current stage of technology the most economic way of producing hydrogen is to reform it from natural gas. The most cost efficient way of reforming natural gas is through a catalytic steam reforming process (SMR), where hydrogen is extracted from natural gas with help of steam. Following the reforming process the produced hydrogen must be cleaned as a tiny fraction of sulfate can interacts with the platinum catalyst used in the fuel cells.

As the natural gas is widely distributed by pipeline system in USA it is assumed that the station can, without major cost, be connected to the existing distribution network. This allows a constant flow of natural gas to the station based on demand.

Another alternative is to use methane produced from Municipal Solid Waste (MSW) either by collecting waste gas from land fillings or by gasification which seems to be a fast growing technology today. Gas collected from land fillings contains about 57% methane by volume which can be used to produce hydrogen through reforming process. The efficiency this energy conversion seams though to be rather poor compared to other methods used to extract energy from MSW. At this stage of our work it is not clear if purification process is necessary before reforming the collected waste gas, but must be worked out later on. On the other hand it is stated by Björklund (Björklund et al, 2001) that gasified MSW can be "used directly as fuel, or feedstock of chemicals such as hydrogen or methanol." This method of energy extraction from MSW is stated to have higher energy efficiency than collection waste gas. As the amount of MSW produced every year is huge and constantly growing, and sites for further land fillings are becoming scarse we plan to explore further the potential of this method to use MSW as a source of renewable energy by gasification.

28.1.3 Conclusion on the Production of Hydrogen

After comparing the capital costs, environmental impact, sustainability requirements, and other outcomes of each of the methods above, we concluded that the most feasible means would be reforming methane from Municipal Solid Wastes (MSW) and Sewage, supported by production from natural gas to satisfy our hydrogen gas market. Indeed, as shown in chapter 13 and in previous sections, production of hydrogen by electrolysis is still economically unfavorable compared to the reforming of natural gas. The fuel station design group felt that in the current state of the art, and for a station planned to start operating in March of 2006, it was a better choice to build upon cheaper techniques of production that would allow a better start for the hydrogen transition. The group also felt that the potential of the energy created by our society in terms of waste production was worth the investment in time and money. Indeed, our societies will keep on producing waste, most probably at an increasing rate, requiring us to process it in one way or another. If this can be done in a way that allows the production of relatively clean energy, the overall loop can become a little cleaner.

28.2 Analysis of Major Components

28.2.1 Storage

With the high volatility rating of compressed gaseous hydrogen a safety concern, various governing bodies have established laws and guidelines that are geared towards ensuring operator and consumer safety while handling hydrogen. These include ANSI/CGA, ASME, NFPA, USDOT, EPA, Federal, State, and local governments in their areas of jurisdiction.

While general standards for compressed gases and pressurized vessels apply, special ones are effected to deal with hydrogen specifically. This is because hydrogen is the smallest, lightest, and most permeating element known. Although hydrogen is non-toxic, its ignition temperatures are as low as 500°C (932°F) at atmospheric pressure, and can cause asphyxiation when it displaces the normal 21% Oxygen in a poorly-ventilated environment.

Gaseous Hydrogen Systems include stationary or portable containers, pressure regulators, pressure relief devices, controls, gas manifolds, and interconnecting pipes. The National Fire Protection Association (NFPA) provides standards NFPA 50A that describe the acceptable setup of gaseous hydrogen systems at consumer sites. These standards give installation guidelines for refueling stations at public sites, subject to approval of the authority having jurisdiction.

So far, we have found out that some of the leading hydrogen storage technology companies include FIBA Technologies, Inc. of Westboro, Massachusetts, Dynetek Industries Ltd. of Calgary, Canada, and Texaco Ovonic Hydrogen Systems of Rochester Hills, Michigan. Our research on this is on-going.

28.2.2 Compressor: Power and Cost

Research conducted at the USDOE's Argonne National Laboratory in Illinois by Marianne Mintz et al. indicates that the cost of compressors depends on their power. They have developed the following relationship between compressor cost and power:

- Single-stage Compressors: $Y = 34037 \times X^{0.3036}$
- Multi-stage Compressors: $Y = 22877 \times X^{0.4561}$

where X is the power rating of the compressor (in kW) and Y is the cost of Compressor (in dollars) (Mintz et. al, 2002, [55])

Whereas this is an acceptable method of determining the cost for a compressor when the power required is known, our initial research was without any knowledge on power requirements for our fueling station design. However, we contacted various industrial experts, and initial response from Shakeel Ahmed of Greenfield Compression Products indicated that their 6000 psi, 100 Nm3/Hr model B65-H compressor sells for $120,000. These specifications seem to match our initial design requirements. The price indicates (from the Argonne Labs results) that the power requirements would be approximately 50kW. While we continue to research on this, we have adopted this as an initial acceptable power rating for the compressor.

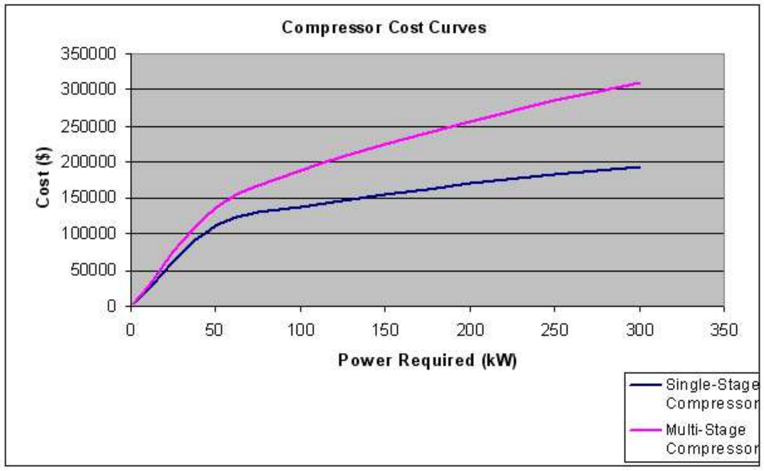


Figure 28.2: Compressor cost curves

28.2.3 Reformer

By continuously reforming natural gas 24 hours a day our preliminary calculations show that the capacity of the reformer must be about 0.5 kg/(day*vehicle). As the consumption rate of hydrogen is assumed to vary during in that period either the capacity of the reformer must exceed the average consumption of vehicle or a hydrogen storage facility must be introduced. The capacity of the reformer and the storage tank must be decided through a trade of analysis where the total cost of components is minimized, as function of fleet size, at acceptable service level.

Several companies produce reformers at the capacity we have been looking into. Price quotes have not been received yet, but from articles and reports we estimate the equipment cost of reformer it to be somewhere between 1,000 - 2,000 ($ /(kg H2/day)).

28.2.4 Hydrogen Fueling Dispenser

Dispensing is the part of the fueling process where customers directly interact with hydrogen. Therefore, the design of a dispenser has to be specifically thought of to encourage a good feeling about it for customers. Here is the flow chart shows the important fueling procedure through dispensers:

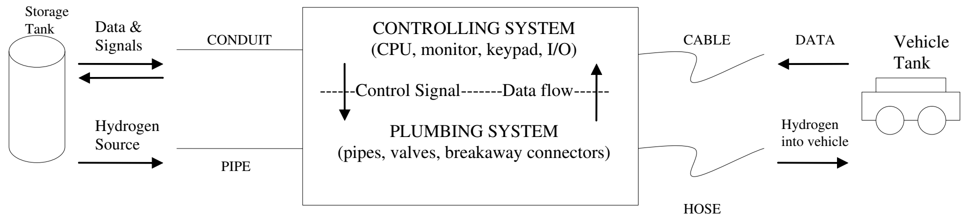


Figure 28.3: Flow chart of the important steps in the fueling process

The role of dispenser is to serve as an interface between the cascade, user and vehicle. It receives compressed hydrogen from the cascade, forwards it to the tank of the vehicle, measures the amount of hydrogen dispensed and is capable of taking care of financial transactions after pumping. It will also include a control system able to control the gas flow based on received information on temperature and pressure of the tank while pumping. One applied strategy is to fill vehicle at 10MPa per minute when the ambient temperature is less than 15°C, at 7.5MPa per minute when the ambient temperature is between 15°C and 30°C and at 5MPa per minute when the ambient temperature is above 30°C. Experience shows that temperature in a tank filled following this process will not exceed 85°C (Campbell, 2003, [43]). Therefore the control system will be the core component in linking the dispenser to other major sub systems. Following is a list and explanation of dispenser components ([113], Campbell, [44]) and figure 28.4 shows all of these components graphically:

- Controls: The hydrogen system will likely need to meet Class 1 Division 1 Group B according to NFPA 52 (Natural Gas). It should have programmable logic controller implemented using semi-auto intelligent fuel algorithms. There are one slot reserved for CPU and 8 I/O slots for connecting other devices. These algorithms are used to calculated heat of compression, ambient temperature, supply pressure and a variety of other measurements. The design has 85% to 95% fill in mind to vehicle storage tank. It satisfies the standard, SAE J2601 (2003, [90]), the refueling communication device and protocol. The fill strategy with communications should allow for a 95%+ fill every time, and for every vehicle in any weather. The fill without communications provides a slower, less complete fill, but allows vehicles to still receive fuel when the communication system is not operational. It connects with measuring device and extra piping and valves. Our 'H' shape design can use one monitor system to control two dispensers. It can simultaneously fill two vehicles at the same time using one controlling system.

- Supply Pipes: It receives hydrogen sources from cascade. It can support 6000 psi. Clean dry air supply also needed at 80 psi minimum
- Emergency shut down: It shuts down the fueling process if an emergency situation happens, but it doesn't close the monitoring system. It is the first level shut-down in a "risk prevent" procedure. It should be used when dangerous amount of hydrogen is leaking from the dispenser.
- Remote shutoff: It is the second level shut-down in the risk prevent procedure. It shuts down all computer systems and fueling processes. It should not be used unless a devastating situation occurs such as computer virus attack, fire, terrorists attack, and etc.
- Fueling Status light: It signals the status of fueling process or emergent situation. Usually, red light is for fault procedure; blue light indicates excess pressure; yellows light shows under filling, and green light tells that the fueling is complete and vehicle can move away.
- Retractor: The device can extend and withdraw the H2 hose.
- Hose: It should have the same design pressure as the pipe for hydrogen supply. It must be designed according to geometry standard, SAE J2600 (SAE, 2003, [90]). The hose is also tied up with data cable which transfers vehicle tank information data back to controlling system.
- H2 Nozzle: It must be designed according to SAE J2600 standards. It is designed to be electrically grounded. Main material could be steel but it has to be covered with rubber-like material to reduce the risk of sparks. It includes an auto shut-off valve and sensor at the front. The sensor is used to detect leakage and send alert data to controlling system.
- Auto Shut-off valve: It shuts off the connection between nozzle and vehicle tank if hydrogen leak is detected. It is controlled by the control

system. Since hydrogen is a small molecule, it can pour into rubbers and plastics material while under high pressure and close the nozzle linkage to the tank hole.

- Hose breakaway connector: If pressure is too high, or hydrogen leakage is detected, the breakaway connector will close the hydrogen flow into hose. This is controlled by control system.
- LCD data display: It displays information on fueling and charging amounts.
- Card acceptor: It can accept credit card, debit card and swipe card for customers' convenience.
- Grounding cable lines: It discharges possible electricity charges on vehicles and operators.
- Weatherproof dummy receptacle: a weather proof container that holds the nozzle.
- Keypad: It is enable customers to enter pin number or password for credit card payment.
- Purged Cabinet: The body of the dispenser is made of metal materials.
- Lever: Lift up the lever when the nozzle has been safely connected to the vehicle. Then the hydrogen will pump into the vehicle tank. It automatically drops down when the tank is full.
- Electric lines: 115V AC digital input module with 8 terminals, and 5-24V DC digital input module with 8 terminals. It is used to operate controlling system. The electricity is shut-off when remote shut-off button is pushed.
- Connection Cable: Links dispenser controlling system to the fuel system monitors. Can be replaced with wireless connection with station computer.
- Station Computer: The fuel station is equipped with data management system which is connected to dispensers.

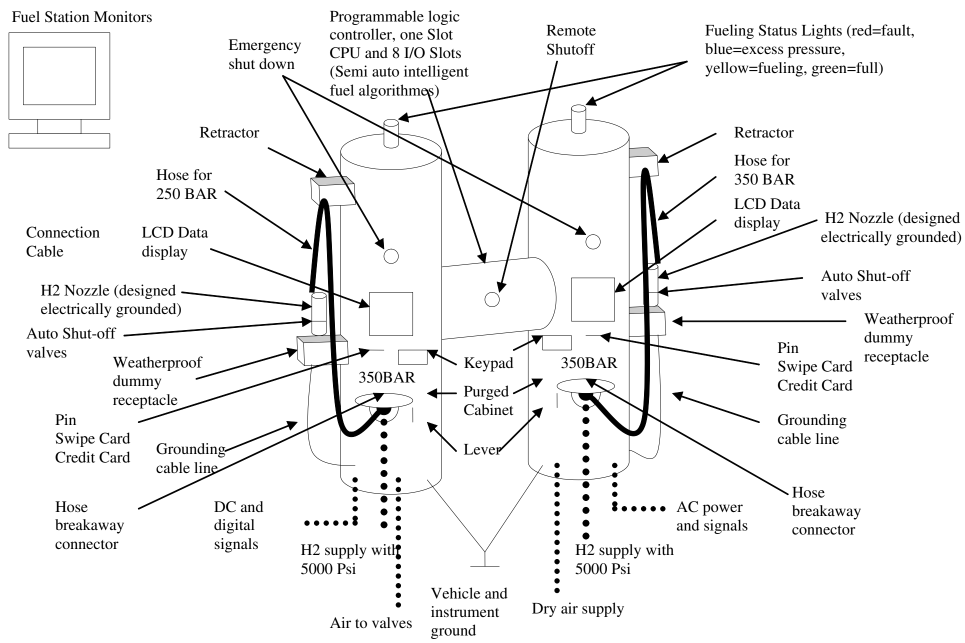


Figure 28.4: Graphical representation of the dispenser

28.3 Process Analysis and Site Plot

A system-based analysis that includes input, throughput and outputs of the fuel station is a necessary step in a sensible design. The figure on the next page shows a simple version of such an analysis in the case of the fuel station under design. It includes 3 majors areas:

1. **Local homes and consumption centers:** Waste is generated as a part of our everyday life, using FCVs and consuming, in small or large quantities products that ultimately imply the creation of solid waste collected by municipalities and brought by trucks to disposal sites.

2. **A waste-to-energy site:** This disposal site, where Municipal Solid Waste (MSW) is being collected, has been upgraded to allow the processing of waste into ashes through a process that produces energy. The resulting gas is purified and separated so as to be plugged into the existing natural gas grid system. Alternatively, if purification is too

expensive, the gas can be directly brought to the natural gas reforming center where it is transformed into hydrogen and by-products.

3. **Fuel station:** The fuel station would ideally be the stage where on-site hydrogen production occurs. This allows to avoid any new transportation cost due to the new nature of hydrogen. Natural gas is thus reformed and stored thereafter in a storage tank holding approximately two days' worth of hydrogen production. This allows small perturbations in natural gas delivery to go unnoticed by customers. The compressor and the cascade storage is used only at the stage right before the dispensing of the fuel. Indeed, our design tries to avoid high pressure hydrogen storage.

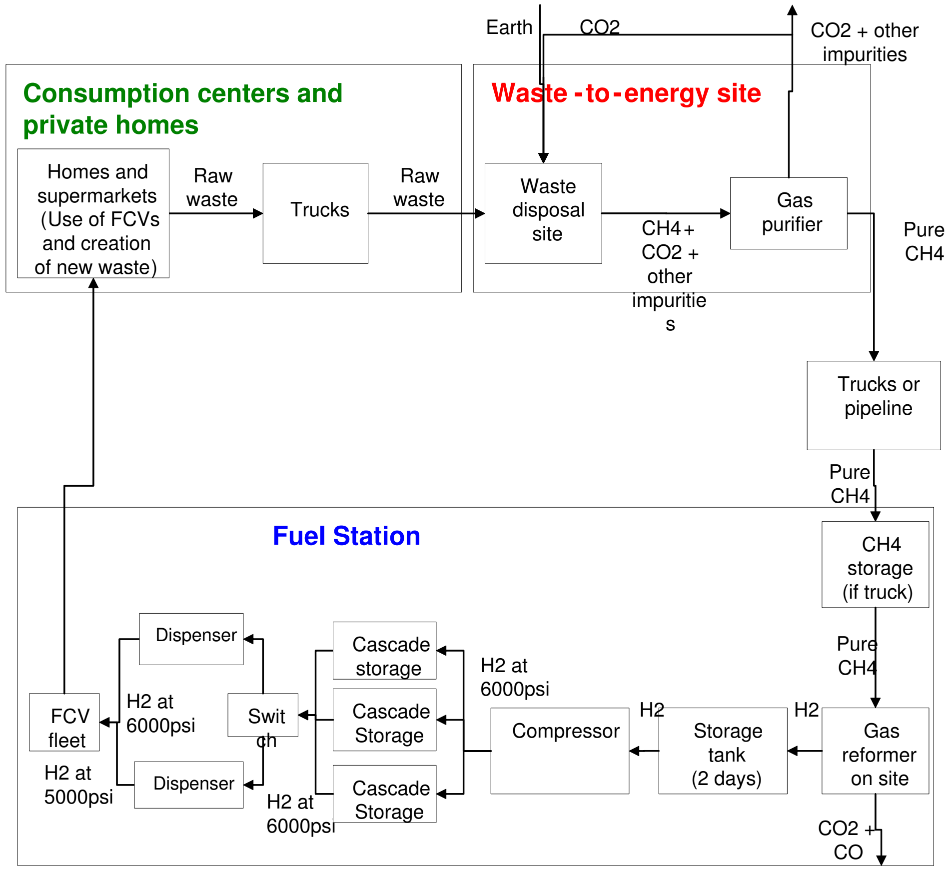


Figure 28.5: Outcome of the process analysis based on the production of hydrogen from Municipal Solid Waste

These 3 steps form a loop, where waste production and energy production are linked into a sensible system. However, as always, this is not a miracle solution, and waste processing would not provide our FCV fleets with enough energy to sustain itself, as was explained in a previous section. Therefore, an input of natural gas from the grid will be necessary. Also, as can be noticed on the graph, carbon emissions are not avoided through the use of this production.

Figure 28.6 gives a preliminary design of the fueling station.

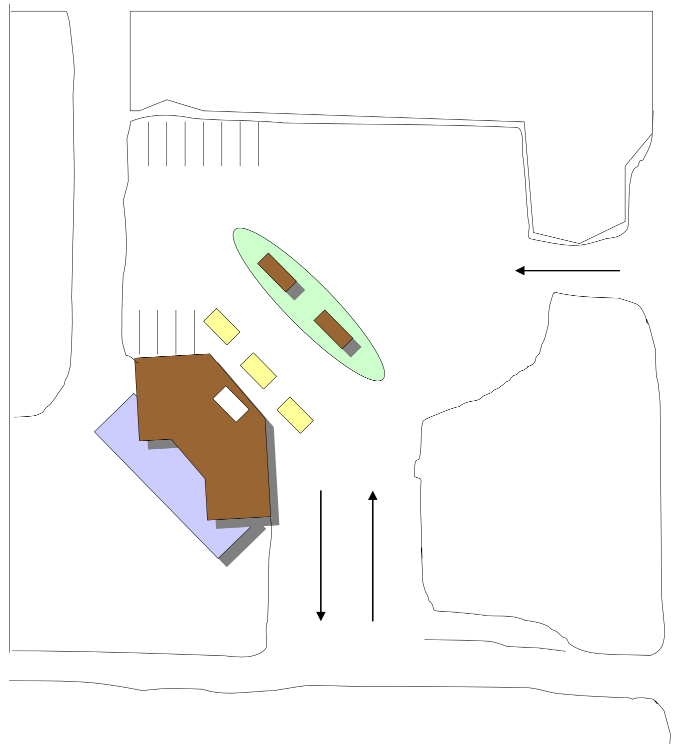


Figure 28.6: Hydrogen fueling Station Preliminary Design

28.4 Marketing our Energy Production from Waste

Seen that the cost of producing hydrogen from Municipal Solid Waste is prohibitive as a stand alone solution, our design group decided to move to a different concept of marketing. We feel the customer should be given the opportunity to choose between two fuel prices, making the relative increase in price due to renewable sources of production a personal choice. This implies that two price options will be given at the pump, with clear indications as to what environmental benefits the greener one implies. Linking this concept to the recycling of waste into energy can be an extremely powerful marketing tool.

Part VI

Conclusion

Chapter 29

Conclusion

The completion of the pilot project should yield a clear answer to the question of the economic, technological and public viability of hydrogen as a mass transportation fuel. Given the significant logistical challenges and costs associated with the program, it is expected that the project will only be undertaken if there is wide enough support for and belief in the use of hydrogen as an eventual replacement for fossil fuels. Therefore, the project, if begun, is expected to succeed and to validate hydrogen as America's future energy source. Regardless of whether the pilot project indicates that hydrogen is the future or not, it should be considered a success if debate is put to rest.

Should hydrogen be demonstrated to be safe and commercially acceptable, the government should take legislative measures to assist in a large national introduction of hydrogen power. The lessons from the unleaded gasoline transition indicate effective ways to slowly guide industry toward desired public policy goals. The pilot project may serve as a rollout model for introducing hydrogen to other metropolitan areas, with follow-on expansion to suburban areas and major traffic arteries slowly but consistently increasing hydrogen's reach.

There have been concerns about the cost of the pilot project. The entire project is expected to cost over $700 million. Compared to President Bush's FreedomCAR initiative at $1.2 billion, this cost is considerably less. In addition, the ability of this project to act as a national rollout model should not be underestimated. Should the need to cut cost arise, there is always an option to reduce the scale of the project to about 4000 cars instead of 8200.

As the hydrogen FCV becomes the accepted transportation system, the cost to stakeholders is expected to diminish and approach a base price allowing manufacturers to recognize profits and returns on their initial investments. The exact timeline as to when these returns will be recognized cannot be determined since there are still many hindrances to overcome. Based on current data, and assuming current trends in technological improvement continue, it is realistic to expect that the transition will occur. However from the models developed it is safe to state that the rates of cost decrease will be dependent upon the number of units produced with a technology that allows for low-cost manufacturing.

Assuming that the hindrances are overcome and the FCV technology finally matures, manufacturers can expect to reap high profits from cost mark-ups. With greater economies of scale from standardized chassis design, decreased costs of fuel stacks and increased efficiency of the stacks, the auto industry is set for a change from the current capital-intensive structure. (Burns, 2001, [42]) However, as with all mature technologies these profits will only be recognized for a while, and another cycle of investment will be required after a period. The plants built or refurbished to accommodate the FCV introduction will need to be upgraded to accommodate faster production rates and newer technologies to prevent the cost of these vehicles increasing exponentially.

For the FCV to successfully compete with similar transportation systems in the future there must be continued investment with the objective of improving the primary component systems especially with the intent of developing a fuel cell system less dependent upon precious metals and a storage system that assures customers of more than a 300 mile range.

In considering long-term issues, we have built an extensive hydrogen transition world model to project future personal vehicle trends such as the number of vehicles, the use of energy or the emission of carbon dioxide. The results have shown that a baseline scenario, where both the FCV and the renewable energy transitions start in 2020 and last 30 years, would not violate the world oil reserves constraint and permit a quick decrease in the emission of carbon dioxide from personal vehicles. Our model shows that known oil reserves are expected to last until 2070. This is further incentive for us to start the transition before it is too late. A renewable energy transition fueled by solar hydrogen has been considered and a first analysis at a continental level demonstrates its feasibility. This is contingent on a substantial investment from industry and/or the government. The indicators already in the model database include data on land area and electricity production time series for all countries which can be useful when analyzing the future production of solar hydrogen. Further studies of the model would probably be worth conducting at a regional or national level in order to get a more detailed analysis of the hydrogen transition.

Our group has analyzed the near-term production issues, long-term environmental concerns and a rollout plan to bring about a hydrogen-based transportation system. We have discussed the potential upsides and downsides that must be considered if the transition is going to take place. Given the slow, but increasing, momentum for a transition to a hydrogen economy, and Congress' pledge of $1.2 billion over the next five years for the FreedomCAR initiative, a future that comprises a hydrogen-based transportation system looks promising.

Recommendations

The teams also came up with some recommendations for future work on such issues. Some of these are already mentioned in the conclusion and others are mentioned below:

1. Possible construction or implementation of a hydrogen delivery network if hydrogen is produced at a centralized location
2. The various marketing and advertising costs of the pilot project
3. The advertising strategy and how best to identify participants
4. A more detailed justification on the time length and magnitude of the pilot project
5. A graphical output for the computer simulation of the pilot project
6. Study the specific role of the industry: in what areas will they be involved and quantify the associated costs

7. Start working on the organization structure of the pilot project administration team

8. Further research in safety concerns and unification of standards and codes

9. Investigations on large-scale H2 sourcing

10. Concurrent investment in both infrastructure and vehicles to be continued

11. Continued research on catalyst (platinum) alternatives for fuel cells

Appendix A

CD Index

1. Final Report [PDF] [PS]
2. Final Presentation [PPT]
3. Files Team 1:
   - Balance of System Cost Model [XLS]
   - FCV and Component Cost Model [XLS]
4. Files Team 2:
   - 2010 Cost Model [XLS]
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5. Files Team 3:
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Appendix B

Gantt Chart and Resource Allocation for the Design of a Fuel Station

Both the Gantt chart and the resource allocation chart can be found on the following 3 pages.

Appendix C

Triangular Distribution for Transitions

When modeling the future transitions of vehicle type and vehicle energy source one likes to be able to model the start time, end time and rate of transition during the transition period. Before the transition of vehicle, for example, majority of vehicles should be of type ICE but after the transition majority should be of type FCV. It looks sensible to try some standard statistic distribution to model the proportion of FCV of the total vehicle fleet. The proportion is low in the beginning but gradually increases during the transition and finally reaching a value close to 1 at the end just as a distribution function. For the following reasons we decided to use a triangular distribution function:

1. The distribution is known on a close form
2. It has a simple density but is still precise enough for our purpose
3. The shape of the density can easily be adjusted
4. It is finite making validation of results easier
5. Is easy to program as no distributions are available in Access

The main drawback of using a triangular distribution is that the density function is not smooth. The transition starts at defined time point at a linearly increasing rate and goes on until the peak rate is reached. Then the rate declines linearly and finally the transition ends as suddenly as it started. Of course other distribution could be used instead of the triangular distribution to model the transition. A set of distribution could be defined requiring the user to select the desired distribution for each transition and appropriate distribution parameters.

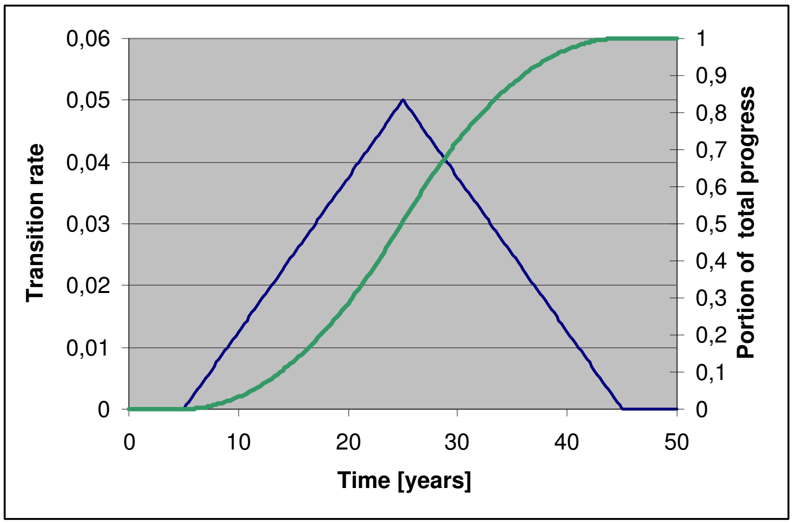

Figure C.1: The distribution function of triangular shape used for modelling both transitions

Figure C.1 shows what this function looks like. The triangular shaped function shows the rate of change, while the S-shaped function shows the actual level the transition has reached over time. In this example, the transition starts in the year 2005, reaches its peak in 2010 and is over in 2015. In the current version of our models it is assumed that the distribution is symmetric. This assumption can be released with minor effort but would require an additional input parameter from user to locate the peak of the density. The density of the symmetric triangular distribution is as follows (Law and Kelton, 1991, [52]):

$$l(t) = \begin{cases} (t-a)\left(\frac{2}{b-a}\right)^2 & \text{if} \quad a \le t \le \frac{a+b}{2} \\ (b-t)\left(\frac{2}{b-a}\right)^2 & \text{if} \quad \frac{a+b}{2} \le t \le b \\ 0 & \text{otherwise} \end{cases}$$

and the distribution is

$$L(t) = \begin{cases} 0 & \text{if} \quad t < a \\ 2 \cdot \left(\frac{t-a}{b-a}\right)^2 & \text{if} \quad a \le t \le \frac{a+b}{2} \\ 1 - 2 \cdot \left(\frac{b-t}{b-a}\right)^2 & \text{if} \quad \frac{a+b}{2} \le t \le b \\ 1 & \text{if} \quad t > b \end{cases}$$

The parameters a and b are recognized in this context as the start- and end year of transition respectively. In the case of symmetric density the peak rate is at $\frac{a+b}{2}$ and the duration of the transition is $(b-a)$.

Appendix D

Tables of Regions and Indicators

Following are two complete tables describing some features of the database: a table assigning regions to continents and a table describing all the indicators appearing in the database.

Region belonging to this	Continent
EASTERN AFRICA	Africa
MIDDLE AFRICA	Africa
NORTHERN AFRICA	Africa
WESTERN AFRICA	Africa
SOUTHERN AFRICA	Africa
SOUTH CENTRAL ASIA	Asia
SOUTHEAST ASIA	Asia
WESTERN ASIA	Asia
OCEANIA	Oceania
CARIBBEAN	South-America
CENTRAL AMERICA	South-America
SOUTH AMERICA	South-America
NORTH AMERICA	North-America
NORTHERN EUROPE	Europe
SOUTHERN EUROPE	Europe
WESTERN EUROPE	Europe
EASTERN EUROPE	Europe

Table D.1: An overview of continents and regions in the database

Name	Description
CountryName	Country name
CountryCode	Country code
Year	Year
RecType	Type of record
VMT	Vehicle Miles Travelled past data
VKT	Vehicle Kilometers Travelled past data
ForPop	Past and forecasted population data from WB
ForGdpCap	Forecasted GDP per capita
ForGdp	Forecasted GDP
ForVkt	Forecasted VKT
AG.LND.TOTL.K2	Land area (sq km)
AG.SRF.TOTL.K2	Surface area (sq km)
EG.EGY.PROD.KT.OE	Commercial energy production (kt of oil equivalent)
EG.ELC.COAL.ZS	Electricity production from coal sources (% of total)
EG.ELC.HYRO.ZS	Electricity production from hydroelectric sources (% of total)
EG.ELC.LOSS.ZS	Electric power transmis. and distribution losses (% of output)
EG.ELC.NGAS.ZS	Electricity production from natural gas sources (% of total)
EG.ELC.NUCL.ZS	Electricity production from nuclear sources (% of total)
EG.ELC.PETR.ZS	Electricity production from oil sources (% of total)
EG.ELC.PROD.KH	Electricity production (kwh)
EG.GDP.PUSE.KO.PP	GDP per unit of energy use (PPP $ per kg of oil equivalent)
EG.IMP.CONS.ZS	Energy imports, net (% of commercial energy use)
EG.USE.COMM.KT.OE	Commercial energy use (kt of oil equivalent)
EG.USE.ELEC.KH.PC	Electric power consumption (kwh per capita)
EG.USE.PCAP.KG.OE	Commercial energy use (kg of oil equivalent per capita)
EN.ATM.CO2E.KD.GD	CO2 emissions (kg per 1995 US$ of GDP)
EN.ATM.CO2E.PC	CO2 emissions (metric tons per capita)
IS.ROD.GOOD.MT.K6	Roads, goods transported (million ton-km)
IS.ROD.PAVE.ZS	Roads, paved (% of total roads)
IS.ROD.TOTL.KM	Roads, total network (km)
IS.VEH.NVEH.P3	Vehicles (per 1,000 people)
IS.VEH.PCAR.P3	Passenger cars (per 1,000 people)
IS.VEH.ROAD.K1	Vehicles (per km of road)
NY.ADJ.DCO2.GN.ZS	Adjusted savings: carbon dioxide damage (% of GNI)
NY.ADJ.DNGY.GN.ZS	Adjusted savings: energy depletion (% of GNI)
NY.ADJ.DPEM.GN.ZS	Adjusted savings: particulate emissions damage (% of GNI)
NY.GDP.MKTP.CD	GDP (current US$)
NY.GDP.MKTP.KD	GDP (constant 1995 US$)
NY.GDP.MKTP.KD.ZG	GDP growth (annual %)
NY.GDP.PCAP.KD	GDP per capita (constant 1995 US$)
SP.POP.TOTL	Population, total
SP.RUR.TOTL	Rural population
SP.URB.TOTL	Urban population
TM.VAL.FUEL.ZS.UN	Fuel imports (% of merchandise imports)
TX.VAL.FUEL.ZS.UN	Fuel exports (% of merchandise exports)

Table D.2: The full list of indicators included in the database

Appendix E

Calculations of Percentage of Carbon Emissions by Passenger Vehicles

E.1 Transportation Compared to Total Energy Emissions

The following figure shows calculations for the proportion of carbon emissions in transportation compared to overall anthropogenic emissions. It is based on data by the Environmental Protection Agency of the United States (EPA, 2003, [106]).

CO2 emissions in transportation		
from petroleum	1747 [Tg CO2 Eq.]	
from NG	33,9 [Tg CO2 Eq.]	percentage of emissions from
Total from transportation	1780,9 [Tg CO2 Eq.]	transportation to total energy
		31,72 %
total emissions due to energy	5614,9 [Tg CO2 Eq.]	
emissions due to energy compared to all emissions		85,50%
transportation compared to all emissions		**27,12 %**

Figure E.1: Calculations and data for evaluating the proportion of Carbon emissions in transportation for passenger vehicles

E.2 Passenger Vehicle Transportation Compared to Total Transportation

The following figure shows calculations for the proportion of carbon emissions in transportation for passenger vehicles based on data from the Czech Republic Transport Yearbook (1998, [105]).

	1997	1998
Total	10.163.400	10.376.600
Individual road passenger transport	4.633.800	4.753.300
Public road passenger transport	156.100	223.400
Road freight transport	4590000	4 628 600
MHD - buses	148100	143 900
proportion passenger/total	**0,486335013**	**0,487557953**

Figure E.2: Calculations and data for evaluating the proportion of Carbon emissions in transportation for passenger vehicles.

Appendix F

Pilot Project Appendix

This section lists relevant raw data from the 2001 National Household Travel Survey and 2001 Statistical Abstract of the United States and presents the derived data obtained from them.

F.1 2001 National Household Travel Survey

Type of trips Type of trips	Total trips (rounded to nearest billion)	Total miles (rounded to nearest billion)
All person trips	411	4012
Person trips by PV	356	3552
Vehicle trips	235	2298

Table F.1: Table 2 - Total Daily Trips and Total Miles Traveled in Daily Trips

	Mean	SE
All persons	4.1	0.02
Driver status*		
Yes, a driver	4.5	0.02
Not a driver	2.6	0.04

Table F.2: Table A-9 - Mean Number of Trips by All Persons by Sex, Age, Driver Status, Worker Status and Medical Condition

	Percent	SE
Work	14.8	0.12
Work-related	2.9	0.08
Family/personal business	44.6	0.22
School/church	9.8	0.11
Social/recreational	27.1	0.21
Other	0.8	0.03

Table F.3: Table A-11 - Distribution of Trips by Trip Purpose, in Percent

Trip start time	Percent	SE	Trip start time	Percent	SE
Midnight-1 a.m.	0.4	0.02	12 - 1 p.m.	7.4	0.08
1 - 2 a.m.	0.2	0.01	1 - 2 p.m.	6.6	0.07
2 -3 a.m.	0.2	0.01	2 - 3 p.m.	7.3	0.09
3 - 4 a.m.	0.1	0.01	3 - 4 p.m.	8.3	0.09
4 - 5 a.m.	0.4	0.02	4 - 5 p.m.	7.8	0.08
5 - 6 a.m.	1	0.03	5 - 6 p.m.	7.9	0.09
6 - 7 a.m.	2.6	0.05	6 - 7 p.m.	6.7	0.09
7 - 8 a.m.	6.2	0.08	7 - 8 p.m.	5.2	0.08
8 - 9 a.m.	5.5	0.08	8 - 9 p.m.	3.9	0.07
9 - 10 a.m.	4.9	0.07	9 - 10 p.m.	2.8	0.06
10 - 11 a.m.	5.9	0.08	10 - 11 p.m.	1.6	0.05
11 a.m. - 12 p.m.	6.6	0.08	11 - 12 p.m.	0.9	0.03

Table F.4: Table A-12 - Distribution of Trips by Time of Day, in Percent

	Percent	SE
Sunday	12.9	0.16
Monday	13.8	0.16
Tuesday	14	0.15
Wednesday	14.7	0.16
Thursday	14.6	0.15
Friday	15.6	0.17
Saturday	14.5	0.18

Table F.5: Table A-13 - Distribution of Daily Trips by Day of the Week, in Percent

	Minutes	SE	Miles	SE
All persons 15 and older	55.1	0.39	29.1	0.31
Sex				
Male	67.3	0.61	37.6	0.5
Female	43.8	0.41	21.2	0.28
Age				
15-19 years	24.6	0.91	12.2	0.51
20-24 years	51.7	1.48	28.9	1.21
25-54 years	64.1	0.58	35	0.48
55-64 years	57.7	0.9	29.7	0.61
65 years and older	39.3	0.76	17	0.45
Worker status				
Employed	65.1	0.51	35.5	0.41
Not employed	34.5	0.48	16	0.33

Table F.6: Table A-16 - Minutes Spent Driving Daily by Persons 15 and Older by Sex, Age and Worker Status and Table A-17 - Miles Driven Daily Persons 15 and Older by Sex, Age and Worker Status

	Total trips (Millions)	SE	Median miles	SE	Total miles (Millions)	SE
Personal vehicle	2336.1	36.89	194	3	760324.7	11695.33
Air	193.3	6.28	2068	45	557609.3	25375.76
Bus	55.4	3.45	287	20	27081.3	3048.33
Train	21.1	2.88	192	26	10546	1998.44
Other	5.8	1.45	188	48	5117.9	1123.89
Total	2611.7	37.7	210	3	1360679.1	28295.42

Table F.7: Table A-22 - Long-Distance Trips and Trip Miles by Mode, in Millions

	Percent	SE
Commute	12.7	0.83
Business	15.9	0.5
Pleasure	55.5	0.76
Personal Business	12.6	0.41
Other	3.4	0.2

Table F.8: Table A-24a - Long-Distance Trips by Purpose, in Percent

	Commute		Business		Pleasure		Pers. Business		Other	
	Percent	SE	Percent	SE	Percent	SE	Percent	SE	Percent	SE
Pers. vehicle	96.4	0.79	79.3	1.08	90.4	0.36	89.3	0.71	96.6	0.83
Air	1.5	0.35	17.8	0.94	6.7	0.29	4.7	0.44	1.9	0.64
Bus	0.5	0.25	0.8	0.25	2.2	0.19	5.6	0.53	0.5	0.25
Train	1.7	0.69	1.6	0.37	0.5	0.08	0.3	0.13	0	0.04
Other	0	0	0.5	0.28	0.2	0.04	0.1	0.05	1	0.53

Table F.9: Table A-24b - Long-Distance Trips by Mode and Purpose, in Percent

	Trips (Percent)	SE	Miles (Percent)	SE
International	2.2	0.15	16.4	1.29
Different region	10.9	0.36	33.3	0.98
Different state. different division. same region	7.5	0.29	9.9	0.42
Different state. same division	17	0.49	13.8	0.53
Same state	62.4	0.63	26.7	0.67

Table F.10: Table A-25 - Long-Distance Trips and Miles by Destination, in Percent

Division: The classification is derived from the household's home address and is based on the 2000 Census definitions. The nine categories are:

New England (ME, NH, VT, CT, MA, RI)
Mid-Atlantic (NY, NJ, PA)
East North Central (IL, IN, MI, OH, WI)
West North Central (IA, KS, MO, MN, ND, NE, SD)
South Atlantic (DC, DE, FL, GA, MD, NC, SC, WV, VA)
East South Central (AL, KY, MS, TN)
West South Central (AR, LA, OK, TX)
Mountain (AZ, CO, ID, MT, NM, NV, UT, WY)
Pacific (AK, CA, HI, OR, WA)

Region: The classification is derived from the household's home address and is based on the 2000 Census definitions. The four categories are:

Northeast (CT, MA, ME, NH, NJ, NY, PA, RI, VT)
Midwest (IA, IL, IN, KS, MI, MO, MN, ND, NE, OH, SD, WI)
South (AL, AR, DC, DE, FL, GA, KY, LA, MD, MS, NC, OK, SC, TN, TX, WV, VA)
West (AK, AZ, CA, CO, HI, ID, MT, NM, NV, OR, UT, WA, WY)

F.2 2001 Statistical Abstract of the United States

Daily vehicle trips per household (1995)	6.36
Average vehicle trip length (1995)	9.06
Average annual vehicle trips per household (1995)	2321
Home to work	553
Shopping	501
Other family or personal business	626
Social and recreational	427
Average vehicle trip length (1995)	9.06
Home to work	11.8
Shopping	5.64
Other family or personal business	6.93
Social and recreational	11.24

Table F.11: from Table No. 1091 – National Personal Transportation Survey (NPTS) — Summary of Travel Trends:1969 to 1995

F.3 Derived Data

	Miles	Percent	Distance
Work	2269	14.8	11.8
Work-related	445	2.9	11.8
Family/personal business	4015	44.6	6.93
School/church	1153	9.8	9.06
Social/recreational	3957	27.1	11.24
Other	94	0.8	9.06
Total	11933		

Table F.12: Table Der-1 - Per-person vehicle miles driven annually by trip purpose From the site below, 1,500 trips per person per year are estimated given 411 billion total daily person trips (table 2). This yields approximately the population of the United States, 274 million. Using this population and the total daily personal vehicle trips by person (table 2), we obtain 1,299 vehicle trips per person per year. This is combined with the percentage of trips by purpose (table A-11) and average vehicle trip length (table 1091) to obtain the miles per trip by purpose. (http://www.bts.gov)

	Miles	Percent	Distance
Work	2620	14.8	11.8
Work-related	513	2.9	11.8
Family/personal business	4636	44.6	6.93
School/church	1332	9.8	9.06
Social/recreational	4569	27.1	11.24
Other	109	0.8	9.06
Total	13779		

Table F.13: Table Der-2 - Person miles driven annually by trip purpose Same as for vehicle miles driven annually per person by purpose except using 1,500 trips per person rather than 1,299 trips per vehicle.

	Percent
Work	19
Work-related	3.7
Family/personal business	33.6
School/church	9.7
Social/recreational	33.2
Other	0.8

Table F.14: Table Der-3 - Percentage miles driven annually by trip purpose Uses the numbers above for annual VMT by purpose

	Trips (millions)	Percent of Trips
Commute	319.7	13.7
Business	329.3	14.1
Pleasure	1310.3	56
Personal Business	293.9	12.6
Other	85.8	3.7
Total	2339	100

Table F.15: Table Der-4 - Number of trips and miles driven annually by personal vehicles in long-distance trips and percentage of all long-distance trips. Combines total personal vehicle trips and miles (table A-22), percentage of all long-distance trips by purpose (table A-24a) and percentage of long-distance trips by mode and purpose (table A-24b).

	Percent of Trips	# Trips	Percent of Miles	# Miles
Long-distance	0.65	8.45	21.4	2774.2

Table F.16: Table Der-5 - Long-distance trips and miles and as percentage of all trips Compares total long-distance trips and miles (table A-22) with total daily trips and miles (table 2). Assumes the sum of these represent all trips and miles traveled. Assumes long-distance trips are vehicle trips and person trips by personal vehicle from daily trip stats correspond to this.

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