A System Dynamics Exploration of Future Automotive Propulsion Regimes

by

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Bachelor of Science in Chemical Engineering, Texas A&M University, 1996
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Submitted to the Sloan School of Management and the Department of Chemical Engineering
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Management

and

Master of Science in Chemical Engineering

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Abstract

In the industrialized world, the automotive industry faces growing environmental regulation in the form of standards for local air pollutant emissions and fuel economy. Yet another target for regulation in the near future could be carbon dioxide, as its greenhouse gas behavior becomes increasingly linked to climate disturbances on a global scale. And as the automotive industry expands its operations to emerging markets with exponential population growth, the appropriateness of a crude oil-dependent internal combustion infrastructure may be called into question for reasons of fuel availability and price.

Out of concern for these developments, some auto companies are working to make the automobile more sustainable. A major part of their efforts involves pursuit of alternative propulsion systems in parallel with the evolving internal combustion engine. In this thesis, I explore how propulsion regimes might shift in the near term (ten-year) future using a set of scenarios generated with a system dynamics model. Moreover, in this way I test the usefulness of the system dynamics methodology for scenario creation.

While a variety of fuels can be used to power a given propulsion system, I limit this study to one fuel option per system. Four specific systems are considered: a gasoline internal combustion engine (ICE); a gasoline hybrid system that combines an ICE with an electric motor to conserve fuel; a battery electric vehicle (EV) charged regularly from the electricity grid; and a fuel cell electric vehicle (FCEV) that electrochemically converts hydrogen to electricity for propulsion.

I first examine the motivation and method for exploring future propulsion regimes, and then provide a technology assessment of propulsion attributes on the basis of existing studies. Next is a description of how these attributes can feed a system dynamics model to explore how technology demand might evolve in consideration of the relative presence of infrastructure, availability, and awareness for each propulsion option. Using this model, a set of three scenarios is created by adjusting model parameters and providing supporting rationale. Finally, I discuss strategic implications both of the scenarios themselves and of insights gleaned through the system dynamics modeling exercise.

Thesis Advisor: Charles H. Fine	Thesis Advisor: Jefferson W. Tester
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Table of Contents

List of Figures

List of Tables

List of Equations

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Chapter 1 Introduction

Automotive companies are struggling to address the transition toward more sustainable propulsion systems in the face of future uncertainties and a myriad of propulsion options. This thesis considers how automotive propulsion regimes might evolve and compete over the next ten years using a set of scenarios. A system dynamics model is developed to create and evaluate the scenarios. As part of this model, attributes of the propulsion systems are assessed on the basis of existing "well to wheel" or life cycle studies. The resulting scenarios can then be used to assess the robustness of alternative propulsion strategies.

The objective of this thesis is to introduce and test a methodology for exploring different propulsion scenarios. The question driving this exploration is: *How might propulsion regimes shift in the near term future?* The near term (e.g., ten-year) future is considered because it necessarily encompasses transitional issues in moving toward a sustainable automotive propulsion system. The propulsion regimes considered include the internal combustion engine (ICE) vehicle, hybrid ICE-electric vehicle, fuel cell electric vehicle (FCEV), and battery electric vehicle (EV). This introductory chapter provides the motivation and approach for exploring future propulsion regimes. In essence, I address *why* we are asking the question above.

1.1 Motivation

This section explores the motivation for addressing the question of how propulsion regimes might shift in the near term future. To begin, conceptual frameworks of sustainability and stakeholders are introduced. Then key concerns about energy supply, air pollution, and climate change are outlined. I conclude this section by taking a strategic perspective of an industry approach to sustainability.

1.1.1 Conceptual Frameworks

I introduce two conceptual frameworks to begin this motivation section. The sustainability framework provides insight into how a long-term vision (not just for propulsion systems but for the industry at large) might encompass ecological, social, and economic dimensions. The stakeholder framework illustrates the interconnections between actors addressing sustainability concerns of the automobile.

Sustainability Framework

The World Council on Economic Development (WCED 1987, p. 43) defines a sustainable society as one that "meets the needs of the present without compromising the ability of future generations to meet their own needs." The needs of this broad definition can be considered as three dimensions, which together comprise the "triple bottom line" of sustainability. These ecological, social, and economic needs are represented in Figure 1-1 below as overlapping circles. The central area where all three needs are simultaneously met constitutes the realm of sustainability. The arrows indicate that sustainability is not a static state, but rather one that can be expanded through efforts in innovation and education.

Figure 1-1. Interrelated Dimensions of Sustainability

Ecological needs must be met to sustain life on this planet. These needs are characterized by the interdependence of living organisms in an environment. Aspects of ecological needs include

- *Resource conservation*. For a sustainable ecosystem, natural resources are not depleted faster than they can be regenerated. For non-renewable resources, this means that they are not depleted faster than renewable alternatives can be substituted in their place.

- *Commons quality*. The quality of the commons, or shared space (such as air and water), is maintained or improved over time. The potential for climate change through carbon dioxide accumulation in the biosphere is an example of a threat to commons quality.
- *Biodiversity*. Biodiversity represents the total complexity of life, of organisms and their interactions. Biodiversity ensures continued possibilities for species adaptation and use in an uncertain world. Natural habitats are preserved to foster biodiversity.
- *Waste minimization*. Byproducts from production and consumption processes that threaten ecosystem health are mitigated through waste minimization and remediation. One means of reducing waste is to consider production systems as closed-loop, so that all outputs return to the system as inputs for other processes.

Social needs span both current and future generations. These needs include basic needs for survival, but span Maslow's hierarchy of needs[1] to include those needs that are non-material. Social needs encompass the following concepts:

- *Equity*. Both intra- and intergenerational equity are critical to satisfying social needs. This component spans nations as well as individuals, highlighting political differences. Ultimately this is equity of the opportunity to develop fully as human beings. Access to basic health and educational services are fundamental to the concept of equity.
- *Respect*. Both self-respect and respect for others are important elements of a sustainable society. This notion of respect also applies to other living things, and land and air quality. Social governance may play a part in establishing rules for respect and conflict resolution. Meaningful employment can also be a source of respect.

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[1] Maslow's hierarchy of needs postulates that basic needs are satisfied before ascending to satisfy higher-level, non-material needs. From the base of the hierarchy to the peak, these needs are: 1) Physiological needs for living; 2) Needs for safety and security; 3) Social needs for belonging and affection; 4) Esteem, or needs for respect and self-respect; and 5) Self-actualization, realization of human potential (Maslow 1968, 1999).

- *Belonging and affection*. This need is satisfied through association with groups. Work and family are key avenues for belonging and affection.
- *Cultural diversity*. This diversity spans gender, generation, religious and ethnic differences. Similar to the importance of biodiversity, cultural diversity fosters adaptability to change for humankind.

Economic needs encompass the production, distribution and consumption of the goods and services for humankind. In a material-constrained world, economics is the science of allocating scarce resources.

- *Efficiency*. Efficient utilization of natural, human, and financial resources. Using the minimum of time or resources necessary for effective satisfaction of life needs.
- *Profitability*. A positive "return on investment" or profitability ensures that wealth can be generated to liberate time and energy, thus propelling advancements in knowledge and innovation.
- *Distribution of wealth*. The profitability of an entity enables wealth distribution across time and space. The ability to distribute wealth in this manner is critical for sustainability.
- *Sufficient consumption*. Economic measures are frequently tied to consumption of goods and services. For sustainability, the notion of sufficient consumption is important. This means that we share goods and services sufficient for life, without hoarding at the expense of others.

Mobility Stakeholders

Figure 1-2 below illustrates the interdependence of stakeholders involved in influencing mobility choices. Insomuch as these relationships apply to automobiles, *Civil Society* consists of consumers, taxpayers, and activists, *Industry* consists of automobile manufacturers and energy providers, and *Government* consists of the federal, state, and city regulatory bodies that monitor and control externalities associated with automobile usage.

Civil Society influences *Industry* by means of demand through the purchase decision. *Industry* in turn influences *Government* decisions through alliances, funding, and corporate lobbying. *Government* then closes this inner loop by influencing *Civil Society* choices through usage regulations such as parking and registration fees, and through fuel taxes. *Civil Society* exercises influence on *Government* through political preferences and activism, and through the voting process. *Government* influence on *Industry* is apparent in the form of design regulations for emissions and safety, and mandates to sell a percentage of vehicles with certain emissions and fuel economy levels. Closing the outer loop, *Industry* influences the choices that *Civil Society* can make by controlling the supply of automobiles and complementary fuel infrastructure. Consumers can only choose from the selection that is made available.

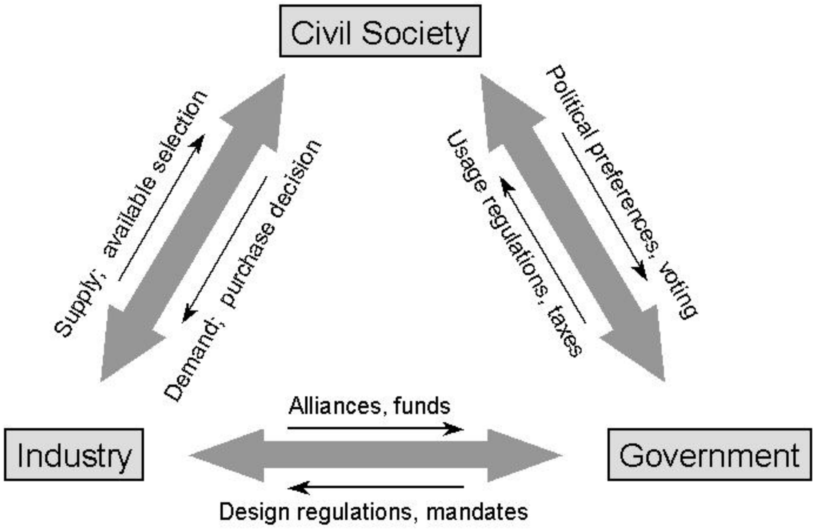

Figure 1-2. Mobility Stakeholders

The interdependencies illustrated in Figure 1-2 demonstrate that no one entity can control the evolution of mobility, or more specifically, the evolution of automotive propulsion systems. The government, civil society, and industry stakeholders act in concert to determine the shape of the future.

1.1.2 Current and Future Concerns

The current means of satisfying personal mobility through automobiles addresses many economic needs (e.g., timely access to work) and social needs (e.g., ability to meet with loved ones). The extent to which the automobile addresses ecological needs is more controversial. At the time automobiles were introduced, they dramatically reduced the pollution caused by horse manure in crowded cities. But additional problems have developed with the widespread use of conventional automobiles. Some of these problems cannot be addressed via alternative propulsion systems (e.g., congestion). In this section, I outline concerns that may be addressed through efforts in seeking sustainable propulsion systems. The extent to which alternatives can really alleviate these concerns is touched on in Chapter 2 as part of propulsion attributes.

Petroleum Supply

The concern with petroleum supply lies not so much whether there is enough, but how stable that supply is. It is certain that the supply is finite, and that demand for energy is increasing worldwide, driven to a large extent by automobile usage. However, it is not certain how much supply exists in many of the untapped oil reserves.

Conglomerates such as OPEC (Organization of Petroleum Exporting Countries) control much of the world’s current supply of petroleum. The United States is increasingly vulnerable to disruptions in this supply, as increasing fractions of the petroleum used domestically is imported. Instability in the Middle East (where OPEC is centered), such as that observed in the Persian Gulf war, can threaten the supply and thereby the price of petroleum. As the automotive industry expands its operations to emerging markets with exponential population, the appropriateness of a petroleum-dependent infrastructure may be called into question for reasons of both fuel availability and price.

In response to the concerns of petroleum supply are efforts toward resource conservation (via increased efficiency) and alternative fuels. Hydrogen as a fuel could become sustainable in the long term, existing in a closed loop of water to water. Hydrogen can power a variety of systems, including the internal combustion engine (ICE). However, it is most efficient to use hydrogen in a fuel cell, because the electrochemical energy conversion of the fuel cell does not face the thermodynamic limitations of a Carnot heat engine (See Chapter 2).

Air pollution

The combustion of hydrocarbon fuels like gasoline produces a variety of byproducts that contribute to urban air pollution. This air pollution is considered local because its negative effects result from the high localized concentration. Certain climates, particularly those in California, contribute to the formation of hazardous compounds in the air.

Although the emissions per mile from internal combustion engine vehicles have declined substantially over the past century, this improvement has coincided with ever-increasing vehicle usage, as measured by vehicle miles traveled per year. Regulatory bodies, particularly in California where the effects of air pollution are severe, have pushed for increasingly stringent standards on emissions. The internal combustion engine has continued to improve alongside the emissions standards, with improved catalytic converters that effectively render the pollutants harmless. However, the internal combustion engine cannot eliminate emissions altogether, even when combined with an electric motor and battery as in the hybrid form. These hybrids can lower air pollution substantially—the Toyota Prius currently on the market achieves SULEV (Super Ultra Low Emission Vehicle) status. Only electric vehicles fueled with energy from the electricity grid, or fueled through the electrochemical fuel cell process can achieve zero emissions during vehicle operation.

The externality costs of air pollution are investigated in Chapter 2. The extent to which these costs are internalized in the consumer choice depends largely on regulatory activity such as fee-bates. The uncertainty of such regulation makes it appropriate for scenario exploration.

Global Climate Change

The greenhouse effect is the phenomenon of “trapping” radiated energy as heat. Molecules such as CO_2, CH_4, N_2O, and H_2O act as greenhouse gases that can trap this energy. A critical concentration of greenhouse gases in the atmosphere enables the earth to remain warm enough support life. Yet recognized methods of analysis indicate that since 1750, the concentration of CO_2 in the atmosphere has risen by 31% to a level that has not been exceeded for at least 420,000 years and at a rate of increase that has been unprecedented for at least 20,000 years (IPCC 2001). While these specific numbers are far from absolute, the trend they represent cannot be ignored. Because automobiles and trucks contribute to a substantial portion (approximately one-third) of CO_2 emissions, the automotive industry has a vested interest in understanding and abating the concerns of climate change.

The increase in CO_2 concentration has coincided with increases in carbon emissions from fossil fuel burning that the industrial revolution has wrought. The CO_2 concentration depends both on these anthropogenic (human-caused) emissions and on natural emissions (e.g., plant decay and animal exhalation). This concentration increase can in turn increase the temperature on earth. While temperature data are more questionable than CO_2 concentration data, warming trends have been identified—over the past century, the average temperature rose by 0.6 degrees Celsius, a substantial increase in the documented history of climate change.

The Intergovernmental Panel on Climate Change notes in its most recent summary for policy makers that “There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities” (IPCC 2001). Sophisticated modeling techniques compare the many feedback mechanisms influencing climate change from both natural and anthropogenic sources, and illustrate that the observed rise in temperature matches with the anthropogenic factors.

Many nations representing diverse interests signed the Kyoto protocol in 1997 as a commitment to stabilizing the climate through reductions of CO_2 equivalent emissions. The agreed-upon limits were the 1990 levels. However, the Kyoto protocol has yet to come into force because details of the agreement have been controversial—and quite simply, difficult to achieve. The United States harbors concern that meeting the goals would cause a collapse in its energy-driven economy. In the meantime, CO_2 emission levels continue to increase, and CO_2 concentration in the atmosphere continues to grow exponentially.

1.1.3 Strategic Perspective

This section explores the strategic perspective surrounding the concerns and frameworks mentioned above. A potential leadership opportunity is first outlined, followed by a reflection on historical leadership domains in the automotive industry. This section concludes with brief commentary on the risks and benefits of leadership in the sustainability domain.

Leadership Opportunity

The concerns outlined in the previous section could either be perceived as a threat to the current way of doing business, or an opportunity to lead industry to a new state. Indeed, some (e.g., McDonough and Braungart 1998) postulate that the time has come for a sustainability revolution that could contain substantial opportunity for industry leadership. Interface Inc.[2], a carpet manufacturer, has become an unlikely hero in the sustainability movement. Having determined its vision of the sustainable enterprise, Interface created incentives to expand the sustainability domain by eliminating waste, investing in the community, and redefining its product as a service. While Interface still has a ways to go to get to its ideal state, it has clearly articulated the intention and means for attaining it. As such, the company serves as an inspiration to other companies in other industries that would like to move toward a more sustainable enterprise.

Automotive manufacturers have quite different concerns from carpet manufacturers. Unlike a carpet, the automobile continues to emit waste during operation. The automotive industry has been subject to a variety of regulations throughout its history. The extent to which automakers pursue the sustainable enterprise (including process and product) is uncertain. The company that creates a clear vision of what this sustainable automotive enterprise looks like may take advantage of a new leadership opportunity.

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[2] The Interface website http://www.interfaceinc.com/us/Company/ includes information about their efforts to move toward a "sustainable enterprise."

Historical Lessons in Automotive Leadership[3]

At the turn of the 20th century, there was not a clear leader in the automotive industry. Innovators, tinkerers, and dreamers in the United States and Europe developed a variety of cars for sporting events and elite enthusiasts. As cars were crafted to suit customers' needs, technologies varied. Wealthy women might prefer electric cars to quietly tour their grounds. Gasoline-powered internal combustion engines tended to be noisy and unwieldy, but their performance was hard to match in terms of speed, acceleration, and ability to traverse rough grounds.

Yet from this original state of the industry, leadership emerged. Below I outline three domains of automotive leadership that prevailed at different times in the 20th century.

1. Ford's mass availability

Henry Ford promised to "build a car for the great multitude" in 1907. He recognized the constraint to his business if cars were only targeted to the elite. By extending the scope of his product price to reach the pocket of the humble working man, Ford was able to dominate the automobile market and build a brand. His strategy was not without risk, however. Ford made the promise, knowing that through efficient production of critical volumes, the manufacturing cost could be driven down. But at the time of making that promise, demand was not seen at the lower income levels. Moreover, if too few cars were sold at the low prices, he might not recover his costs. In hindsight the decision seems perfectly reasonable, but there were many reasons both then and now, that companies would prefer to stay in premium-priced markets.

2. Sloan's customer connection

While Ford made great strides in making the automobile available, it was Alfred Sloan at General Motors who, in the late 1920's, developed the idea of a "car for every purse and purpose." Sloan recognized the role that consumer choice played, and capitalized on an ability to offer a wide variety of product platforms. Rather than

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[3] Much of the historical developments mentioned in this section were derived from the *Automotive News* series titled "American Automobile Centennial: 1896-1996."

innovating through process efficiency as Ford had, Sloan innovated through product variety. This became a new platform of leadership in the automotive industry.

3. <u>Toyota's mass flexibility</u>

In the early 1970's, many Americans became aware of Toyota's automobile offerings as efficient alternatives to American-made gas-guzzlers in a time of oil supply crisis. What made Toyota ultimately successful was not its fortuitous timing, but rather its process of manufacturing, a sort of mass flexibility system or "lean manufacturing." Taiichi Ono pioneered the Toyota Production System as a means of minimizing waste in production (material, energy, or temporal waste) and maximizing human resources. Two decades passed before the benefits of lean manufacturing were fully comprehended throughout the automotive industry (and beyond). The leadership edge that Toyota gained through its system of learning has not been lost.

Uncertain Risks and Benefits of Leadership

What will be the next domain of automotive leadership? Given the central role of the automobile in many of today's environmental concerns, leadership might involve innovation to expand the realm of sustainability as it applies to the automobile. In terms of Figure 1-1, this means extending the arrows around sustainability.

Drucker (1999) reflects on the so-called information revolution in the context of other revolutions like the industrial revolution and the printing revolution. The key to these revolutions, he claims, is not the generation of information, but the process standardization for information, industry, or printing that then enable a variety of unexpected businesses to emerge. For the automotive industry entering the sustainability domain, this might mean new services (e.g., car sharing) or new technologies (e.g., fuel cells) could come into play.

Businesses face tradeoffs in considering whether to lead or follow a new product or process concept. If they lead, they could either be very successful or could fall by the wayside. An understanding of timing issues, market acceptance, and the role of regulators is critical to choosing which path to take.

This understanding can be derived in part through an exploration of alternative futures, or scenarios. In this thesis, the scenarios focus on propulsion options as an example of the motivation to move toward sustainability. Many questions arise in the scenario modeling process that help to think through the appropriateness of alternative strategies.

1.2 Approach

As mentioned before, the objective of this thesis is to introduce and validate a methodology for exploring different propulsion scenarios. In this section, I introduce the project methodology, the modeling process, and the thesis structure.

1.2.1 Methodology

The project methodology illustrated in Figure 1-3 below was emergent rather than planned from the start. The framing step alone was critical: it took time to clarify the questions to be addressed. During this time I researched scenario processes and ultimately settled on a mix of both scenario planning and system dynamics approaches to address the question. Then an initial outline for the system dynamics model that would be used to create scenarios was formulated. With this model as a backbone, I set up a series of interviews to explore drivers of future propulsion regimes.

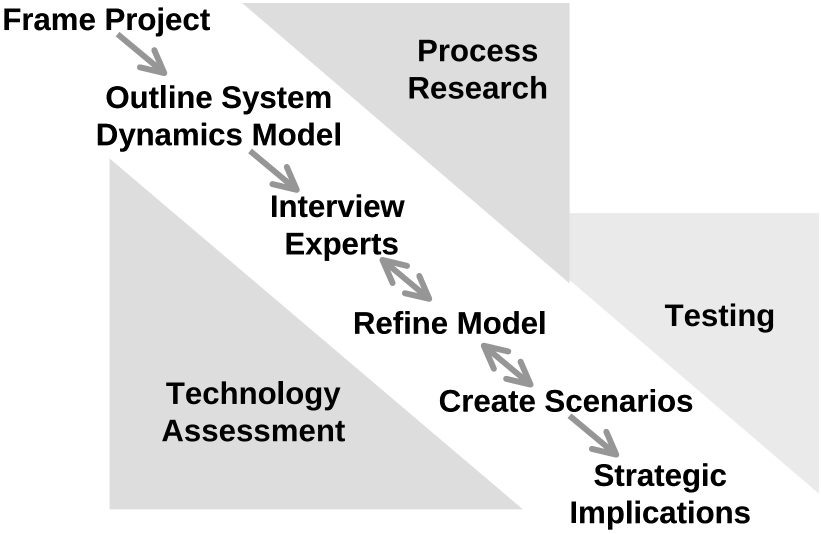

Figure 1-3. Project Methodology

Exploratory interviews were conducted with a wide variety of experts to gather insights about what to include in the system dynamics model. The interviewees' expertise ranged from specific technological backgrounds (e.g., fuel cells, electric propulsion, internal combustion) to perspectives on regulatory, competitive, and marketing issues. Regardless of their particular backgrounds, most interviewees were very receptive to thinking broadly about the future. The interviews were generally 1 ½ hour long. Most of the interviews conducted were one-on-one; however, some particularly fruitful sessions were conducted with two or three interviewees together. In these cases, the interviewees were already familiar with each other, and enhanced the discussion by extending each other's thoughts. Consult *Appendix A: Interview Guide* for examples of questions that were asked during interviews. In devising the interview structure, I consulted Van der Heijden (1996).

Major driving forces that emerged from the interview process are listed below:

- *Fuel price*. Will the government impose higher taxes to encourage use of alternative energy sources? Will the price increase because of supply volatility?
- *Fuel availability*. Will turbulence in the Middle East cause issues with oil supply? Will alternative fuels like hydrogen ever become convenient?
- *Environmental crises*. What more will we know about climate change in the next 10 years?
- *Regulation*. What sort of mandates might be imposed on the automotive industry? Will regulators design fee-bates to capture environmental damage costs?
- *Consumer value*. How will people consider the propulsion system in their purchase decision? Will they be concerned about environmental attributes that are not a major factor today?
- *Disruptive forces*. Will the automotive industry undergo a discontinuous disruption from an alternative technology? How might this disruption affect the economies of scale and established business models?

I refined the model while assimilating information from the interviews. My efforts at interviewing and refining the model were iterative, as indicated by the double arrow in Figure 1-3. Correspondingly, my efforts intensified in understanding and assessing the technologies (internal combustion engines, hybrids, fuel cells, and electric vehicles) to be considered as part of this work. After the interviews were complete, the scenario creation began. Scenario creation again was an iterative step with refining the model, as I learned more about the model by testing the scenarios.

1.2.2 Modeling

The value of modeling is two-fold: to generate results and provide a framework for understanding the system. Although the future propulsion scenario set is the official deliverable, the model in itself is particularly useful because the parameter assumptions and relationships are adjustable. Thus, in this thesis, I attempt to make the model assumptions and relationships as transparent as possible.

In addressing the question, *How might propulsion regimes shift in the near term future?*, I focus on insights rather than specific answers. Understanding the model structure is central to understanding model behavior. Because so much uncertainty exists in many of the assumed parameter values, much insight can be gleaned from understanding patterns of behavior, rather than specific percentages of market share at a particular time.

Figure 1-4 below outlines the system dynamics model structure developed to create the propulsion scenarios in this thesis. For each propulsion technology, demand (measured by technology market share) is determined by specific attributes of the technology and how these attributes are valued. Also, reinforcing feedback effects from the extent of fueling infrastructure, the availability of the technology in the marketplace, and consumer awareness of the technology influences this demand. Finally, each propulsion technology faces balancing feedback from competition with other propulsion technologies. For those new to the field of system dynamics, see *Appendix B: System Dynamics Basics* for an overview of types of feedback structures.

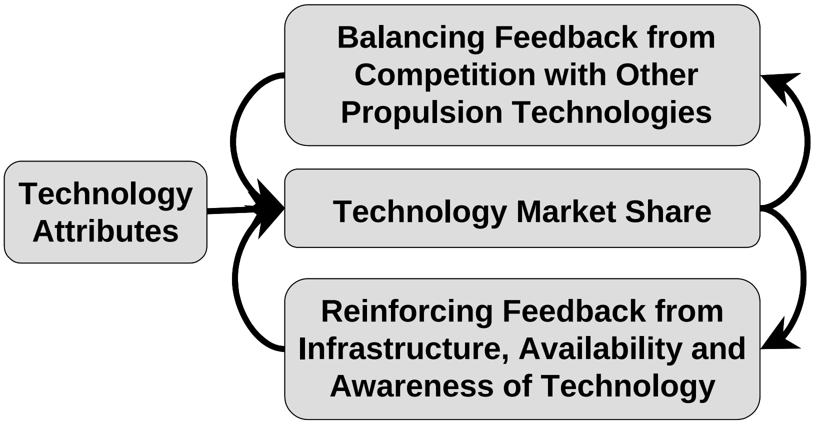

Figure 1-4. Outline of System Dynamics Model Structure

1.2.3 Structure of Thesis

The structure of this thesis reflects the development of the model and an attempt to address the question, *How might propulsion regimes shift in the near term future?* This introductory chapter has attempted to answer *Why are we asking this question?* through the project motivation, and open the question of *How can we explore different scenarios?* through the system dynamics methodology.

As part of the exploration, the questions *What propulsion options should we consider?* and *What attributes might they possess?* then arise. To ensure robustness of model input, Chapter 2 provides a technology assessment of the four selected propulsion systems (ICE, hybrid, fuel cell, and electric vehicle). The attributes assessed include environmental damages and their costs (e.g., local air pollution, net carbon dioxide emissions), operating costs (e.g., fuel type and usage, maintenance, insurance), capital cost, performance and range relative to an evolving internal combustion baseline. Estimates for these attributes are obtained from existing literature using a consistent comparison methodology and set of assumptions. Aspects of technologies such as relative maturity and reliability of the technology are not considered explicitly in this thesis, but are indirectly explored through sensitivity testing in Chapters 3 and 4 using aggregate sources of consumer value.

With this foundation, Chapter 3 explains how the technology attributes connect to consumer value formation. Beyond the attribute-determined value, other feedback effects such as infrastructure coverage, technology availability, and consumer awareness are explored. In this way the question of *What model structure is appropriate for exploration?* is addressed.

Chapter 4 explains how scenarios were created using the model. Scenario variables are selected as an attempt to address *What could cause propulsion regimes to shift*? and via simulation propose an answer to *What might the scenarios look like?* The scenario set is created from a range of conditions for the most critical uncertainties as determined by research, interviews and simulation. The scenario set spans a spectrum of possible outcomes at the ten-year horizon. Sensitivity testing is performed where appropriate for each scenario.

To conclude in Chapter 5 of this thesis, the strategic implications of the scenarios and the modeling process are considered. The questions of concern in the conclusion are *What can we learn from this process?* and *What are the implications for strategy?* I make recommendations for next steps (strategies and further modeling) and reflect on the effectiveness of using system dynamics to create scenarios.

Chapter 2 Technology Assessment

In this chapter I examine four different propulsion systems for application in the near term: internal combustion engine (ICE) vehicles, hybrid ICE – electric vehicles, fuel cell electric vehicles (FCEV), and battery electric vehicles (EV). These systems span a variety of specific propulsion architectures and fuels. For simplicity in the modeling efforts described in Chapter 3, one fuel/propulsion option is selected to represent each propulsion system. The rationale for system selection is provided in Sections 2.3 through 2.6 below, along with the attributes of those systems that are relevant to the consumer purchase decision.

This assessment of propulsion technologies begins by reviewing recent studies that compare such systems on different dimensions. With this foundation, I propose a set of attributes to characterize the propulsion systems as an input to the model described in Chapter 3. Following the description of these attributes, the propulsion systems are explored in more detail, including the current state of technology and possible paths of technology development in the near future, and outlining specific attribute levels for the selected fuel/propulsion systems. This chapter concludes with a summary that provides a side-by-side comparison of technologies and their role in the subsequent modeling work.

A Note on Numbers

The quantitative estimates presented throughout this chapter a) contain no more than three significant figures, b) are shown without confidence bounds, and c) draw from Weiss et al (2000) where possible. The literature from which the estimates were drawn often reported more significant figures, and these figures were retained in calculating attribute levels. For consistency and transparency, no more than three significant figures are reported here.

While no uncertainty bounds are demonstrated in this chapter for the baseline attribute calculations, uncertainty exists in every parameter examined, and naturally the alternative propulsion technologies contain greater uncertainty for attribute levels than the ICE technology. To retain as much simplicity and transparency as possible, I calculate attributes deterministically here. Once these attribute levels have been translated into consumer value, sensitivity tests are performed on the direct value to the consumer in Chapters 3 and 4 using the *Other Sources of Value* model parameter. In this way the effects of smaller variations can be considered in the context of the aggregated consumer value, enabling "bigger picture" insights from scenario modeling process.

While a variety of studies were consulted, the report by Weiss et al (2000) was selected as the primary source for determining attribute levels across the four propulsion systems. The rationale for this selection was to ensure a consistent comparison set. For example, an inconsistent comparison set might compare an advanced body hybrid to a conventional body ICE. For a given vehicle, one would not want to estimate a value for range from one source, and then estimate the fuel economy from a different source—so the source used must address all the attributes of interest. The Weiss et al (2000) report addresses the comprehensiveness of systems and attributes considered, with one exception—local air pollutant emissions are not estimated. As these estimates are necessary to determine environmental damage costs, I utilize Wang (1999) emission estimates for the same vehicles across the set of propulsion systems.

2.1 Literature Review

Several studies available in the literature compare automotive propulsion systems to elucidate what the real options are for sustainable propulsion. Many of these studies employ some form of a "well to wheels" or life cycle analysis to consider attributes such as energy efficiency, emissions, and cost over the entire fuel and/or vehicle cycle. Systems that appear to be optimal for one part of the life cycle may incur repercussions upstream of vehicle operation. For example, the battery electric vehicle that uses electricity from the conventional grid still emits greenhouse gases and local air pollutants at the power generation plant, though it qualifies as a Zero-Emissions Vehicle (ZEV) in terms of its clean vehicle operation.

As mentioned above, a recent study conducted by the MIT Energy Laboratory (Weiss et al 2000) explored a variety of vehicle options that could be available in the year 2020. The analysis utilized an "evolved baseline" of the conventional internal combustion engine by which to compare alternatives. This evolved baseline was used to avoid comparing future technologies to current conventions. The alternatives were then evaluated for energy consumption, greenhouse gas emission, and cost to consumer in consideration of both fuel and vehicle cycles. In the evaluation, effects from vehicle operation were simulated, while upstream fuel characteristics were determined from a cross-section of existing literature. Beyond the quantitative characteristics, impacts of the alternatives were considered for industry, government, and consumer stakeholders. Among its conclusions, the report noted that internal combustion improvements could be substantial, making the ICE a formidable incumbent for the alternatives to face. In terms of environmental sustainability, the hybrid ICE or fuel cell vehicles appeared most promising on the dimensions measured. As detailed later in this chapter, I utilize this study as much as possible to ensure consistent comparison of systems.

To facilitate comparisons across different studies, researchers at the Argonne National Laboratory have developed models to assess the emissions, energy use, and costs of transportation technologies given a set of assumptions (Wang 1999, Mintz et al 1994). In a recent report (Mintz et al 1999), these models are used to assess characteristics of vehicles meeting the tripled fuel economy (80 mpg) goal espoused by the Partnership for a New Generation of Vehicles (PNGV). Impacts of the tripled fuel economy vehicles were assessed at a fleet level over a 30-year horizon, with varied degrees of market penetration. The report concluded that the impact of high fuel economy performers on fleet emissions and energy consumption depended on the extent of market penetration. Hydrogen fuel cells showed the greatest potential for energy and emissions benefits, but at the largest costs. In contrast, fuel cells with methanol or gasoline reformers held more attractive benefit-to-cost ratios.

Taking a broad perspective in terms of both vehicle and fuel cycles, Lave et al (2000a, 2000b) performed life cycle assessments of alternative fuel/propulsion systems over a 20-year time horizon. The scope of this analysis went beyond the direct energy consumption in the fuel and vehicle manufacturing costs, to include elements further up the supply chain using Environmental Input-Output Life Cycle Analysis software (EIOLCA 1999). As a result of their analysis, the team concluded that the environmental benefits of alternative technologies such as fuel cells and hybrids would not offset their costs in the near term.

Focusing on energy efficiency, Brekken and Durbin (1998) compared the total energy required by alternative propulsion systems to perform the same amount of useful work. They assessed efficiencies in three stages: transportation and conversion of the source, efficiency in performing road work, and added energy needed to support the weight and operation of alternative vehicle components, assuming equal performance across vehicles. For the combined well-to-wheels efficiency, the authors provided a sensitivity analysis exploring parameters with the highest leverage for improvement. They concluded that when the total fuel cycle was considered, benefits of the alternatives were largely diminished.

Spanning the dimensions of sustainability, Thomas et al (1998) explored the extent to which alternative vehicles have a measurable societal cost benefit from environmental performance. Thomas et al then compared this benefit with the additional costs of making the vehicles available in the marketplace (e.g., manufacturing components and infrastructure requirements). After taking these considerations into account, the authors noted that the optimal solution depends on the objective sought, be it local emissions, greenhouse gas emissions, or vehicle cost. More specifically, they concluded that natural gas is a particularly attractive alternative to petroleum as a feedstock for either hybrid ICE-electric systems, or for hydrogen fuel cell vehicles.

Focusing on fuel cell prospects, Ogden, Steinbugler and Kreutz (1999) investigated the costs required for various types of fuel cells in infrastructure, vehicle components, and vehicle operation. In consideration of the full lifecycle costs, the authors concluded that hydrogen from natural gas appeared to be least costly fuel cell option. However, the transition to a hydrogen option was acknowledged to be far from straightforward. The authors explored scenarios illustrating alternative paths by which the ultimate “hydrogen economy” could be achieved.

The above-mentioned studies are a small sampling of the many recent and ongoing efforts to assess fuel/propulsion alternatives. The areas of greatest dispute involve the tremendous uncertainty that confronts not just technology development, but also its proliferation. Critical uncertainties involve the costs of technology and infrastructure development for alternative fuels. While many of the studies discuss the importance of market acceptance and regulation, these issues are largely left out of the determination of the “optimal” technology. In contrast, the goal of this work is *not* to determine the optimal or most sustainable technology, but rather to provide a sound relative comparison that will enter into the consumer’s decision.

2.2 Attributes Examined

In this section I consider what technology attributes differ substantially across propulsion regimes and thus could factor into different consumer purchase behavior. To focus on a comparison of vehicle propulsion systems, vehicle bodies are assumed to be the same across categories, congruent with the advanced body design examined by Weiss et al (2000). The attributes specific to propulsion system include environmental damage cost, operating cost, capital cost, performance, and range. In estimating these attributes, I draw from a variety of published sources.

The breadth of this work is such that it is difficult to determine values for all of these attributes using a single source. For example, Weiss et al (2000) provide an excellent comparison of costs and performance across propulsion systems but do not consider air pollution effects that would be included in an environmental damage cost assessment. Wang (1999) provides air pollution, energy usage, and greenhouse gas effects of alternative vehicles, but does not explicitly address capital costs. Where possible, estimates from Weiss et al (2000) are applied here for consistency across the set of options.

The following sections describe the general method used to assess attribute levels. This method is used in Sections 2.3 through 2.6 to assess attributes for each technology, which are then summarized in Section 2.7. Chapter 3 then explains how these attributes can translate into the consumer purchase decision.

2.2.1 Environmental Damage Costs

Environmental damage costs reflect the societal cost incurred from emissions of both local air pollutants and greenhouse gases. Assessing these costs are distinct from how costs are internalized by the consumer (an internalization fraction is considered as a scenario variable in Chapter 3). I undertake a two-step process of estimating the environmental damage cost: the first step is to determine what emissions levels are incurred over the lifetime of vehicle use, and the second step is to assign a value per unit mass of emission.

For local air pollutant emissions, I cite the default assumptions from long-term (model year 2010) options in the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model developed by Wang (1999). Though these emission levels were published along with specific fuel economy levels, I decouple this information so that fuel economy can be considered distinctly from local air pollutant emissions. Greenhouse gas emissions, however, will remain coupled to fuel economy, so that the reported fuel economy levels correspond to greenhouse gas emissions.

I utilize the greenhouse gas emission levels from the work of Weiss et al (2000), reported here in grams CO_2-equivalent per mile. CO_2-equivalency ensures that greenhouse gases other than CO_2 are considered for their potential climate-changing effects. CO_2-equivalency is determined for the 100-year time horizon, roughly the amount of time that a molecule of CO_2 remains in the atmosphere after its initial release. CH_4, also a greenhouse gas, can be expressed as a CO_2-equivalent by using a multiplier of 21, which corresponds to its greenhouse effect over the 100-year time horizon. Weiss et al (2000) consider the greenhouse gas effects of CO_2 and CH_4, but do not consider the effects of N_2O because it accounts for less than 1.5% of the total greenhouse contribution.

Thomas et al (1998) estimated the environmental damage cost from the lowest published “avoided costs” that would be incurred by utilities to reduce the pollutant by a unit mass. By comparison, Wang and Santini (1995) estimated the cost of air pollution both by assessing damage caused in terms of human health, and by estimating costs incurred to control the emissions. Rabl and Spadaro (2000) investigate environmental damage cost of air pollution via consideration of the public health impact of emissions.

Table 2-1 below contains the assumed environmental damage costs per unit mass (metric tonne) of pollutant. The first five pollutant costs were obtained from the median Wang and Santini (1995) estimates, adjusted to year 2000 values using the Consumer Price Index (CPI). The cost of greenhouse gas emissions (as CO2-equivalents) was determined from 1992 estimates by the Economic Research Associates, and again converted to year 2000 dollars (Peters et al 2000).

Table 2-1. Assumed Environmental Damage Costs of Emissions

Pollutant	Cost, $(2000)/$10^6$ g pollutant
Volatile Organic Compounds (VOC)	3700
Carbon Monoxide (CO)	2810
Oxides of Nitrogen (NOx)	7660
Particulate Matter ≤ 10μm (PM10)	4060
Oxides of Sulfur (SOx)	3660
Carbon Dioxide (CO2) equivalent	29

In sections 2.3 through 2.6 below, emissions in gram per mile are estimated for each propulsion system. These emissions are then multiplied by the costs illustrated in Table 2-1 above to determine the overall Environmental Damage Cost (EDC) for each propulsion system, using the following relationship:

Equation 2-1. Environmental Damage Cost

$$EDC = C * Emiss * VMT * Life$$

where

EDC = Environmental Damage Cost, in $/vehicle
C = Cost per unit mass emission, in $/g
$Emiss$ = Emissions, in g/mile
VMT = Vehicle Miles Traveled, in miles/vehicle-year
$Life$ = Average Vehicle Lifetime, in years

In the relationship described by Equation 2-1, no discount rate is imposed on future environmental damage costs. Vehicle Miles Traveled (VMT) are assumed to be constant at 12,000 miles/vehicle-year, and the Average Vehicle Lifetime (Life) is assumed to be 14 years (Davis 2000).

2.2.2 Operating Cost

Operating cost consists of both variable and fixed costs incurred from vehicle operation over time. Variable costs (e.g., fuel and maintenance cost) depend on the number of miles driven, while fixed costs (e.g., insurance) are specified for a period of time. The operating costs that would be expected to differ the most across propulsion regimes are variable fuel costs. These costs are in turn determined from fuel price, fuel economy, and vehicle miles traveled.

In 1999, automotive fuel costs in the United States averaged less than 10% of the total operating cost of the vehicle (Davis 2000), driven by extraordinarily low gasoline prices. While prices have risen more recently, much uncertainty remains about the future price and supply of the crude oil source, as well as the possibility of increased taxation. A gasoline fuel price of $1.22/gallon is utilized for the base case assumption, but this fuel price is also considered to be a "scenario variable" that can be adjusted (see Chapter 3). In this section we are concerned with fuel economy as the primary differentiator between propulsion regimes. Assumptions for the other components of operating cost are summarized in Table 2-2 below (from Davis 2000, adjusted using the Consumer Price Index). Depreciation and finance charges are excluded from fixed costs, as these costs will be considered as part of the capital cost and corresponding vehicle purchase price.

Table 2-2. Assumed Variable and Fixed Operating Cost Base

Variable Costs, $/mile		**Fixed Costs, $/year**	
Maintenance	0.0341	Insurance	1010
Tires	0.0176	Fees	233
Total	*0.0517*	*Total*	*1240*

In this section, fuel economy is considered on a "tank to wheel" or operating basis as would affect the consumer purchase decision. The fuel economy values determined by Weiss et al (2000) are utilized for advanced ICE, hybrid, fuel cell, and electric vehicles.

The calculated fuel economy depends on how the vehicle is driven. The drive cycle underlying the fuel economy values is the standard EPA Federal Testing Procedure (FTP) cycle, with a mix of 55% city and 45% highway driving. Weiss et al (2000) simulate the drive cycle by determining what amount of energy must be supplied to the wheels at any given moment via backwards calculation logic.

For ready comparison of fuel economy across different fuel/propulsion systems, fuel economy can be expressed as miles per gallon of gasoline equivalent. What does a "mile per gallon of gasoline equivalent" mean? This metric can be determined from drive cycle data. As a result of their drive cycle modeling, Weiss et al (2000) determine the fuel energy use in MJ/km for the vehicles considered. The lower heating value (LHV), or net heating value, for gasoline is 43.7 MJ/kg. This LHV represents the heat of combustion of one kilogram of gasoline that generates H2O vapor as a byproduct. The higher heating value (HHV), or gross heating value, can also be used to represent the heat of the same combustion and subsequent generation of H2O *liquid* as a byproduct (Heywood 1988). Conventionally, the LHV is used to represent the combustion process. The gasoline fuel density is 0.737 kg/L. With this information, the fuel consumption can be expressed as

Equation 2-2. Gasoline Equivalent Consumption

$$GEC = \frac{EnergyUse_{calc}}{LHV_{gasoline} * \rho_{gasoline}}$$

where

GEC = Gasoline Equivalent Consumption, in L/km

$EnergyUse_{calc}$ = Calculated fuel energy use from tank to wheel, in MJ/km

$LHV_{gasoline}$ = Lower Heating Value of gasoline, in MJ/kg

$\rho_{gasoline}$ = Density of gasoline, in kg/L

In the above equation, the calculated fuel energy use ($EnergyUse_{calc}$) is determined from the Weiss et al (2000) drive cycle simulation for each propulsion system. Fuel consumption can then be converted to fuel economy using the conversion factors of 3.7854 L/gallon and 1.6093 km/mile:

Equation 2-3. Gasoline Equivalent Fuel Economy

$$GEFE = \frac{3.7854}{1.6093 * GEC} = \frac{2.3522 * LHV_{gasoline} * \rho_{gasoline}}{EnergyUse_{calc}}$$

where

$GEFE$ = Gasoline Equivalent Fuel Economy, in miles/gallon

As demonstrated in Equation 2-3 above, fuel economy is inversely proportional to fuel consumption. This relationship is depicted graphically in Figure 2-1 below. While straightforward, the relationship between fuel economy and fuel consumption has important implications. A doubling of fuel economy results in a halving of fuel consumption. As fuel economy values increase, it takes more and more effort to reduce fuel consumption. For example, increasing the fuel economy from 10 mpg to 20 mpg doubles fuel economy and thus halves consumption. But an increase of 10-mpg fuel economy from 40 mpg to 50 mpg would not reduce consumption nearly as much, as evident in Figure 2-1 below.

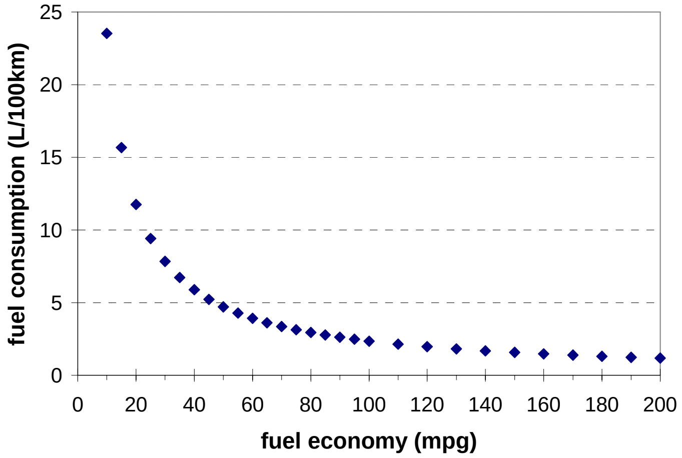

Figure 2-1. Relationship between fuel consumption and fuel economy

Fuel consumption asymptotically approaches zero for very large values of fuel economy, but the costs of achieving those fuel economy increases may be greater than the benefit of reduced fuel consumption (NRC 1992). Corporate Average Fuel Economy (CAFE) values reflect the importance of fuel consumption: when these values are calculated, the average is actually taken of fuel consumption, and then converted back into fuel economy terms.

After estimating values for fuel economy in miles per gallon (mpg) of gasoline equivalent, the next task is to determine fuel cost per gallon gasoline equivalent. First, a cost per unit energy delivered is derived from estimates for transportation and distribution of the fuel. I derive these cost estimates per unit energy from Weiss et al (2000). Again, the LHV and density of gasoline are used to convert these costs to a cost per gallon equivalent:

Equation 2-4. Cost per Gasoline Equivalent Gallon

$$CGEG = 3.7854 * CE * LHV_{gasoline} * \rho_{gasoline}$$

where

CE = Cost per unit energy ($/MJ)

$CGEG$ = Cost per Gasoline Equivalent Gallon, in $/gallon

The remaining terms are as defined previously: 3.7854 L/gallon, 43.7 MJ/kg LHV, and 0.737 kg/L density.

2.2.3 Capital Cost

The capital cost of alternative propulsion vehicles consists of two major parts: the cost of the propulsion system itself, and the cost of the rest of the vehicle. Here the propulsion system consists of the fuel tank, engine, electricity generator, motor, battery storage, transmission, and control system elements. For the baseline assumption, the "rest of the vehicle" cost remains the same across technologies. If, however, one were to compare an advanced body plus alternative propulsion system against a conventional body and propulsion system, one would have to look beyond propulsion systems for cost differences.

The vehicle capital cost, not including the propulsion system, is here assumed to be approximately $15,730 for all systems. This value is determined from Weiss et al (2000) for the advanced body design, including costs of reduced weight and aerodynamics, and adjusted to 2000 dollars using the Consumer Price Index.

Weiss et al (2000) and Thomas et al (1998) have investigated component costs of propulsion systems. These costs are assumed to be at mass-production levels and thus incorporate economies of scale. These levels do not, however, incorporate learning that can occur through production experience. As such, I do not treat them as minimum values. I do constrain learning from bringing costs lower than that of the comparable ICE technology. The assumption of learning curve can be readily "switched off" with a simple model parameter adjustment (Fractional Cost Reduction per Production Doubling), as described in Chapter 3.

2.2.4 Performance and Range

Performance of a vehicle depends on many factors—some technical, some subtler. Technical performance characteristics include the power-to-weight ratio (PWR) of the vehicle, acceleration (often characterized by the time it takes to accelerate from 0 to 60 mile per hour), and top speed. More subtle performance characteristics might include handling (how well a vehicle turns corners), hill-climbing ability, and reliability.

Because the assessment of vehicle performance encompasses subtle features as well as technical performance levels, I utilize performance as a "scenario variable" for the model described in Chapter 3 to explore technologies under different levels of capability.

Weiss et al (2000) held technical performance in PWR constant across vehicles at 75 Watt/kg. The component performances required to achieve this overall vehicle PWR are based on projections of technology development by the year 2020.

After standardizing vehicles to 75 Watt/kg PWR, Weiss et al (2000) estimate range based on the size of an energy storage unit (tank or battery) needed to supply the vehicle. To the extent possible, they attempt to keep range constant, but range varies with the fuel economy achieved over the specific drive cycle and thus varies over different vehicle systems. Indeed, the electric vehicle range is considerably less than range of the other vehicles.

I assume that a large negative range penalty exists for the electric vehicle. For the other vehicles, ranges are comparable to the baseline ICE system. The range level does not encompass the relative convenience of refueling, although this convenience may vary for vehicles that require longer refueling times.

2.3 Internal Combustion Engine Vehicle

The first propulsion technology I consider is the internal combustion engine (ICE). Internal combustion engine technology was developed in the 1860’s and first applied to automobiles in the late 1880’s (Heywood 1988). Since its initial inception, much development has improved the automotive ICE capability along many dimensions, making it a powerful incumbent for alternative propulsion systems to match. In this section, I describe an overview of the ICE and then discuss characteristics for the specific ICE technology selected for use in the model.

2.3.1 Internal Combustion Engine Overview

Figure 2-2 below illustrates a schematic of the internal combustion engine (ICE) vehicle. The black arrows indicate the flow of energy for propulsion. Energy flows in the form of fuel from the fuel tank to the heat engine, where the fuel is combusted to release energy in the form of heat. The expansion of gases during heat release of the combustion process forces piston movement in the engine, thus generating mechanical energy that is then translated into vehicle motion.

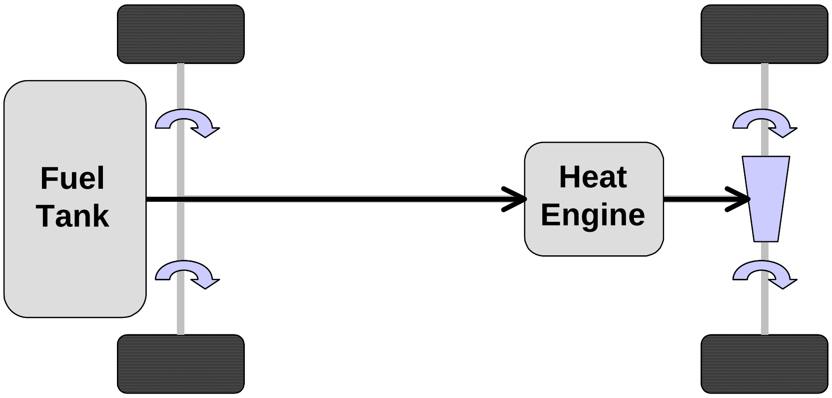

Figure 2-2. Schematic of ICE Vehicle

Internal combustion engines are generally classified by the means of combustion and the means of fuel injection. For combustion, the options are spark-ignition (usually gasoline) or compression-ignition (usually diesel). Conventional gasoline ICE technology mixes fuel with air prior to entering the combustion chamber. For future technologies, direct-injection of gasoline fuel into the combustion chamber is an attractive possibility, classified as spark-ignition direct-injection (SIDI). Diesel engines are often compression-ignition direct-injection (CIDI) technologies.

The ICE is an open cycle heat engine that produces work from heat in a cyclic process of compression and expansion through piston movement. Thermodynamically, the thermal efficiency of the engine, η, can be expressed in terms of Q_h and Q_c, the amount of heat absorbed by the engine from a hot reservoir and the amount of heat released to a cold reservoir, respectively. The thermal efficiency is always less than unity (100 percent) because real systems do not have Q_c of zero.

The theoretical limit for heat engines can be estimated using the reversible, closed-cycle Carnot process. For this cycle under ideal gas conditions, thermal efficiency can be expressed in terms of T_h and T_c, the temperature (in Kelvin) of the hot and cold reservoirs, respectively. These relationships are as follows (Tester and Modell 1997, p. 78):

Equation 2-5. Carnot Engine Thermal Efficiency

$$\eta_{Carnot} = 1 - \frac{|Q_c|}{|Q_h|} = 1 - \frac{T_c}{T_h}$$

For most heat engines, T_c is near 300 K and T_h is near 600 K, so that η_{Carnot} approximates 50% efficiency. However, real heat engines are not reversible, and normally have thermal efficiencies of less than 35% (Smith and Van Ness 1987). The actual ICE thermal efficiency would be determined from the ratio of actual work to maximum work, where the maximum work is proportional to the availability of fuel. To understand overall efficiency, one must take into account the volumetric and mechanical efficiency of the engine as well as the thermal efficiency (Heywood 1988). Mechanical losses often outweigh thermal losses, as mechanical efficiency is zero during idling. The ICE typically has an overall efficiency of 18% (Brekken and Durbin 1998) due to losses from its open cycle configuration.

The Carnot engine efficiency as described in the Equation 2-5 simply highlights the limitations that would be imposed on a heat engine if it were reversible and closed-cycle. This Carnot limit is often mentioned in educational literature for the fuel cell (e.g., Thomas and Zalbowitz 1999), noting that the fuel cell system is not constrained by this limit, because the fuel cell relies on an electrochemical energy conversion process rather than a heat to work energy transfer.

The standard fuel for the internal combustion engine is gasoline, which is in turn derived from crude oil (petroleum). While petroleum-derived fuels have the greatest energy density, a variety of fuels can be used in combustion. Diesel is another common petroleum-derived fuel used in compression-ignition direct injection (CIDI) internal combustion engines. In addition, alternatives such as Fisher-Tropsch diesel from natural gas, compressed natural gas, methanol, and hydrogen all have the potential for use in combustion. The fuel energy density is critical to consider for automobiles that can only store a limited quantity of fuel on board. I did not explore diesels because of the high emissions, although it is quite feasible that sufficient emission abatement mechanisms will be in place for diesels in the near term. To choose a single platform, I kept with gasoline, the most abundantly used fuel for the standard sedan vehicle.

A technical challenge of the ICE, despite its many advantages, is that it is limited by Carnot cycle, as mentioned above. Thus far, this limitation has been compensated for in other areas, so that we have high-performing ICE vehicles. In addition, as mentioned in the introductory chapter, the ICE cannot be a zero-emission vehicle during operation, although it may be an attractive technology over the fuel cycle. The advantages of incumbency and industry knowledge of the ICE are in its favor for continued improvement. Over the history of ICE domination for the past century or so, it has improved substantially in terms of efficiency and performance capability. Moreover, ICE vehicle can also be improved by looking beyond the propulsion system at the way the vehicle is integrated (e.g., advanced body design, aerodynamics). This continued improvement creates a moving target for alternative technologies to compete against.

2.3.2 Gasoline Internal Combustion Engine Attributes

In this section I apply the methods and equations discussed in section 2.2 to the ICE. The ICE system considered is a gasoline-fueled spark ignition direct injection (SIDI) engine with an advanced body.

Environmental Damage Costs

The local air pollutant emissions levels for the SIDI ICE are noted in Table 2-3 below, as determined from Wang (1999). The CO2-equivalent emissions are determined from Weiss et al (2000) for the advanced ICE SIDI vehicle.

Table 2-3. Emissions of Gasoline ICE Vehicle

Emissions (g/mile)	Upstream	Operation	Total
VOC	0.067	0.119	*0.186*
CO	0.118	2.76	*2.88*
NOx	0.141	0.036	*0.177*
PM10	0.013	0.035	*0.048*
SOx	0.062	0.006	*0.068*
CO2-equivalent	69.6	178	*248*

The emission levels in Table 2-3 are multiplied by the costs in Table 2-1 to yield an environmental damage cost per mile. The total environmental damage cost (EDC) is then determined according to Equation 2-1. The resulting environmental damage cost is described in Table 2-4 below, with a combined cost of 1.78 cents per mile, or $2980 over the vehicle life (14 years at 12,000 miles per vehicle-year).

Table 2-4. Environmental Damage Cost of Gasoline ICE Vehicle

Emission Source	Cost (cents/mile)	Total EDC ($/vehicle)
VOC	0.07	116
CO	0.81	1360
NOx	0.14	228
PM10	0.02	33
SOx	0.02	42
Local Air Pollutants	1.06	1780
CO2-equivalents	0.72	1210
Total	1.78	2980

Operating Cost

The operating cost of the gasoline SIDI ICE vehicle is determined according to the series of equations outlined in Section 2.2.2, from energy use of 1.543 MJ/km to a fuel economy of 49.1 mpg. This fuel economy is much higher than would be expected for current technology. I use this as a frame of reference to compare with the advanced technologies, under the same rationale that Weiss et al (2000) used for the evolved baseline. Here I am only interested in comparing propulsion systems, so I need to keep the vehicle body the same across technologies. Relative differences are what matter most in this work, not the absolute value.

This fuel economy is combined with the $1.22/gallon gasoline price to yield the variable fuel cost. The variable fuel cost is less than half as much as the other variable cost assumed, as demonstrated in Table 2-5 below. The total operating cost for the ICE is then determined to be $2157/year.

Table 2-5. Operating Cost of Gasoline ICE Vehicle

Operating Cost Component	Value
Energy Use (MJ/km)	1.54
Gasoline-Equivalent Consumption, GEC (L/100km)	4.79
Gasoline-Equivalent Fuel Economy, GEFE (miles/gallon)	49.1
Fuel Price ($/gallon)	1.22
Variable Cost from Fuel Use ($/mile)	0.0248
Other Variable Cost ($/mile)	0.0517
Total Variable Cost ($/mile)	0.0765
Yearly Variable Cost ($/year)	919
Fixed Cost ($/year)	1240
Total Operating Cost ($/year)	*2160*

Capital Cost

The capital cost for the ICE vehicle is determined from Weiss et al (2000), on the basis of component retail price increments. I have used these retail price increments as an indicator of capital cost, and have scaled the costs according to the Consumer Price Index. Table 2-6 below explicates the capital costs for the SIDI ICE. In sum, the component cost is $4770 and the total vehicle cost is $20,500 for the SIDI ICE.

Table 2-6. Capital Cost of Gasoline ICE Vehicle

Component	Cost ($/vehicle)
Base Powertrain	4280
Credit from Engine Downsizing	-380
Gasoline Direct Injection	396
Variable Valve Lift and Timing	238
Exhaust Treatment	238
Component Cost for Propulsion System	4770
Other Vehicle Cost	15700
Total Vehicle Cost	20500

Performance and Range

Performance and range for the gasoline SIDI ICE vehicle are again drawn from Weiss et al (2000). Table 2-7 provides some key parameters including vehicle mass, the power-to-weight ratio (which was standardized across platforms), and the resulting maximum engine power that could be obtained for that sedan size. I convert this power-to-weight ratio to a dimensionless relative performance level of 1, to which other systems can be compared. The range between refuelings is averaged for the urban and highway drive cycles according to the EPA FTP, and is 396 miles for the SIDI ICE.

Table 2-7. Performance and Range of Gasoline ICE Vehicle

Performance or Range Component	Value
Vehicle Mass (kg)	1140
Power:Weight Ratio, PWR (W/kg)	75
Maximum Engine Power (kW)	85.2
Relative Performance (dmnl)	1
Range Between Refuelings (miles)	396

2.4 Hybrid Internal Combustion Engine – Electric Vehicle

Beyond the pure ICE vehicle, the alternative propulsion systems considered all include some form of electric propulsion. This commonality has been noted as a potentially fundamental shift entering the 21st century (Amann 1999). Hybrid ICE-electric vehicles offer an opportunity to improve fuel economy via engine off during idle and regenerative braking. The basic system is a heat engine plus a battery. Hybrid systems are more complex than pure systems and thus employ sophisticated control systems.

Hybrids can be classified in many ways, including the configuration (as discussed below), and the distance they can run on electricity (which could be important for urban areas where a hybrid can camouflage as an EV). A spectrum of hybrids exists from a more electric and battery-intensive system to a supplement to the ICE (Botti and Miller 1999). In general, adding a battery and electric motor to the conventional ICE system can make substantial fuel economy and emission improvements.

In this section I provide an overview of hybrid propulsion systems and then outline the attributes specific to the gasoline-fueled hybrid SIDI ICE system selected for the modeling work in Chapter 3.

2.4.1 Hybrid ICE-Electric Vehicle Overview

The term "hybrid" literally can mean "something... having two kinds of components that produce the same or similar results (American Heritage Dictionary 2000)." As such, many types of hybrid propulsion systems can exist. Here, "hybrid" refers the specific contributions of an ICE heat engine and an electric motor providing propulsion power for the vehicle.

Figure 2-3 below illustrates a series hybrid configuration. The arrows represent energy flow: first, energy flows from the fuel tank to the heat (ICE) engine; then, instead of directly converting this heat energy into mechanical energy, it is converted into electricity using an electricity generator, before it passes either directly to the electric motor or to battery storage for later use. The electric motor provides mechanical energy for vehicle propulsion, and receives some energy from the regenerative braking process. The electric motor can redirect energy to the battery that is not needed for movement, and also draws electricity from the battery.

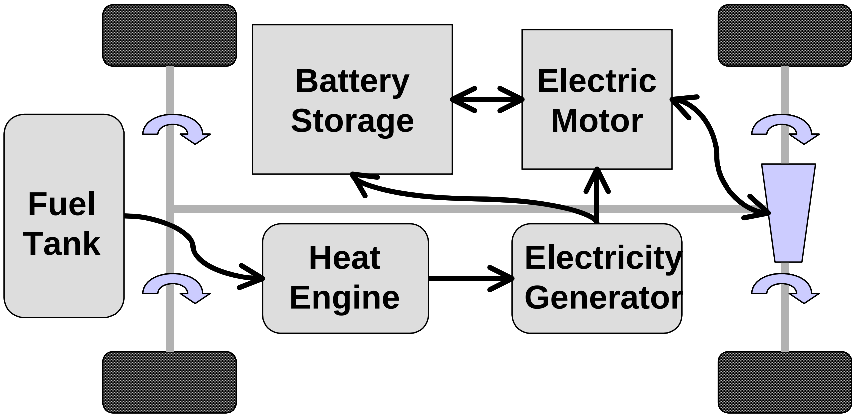

Figure 2-3. Schematic of Series Hybrid ICE Vehicle

In contrast to the series hybrid (Figure 2-3), the parallel hybrid illustrated in Figure 2-4 below can draw energy from either the electric motor or the heat engine for propulsion. Again, energy flow is illustrated with arrows: energy flows from the fuel tank to the heat engine, where it can directly propel the vehicle; also, energy flows between the wheels and the electric motor via regenerative braking; finally, energy can flow between the electric motor and the battery as needed. In a pure parallel hybrid, the electric motor does not run in isolation, but only when coupled with the heat engine.

Hybrids do not necessarily fall into the category of “series” or “parallel” as described above. For instance, the Toyota Prius currently (in year 2001) on the market has a parallel structure with an additional capability for the heat engine to power the electric motor directly. In other words, the Prius is neither parallel nor series—it has the capability to switch between parallel and series configurations through a sophisticated control system. Despite the many variations, understanding the basic configurations of series versus parallel hybrids provides a useful frame of reference for alternative configurations.

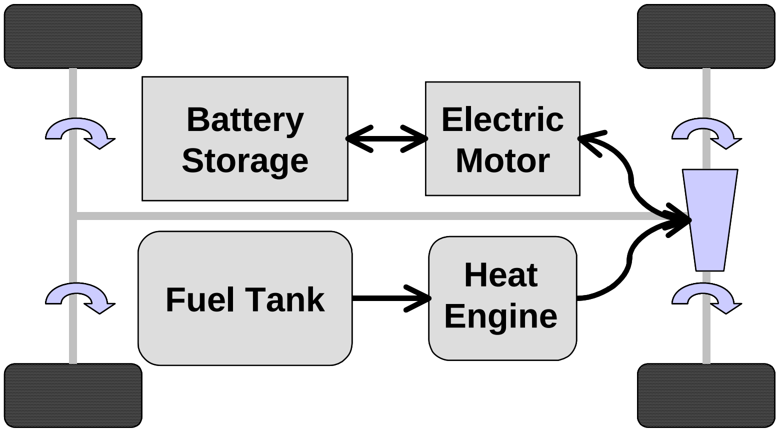

Figure 2-4. Schematic of Parallel Hybrid ICE Vehicle

The fuels for the hybrid propulsion system are the same as those used by the internal combustion engine—namely gasoline, diesel, compressed natural gas, and hydrogen. The relative advantages of these different fuels correspond with those of the ICE as well, so that diesels are most efficient but emit more local air pollution, compressed natural gas (CNG) emits the least greenhouse gases. Hydrogen and methanol are less efficient because they require additional upstream processing to be utilized in the fuel form.

For consistency with the baseline ICE assumptions, I use a spark-ignition direct injection (SIDI) fueled by gasoline as the ICE component of the hybrid system for the modeling work in this thesis.

Hybrid systems face the challenge of inherent complexity that results from combining electric propulsion capability with an ICE. Depending on the particular hybrid configuration, performance issues may come into play. For instance, the partial reliance on a battery may limit the vehicle’s capability for accelerating quickly or ascending a hill. The addition of the battery and the control system also adds substantial cost.

Opportunities exist for hybrids to penetrate the market because the fuel infrastructure is already present. When gasoline prices are higher, the added efficiency of the hybrid system can work in its favor, as the hybrid can shut the motor off when idling and regenerate energy when braking. Hybrids also have the opportunity to be super-clean with respect to air pollution, such as the Toyota Prius and Honda Insight that are already on the market.[4]

2.4.2 Hybrid ICE-Electric Vehicle Attributes

In this section I apply the methodology of Section 2.2 to the gasoline hybrid ICE-electric vehicle. The ICE component of this hybrid system is a spark ignition direct injection (SIDI) engine. The vehicle also has an advanced body, consistent with the other vehicles considered.

Environmental Damage Costs

Table 2-8 below illustrates the fuel cycle emissions for a gasoline SIDI ICE hybrid vehicle, based on Wang (1999) for air pollutant emissions and on Weiss et al (2000) for CO2-equivalent greenhouse gas emissions.

Table 2-8. Emissions of Gasoline Hybrid ICE Vehicle

Emissions (g/mile)	Upstream	Operation	Total
VOC	0.044	0.106	*0.15*
CO	0.077	2.76	*2.84*
NOx	0.093	0.036	*0.129*
PM10	0.008	0.033	*0.041*
SOx	0.041	0.004	*0.045*
CO2-equivalent	53.7	123	*177*

I multiply the emission levels in Table 2-8 by the costs in Table 2-1 to yield the environmental damage cost per mile. The total environmental damage cost (EDC) is then determined according to Equation 2-1. The resulting environmental damage cost is described in Table 2-9 below, with a combined cost of 1.5 cents per mile, or $2520 over the vehicle life of 14 years at 12,000 miles per year. In comparison with the pure ICE system, the hybrid system exhibits lower environmental damage costs.

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[4] Attributes of the model year 2001 Toyota Prius (5-seat sedan) and Honda Insight (2-seat hatchback) are available at http://www.autoweb.com. Both vehicles have a selling price near $20,000. The Insight fuel economy is 61 mpg in the city and 68 mpg on the highway. In contrast, the Prius fuel economy is 52 mpg in the city and 45 mpg on the highway.

Table 2-9. Environmental Damage Cost of Gasoline Hybrid Vehicle

Emission Source	Cost (cents/mile)	Total EDC ($/vehicle)
VOC	0.06	93
CO	0.80	1340
NOx	0.10	166
PM10	0.02	28
SOx	0.02	28
Local Air Pollutants	0.98	1650
CO2-equivalents	0.51	862
Total	1.50	2520

Operating Cost

The operating cost of the hybrid vehicle is determined according to the series of equations outlined in Section 2.2.2, from energy use of 1.07 MJ/km to a fuel economy of 70.8 mpg. This fuel economy represents over 40% improvement relative to the advanced body ICE system. This variable fuel cost is obtained from this fuel economy and the $1.22/gallon gasoline price. The total operating cost for the hybrid is then determined to be $2070/year, slightly less than $100/year savings relative to the ICE vehicle.

Table 2-10. Operating Cost of Gasoline Hybrid ICE Vehicle

Operating Cost Component	Value
Energy Use (MJ/km)	1.07
Gasoline-Equivalent Consumption, GEC (L/100km)	3.32
Gasoline-Equivalent Fuel Economy, GEFE (miles/gallon)	70.8
Fuel Price ($/gallon)	1.22
Variable Cost from Fuel Use ($/mile)	0.0172
Other Variable Cost ($/mile)	0.0517
Total Variable Cost ($/mile)	0.0689
Yearly Variable Cost ($/year)	827
Fixed Cost ($/year)	1240
Total Operating Cost ($/year)	*2070*

Capital Cost

The capital cost for the hybrid vehicle is determined from Weiss et al (2000), on the basis of component retail price increments. I have outlined these retail price increments as an indicator of capital cost in Table 2-11 below. In sum, the component cost is $6670 and the total vehicle cost is $22,400 for the hybrid vehicle, nearly $2000 more expensive than the pure ICE system.

Table 2-11. Capital Cost of Gasoline Hybrid ICE Vehicle

Component	Cost ($/vehicle)
Base Powertrain	4280
Credit from Engine Downsizing	-380
Gasoline Direct Injection	396
Variable Valve Lift and Timing	238
Exhaust Treatment	282
Electric Motor	457
Battery	1390
Component Cost for Propulsion System	6670
Other Vehicle Cost	15700
Total Vehicle Cost	22400

Performance and Range

Performance and range for the hybrid vehicle are again drawn from Weiss et al (2000). Table 2-12 below outlines the vehicle mass, the power-to-weight ratio (which was standardized across platforms), and the resulting maximum engine power that could be obtained for a hybrid of sedan size. Because the power-to-weight ratio has been normalized by Weiss et al (2000) to be the same as the ICE system, the relative performance level for the hybrid is unity. The range between refuelings is 407 miles for the hybrid, only slightly more than the ICE by the design that Weiss et al used.

Table 2-12. Performance and Range of Gasoline Hybrid ICE Vehicle

Performance or Range Component	Value
Vehicle Mass (kg)	1150
Power:Weight Ratio, PWR (W/kg)	75
Maximum Engine Power (kW)	57.7
Maximum Motor Power (kW)	28.8
Relative Performance (dmnl)	1
Range Between Refuelings (miles)	407

2.5 Fuel Cell Electric Vehicle

Fuel cell electric vehicles have enjoyed much attention in the media lately as a recent innovation potentially applicable to automobiles. Yet the principle of a fuel cell was discovered in 1839 when William Grove produced electric power using a set of cells containing hydrogen and oxygen, and then used that power to split the resultant water byproduct into more hydrogen and oxygen (Thomas and Zalbowitz 1999). Fuel cells have been used commercially on NASA space shuttle missions both to provide electricity and drinking water for astronauts.

A fuel cell electrochemically converts hydrogen and oxygen into electricity and water. Hydrogen flows into the anode side of the fuel cell, where a catalyst converts it into hydrogen ions (protons) and electrons. The protons pass through an electrolyte (composed of positive and negative ions) to combine with oxygen at the cathode side to form water. The electrons cannot pass through the electrolyte, and thus travel around the electrolyte from the anode to the cathode, creating electric power in the process (Thomas and Zalbowitz 1999).

While a variety of electrolytes can be used to transfer protons in a fuel cell, the advent of PEM (which stands for either Polymer Electrolyte Membrane or Proton Exchange Membrane) electrolyte technology in the 1980s opened opportunities for fuel cells in a broad range of applications including automobiles. The PEM technology enables fuel cell stacks to shrink in size as the technology comes down the learning curve. Many PEM fuel cell systems are now considered for the automobile (Fronk et al 2000).

2.5.1 Fuel Cell Electric Vehicle Overview

Figure 2-5 below illustrates the configuration for a direct fuel cell vehicle. For the direct fuel cell configuration, hydrogen is most often considered as the fuel, although recently direct methanol fuel cells have been developed that could process methanol as a fuel without the reforming step. Illustrated by the black arrows, energy flows from the fuel tank to the fuel cell where the hydrogen fuel is combined with oxygen from air to electrochemically produce both electricity and water. This electricity then feeds the electric motor to propel the vehicle. Energy regained from the regenerative braking process is fed back to the battery. The electric motor can redirect energy from the fuel cell to the battery that is not needed for movement, and also draws electricity from the battery.

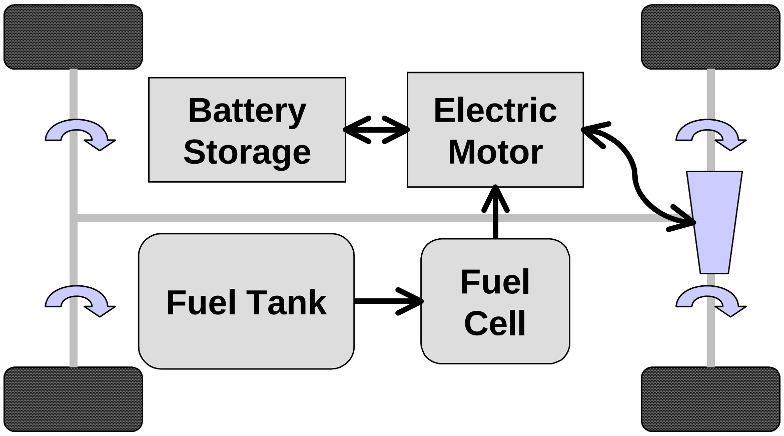

Figure 2-5. Schematic of Direct Fuel Cell Electric Vehicle (FCEV)

An alternative to the direct fuel cell configuration is one in which a hydrocarbon fuel such as gasoline or methanol is stored on board, and then processed as necessary to produce hydrogen as the direct feed to the fuel cell stack. This configuration is illustrated in Figure 2-6 below. Energy flows from the fuel tank to a fuel processor, where it is converted into a form that can be used directly by the fuel cell. The electricity from the fuel cell is then used as described above to propel the vehicle. Again a battery is present so that energy can flow between the electric motor and the battery as needed. The battery is useful for both direct and processed fuel cell systems to provide auxiliary peak power, and to ensure a short start-up time.

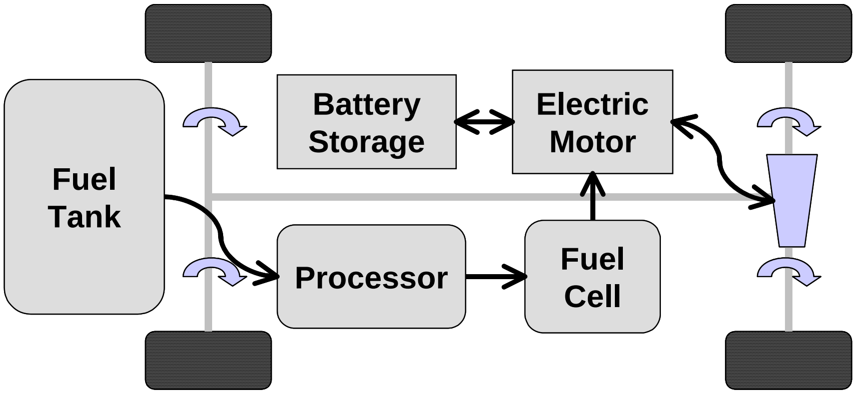

Figure 2-6. Schematic of FCEV with Fuel Processor

Hydrogen, methanol, and gasoline are the three dominant fuels under consideration for a fuel cell electric vehicle. Lave et al (2000) and Weiss et al (2000) conclude that gasoline-reforming fuel cell vehicles do not provide significant environmental benefit over conventional ICE vehicles. However, Mintz et al (1999) see a benefit-to-cost opportunity in gasoline reformers because of the lack of infrastructure capital required. A methanol fuel cell could be substantially more efficient than a gasoline fuel cell, but faces safety challenges in its toxicity and solubility with water.

Hydrogen is viewed by some as the fuel choice of the future for fuel cells (Ogden et al 1999) from both an overall capital cost relative to other fuel cell fuels, and from a consideration of the ultimate ecological benefits that can be derived from hydrogen. I have selected a hydrogen fuel cell system to study in the FPR model primarily because a future hydrogen economy is often cited as the ideal state to make the automobile sustainable. Moreover, the hydrogen fuel cell electric vehicle affords an opportunity to scrutinize the very real infrastructure and economic challenges that pave the transitional path.

I assume that the hydrogen used to fuel the fuel cell electric vehicle is derived from natural gas through a process known as steam reforming. This process is considered to be the most cost-effective under current conditions, and generates substantial energy efficiency advantages relative to the ICE. Natural gas already has a higher hydrogen-to-carbon content than gasoline, so it makes sense that this process should generate fewer carbon-based emissions such as greenhouse gases.

The fuel cell electric vehicle faces many technical challenges. The question of how to store hydrogen is among the most critical. Many possibilities exist, but none can match the capability of gasoline as an energy carrier. Similarly, the fuel infrastructure does not currently exist for hydrogen (Brydges 2000). As explored later, this barrier is no small hurdle to overcome. Because of this infrastructure barrier and the storage challenge, on-board conversion of gasoline to hydrogen is considered an attractive option despite the increased cost of system integration. Regardless of the fuel, fuel cells are currently quite expensive, and thus have a ways to go before becoming commercially viable. The perception of safety could be another issue for high-pressure gaseous hydrogen fuel cells, given hydrogen’s volatile nature (Motevalli and Bulusu 2000).

Despite its many challenges, fuel cells are viewed by many as the ultimate sustainable choice from a fuel cycle perspective. This status—this role in a long-term vision—can represent a great opportunity for fuel cells (Fairley 2000). Such a “halo effect" for the technology could encourage regulation or mandates for the technology to boost availability in the marketplace. Fuel cells also have opportunities to penetrate the market for stationary power generation applications and thus accelerate the learning curve. To address infrastructure issues, the opportunity for fixed hydrogen fleet applications could be pursued.

2.5.2 Fuel Cell Electric Vehicle Attributes

Of the four propulsion systems considered in this thesis, the fuel cell vehicle is most uncertain in terms of attributes. This uncertainty is due to the early stage of technology development for the fuel cell vehicle. For consistency, I again draw from Weiss et al (2000) where possible for the fuel cell system. With this information for the advanced body fuel cell vehicle, I apply the methodology of Section 2.2 to determine attribute levels.

Environmental Damage Costs

In Table 2-13 below I outline the fuel cycle emissions for the hydrogen fuel cell vehicle, based on Wang (1999) for air pollutant emissions and on Weiss et al (2000) for CO2-equivalent greenhouse gas emissions. The hydrogen fuel cell notably has no operational emissions, except some particulate matter from tire rubber which is common to all propulsion systems. Carbon dioxide and its greenhouse gas equivalents are still produced upstream of vehicle operation through the steam reforming process by which hydrogen is produced from the natural gas (predominately CH_4) feedstock. Indeed, the upstream greenhouse gas emissions are greater than the total for the hybrid system, under the assumptions of Weiss et al (2000). In contrast, if the hydrogen were produced using renewable or nuclear energy, such upstream emissions would be virtually eliminated.

Table 2-13. Emissions of Hydrogen FCEV

Emissions (g/mile)	Upstream	Operation	Total
VOC	0.011	0	*0.011*
CO	0.119	0	*0.119*
NOx	0.147	0	*0.147*
PM10	0.004	0.021	*0.025*
SOx	0.007	0	*0.007*
CO2-equivalent	201	0	*201*

I multiply the fuel cell emission levels in Table 2-14 by the costs in Table 2-1 to yield the environmental damage cost per mile and then determine total environmental damage cost (EDC) according to Equation 2-1. These environmental damage costs are reported in Table 2-14 below, with a combined cost of 0.74 cents per mile, or $1250 over the vehicle life. In terms of these environmental damage costs, the fuel cell is half as damaging as the hybrid (compare with Table 2-9). The biggest improvements are in the local air pollutant emissions.

Table 2-14. Environmental Damage Cost of Hydrogen FCEV

Emission Source	Cost (cents/mile)	Total EDC ($/vehicle)
VOC	0.00	7
CO	0.03	56
NOx	0.11	189
PM10	0.01	17
SOx	0.00	4
Local Air Pollutants	0.16	274
CO2-equivalents	0.58	977
Total	0.74	1250

Operating Cost

In determining the operating cost for the fuel cell, controversial values for equivalent fuel economy emerge because of the inherent uncertainty about how fuel cell technology will develop. In addition, the fuel price for hydrogen reformed from natural gas and available at refueling stations is also quite uncertain. The value of $2.20/gallon gasoline equivalent was determined from Weiss et al (2000), based on assumptions for the cost of the hydrogen infrastructure.

The operating cost of the fuel cell vehicle is determined according to the series of equations outlined in Section 2.2.2, from energy use of 0.805 MJ/km to a fuel economy of 94.1 mpg, a 90% fuel economy improvement over the ICE system for the same advanced body. The variable fuel cost is obtained from this fuel economy and the $2.20/equivalent gallon hydrogen fuel price. The total operating cost for the fuel cell system is then determined to be $2140/year, roughly equivalent to the ICE vehicle despite the fuel economy improvement.

Table 2-15. Operating Cost of Hydrogen FCEV

Operating Cost Component	**Value**
Energy Use (MJ/km)	0.805
Gasoline-Equivalent Consumption, GEC (L/100km)	2.5
Gasoline-Equivalent Fuel Economy, GEFE (miles/gallon)	94.1
Fuel Price ($/gallon)	2.2
Variable Cost from Fuel Use ($/mile)	0.0234
Other Variable Cost ($/mile)	0.0517
Total Variable Cost ($/mile)	0.0751
Yearly Variable Cost ($/year)	901
Fixed Cost ($/year)	1240
Total Operating Cost ($/year)	*2140*

Capital Cost

The capital cost for the fuel cell vehicle is determined from Weiss et al (2000) on the basis of component retail price increments as outlined in Table 2-16 below. In sum, the component cost is $7660 and the total vehicle cost is $23,400 for the fuel cell vehicle, nearly $1000 more expensive than the hybrid system.

Table 2-16. Capital Cost of Hydrogen FCEV

Component	**Cost ($/vehicle)**
Exhaust Treatment (Credit)	-450
Electric Motor	1560
Battery	1540
Fuel Cell	4160
Fuel Tank Adjustment	687
Single-Stage Reduced Transmission	160
Component Cost for Propulsion System	7660
Other Vehicle Cost	15700
Total Vehicle Cost	23400

Performance and Range

Performance and range levels for the fuel cell vehicle from Weiss et al (2000) are outlined in Table 2-17 below. The vehicle mass for the FCEV is heavier than that of the ICE system to attain the same power-to-weight ratio of 75 W/kg. Because the power-to-weight ratio is the same as the ICE system, the relative performance level for the fuel cell vehicle is again unity. The range between refuelings is 375 miles for the fuel cell vehicle, somewhat less than the ICE for the same advanced body.

Table 2-17. Performance and Range of Hydrogen FCEV

Performance or Range Component	**Value**
Vehicle Mass (kg)	1310
Power:Weight Ratio, PWR (W/kg)	75
Maximum Motor Power (kW)	98.5
Relative Performance (dmnl)	1
Range Between Refuelings (miles)	375

2.6 Battery Electric Vehicle

The fourth propulsion system considered in this work is the battery electric vehicle (EV), a straightforward propulsion system that has been considered an alternative to the ICE since the turn of the 20th century. The battery EV holds promise in many areas, but has substantial limitations that have thus far relegated it to niche markets. In this section, I provide a brief overview of the battery EV and then outline specific characteristics of a battery EV using energy from the U.S. electricity grid.

2.6.1 Battery Electric Vehicle Overview

The battery electric vehicle has a relatively simple configuration, as illustrated in Figure 2-7 below. The system begins with a battery that stores electric energy and is periodically recharged (e.g., every night at home). The electric motor siphons energy from the battery as needed to propel the vehicle. Again, as with the other electric propulsion alternatives, the electric motor can also redirect energy from regenerative braking back to the battery.

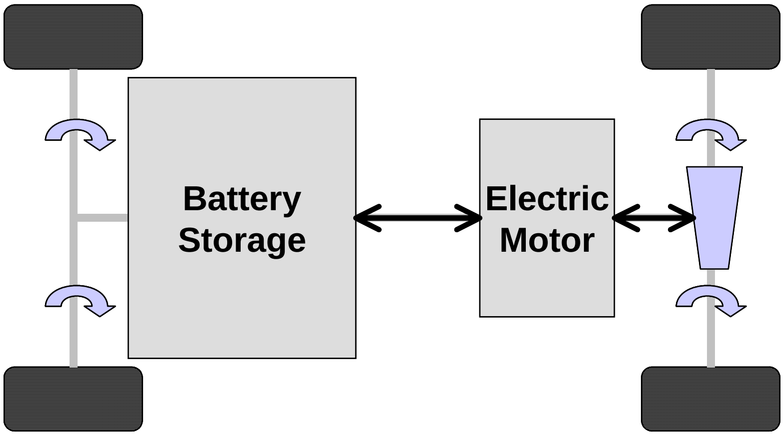

Figure 2-7. Schematic of Battery Electric Vehicle (EV)

The fuel for a battery EV is electricity from the grid. Practically, the electricity grid mix utilizes a variety of sources including coal, natural gas, petroleum, nuclear power, and renewable energy.

Although the battery EV has already been introduced in some markets, it faces many challenges to gain wider acceptance. Predominant among the challenges are the limited range that the vehicle can offer. This limit stems from the fact that additional batteries to extend range would add such bulk and weight as to limit efficiency (Brekken and Durbin 1998). Moreover, batteries of the extent that are needed for automotive propulsion are quite expensive, as explored below.

Like the fuel cell, the battery EV could be perceived as a sustainable alternative. If the electricity used to power the vehicle were derived from renewable sources, this alternative would indeed address the concerns that were mentioned in the introductory chapter. The transition to such a state is also important to consider, and the interim possibilities of overwhelming the grid capacity are not attractive, in light of recent blackouts in states like California.

Other opportunities involve technological developments in the area of electric storage. Alternative storage media such as ultra-capacitors could alleviate the range limitation by providing much greater energy storage density. Unfortunately, at this stage such alternatives do not appear feasible yet from a cost perspective.

2.6.2 Battery Electric Vehicle Attributes

This section outlines the technology attributes for the battery electric vehicle, drawn primarily from Weiss et al (2000). I again apply the methodology of Section 2.2 to determine attribute levels for the advanced body battery electric vehicle.

Environmental Damage Costs

Table 2-18 documents the fuel cycle emissions for the battery electric vehicle, based on Wang (1999) for air pollutant emissions and on Weiss et al (2000) for CO2-equivalent greenhouse gas emissions. Like the hydrogen fuel cell, the battery electric vehicle is emission-free during vehicle operation except for the effect of tire rubber. Carbon dioxide and its greenhouse gas equivalents are still produced upstream of vehicle operation through the electricity generation process by which electricity is produced from the variety of fuels in the grid (predominantly coal). As for the hydrogen fuel cell, the upstream greenhouse gas emissions are greater than the total for the hybrid system, under the assumptions of Weiss et al (2000). Costs of recycling batteries are not considered in these environmental damage costs, although these costs could be substantial.

Table 2-18. Emissions of Battery EV

Emissions (g/mile)	**Upstream**	**Operation**	**Total**
VOC	0.022	0	*0.022*
CO	0.071	0	*0.071*
NOx	0.432	0	*0.432*
PM10	0.035	0.021	*0.056*
SOx	0.408	0	*0.408*
CO2-equivalent	195	0	*195*

I use the emission levels from Table 2-18 with the costs of Table 2-1 to yield the environmental damage cost per mile and then determine total environmental damage cost (EDC) according to Equation 2-1. These environmental damage costs are reported in Table 2-19 below, with a combined cost of 1.10 cents per mile, or $1840 over the vehicle life. In terms of these environmental damage costs, the electric vehicle is more damaging than the fuel cell, but represents a substantial improvement over the hybrid and ICE.

Table 2-19. Environmental Damage Cost of Battery EV

Emission Source	Cost (cents/mile)	Total EDC ($/vehicle)
VOC	0.01	14
CO	0.02	34
NOx	0.33	556
PM10	0.02	38
SOx	0.15	251
Local Air Pollutants	0.53	892
CO2-equivalents	0.56	949
Total	1.10	1840

Operating Cost

The operating cost of the battery electric vehicle is determined according to the series of equations outlined earlier in Section 2.2.2, from its energy use of 0.508 MJ/km to a fuel economy of 149 mpg, an improvement of over 50% in fuel economy relative to the fuel cell system, and three times the fuel economy of the ICE system for the same advanced body. The variable fuel cost is obtained from this fuel economy and the assumed $1.62/equivalent gallon electricity fuel price, again from Weiss et al (2000). The total operating cost for the electric vehicle is then determined to be $1990/year, the lowest of all the propulsion systems considered.

Table 2-20. Operating Cost of Battery EV

Operating Cost Component	Value
Energy Use (MJ/km)	0.508
Gasoline-Equivalent Consumption, GEC (L/100km)	1.58
Gasoline-Equivalent Fuel Economy, GEFE (miles/gallon)	149
Fuel Price ($/gallon)	1.62
Variable Cost from Fuel Use ($/mile)	0.0109
Other Variable Cost ($/mile)	0.0517
Total Variable Cost ($/mile)	0.0626
Yearly Variable Cost ($/year)	751
Fixed Cost ($/year)	1240
Total Operating Cost ($/year)	*1990*

Capital Cost

I determine the capital cost for the battery electric vehicle from Weiss et al (2000) on the basis of component retail price increments as outlined in Table 2-22 below. In sum, the component cost is $12,800 and the total vehicle cost is $28,500 for the battery electric vehicle, the most expensive propulsion option considered. The major source of this immense capital cost is the cost of the battery, at $11,700 for the battery needed to propel the vehicle.

Table 2-21. Capital Cost of Battery EV

Component	Cost ($/vehicle)
Exhaust Treatment (Credit)	-454
Electric Motor	1560
Battery	11700
Fuel Tank (Credit)	-106
Single-Stage Reduced Transmission	160
Component Cost for Propulsion System	12800
Other Vehicle Cost	15700
Total Vehicle Cost	28500

Performance and Range

The performance and range levels for the battery electric vehicle are outlined in Table 2-22 below, as determined from Weiss et al (2000). The vehicle mass for the battery electric vehicle is heavier than that of the ICE system to attain the same power-to-weight ratio of 75 W/kg, but similar to that of the fuel cell vehicle. The relative performance level based on the power-to-weight ratio is again unity for the battery electric vehicle.

The range between refuelings for the battery electric vehicle is limited to 261 miles for the battery electric vehicle, substantially less than the other propulsion systems in the same advanced body. This range level is much higher that what is currently considered to be the capability for battery electric vehicles already on the market. The reason for this discrepancy is that Weiss et al (2000) consider the battery electric vehicle as one of the options on the twenty-year time horizon, and so account for some improvements in battery technology, combined with the efficiency awarded by the advanced body design. The important consideration is the relative value, though. The other propulsion systems have range levels of close to 400 miles between refuelings. Thus, as I explore further in Chapter 3, the lessened range of the electric vehicle is still likely to weigh negatively in the consumer purchase decision.

Table 2-22. Performance and Range of Battery EV

Performance or Range Component	Value
Vehicle Mass (kg)	1310
Power:Weight Ratio, PWR (W/kg)	75
Maximum Motor Power (kW)	98.4
Relative Performance (dmnl)	1
Range Between Refuelings (miles)	261

2.7 Summary

In this section I recap the attribute levels determined in the previous sections and compare them across technologies. These attributes are deterministic at this point, but as model inputs can be easily adjusted to account for differences in assumptions.

Table 2-23 below outlines the propulsion technology attributes across the four systems considered. For each attribute, I have highlighted the "best in class" in ***bold italics***. A quick glance at this table illuminates why so many studies continue to assess the "optimal" technology. The FCEV appears optimal in terms of environmental damage cost; the battery EV appears optimal in terms of operating cost; the ICE carries the lowest capital cost; and the hybrid vehicle, occupying middle ground for many of the attribute levels, has the longest range between refuelings. The range level does not vary significantly over propulsion systems, so this latter "best in class" is somewhat accidental, a byproduct of the drive cycle modeling by Weiss et al (2000).

Table 2-23. Summary of Propulsion Technology Attributes

Technology Attribute	ICE	Hybrid	FCEV	EV
Environmental Damage Cost, EDC ($/vehicle)	2980	2520	***1250***	1840
Operating Cost ($/vehicle-year)	2160	2070	2140	***1990***
Total Capital Cost ($/vehicle)	***20500***	22400	23400	28500
Propulsion Component Cost ($/vehicle)	4770	6670	7660	12800
Performance (dmnl)	1	1	1	1
Range Between Refuelings (miles)	396	***407***	375	261

With these four propulsion systems in mind, the next step is to consider how these attributes affect consumer choice. Chapter 3 provides a glimpse of how this relationship can be formulated as part of the system dynamics model.

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Chapter 3 System Dynamics Model Development

In this chapter, I describe how the technology attributes introduced in Chapter 2 combine with a set of feedback effects to affect the evolution of technology market share for each of the propulsion alternatives. These relationships and feedback mechanisms are congruent with the broad framework for technology adoption that, as presented in Figure 1-4 above. The discussion in this chapter occurs at a more detailed level, with the intent of making assumptions transparent for ready replication and/or revision of these scenarios.

For detailed documentation of the model, with Vensim DSS software sketch views, equations, and variable definitions, consult *Appendix C: Model Documentation*. The appendix provides a listing of the 95 sketch variables in the model. Most (68) of these variables are in fact vectors containing distinct values for each of the four propulsion regimes. In all, 298 elements comprise the model, with 195 endogenous relationships and 103 exogenous parameters.

Figure 3-1 below illustrates the major elements and feedback effects of the system dynamics model.

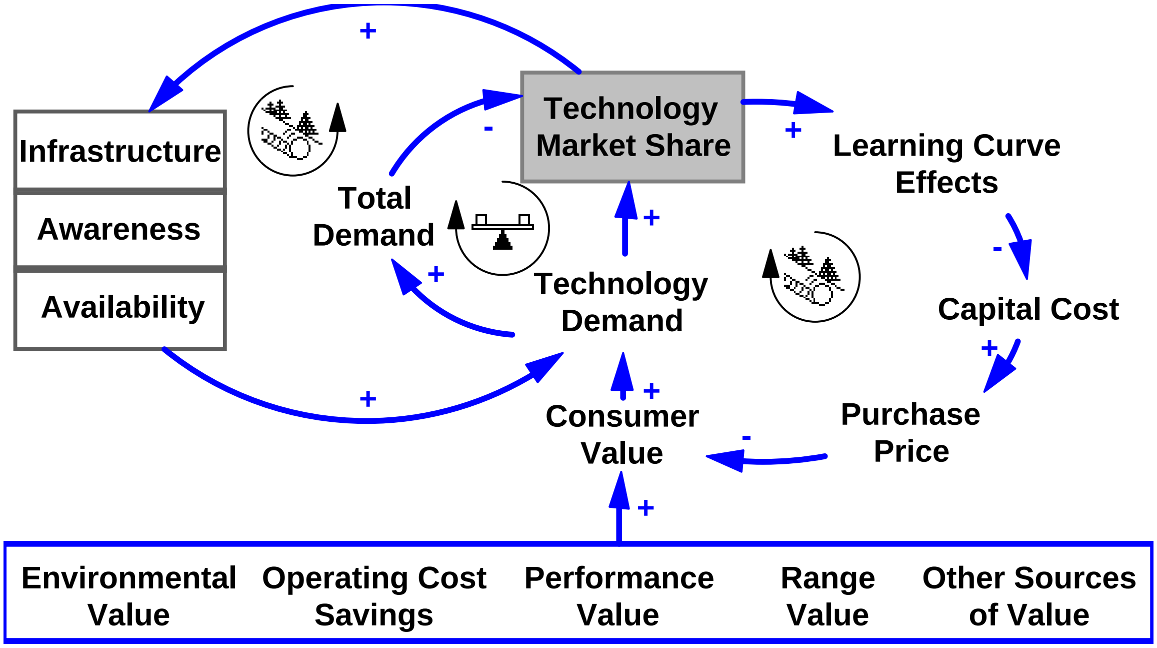

Figure 3-1. Overview of System Dynamics Model Structure.

Three feedback effects are illustrated at the left of Figure 3-1: infrastructure, availability, and awareness. Each of these effects results in both reinforcing (represented by the snowball) and balancing (represented by the scale) behavior in the system because of the way that *Technology Demand* connects to *Technology Market Share*. Infrastructure represents the complementary fuel service stations that are required to fuel the vehicle. Availability represents the extent to which a propulsion system is offered in the market, and thus reflects the degree of access consumers have to the technology. Awareness represents the fraction of the population that are sufficiently aware of a technology to consider it as an option in the purchase decision. The relationship of these three effects to demand, as measured by technology market share, is analogous to the "chicken-and-egg" dilemma. The "chicken-and-egg" dilemma posits that it is uncertain which one would come first, the chicken or the egg. Without these effects, market share for the technology cannot exist. And without market share as a signal of demand, there are no incentives for building infrastructure, availability, and awareness. One can circumvent this problem by providing an external boost to infrastructure, availability, and awareness levels beyond what they would be inherently. This intervention could represent government regulation. These feedback mechanisms are explored in more depth in Section 3.2.

The connection between *Technology Demand* and *Technology Market Share* generates both reinforcing and balancing effects. The balancing effect exists because *Technology Demand* (for each system) increases *Total Demand* (for all systems), which is then used to normalize *Technology Market Share* (see Equation 3-9 in Section 3.2 below). This balancing feedback represents the competition between propulsion technologies for *Technology Market Share*, and is congruent with the model outline presented in Figure 1-4 earlier.

Another reinforcing feedback mechanism is illustrated at the right of Figure 3-1 above. As more units are adopted in the market via *Technology Market Share*, costs decline, enabling a more attractive *Purchase Price*. This feedback constitutes a "learning curve" effect. The learning curve is discussed in the context of *Capital Cost* evolution over time in section 3.1 below. The relative strengths of these feedback mechanisms can be controlled through parameter adjustment, as explored in the following sections.

Sources of value to the consumer that specifically vary across propulsion regimes depend on the technology attributes explored in Chapter 2. These attributes are *Environmental Cost, Operating Cost, Performance, Range,* and *Other Sources of Value*. *Capital Cost* translates into *Price*, which is considered via the learning curve effect. Section 3.1 describes how the relative attribute levels translate into a consumer willingness to pay for the technology.

3.1 Effect of Technology Attributes on Consumer Demand

In this section, I describe how environmental damage cost, operating cost, capital cost, range, and performance can translate into consumer value.

3.1.1 Assessing Attribute Value

Internalized Environmental Value

Environmental damage costs for the propulsion technologies were determined in the previous chapter. Specifically, I determined costs per mile of air pollution and greenhouse gas emissions as outlined in Chapter 2. These costs can be directly translated into annual costs under the assumption of 12,000 vehicle miles traveled per year and a vehicle lifetime of 14 years. The full cost of environmental damage is calculated assuming no discounting of future costs. (A zero discount rate is appropriate for costs that reflect environmental and societal externalities. For example, how does one "discount" the value of future generations' health?) Once the full cost of environmental damage incurred by the propulsion technologies is determined, it is converted into a relative *value* by comparing the cost of an alternative propulsion system to that of the ICE system.

To distinguish the theoretical environmental value from that which is realized, I define a variable that represents the cost fraction internalized by the consumer at the time of purchase. For the base case assumptions, this fraction is zero. However, the internalization fraction can be considered a "scenario variable" for an alternative future. In such a future, regulatory incentives like fee-bates might facilitate internalization of environmental value. Additionally, it is conceivable that some degree of environmental value could be incorporated into the consumer purchase decision, through greater awareness and societal pressure. Such societal pressure might be analogous to that used to ban smoking in many public areas.

The environmental value internalized by the consumer can then be expressed as

Equation 3-1. Environmental Value

$$EnvValue_i = f_{internal} * \left(EDC_{ICE} - EDC_i\right)$$

where

$EnvValue_i$ = *Environmental Value* internalized (Figure 3-1), \$/vehicle

EDC_i = Environmental Damage Cost (Equation 2-1), \$/vehicle

$f_{internal}$ = Internalization Fraction, dmnl

According to the equation above, the internalization of environmental value is zero or positive unless the technology of interest actually does more damage to the environment than the baseline ICE. In this case, the alternatives are chosen in part because of their environmental prospects, and so the environmental value is non-negative for all options. This articulation helps in formulating the aggregate willingness to pay, as discussed below.

If one wished to utilize a non-zero discount rate in assessing environmental damage costs, it would only affect the internalized environmental value if the internalization fraction were also non-zero. The scenarios in the next chapter illustrate what behavior results from fully internalized environmental value. If a discount rate were then applied, it would reduce the value realized at the time of purchase. Additionally, sensitivity tests demonstrate the effect of lowered value on the technology market share.

Operating Cost Savings

In Chapter 2, I compared the operating cost of different technologies, with variability dependent on fuel cost and fuel economy. For the assumed vehicle miles traveled of 12,000 miles per vehicle each year, a total operating cost per year is generated that combines both variable and fixed costs. The next task is to understand how these costs might be internalized at the time of purchase.

To determine what role operating cost plays in the consumer purchase decision, I apply a discount rate. This discount rate represents the annual rate of return that is implicitly applied to future cash flows by the consumer at the time of purchase. Normal discount rates used for financial analysis vary from 5-10% per year, congruent with the interest rate applied to short-term loans (Brealey and Myers 2000). However, consumers do not necessarily incorporate this “reasonable” discount rate when making a vehicle purchase. Studies have shown that consumers often implicitly apply a substantially higher discount rate to energy savings, up to 50% per year, when making the purchase decision (Revelt and Train 1997, Greene and DiCicco 2000). This higher implicit discount rate might result from consumers not knowing how long they will retain the vehicle, not intending to drive it much and thus incurring lower variable cost, or simply not considering and calculating what the real operating costs would be.

The discount rate is assumed to be 30% for the base case assumption, consistent with a relative lack of internalization of operating costs at the time of purchase. However, this discount rate is considered a “scenario variable” that can be adjusted to reflect greater sensitivity to operating cost. While income is not explicitly included in this model, this sensitivity could correspond with operating costs taking up a greater fraction of consumer disposable income. To keep the model flexible with respect to the choice of discount rate, I created a table function that converts the specified discount rate into an appropriate multiplier that would be applied to a yearly cash flow over the time horizon of 14 years. This multiplier was determined by taking the present value of a stream of yearly payments of $1 for different discount rates. The multiplier, and then the operating cost internalized at the time of purchase can be expressed as

Equation 3-2. Operating Cost Multiplier

$$Multiplier = \sum_{n=1}^{14} \frac{1}{(1+dr)^n}$$

$$OpCost_i = Multiplier * AnnualOpCost_i$$

where

$Multiplier$ = *Operating Cost Multiplier* (Figure 3-2), year

dr = Discount rate, 1/year

n = Period over which present value is taken, from 1 to 14 years

$OpCost_i$ = Operating Cost internalized at time of purchase, \$/vehicle

$AnnualOpCost_i$ = Annual Operating Cost, \$/vehicle-year

Figure 3-2 below illustrates the function for the operating cost multiplier with the decreased emphasis on operating cost apparent at higher discount rates. The 30% base case assumption results in a much lower multiplier than that for the standard range of 5-10% in financial analysis.

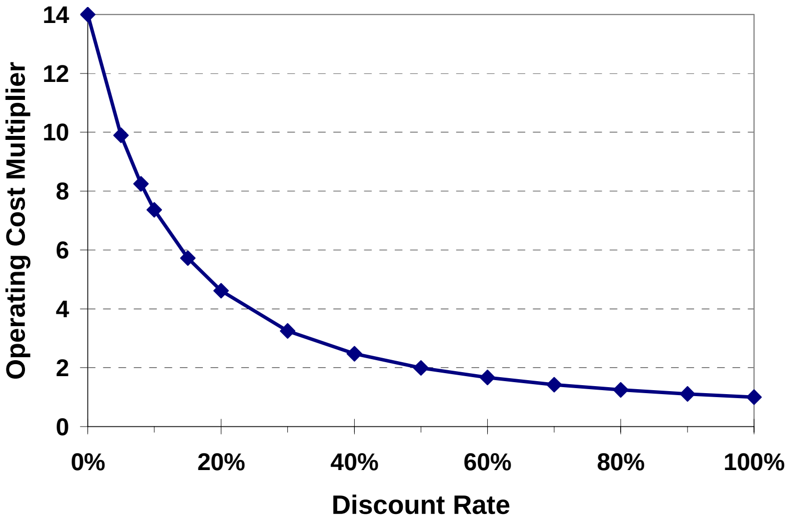

Figure 3-2. Effect of Discount Rate on Operating Cost Multiplier

The total operating cost internalized at the time of purchase is thus the operating cost multiplier, multiplied by the annual operating cost. I translate this cost into a relative value by comparing the operating cost of different propulsion technologies against the ICE operating cost.

Equation 3-3. Operating Cost Savings

$$OpSavings_i = OpCost_{ICE} - OpCost_i$$

where

$OpSavings_i$ = *Operating Cost Savings* (Figure 3-1), \$/vehicle

Capital Cost

The capital cost of a vehicle is incorporated into the purchase decision insomuch as it is incorporated into the vehicle price. Two factors are critical here: at what rate learning occurs that might bring capital costs down, and what profit margin is attached to those costs. Vehicle manufacturers might opt to take a loss early in the technology introduction phase in hopes that the product will be more attractive to the consumer. This demand might then enable the manufacturers to move down the experience curve, as described in the previous chapter.

Important parameters for the learning curve include: initial cost, minimum cost, initial production experience (in terms of units produced), cumulative production experience, and the fractional cost reduction per doubling of production experience. The equations below illustrate how the learning curve is formulated, and the translation of cost to price:

Equation 3-4. Purchase Price Formulation with Learning Curve

$$e_{learn} = \frac{\ln\left(1 - f_{reduction}\right)}{\ln(2)}$$

$$Effect(t) = \left(\frac{CP(t)}{IP}\right)^{e_{learn}}$$

$$CompC(t) = \left(IC - MinC\right) * Effect(t) + MinC$$

$$CapC(t) = CompC(t) + OtherC$$

$$P(t) = \left(1 + pm\right) * CapC(t)$$

where

e_{learn} = Learning Elasticity, dmnl
$f_{reduction}$ = Fractional Cost Reduction per production doubling, dmnl
$Effect(t)$ = *Learning Curve Effect* over time (Figure 3-1), dmnl
$CP(t)$ = Cumulative Production Experience over time, vehicles
IP = Initial Production Experience, vehicles
$CompC(t)$ = Component Cost over time, \$/vehicle
IC = Initial Component Cost, \$/vehicle
$MinC$ = Minimum Component Cost, \$/vehicle
$CapC(t)$ = *Capital Cost* over time (Figure 3-1), \$/vehicle
$OtherC$ = Other Vehicle Cost, \$/vehicle
$P(t)$ = *Purchase Price* over time (Figure 3-1), \$/vehicle
pm = Profit Margin (a “scenario variable”), dimensionless

Estimations of capital cost for the propulsion technologies were described in Chapter 2. These costs serve as initial guideposts for the learning curve effect. Here “initial cost” means the initial cost at which the technology is available for commercialization (according to the availability targets), so it is expected to be lower than that of the development costs. It is also possible to spread development costs among other vehicle platforms to garner learning more quickly (e.g., Toyota Prius expenses are partially absorbed by using profits for other models like the Camry). These assumptions can be easily adjusted to generate more conservative or optimistic estimates about the path of technology development. The minimum cost is assumed to be $4000/vehicle, slightly less than the initial cost assumed for the ICE technology.

The level of initial production experience must be non-zero for the above equation to work. For alternative technologies, some experience may have accumulated from the ICE propulsion system that can affect the shape of the learning curve, even before such technologies become commercialized. Ultimately, this initial production experience represents the initial state of learning and is thus subjective. This experience combined with the fractional cost reduction per production doubling determines the shape of the learning curve. The entire learning curve can be turned “off” by setting the fractional cost reduction to zero. These learning parameters could be used as scenario variables, although I have kept them constant across the scenario set illustrated in the next chapter.

Range

In Chapter 2, I outlined range levels in accordance with the study by Weiss et al (2000). But how does range translate into value to the consumer? Train (2000) considered the range value in the context of preferences for electric vehicles as they compare to conventional vehicles. Train demonstrated using survey data and subsequent analysis that consumers place a strong negative value on range in the purchase decision, such that the negative cost of this loss in range is greater than a positive benefit for the corresponding range increase. There appears to be a sort of range “convenience threshold” that is crossed, where convenience refers to how often the tank must be filled. Above this critical threshold, the marginal benefit is less because of the ubiquity of refueling stations. I translate this insight into an s-shaped “table function” relating range to value as illustrated in Figure 3-3 below.

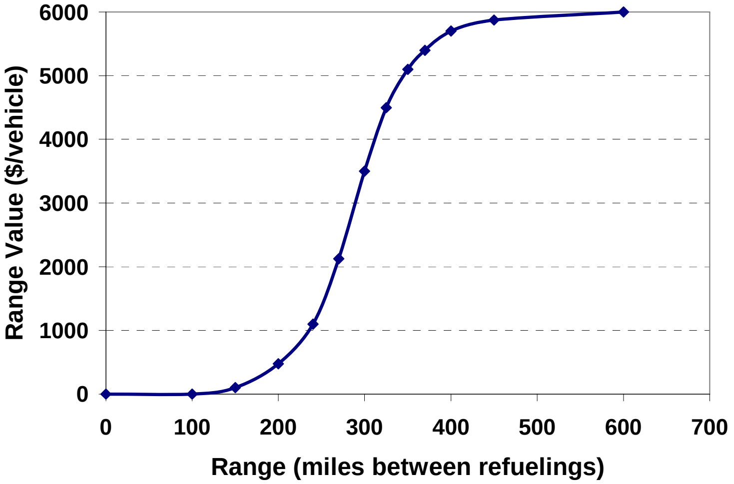

Figure 3-3. Assumed Range Value Function[5]

The function in Figure 3-3 is one of several s-shaped functions that are employed in the model. Rather than formulating an "if…then" construct to represent a threshold, illustrating a continuous s-shaped function better represents reality and results in a more seamless model integration (Sterman 2000). The steepness of the slope can vary for these s-shaped functions, but are assumed to be constant throughout these analyses. On the whole, variations in slope do not affect scenario outcomes as dramatically as other parameter variations that will be explored in the next chapter.

Performance

Performance levels of the alternative propulsion systems have been estimated on a relative scale, where ICE performance is unity. These scales incorporate both measurable technical parameters (e.g., power-to-weight ratio, acceleration, top speed), as well as more subtle ones (e.g., handling, hill-climbing ability). For the baseline assumption, the performance level is determined using the technical power-to-weight ratio described Chapter 2, in which case all alternatives are equal. Since performance is a scenario variable, it can easily be adjusted to reflect other components even if they are difficult to quantify.

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[5] The slope of the s-shape in Figure 3-3 is assumed in this analysis, while the magnitude of the drop-off in value is based on Train (2000).

But even if we think we know the performance levels of alternative, how can we translate these levels into a meaningful value? It is assumed here that performance would incur a drop-off in valuation similar to range if it is less than the comparable ICE vehicle. However, the marginal improvement in performance would likely result in a lesser value advantage. As such, a threshold table function was created to translate performance into value. This function is illustrated in Figure 3-4 below.

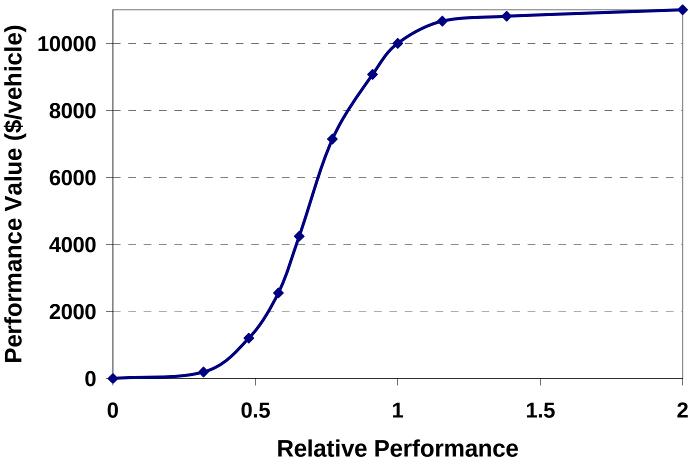

Figure 3-4. Assumed Performance Value Function

As mentioned above, relative performance is another "scenario variable" that can be altered to create a different future under different assumptions of technology development. While performance itself might change, the performance value function would be expected to be consistent across scenarios, but could be adjusted in shape or magnitude to create a new set of scenarios. The rationale for keeping the performance value curve consistent across the scenarios is the subjectivity of the curve shape. It is harder to justify a radically different shape from one scenario to the next. If value exists that is not comprehended in this function, it would be simpler to adjust *Other Sources of Value* instead.

3.1.2 Consumer Value

Other Sources of Value

The variable "Other Sources of Value" represents a broad range of categories. Other sources of consumer value include anything that has not been captured in the environmental cost, capital cost, operating cost, performance or range attributes discussed above. Examples of other sources of consumer value include:

- Ability to provide auxiliary residential power generation.
- Safety considerations.
- Ease of refueling.
- Additional maintenance costs not encompassed in the standard operating cost.

Here, the default assumption is that this other source of value is $17,000/vehicle. This value was chosen to ensure that the net value for the propulsion technologies was positive under default assumptions by offsetting baseline vehicle price when added to the above-mentioned attribute values (see Equation 3-6 below). Clearly this determination is subjective but is reasonable for the model conditions. Moreover, *Other Sources of Value* can serve as a useful model parameter in sensitivity testing, as discussed later.

Consumer Willingness to Pay

In the previous sections, I explored how different technology attributes translate into value to the consumer. The consumer *Willingness to Pay* is then the sum of these distinct sources of value, and can be represented as follows:

Equation 3-5. Willingness to Pay

$$WTP_i = EnvValue_i + OpSavings_i + RangeValue_i + PerfValue_i + OtherValue_i$$

where

WTP_i = *Willingness to Pay* for technology *i*, \$/vehicle

$EnvValue_i$ = *Environmental Value* of technology *i* (Equation 3-1), \$/vehicle

$OpSavings_i$ = *Operation Cost Savings* of technology *i* (Equation 3-3), \$/vehicle

$RangeValue_i$ = *Range Value* of technology *i* (Figure 3-3), \$/vehicle

$PerfValue_i$ = *Performance Value* of technology *i* (Figure 3-4), \$/vehicle

$OtherValue_i$ = *Other Sources of Value* for technology *i*, \$/vehicle

Purchase Price

The purchase price is determined from the capital costs, with the addition of a profit margin term. This price may change over time if the profit margin is constant but the capital cost declines through learning effects. The net value to the consumer is then the willingness to pay for a technology minus the price of that technology. As discussed above in formulating *Other Sources of Value*, this *Consumer Value* should in general be non-negative for realistic purchase behavior.

Equation 3-6. Consumer Value

$$Value_i = WTP_i - P_i$$

where

$Value_i$ = *Consumer Value* of technology *i* , in \$/vehicle

WTP_i = *Willingness to Pay* for technology *i*, in \$/vehicle

$P_i(t)$ = *Purchase Price* of technology *i*, in \$/vehicle

3.1.3 Probability of Purchase

The formulation used to translate consumer value (as defined in Equation 3-6 above) into a probability that the average consumer will purchase the technology is as follows:

Equation 3-7. Probability of Purchase Logit Formulation

$$Util_i = \frac{Value_i}{b_i}$$

$$\Pr_i = \frac{\exp(Util_i)}{\sum_{j=1}^{n} \exp(Util_j)}$$

where

$Util_i$ = Consumer Utility for technology *i*, utils (dmnl)

$Value_i$ = *Consumer Value* of technology *i* , \$/vehicle

b_i = Normalizing Constant, \$/vehicle

$\Pr_i$ = Probability of Purchase for technology *i*, dmnl

Equation 3-7 is a form of the multinomial logit model used commonly in marketing research (e.g., Horsky and Nelson 1992, Brownstone et al 2000). The assumptions required for the logit model are that any error terms are identically distributed for all technologies and that the distribution of the error is double exponential, or extreme value (Lilien et al 1992). Under these assumptions, the error terms can be integrated out to create the form of Equation 3-7.

The normalizing constant b_i is used to convert *Consumer Value* to a dimensionless form of *Consumer Utility* appropriate for exponentiation in assessing *Probability of Purchase*. The selection of the normalizing constant, however, is no easy task. A starting point for determining the normalizing constant is to consider the expected price elasticity of a technology at a certain price. The price elasticity represents the percent reduction in market share that is observed with a percent increase in price. At this point, this "market share" does not represent actual market share, but rather what market share might exist in the absence of infrastructure, availability, and awareness effects. Those feedback effects are considered external to the logit formulation for probability of purchase, and are thus are independent from the normalizing constant. The expression for this elasticity can be written as the following (Bucklin et al 1998):

Equation 3-8. Determination of Normalizing Constant

$$e_{price} = (1 - share)\frac{P}{b}$$

where

e_{price} = Price elasticity, dimensionless

share = Share of technology independent of feedback effects, dimensionless

Standard price elasticities are on the order of –2 (Bucklin et al 1998). With this in mind, I rearrange the terms in Equation 3-8 to solve for the normalizing constant b for a known price P and *share*. The difficult part, then, is determining what P and *share* levels to use. As demonstrated in Equation 3-4, price can change over time as component costs lower due to learning. The starting market *share* could be estimated using the probability of purchase described in Equation 3-7. Using this starting market share and the initial price level, unique normalizing constants could be determined for each technology under the baseline assumptions. However, changes in these baseline assumptions for price or willingness to pay as part of scenario creation or sensitivity testing then disrupt the conditions of Equation 3-8 for an elasticity of –2. Although it is natural for price elasticity to change at different levels of market share, the selection of the normalizing constant alone should not bias the probability of purchase for one technology over another when circumstances change. To prevent this bias, I use the same normalizing constant for each technology. This ensures that the probability of purchase is based upon the technology attributes that vary across technology, rather than on the convention used to normalize value into a dimensionless utility form.

I assume a normalizing constant of \$8625/vehicle for all technologies. This assumption depends on a price of \$23,000/vehicle (in the range of the starting prices for all technologies) and an equally divided market in the absence of infrastructure, availability or awareness challenges, so that each technology has a *share* of 0.25. Using Equation 3-8 with a price elasticity of –2, the \$8625/vehicle normalizing constant is then generated. Elasticity still varies for the different technology values, but stays in a range between –1 and –3. Moreover, so long as the normalizing constant remains the same for different technologies, the simulation results are relatively insensitive to adjustments in the normalizing constant.

3.2 Feedback Effects on Consumer Demand

The previous section explained how technology attributes translate to consumer value and then to probability of purchase using the multinomial logit function. As mentioned in context of the dilemma of assigning a single robust normalizing constant to use in the logit formulation, technology market share as determined by probability of purchase neglects other important effects on the purchase decision. These effects—namely infrastructure, awareness, and availability, were mentioned briefly in the beginning of this chapter, and are discussed in more depth in the following sections as feedback mechanisms.

The aggregated effect of these feedback mechanisms on technology market share can be described in the following equation:

Equation 3-9. Technology Demand and Technology Market Share

$$Demand_i = \Pr_i * Infra_i * Aware_i * Avail_i$$

$$TMS_i = \frac{Demand_i}{\sum_{j=1}^{4} Demand_j}$$

where

$Demand_i$ = *Technology Demand* for *i*, dmnl

TMS_i = *Technology Market Share* for technology *i*, dmnl

Pr_i = Probability of Purchase for technology *i* (Equation 3-7), dmnl

$Infra_i$ = *Infrastructure Coverage* for technology *i*, dmnl

$Aware_i$ = *Consumer Fraction Aware* of technology *i*, dmnl

$Avail_i$ = *Total Availability* of technology *i*, dmnl

The infrastructure, awareness, and availability terms in Equation 3-9 are discussed in the sections below. Because each of these terms directly correlates to technology market share, the level of infrastructure coverage, awareness, and availability for a technology will be greater than or equal to demand for the technology.

3.2.1 Infrastructure Feedback

The presence of a fuel infrastructure is a necessary complement to vehicle operation. As such, the extent of this coverage is a factor in the purchase decision. Figure 3-5 below provides a visual tracing of the relationships connecting infrastructure coverage to market share through the purchase decision.

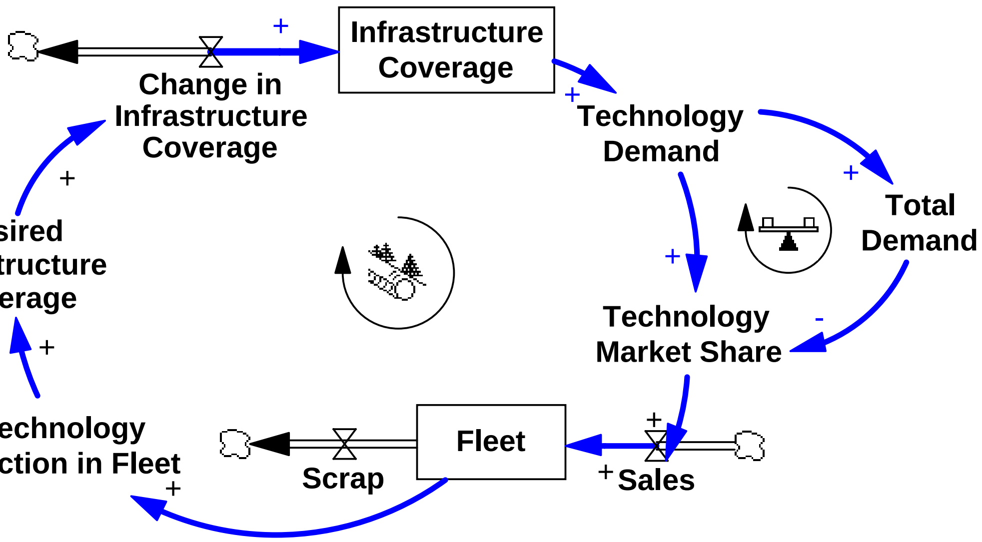

Figure 3-5. Infrastructure Coverage Feedback.

The system dynamics feedback structure sketched in Figure 3-5 includes a stock that represents the extent of fuel infrastructure coverage. *Infrastructure Coverage* is considered to be unity (100%) for gasoline-fueled propulsion systems such as the ICE and hybrid configurations. Alternatively fueled propulsion options (here, the hydrogen FCEV and electricity-dependent EV) have limited infrastructure coverage—close to zero under the baseline assumption. The infrastructure coverage can be increased if the *Desired Infrastructure Coverage* increases, but over a period of delay because it takes time to implement such coverage. I assume that once an increase in fuel infrastructure coverage is implemented, it does not decline. Rather, any underutilized coverage might be considered "excess capacity." In reality, the infrastructure coverage could be removed over a long period of underutilization, but this removal is beyond the scope of this work.

As infrastructure coverage increases, the demand for technology that utilizes that infrastructure increases (with all else equal), as expressed in Equation 3-9. The increase in *Technology Market Share* in turn increases the overall fraction of the technology in the fleet. This relationship can be described through the following set of equations:

Equation 3-10. Translation of Technology Market Share to Fraction in Fleet

$$Sales_i = TMS_i * MktSize$$

$$Scrap_i = \frac{Fleet_i}{Life}$$

$$Fleet_i(t) = \int_{t_0}^{t} \left(Sales_i(s) - Scrap_i(s)\right) ds + Fleet_i(t_0)$$

$$Fraction_i = \frac{Fleet_i}{\sum_{j=1}^{4} Fleet_j}$$

where

$Sales_i$ = *Sales* Rate of technology *i*, vehicles/year

TMS_i = *Technology Market Share* for *i* (Equation 3-9), dmnl

MktSize = Market Size for all propulsion technologies, vehicles/year

$Scrap_i$ = *Scrap* Rate of technology *i*, vehicles/year

$Fleet_i$ = *Fleet* of vehicles with technology *i* in operation, vehicles

t_o, t = Initial time and current time, respectively, years

s = Point in time between initial and current time, years

ds = Time period for integration, years

$Fraction_i$ = *Technology Fraction in Fleet* for *i*, dmnl

The expression for the fleet of propulsion technologies on the road in Equation 3-10 is the standard form for a stock (or state) variable in system dynamics. In that form, the dependence of terms on time is noted explicitly. For simplicity, in other equations, I do not include the time notation.

The *Technology Fraction in Fleet* increases *Desired Infrastructure Coverage* through an s-shaped function, illustrated in Figure 3-6 below. This nonlinear function incorporates a regime below a technology fraction of 5%, in which the desired infrastructure coverage increases sufficiently to support that fraction without any additional boost. Between fleet fractions of 5 and 10%, coverage increases substantially for small increases in fleet fraction. I assume that at or above a 20% fleet fraction, desired infrastructure coverage is 100%. This function represents an implicit “decision rule” that fuel suppliers might use when considering the benefits of expanding their coverage on the basis of demand. This function could be adjusted to represent different decision rules, although it is fixed for the scenario set considered in this thesis.

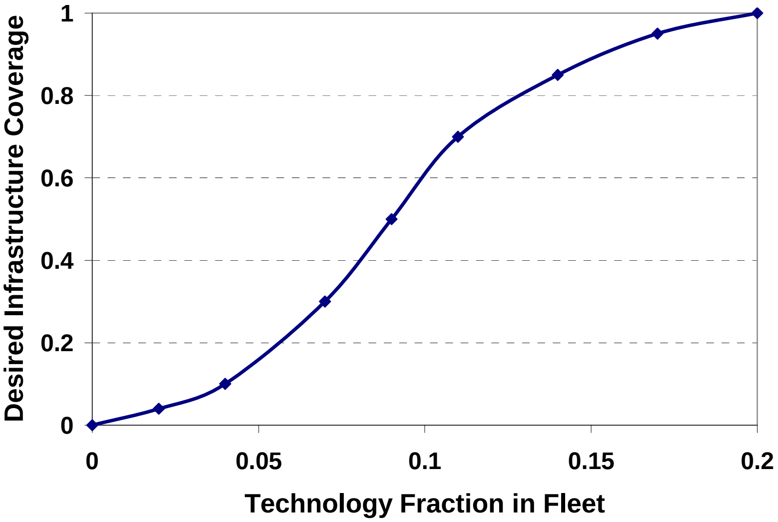

Figure 3-6. Assumed Desired Infrastructure Coverage Function

Once *Desired Infrastructure Coverage* is specified for a given technology fraction, *Infrastructure Coverage* is changed according to the following relationships:

Equation 3-11. Infrastructure Coverage Formulation

$$\Delta Infra_i = MAX\left(\frac{Desired_i - Infra_i}{\tau_{build}}, 0\right)$$

$$Infra_i(t) = \int_{t_0}^{t} \Delta Infra_i(s)ds + Infra_i(t_0)$$

where

$\Delta Infra_i$ = *Change in Infrastructure Coverage* for technology *i*, 1/year

$Desired_i$ = *Desired Infrastructure Coverage* (Figure 3-6), dmnl

$Infra_i$ = *Infrastructure Coverage* for technology *i*, dmnl

τ_{build} = Time to Build Infrastructure, years

MAX = Function returning maximum of values within

As mentioned earlier, the infrastructure feedback mechanism creates a “chicken and egg” dilemma. In the absence of a complementary infrastructure, demand for the technology will not grow (Gupta et al 1999). This infrastructure feedback proves to be a considerable barrier for alternatively fueled propulsion technologies, as explored in the scenarios described in Chapter 4.

3.2.2 Awareness Feedback

Consumer awareness of a technology is critical to its adoption. In this section, I explore how this awareness can be considered explicitly in determination of technology market share as described in Equation 3-9 at the beginning of this section. The awareness feedback mechanism incorporates the concept that if consumers do not know that a product exists, they are unable to exercise demand for the product (through technology market share). In effect, the fraction of *Consumers Aware* reduces the effective market size for a new technology.

Figure 3-7 below illustrates the feedback structure of consumer awareness. Two interdependent system dynamics stocks comprise this structure, together representing the total consumer population. Unaware consumers are converted to aware consumers through the process of enlightenment, which can occur through marketing spending and media, or through word of mouth effects. Over time, even enlightened consumers undergo a process of "forgetting" if the awareness is not reinforced, though this is a slower process than enlightenment.

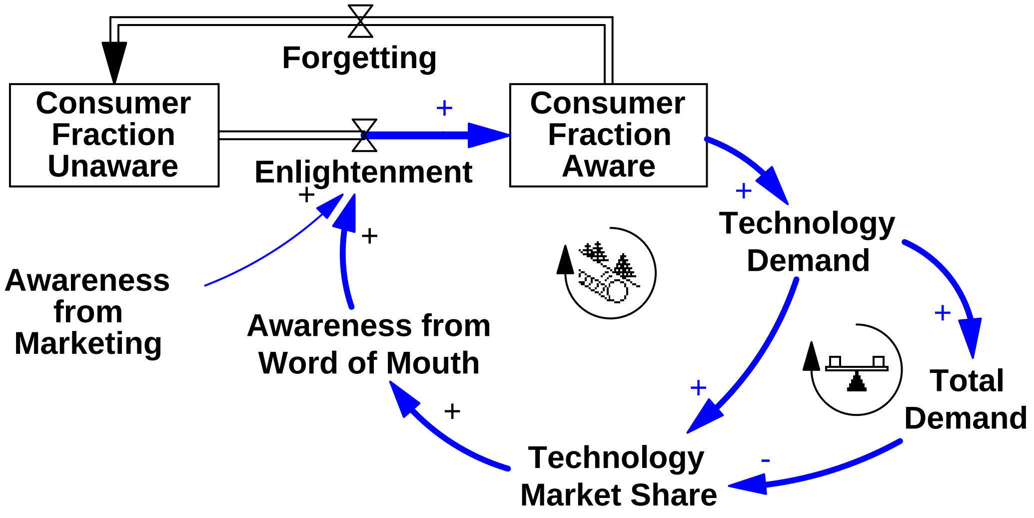

Figure 3-7. Consumer Awareness Feedback.

The *Word of Mouth* means to *Enlightenment* forms a reinforcing feedback loop in Figure 3-7. The structure in which awareness diffuses through the population is congruent with the Bass diffusion model as presented by Sterman (2000). As more consumers become aware, more consider the technology in their purchase decision and thus increase the technology market share. This in turn increases the number of owners that are liable to spread the word. The word of mouth "effect" translates to the fraction of people that are informed per new vehicle owner. The strength of this effect is assumed to be a fraction between zero and one on average – in this case, 0.5 (i.e., one person is enlightened for every two new owners). Alternatively, if a product does not meet customer expectations, the word of mouth effect could be negative and thus result in a balancing feedback mechanism (imagine the connection between *Technology Market Share* and *Awareness from Word of Mouth* with a negative sign).

Equation 3-12. Awareness through Word of Mouth and Marketing

$$WOM_i = Strength_{WOM} * TMS_i$$

$$Mktg_i = Base_{Mktg} * \left(Strength_{Mktg,i}\right)^{e_{Mktg}}$$

where

WOM_i = *Awareness from Word of Mouth* for technology *i*, 1/year

$Strength_{WOM}$ = Strength of Word of Mouth Effect, 1/year

$Mktg_i$ = *Awareness from Marketing* for technology *i*, 1/year

$Base_{Mktg}$ = Baseline Awareness from Marketing, 1/year

$Strength_{Mktg,i}$ = Relative Strength of Marketing Efforts for *i*, dmnl

e_{Mktg} = Marketing Elasticity, dmnl

Elasticity represents the percent increase in awareness for a percentage increase in marketing spending or equivalent media effort. While the elasticity in Equation 3-12 above represents both marketing and media effects, marketing spending is much easier to measure. For simplicity, the model itself considers input in terms of marketing spending, although some of this spending could be considered "media-equivalent" spending.

Equation 3-13. Formulation for Consumer Fractions Aware and Unaware

$$Enlighten_i = Unaware_i * \left(Mktg_i + WOM_i\right)$$

$$Aware_i(t) = \int_{t_o}^{t} \left(Enlighten_i(s) - Forget_i(s)\right)ds + Aware_i(t_o)$$

$$Forget_i = Aware_i * f_{forget}$$

$$Unaware_i(t) = \int_{t_o}^{t} \left(Forget_i(s) - Enlighten_i(s)\right)ds + Unaware_i(t_o)$$

where

$Enlighten_i$	= *Enlightenment* Rate for technology *i*, 1/year
$Unaware_i$	= *Consumer Fraction Unaware* of technology *i*, dmnl
$Aware_i$	= *Consumer Fraction Aware* of technology *i*, dmnl
$Forget_i$	= *Forgetting* Rate for technology *i*, 1/year
f_{forget}	= Forgetting Fraction, 1/year

The word of mouth feedback mechanism cannot take off unless awareness becomes positive, so some marketing spending for the particular propulsion technology would be needed to seed awareness. The effectiveness of this spending is depends on the elasticity, and the spending relative to the baseline (ICE spending).

3.2.3 Availability Feedback

The effect of technology availability on market share is another significant feedback to technology market share. *Availability* refers to the fraction of vehicle platforms that offer the particular propulsion technology. Availability is tightly correlated to the notion of access to a technology. The population that has access to a technology is able to purchase it. 100% availability of a technology for the platform (in this case a sedan) implies that all consumers who are aware of the technology also have access to it. Less than 100% availability implies that not all consumers, even if aware, can have access to the technology. The level at which I consider access and availability is simplified, as in reality different factors go into access (such as distribution) than go into availability on a fraction of platforms. But this differentiation is beyond the scope of this work.

Figure 3-8 below illustrates the major feedback effects from availability. The availability feedback mechanism incorporates two distinct reinforcing loops. The *Target Availability* refers to the goal for this availability. This target translates to *Actual Availability* over a delay that represents the time required to bring the technology to the required production levels (this delay is represented by the hatchet mark on the connecting arrow between target and actual availability). Actual Availability then is combined with the competitor availability to generate the total availability. Total Availability enables Technology Market Share to increase because consumers will only choose from the systems available.

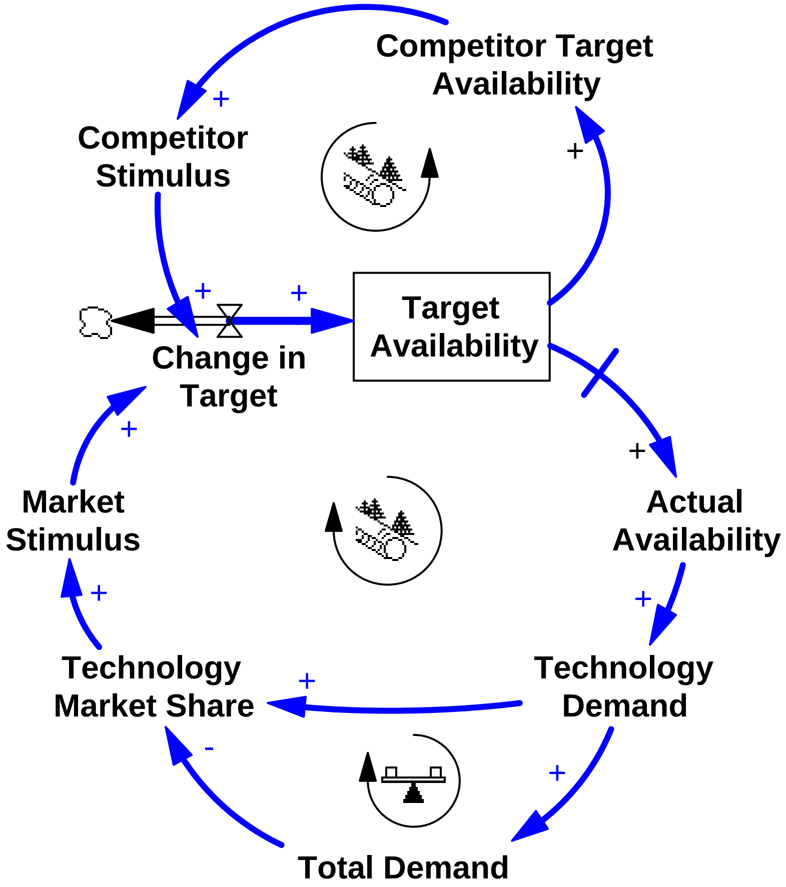

Figure 3-8. Technology Availability Feedback.

The formulation for *Change in Target Availability* is based on a combination of competitor activity (*Competitor Stimulus*) and market demand (*Market Stimulus*) for a company. In this model, one company responds to both (as described below), and the other company responds solely to competitor activity (a "fast-follower" strategy). I first focus on *Market Stimulus* and its dependence on *Technology Market Share*, as connection between *Technology Market Share* and the *Market Stimulus* warrants some explanation. *Technology Market Share* is first translated into *Consumer Acceptance* via the following relationship:

Equation 3-14. Consumer Acceptance of Technology

$$Accept_i = \frac{TMS_i}{Avail_i}$$

where

$Accept_i$ = *Consumer Acceptance* of technology *i*, dmnl

Consumer Acceptance represents the sales realized for a given technology, divided by the vehicles made available of that technology. The formula is *Technology Market Share* (vehicles sold with technology *i*/total vehicles) divided by *Total Availability* (cars available with technology *i*/total vehicles). To translate this *Consumer Acceptance* into the *Market Stimulus*, I define an *Adjustment Fraction* as a function of *Consumer Acceptance*. This relationship is illustrated Figure 3-9 below as a gently sloping s-shaped curve peaking at 20% adjustment of the target per year at the maximum *Consumer Acceptance*.

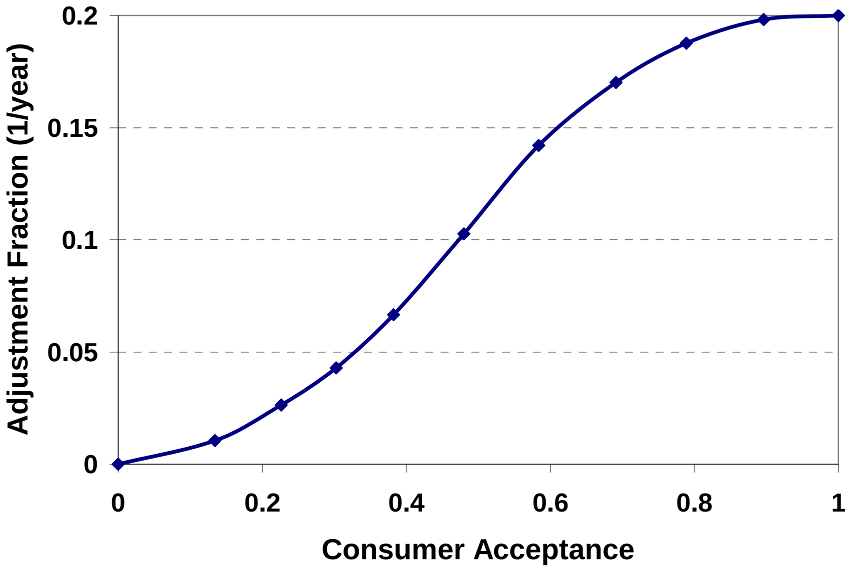

Figure 3-9. Assumed Adjustment Fraction Function for Technology Availability

The *Adjustment Fraction* can then be combined with the existing *Target Availability* to create the *Market Stimulus* as follows:

Equation 3-15. Market Stimulus to Change Target Availability

$$MktStim_i = (1 - Tgt_i) * f_{adj}$$

where

$MktStim_i$ = Market Stimulus for technology *i*, 1/year

Tgt_i = *Target Availability* for technology *i*, dmnl

f_{adj} = *Adjustment Fraction* (Figure 3-9), 1/year

The *Market Stimulus* takes the maximum increase in *Target Availability* and multiplies it by the *Adjustment Fraction*, thus responding in a limited way to the *Technology Market Share*.

In addition to the *Market Stimulus*, *Change in Target Availability* can respond to a *Competitor Stimulus*. Through competitive intelligence activities, the firm learns of the *Competitor Target Availability* and can then adjust its own target availability accordingly. The *Competitor Stimulus* is formulated as follows:

Equation 3-16. Competitor Stimulus to Change Target Availability

$$CompStim_i = \frac{(CompTgt_i - Tgt_i)}{\tau_{react}}$$

where

$CompStim_i$ = *Competitor Stimulus* for technology *i*, 1/year

$CompTgt_i$ = *Competitor Target Availability* for *i*, dmnl

τ_{react} = Reaction Time required to adjust Target Availability, years

The competitor stimulus from the competitor's perspective would be equal in magnitude and opposite in sign to the one outlined above.

Equation 3-17. Change in Target and Actual Availability

$$\Delta Tgt_i = MAX\left(MktStim_i, CompStim_i\right)$$

$$Tgt_i(t) = \int_{t_0}^{t} \Delta Tgt_i(s)ds + Tgt_i(t_o)$$

$$Actual_i = DELAY3(Tgt_i, \tau_{actual})$$

where

ΔTgt_i = *Change in Target Availability* of technology *i*, 1/year

$Actual_i$ = *Actual Availability* of technology *i*, dmnl

DELAY3 = Third-order Delay Function

τ_{actual} = Time to Change Actual availability, years

As the target availability increases, with all else equal, a company's competitors are likely to increase their own target availability once they become aware of the increase through competitive intelligence. And again, all else equal, this increase in competitor availability can result in an increase in the target availability.

3.3 Putting it All Together

To conclude this chapter, I illustrate how the formulations discussed in the previous sections interact under the baseline assumptions.

3.3.1 Compounding Feedback Effects

The bar chart in Figure 3-10 illustrates how the feedback mechanisms compound to reinforce status quo behavior in the baseline simulation at the ten-year time horizon. The y-axis represents relative technology market share, and the x-axis represents portions of the model as they are "added" together.

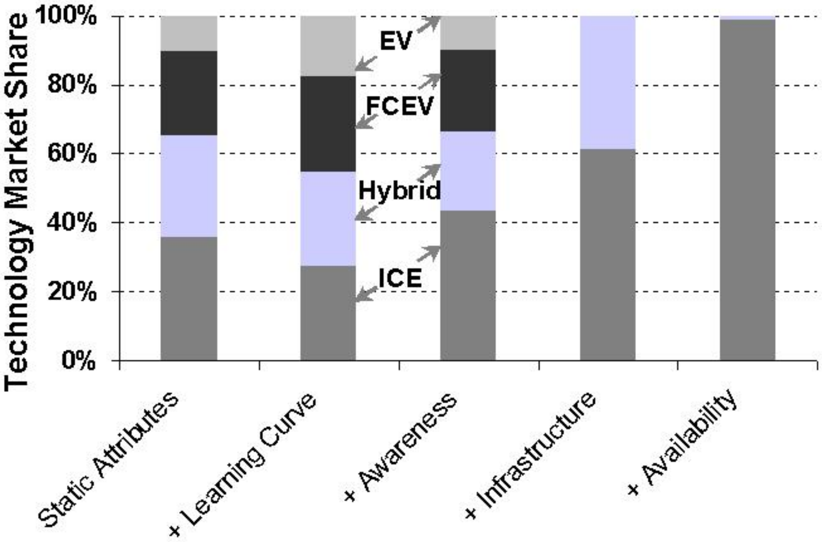

Figure 3-10. Compounding Feedback Effects on Technology Market Share

Starting from the left in Figure 3-10, the *Static Attributes* bar indicates that if technology attributes alone were considered (operating cost, performance, etc.), the *Probability of Purchase* would ensure that market share was distributed among all four alternatives according to their benefit. This distribution would not be dynamic and would not represent the reality of the starting conditions because it neglects the availability and awareness considerations.

The next bar in Figure 3-10 illustrates the *Learning Curve* effect on the baseline simulation. The learning curve enables a more equitable distribution of *Technology Market Share* across technologies, as the more expensive technologies become cheaper over the ten-year horizon. Again, this distribution is not realistic because it neglects other factors, but it helps to elucidate the impact learning can have.

The *Awareness* feedback effect enables alternatives to penetrate the market, but retains much of ICE dominance. At this point in compounding, the initial state is 100% *Technology Market Share* for the ICE—a more realistic starting point. What we see at the ten-year horizon, then, is just a snapshot in time along a dynamic curve that equilibrates later in the simulation.

When *Infrastructure* feedback is added to *Awareness* and *Learning Curve* effects, it serves as a barrier to the alternatively-fueled FCEV and EV options, leaving the distribution of market share to be divided among the ICE and hybrid options. Finally, when *Availability* feedback is added to complete the model, the ICE option overwhelms the market. *Availability* (under the baseline assumptions) exacerbates the delays that hybrids must overcome to penetrate the market.

3.3.2 Baseline Simulation

With all the feedback effects considered together, the ICE dominates over the alternatives at the ten-year horizon, as illustrated by the right-hand bar in Figure 3-10 above. Beyond this snapshot in time, it is useful to investigate how the market share of each propulsion technology evolves over time in the baseline scenario. Figure 3-11 below illustrates such an evolution of technology market share. In this graphical display, we see that while the alternatives are suppressed in the near term, hybrid technology eventually penetrates the market, stealing market share from the ICE as it goes. The growth of hybrid penetration is the early stages of s-shaped growth, although the completion of the s-shape is not apparent in the 30-year simulation horizon.

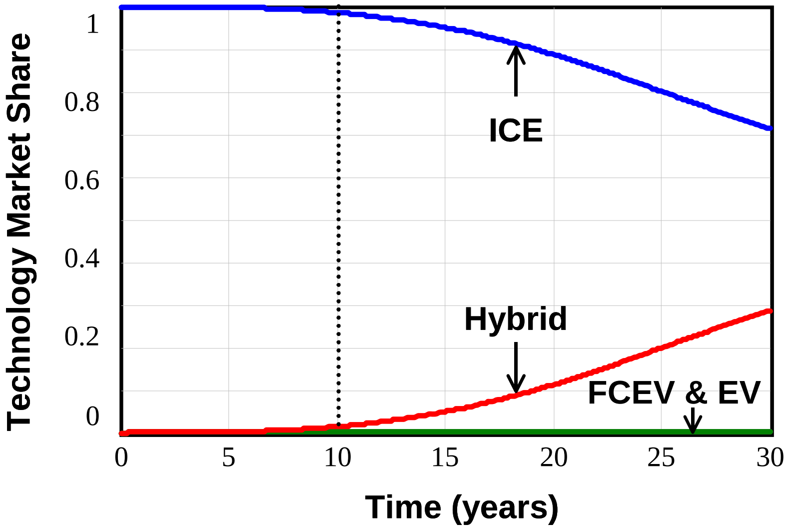

Figure 3-11. Technology Market Share in the Baseline Simulation

Also apparent in the simulation shown in Figure 3-11 is the lack of penetration by the FCEV and EV alternatives. The major reason for this lack of penetration is the limited infrastructure coverage (1% initial coverage) available for those options. The chicken-and-egg dilemma between technology market share and infrastructure coverage thwarts the success of the FCEV and EV at such low levels.

3.3.3 Testing the Baseline

In this section, I demonstrate a sampling of sensitivity analyses that could be performed on a given model run, using the baseline simulation as a starting point. The analysis portion of system dynamics that I touch on here is often the most time-consuming part of modeling projects. Unfortunately, this analysis is also often neglected because it comes at the end of the project work. While I have performed some sensitivity analyses, I have by no means exhausted the possibilities. The interested reader can consult *Appendix D: Model Usage Notes* and Vensim software documentation to learn more about sensitivity analyses for this model.

Figure 3-12 illustrates the sensitivity of technology market share in the baseline simulation to changes in other sources of value for the hybrid. The single line represents the baseline simulation, and the shaded areas surrounding that line represent different confidence levels for the sensitivity analysis. The sensitivity test was performed using discrete runs for each value, from $11,000 to $23,000 per vehicle at increments of $1000/vehicle (the baseline is $17,000/vehicle). The *Other Sources of Value* parameter is adjusted for the hybrid system while remaining at $17,000/vehicle for the other propulsion systems. The confidence bounds represent the level of certainty within this range of discrete simulation runs.

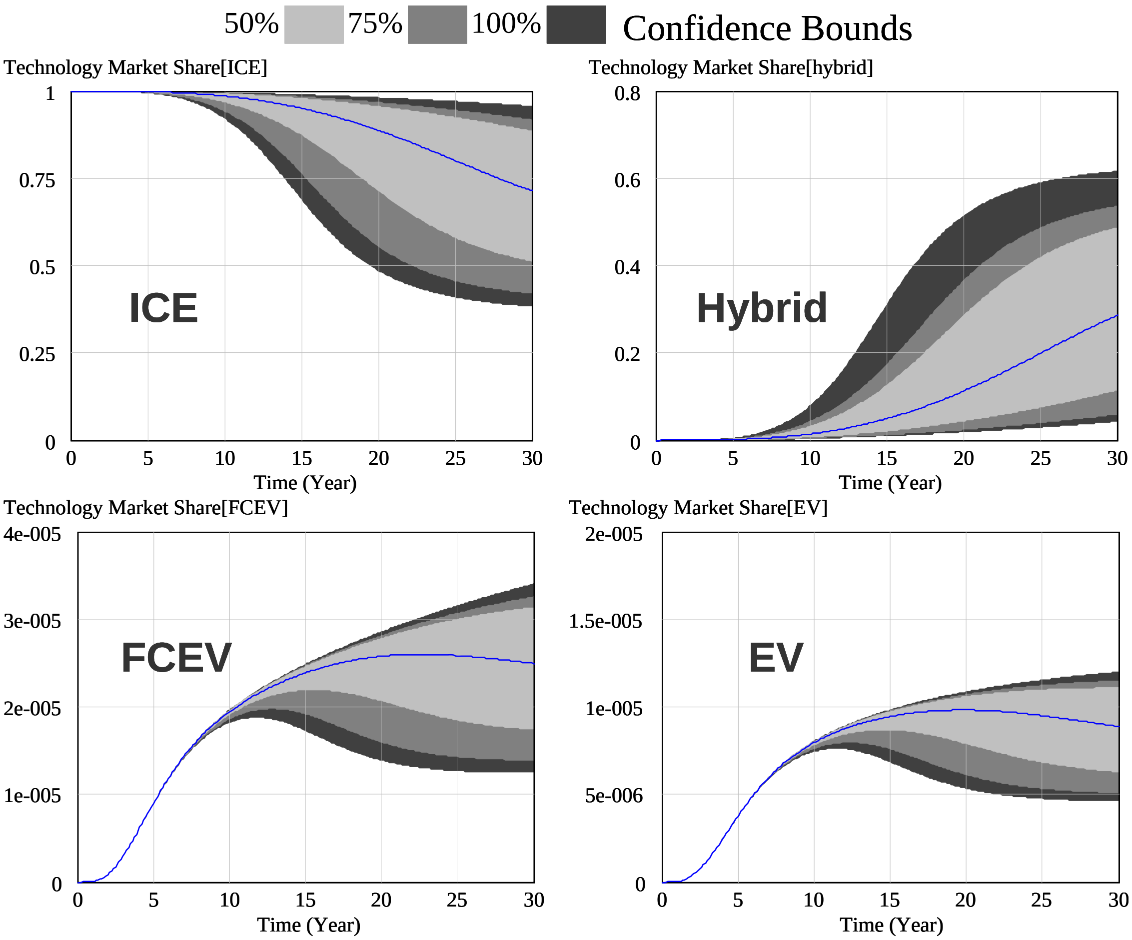

Figure 3-12. Sensitivity to Other Sources of Hybrid Value in Baseline Simulation

The variation in *Other Sources of Value* for the hybrid system results in a broad range of hybrid market share penetration possibilities, with greater share as the value increases relative to other systems. This value sensitivity can be considered to represent similar adjustments in more specific attribute levels. When value is increased, the hybrid market share level plateaus earlier in the simulation, completing the s-shaped growth after a steeper penetration period. Correspondingly, the ICE share declines more steeply with greater hybrid value. The FCEV and EV systems also exhibit fluctuation in market share when the hybrid value is adjusted, though the fluctuations are on a scale that is negligible relative to the hybrid and ICE systems.

The purpose of the sensitivity testing illustrated above and in the next chapter is not to elucidate the “right answer” but rather to give a sense of the relative ease of affecting market share penetration through value adjustments, given the other dynamics in the scenario. In the next chapter, three distinct scenarios are described, and then a similar sensitivity analysis is performed on each.

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Chapter 4 Future Propulsion Scenarios

With this understanding of the model formulation and baseline simulation, I now turn to the future propulsion scenarios used to explore different possibilities. In this chapter I unfold three propulsion scenarios for consideration. I first explain how the scenarios were generated in the context of the model parameters, and then explain the conditions and plausibility of each scenario. I also explore the bounds of the scenarios through sensitivity testing.

4.1 Scenario Generation

What is a scenario? Scenario planners, modelers, and others often have different implicit meanings and connotations for the term “scenario.” The American Heritage Dictionary (2000) considers a scenario to be “an outline or model of an expected or supposed sequence of events.” This definition is congruent with the modeling approach taken in this thesis. Focusing more on the use of scenarios, Schwartz (1996, p.3) contends that “Scenarios are a tool for helping us to take a long view in a world of great uncertainty.” More specifically, Van der Heijden identifies value-free external scenarios as appropriate for strategic conversation (1996, p.5):

> “External scenarios are derived from shared and agreed upon mental models of the external world... internally consistent and challenging descriptions of possible futures... intended to be representative of the ranges of possible future developments...”

As noted in the above quote, it is important to ensure internal consistency within the scenario. For modeling, this means that to the extent possible, the external parameters are input consistently. To achieve such consistency, I have drawn primarily from a single study (Weiss et al 2000) for as many of the attribute parameters as possible. If one wishes to adjust one of these parameters, it must be justified relative to the others.

4.1.1 Scenario Variables

Throughout this paper thus far, I have noted variables that are “scenario variables.” In this section, I summarize the key scenario variables to segue into the next section. Beyond noting that a variable *is* a scenario variable, I note what rationale would justify its change for an alternative scenario. The interested reader may consider other variables to be potential scenario variables, after reviewing this formulation and the details in *Appendix C: Model Documentation*. I make no claims to be comprehensive in all possible scenario variables. The key to scenario construction using a model is to make the minimum number of changes in order to generate a distinct scenario. Keeping changes to a minimum ensures that the scenarios are as plausible as possible and straightforward to change. Given the abundance of model parameters, the model user must decide what variables to fix across the scenario set (though they may be different values and functions from those used here), and to specify explicitly which variables change along with the supporting rationale.

The following eight variables comprise the scenario variables that I explicitly used to create the scenarios that are discussed in the next chapter.

1. *Relative Performance.*

The relative performance is a scenario variable in that performance could evolve quite differently for alternative propulsion technologies. This variable is normalized relative to the ICE, and the default assumption is that all technologies have equal performance, on the basis of the study performed by Weiss et al (2000) where performance in terms of power-to-weight ratio (PWR) was explicitly normalized to compare other vehicle characteristics. The extent to which this performance should be used as a scenario variable is to consider other performance aspects, besides PWR in the performance category. For instance, this variation in performance might include the difficulty hybrids can experience in accelerating or hill-climbing because of its dependence on the battery state of charge.

2. *Relative Strength of Marketing Effort.*

The relative strength of marketing effort implicitly represents a ratio of the spending for the technology in consideration divided by the baseline marketing spending for the vehicle platform (sedan in this case). Thus a relative strength of marketing spending of 1 (the default assumption) means that the same marketing and media efforts are made for the technology in consideration as in the baseline. To promote alternative technologies, this ratio might be increased either directly through marketing efforts or through greater media coverage.

3. *Initial Target Availability.*

The initial target availability for alternative propulsion technologies (hybrid, FCEV, and EV) is presumed to be near zero (1%) as a default. This is a scenario variable in that the Target Availability for the sedan vehicle platform can be increased for an alternative technology to reflect a more aggressive plan for the future. Moreover, an increase in this target availability could conceivably stem from a mandate akin to the ZEV mandate, requiring that a certain percentage of automobiles be sold that have zero tailpipe emissions.

4. *Initial Infrastructure Coverage.*

The initial infrastructure coverage for a given propulsion technology represents the extent to which fuel and maintenance are available at the start of simulation to seed vehicle demand. This initial infrastructure coverage is a scenario variable specifically for the FCEV and EV, in that it can be increased to reflect intensive investment in infrastructure prior to demand to circumvent the chicken-and-egg dilemma. Such investment might be induced or subsidized through regulation. The default initial infrastructure coverage values for the FCEV and EV are barely non-zero at 0.01 (1% coverage).

5. *Profit Margin.*

Profit margin is specified as the fraction of cost that is added to give vehicle price. The profit margin can be zero if the vehicle is to be sold at cost, or it can be negative if the vehicle is to be sold at a loss. The default assumption is a 5% profit margin for all technologies except EVs (which are assumed to be sold at cost because of their high Capital Cost). The profit margin is a scenario variable, in that it can be lowered to seed greater demand.

6. Internalization Fraction

The internalization fraction represents the fraction of environmental damage costs that are recognized by the consumer at time of purchase. A fraction of zero (the default) represents that the environmental cost is not a consideration in the purchase decision. A fraction of 1 indicates that somehow this damage cost is recognized, perhaps through fee-bates imposed by the government. In this way, the internalization fraction is a scenario variable.

7. Discount Rate

The discount rate determines to what extent future operating costs are internalized at the time of purchase. A high discount rate represents that these costs are not internalized very much. As discussed in the previous chapter, the baseline 30% discount rate would be considered high relative to standard discount rates used in financial analysis, although high implicit discount rates have been shown to better reflect the consumer purchase behavior. The discount rate is also a scenario variable, in that it can be lowered to create a future where operating costs are considered to a greater extent at the time of purchase.

8. Gasoline Price Increase

The gasoline price increase represents the amount by which gasoline prices change, either due to taxes or supply and demand shifts. The baseline assumption is a zero gasoline price increase. As a scenario variable, an increase can be imposed to represent external changes congruent with other scenario adjustments.

4.1.2 Scenario Stakeholders

The first chapter of this thesis introduced the idea of interdependent stakeholders. In this section, I attempt to connect the notion of these interdependent stakeholders to the structure of the model. What role does each stakeholder play in influencing the future? The final chapter then concludes with strategic implications for these stakeholders.

Industry

The industry stakeholders consist both of the automotive industry and the energy industry. Of the parameters in the model, automotive players influence target and actual availability the most by setting the direction for the company. In addition, the automotive industry can influence the rate of technology development and corresponding learning curve effects to influence vehicle attributes. In contrast, the energy industry has the greatest influence over the extent of fuel infrastructure coverage. More subtly, the energy industry shapes the implicit decision rule that determines when desired infrastructure coverage should change. The assumed decision rule is an s-shaped function for desired infrastructure coverage with technology market share as an input, implying a return on investment limitation at low fleet fraction levels.

Civil Society

The stakeholders in civil society most notably affect the consumer awareness in the model. While I have not explicitly accounted for media effects, these efforts combined with education and activism are an area where civil society plays a major role. In addition, civil society can affect the way that technology attributes are valued. Social premiums on environmental benefits can be influenced through some of the same means that awareness is generated, analogous to the efforts made to deter smoking. Civil society could potentially redefine the role and importance of attributes such as operating cost, performance, and range.

Government

The role of government is implicitly embodied in a variety of scenario variable adjustments. The internalization fraction could be increased through fee-bates in which fees are charged for more damaging vehicles, and rebates are given for more friendly vehicles. The government could also adjust gasoline and other fuel prices through taxes or subsidies. In addition, the government could increase in target availability that the automotive industry must meet through mandated sales requirements. The government could also influence the rate and path of technology development by tightening fuel economy and emissions requirements.

4.1.3 Characteristics of the Scenario Set

With the scenario variables defined, and the roles of stakeholders considered, I now turn to the specific characteristics of the scenario set. Table 4-1 below outlines the scenario variable adjustments made to create each of the three scenarios discussed in this chapter.

Table 4-1. Scenario Variable Adjustments

Scenario Variable	**Scenario 1: ICE Domination**	**Scenario 2: Hybrid Competition**	**Scenario 3: Fuel Cell Transition**
Relative Performance	ICE: 1 Hybrid: **0.8*** FCEV: **0.8** EV: **0.8**	ICE: 1 Hybrid: 1 FCEV: 1 EV: 1	ICE: 1 Hybrid: 1 FCEV: 1 EV: 1
Relative Strength of Marketing Effort	ICE: 1 Hybrid: 1 FCEV: 1 EV: 1	ICE: 1 Hybrid: **2** FCEV: 1 EV: 1	ICE: 1 Hybrid: **2** FCEV: **6** EV: 1
Initial Target Availability	ICE: 1 Hybrid: 0.01 FCEV: 0.01 EV: 0.01	ICE: 1 Hybrid: **0.2** FCEV: 0.01 EV: 0.01	ICE: 1 Hybrid: **0.2** FCEV: **0.2** EV: 0.01
Initial Infrastructure Coverage	ICE: 1 Hybrid: 1 FCEV: 0.01 EV: 0.01	ICE: 1 Hybrid: 1 FCEV: 0.01 EV: 0.01	ICE: 1 Hybrid: 1 FCEV: **0.2** EV: 0.01
Profit Margin	ICE: 0.05 Hybrid: 0.05 FCEV: 0.05 EV: 0	ICE: 0.05 Hybrid: 0.05 FCEV: 0.05 EV: 0	ICE: 0.05 Hybrid: 0.05 FCEV: **0** EV: 0
Internalization Fraction	0	0	**1**
Discount Rate	0.30	0.30	**0.10**
*Gasoline Price Increase***	0	0	**4**

*Throughout this table, adjustments made to the baseline are highlighted in **boldface** font.
**The *Gasoline Price Increase*, if applied, is *added* to the *Base Gasoline Price of* $1.22/gallon.

From the table above, we see that to create the *ICE Domination* scenario, we adjust only relative performance of the alternatives. As noted in the baseline simulation above, the ICE propulsion technology already dominates in the short term under the default assumptions. By lowering relative performance of the alternatives, we simply reinforce this status quo. To create the *Hybrid Competition* scenario from baseline assumptions, we adjust two parameters from the default assumptions: relative strength of marketing efforts and initial target availability to increase awareness and availability of the hybrid alternative, respectively. In contrast, several changes are made to create the *Fuel Cell Transition* scenario in addition to the changes made to create the *Hybrid Competition* scenario. These changes are relative strength of marketing efforts for the FCEV, initial target availability for the FCEV, and initial infrastructure coverage to enhance all three feedback effects. In addition, the relative attractiveness of the FCEV is improved by lowering the profit margin and the discount rate while raising the internalization fraction and the price of gasoline.

Under the conditions outlined above, I discuss the scenario behavior, basis, and sensitivity in the following sections.

4.2 Scenario 1: ICE Domination

Figure 4-1 below illustrates graphically what was simulated under the scenario conditions described in the previous section. At the ten-year time horizon (shown with a dotted line), the ICE dominates the market. The model runs for 30 years for illustration, and we see that hybrids do slowly emerge over time, though to a lesser extent than in the baseline simulation.

Hybrids emerge eventually in the *ICE Domination* scenario because so long as the infrastructure barrier is removed (as it would be for hybrids), the awareness and availability (which are both barely non-zero) enable it to grow through the reinforcing mechanisms discussed in the last chapter. A baseline marketing effort seeds awareness, but provides no advantages over ICE. The time delays ensure that hybrid entry occurs only gradually.

Of course, the market share growth of hybrids is determined by model assumptions and inputs. Hybrids could be prevented from growing at all in the model by keeping hybrid awareness (through no marketing efforts) or availability (through no development) at zero. These conditions do not seem plausible, as auto manufacturers are already making hybrids available in the marketplace. Moreover, the media can serve to promote awareness even if marketing efforts are lacking.

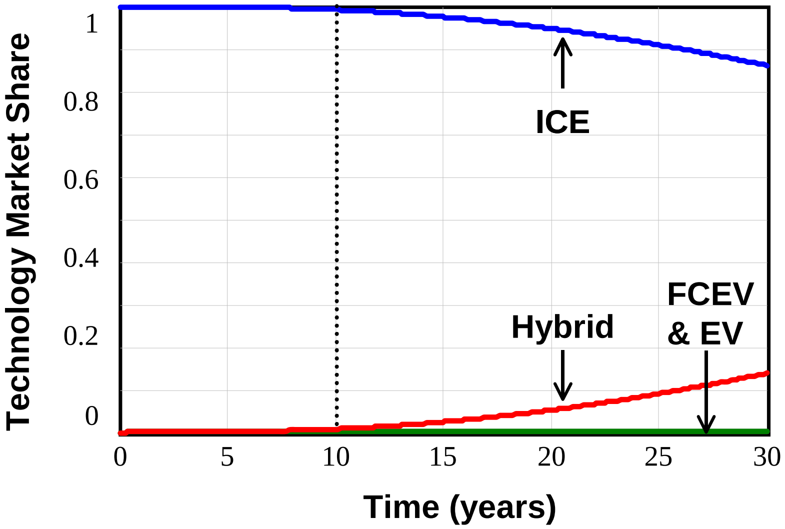

Figure 4-1. Technology Market Share in the ICE Domination Scenario

Scenario Basis

In the *ICE Domination* scenario, ICE vehicles are assumed to be superior on technical performance. This means that for the relative scale, the alternatives are inferior—perhaps due to the "turtle effect" of going up hills in a hybrid, or a lower power-to-weight ratio, or a limitation of top speed.

Infrastructure issues prevent FCEV and EV technologies from penetrating the market in this scenario because of the "chicken-and-egg" dilemma discussed earlier. Gasoline prices remain relatively low ($1.22/gallon in today's terms). Environmental costs are not internalized to the consumer purchase decision in this base case.

The discount rate applied to operating costs refers to the annual rate at which operating costs are internalized to the consumer over the vehicle lifetime (12 years). A high discount rate indicates that this operating cost is not a major factor in the consumer purchase decision. Here, a high discount rate indicates 30%. This assumption is consistent with studies that show how consumers evaluate the energy efficiency of appliances at the time of purchase (Train 1997). The high discount rate serves to prevent fuel price from playing a significant role in the purchase decision, supporting decisions for less fuel-efficient vehicles that are attractive on other dimensions.

Sensitivity

Figure 4-2 illustrates the sensitivity of technology market share in the *ICE Domination* scenario to changes in other sources of value for the hybrid. The single line represents the scenario itself, and the shaded areas surrounding that line represent different confidence levels for the sensitivity analysis. As with the baseline sensitivity test, this sensitivity test utilizes discrete runs from $11,000 to $23,000 per vehicle at increments of $1000/vehicle. The *Other Sources of Value* parameter is adjusted for the hybrid system while remaining at $17,000/vehicle for the other propulsion systems. The confidence bounds illustrated result from the discrete simulation runs that change values over the indicated range.

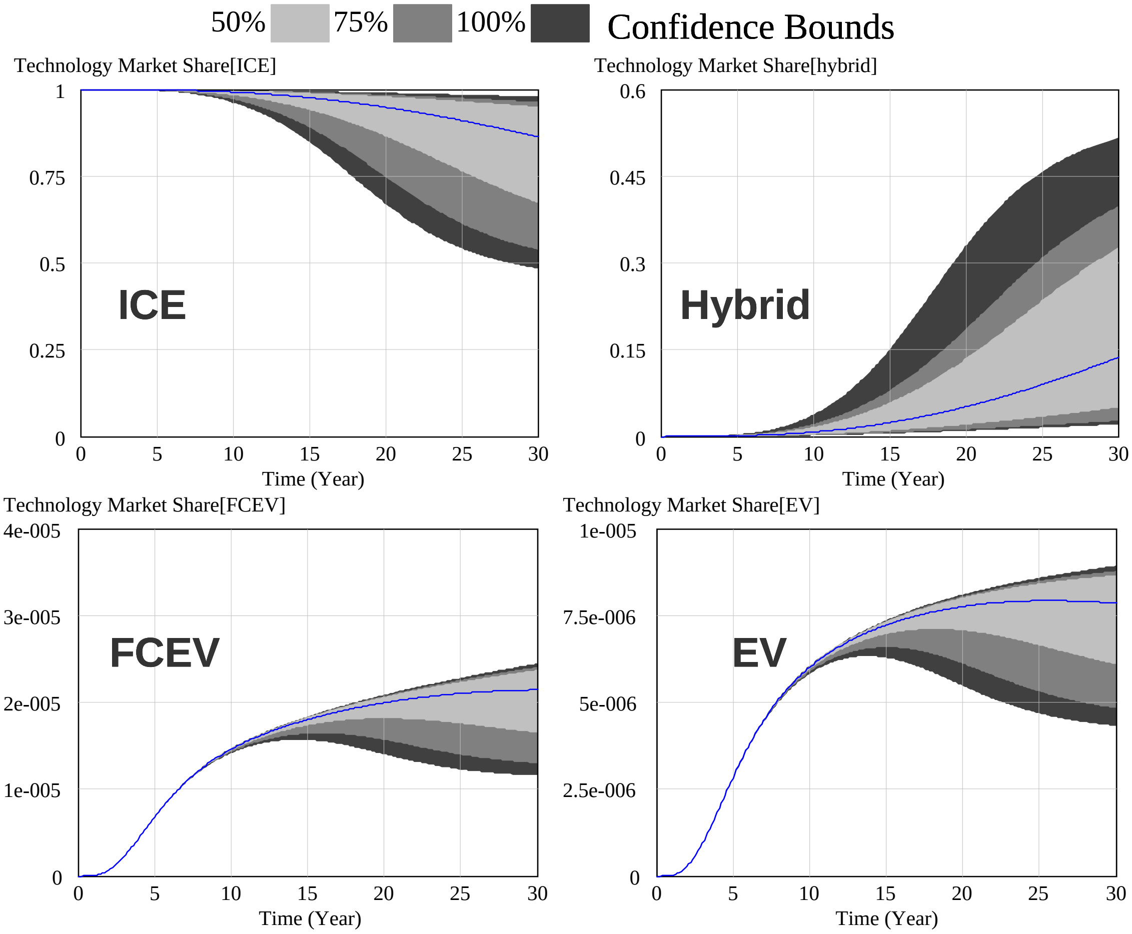

Figure 4-2. Sensitivity to Other Sources of Hybrid Value in Scenario 1

The variation in *Other Sources of Value* for the hybrid system results in a broad range of hybrid market share penetration possibilities, similar to but to a lesser extent than that visible in the baseline simulation test. On the high end of hybrid value, the ICE share declines more rapidly. As in the baseline, the FCEV and EV systems exhibit fluctuation in market share when the hybrid value is adjusted that is negligible relative to the hybrid and ICE systems. Though many factors play a part in the market share behavior for the propulsion systems, in this scenario the FCEV and EV systems are thwarted primarily by the fuel infrastructure barrier.

4.3 Scenario 2: Hybrid Competition

Figure 4-3 below illustrates the *Hybrid Competition* scenario. What we see, in comparison with the *ICE Domination* scenario, is that hybrids penetrate the market sooner than before. The s-shaped growth in hybrid market share is retained, but the delays are reduced by efforts to get awareness out (*Relative Strength of Marketing Effort*) and to commit to the hybrid product (*Initial Target Availability*).

The exact percentage of market share that hybrids capture at ten years is not relevant—indeed, it could be more or less depending on the particular parameter adjustments and assumptions. However, we can see that hybrids emerge "easily" (i.e., without many parameter adjustments). The infrastructure barrier again prevents the FCEV and EV from gaining market share in the Hybrid Competition scenario.

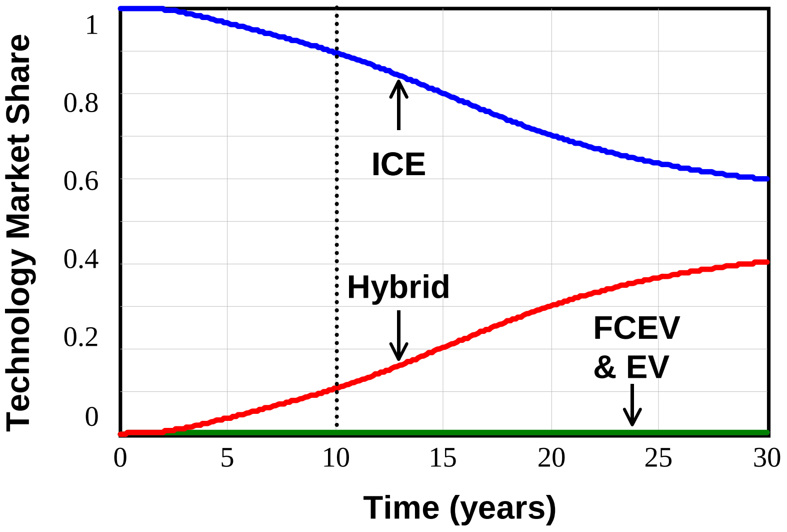

Figure 4-3. Technology Market Share in the Hybrid Competition Scenario

Scenario Basis

The first condition for the *Hybrid Competition* scenario is a strong marketing push for the hybrids to increase awareness. In addition, there is an increase in target availability at the outset. Like the baseline simulation but unlike the *ICE Domination* scenario, the hybrids considered comparable in this scenario in terms of relative technical performance. This performance plays a major part in determining product attractiveness because there is a strong negative valuation imposed by the consumer if the performance is less than the ICE (see the discussion on performance in Chapter 3).

The remaining conditions for the *Hybrid Competition* scenario are the same as those in the *ICE Domination* scenario. It is important to note here that we have not created a “green world”; with a little bit of push, the hybrids penetrate the market.

Sensitivity

Figure 4-4 illustrates the sensitivity of technology market share in the *Hybrid Competition* scenario to changes in other sources of value for the hybrid. The single line in Figure 4-4 represents the scenario simulation, and the shaded areas surrounding that line represent different confidence levels for the sensitivity analysis. As with the previous sensitivity tests, this test adjusts *Other Sources of Value* for the hybrid system from $11,000 to $23,000 per vehicle in increments of $1000/vehicle.

For the same variation in *Other Sources of Value* for the hybrid system as performed on the *ICE Domination* scenario, the range of possibilities for hybrid market share penetration possibilities is extended in the *Hybrid Competition* scenario. Even at the low end of hybrid value, the hybrid technology penetrates the market more rapidly than in the *ICE Domination* scenario. Again however, the FCEV and EV market share fluctuation when the hybrid value is adjusted is negligible relative to that for the hybrid and ICE systems.

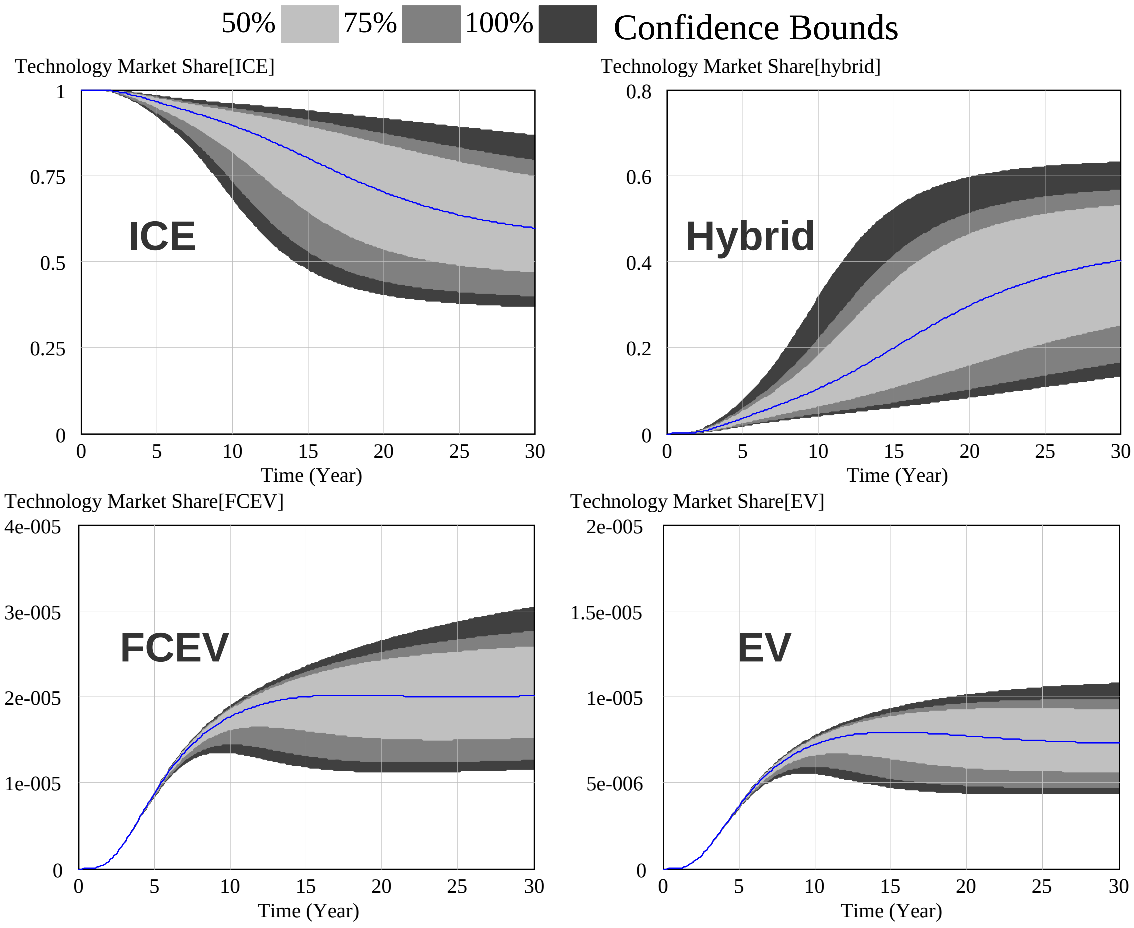

Figure 4-4. Sensitivity to Other Sources of Hybrid Value in Scenario 2

4.4 Scenario 3: Fuel Cell Transition

In the third and final scenario, the hybrids increase along with fuel cells at first, but then market share of fuel cells plateaus for nearly a decade before increasing again to the ultimate attribute-determined level. In the 30-year time horizon shown in Figure 4-5 below, fuel cell market share has not yet reached the attribute-determined equilibrium level, but rather is in the early stages of another s-shaped growth curve.

Why does fuel cell market share plateau? As noted before, we seeded the infrastructure and demand increased accordingly. But as discussed in Chapter 3, the function for increasing desired coverage is non-linear, based on a threshold that the technology must cross in the *fleet*. Figure 4-5 shows market share that then corresponds to sales per year. Therefore it takes a number of years of fuel cell sales before they cross the fleet threshold so that energy companies have an incentive to invest in greater infrastructure coverage.

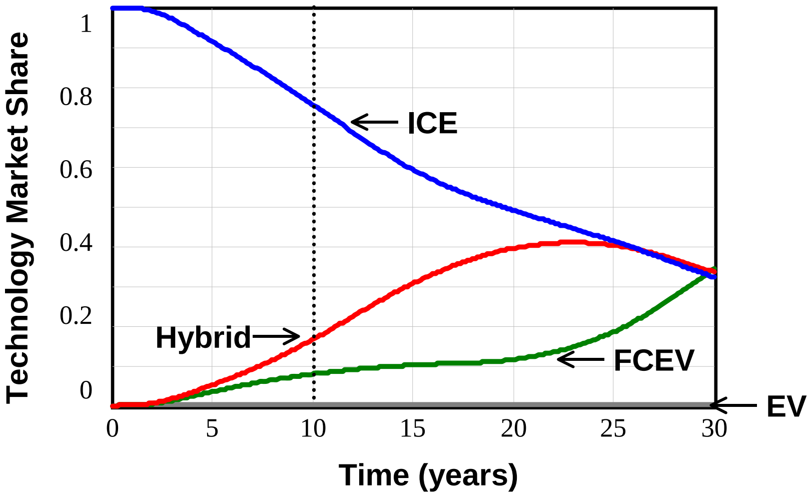

Figure 4-5. Technology Market Share in the Fuel Cell Transition Scenario

During this FCEV market share plateau, hybrids penetrate the market as the dominant alternative to the ICE. Once fuel cells gain enough momentum in the fleet fraction, their market share increases again, and the hybrids and ICE decline accordingly.

Scenario Basis

In the *Fuel Cell Transition* scenario, an initial infrastructure investment helps to seed demand for the FCEV. The translation of this modeling condition to the real world might be through government intervention, or through a coordinated commitment among energy and automobile companies. For modeling simplicity, the investment is seeded at the start of simulation—in reality, there would be a delay—but we can learn from this scenario nonetheless, because the insights come from the patterns (not the percentages).

Relative to the other scenarios, this scenario is more of a “green world” with greater governmental intervention and consumer sensitivity to environmental issues. The gasoline price is quite high (raised to $5.22/gal through taxes or an oil supply crisis), and environmental damage costs are internalized (likely through a system of fee-bates). Also, the operating cost discount rate is lower (10% instead of 30%), indicating a greater sensitivity to future costs at the time of purchase than there was in the base case scenario. This sensitivity might well correspond with tighter macroeconomic conditions.

In technical performance, the fuel cell is considered equal (there is no start-up delay and it has an equal power-to-weight ratio). A strong marketing push and learning curve effect have been imposed to create this scenario, both on fuel cells and on hybrids.

Sensitivity

Because the *Fuel Cell Transition* scenario exhibits the most competition from alternatives of the scenario set, I perform sensitivity tests on both FCEV and hybrid sources of value to examine the effect on the market share of all four technologies. Figure 4-6 below illustrates the sensitivity of technology market share to other sources of *FCEV* value.

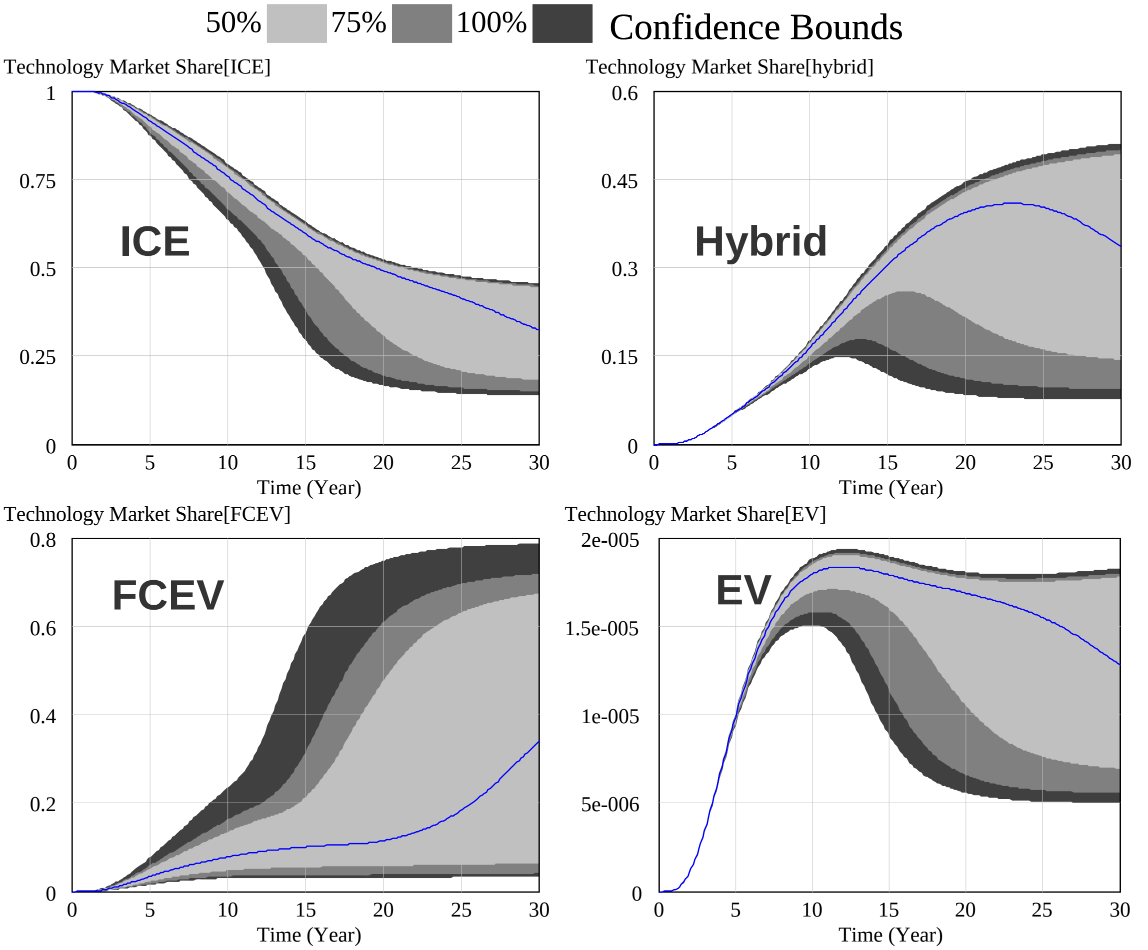

Figure 4-6. Sensitivity to Other Sources of FCEV Value in Scenario 3

The single line in Figure 4-6 above represents the scenario simulation, and the shaded areas surrounding that line represent different confidence levels for the sensitivity analysis. The testing range of *Other Sources of Value* for the FCEV system is from $11,000 to $23,000 per vehicle in increments of $1000/vehicle.

The market share behavior exhibited by the four technologies spans a broad range of possibilities in response to the FCEV value adjustments. The exchange of market share occurs between the ICE, hybrid and FCEV alternatives—as FCEV value increases, the market share of the ICE and hybrid decline. At the low end of FCEV value, little variation is observed in FCEV market share. This lack of variation indicates that below a threshold where product attractiveness is insufficient to generate fleet fractions of the technology that will increase the infrastructure coverage, so the plateau remains low for a long time. At the high end of FCEV value, the plateau in market share is shorter and occurs at higher levels, because the product carries greater value than the alternatives.

Because hybrid systems also play a major role as the "interim" technology in the *Fuel Cell Transition* scenario, it is worthwhile to explore variations in *hybrid* value as well, with all else equal. Figure 4-7 below illustrates the sensitivity of technology market share of alternatives in the *Fuel Cell Transition* scenario to changes in other sources of value for the hybrid system.

When *Other Sources of Value* for the hybrid system are varied in the *Fuel Cell Transition* scenario, the effects are visible for both the FCEV and ICE alternatives. When hybrid value is high, hybrids penetrate the market early, stealing market share from the ICE and effectively holding the FCEV to an extended plateau. For low hybrid values, the ICE retains higher market share in the short term and the FCEV ultimately dominates the market in the long term. At the 30-year time horizon, the ICE market share occupies a relatively small range of values despite the range for the FCEV and hybrid.

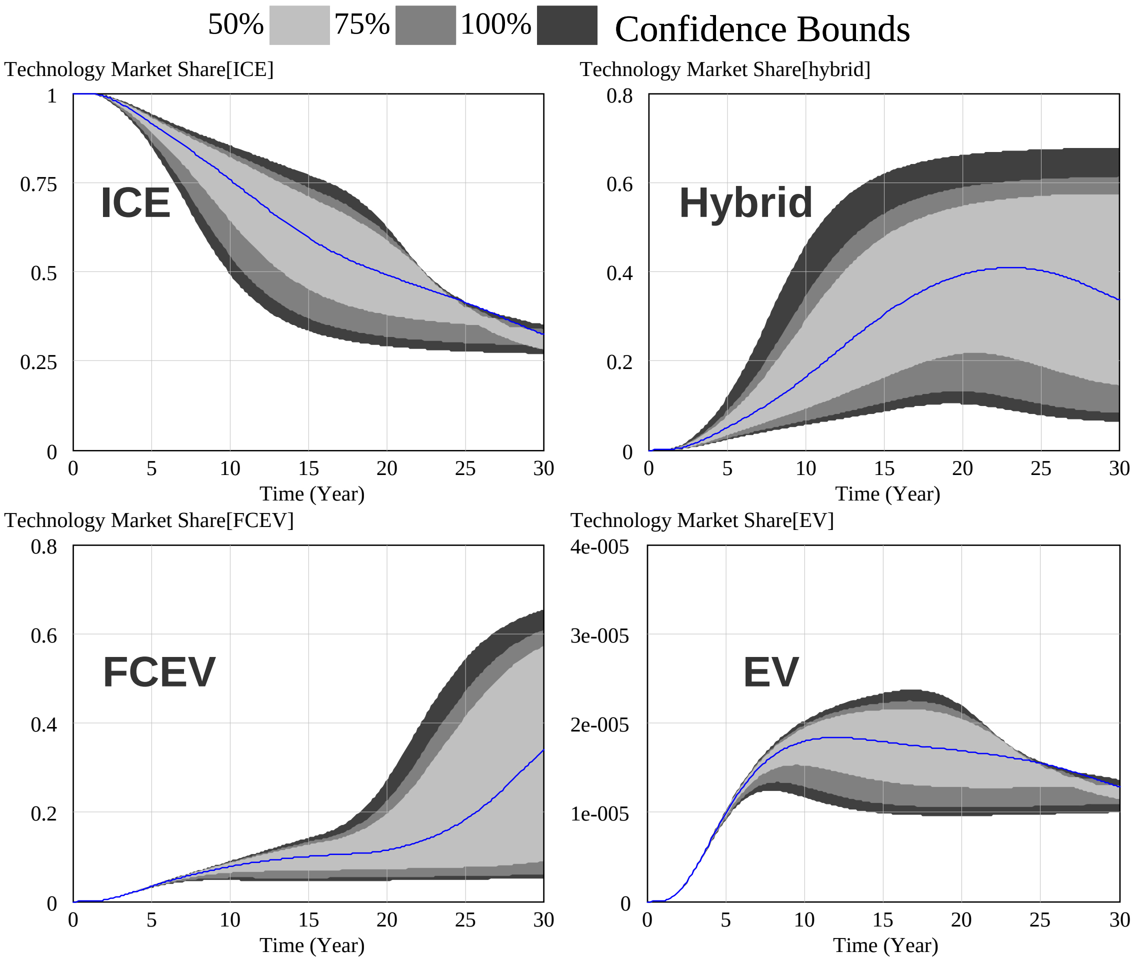

Figure 4-7. Sensitivity to Other Sources of Hybrid Value in Scenario 3

With the *Fuel Cell Transition, Hybrid Competition, and ICE Domination* scenarios in mind, I now transition to the final chapter of this thesis, in which I reflect on aspects of the modeling process as well as the scenarios themselves.

Chapter 5 Conclusions

The previous chapters outlined critical technology attributes and connected them with a dynamic model of how demand for propulsion technologies might evolve. This model was then used as a template for creating scenarios that span a wide range of possibilities for the near-term future, from the status quo of ICE domination in the market to a visible transition to fuel cell vehicles. In short, I have explained how one could begin to explore the propulsion possibilities over the time horizon of interest. So while this thesis must now conclude, my conclusions regard what I learned in this process, and my recommendations for further efforts. It is my earnest hope that this thesis exploration will serve as a beginning for other interested researchers.

The following sections describe conclusions about the scenario modeling process, and a discussion of how the scenarios can be connected to stakeholder strategies.

5.1 Scenario Modeling Process

Regarding the scenario modeling process used in this thesis, I broadly conclude that the system dynamics methodology helped to articulate the underlying scenario connections and assumptions. The use of a model necessitated explicit and transparent assumptions. This transparency makes it easier to criticize and question assumptions for further refinement. Inconsistent assumptions are also easily identified through the process.

I also learned from the modeling process how important it is first to understand the model as fully as possible, and also to share the model as openly as possible. Sharing the model during the model creation process is challenging—on the one hand, sharing enables critical input throughout the process; on the other hand, it requires much effort to explain the essential without being hindered by excessive detail. A model that is introduced with insufficient understanding can be readily misinterpreted, so this is a fine line to tread.

In this modeling work, as discussed in the beginning of this thesis, I utilized input from a variety of stakeholders while creating the model to serve as a check on my assumptions. I anticipate that the explicit model sharing that comes forth in this thesis will invite further criticisms and questions for further exploration. Here I attempt to seed such input by offering my own insights and recommendations first.

5.1.1 Modeling Insights

In this section I discuss critical insights gained from the modeling process regarding the extent and timing of alternative penetration in the market. To illustrate these insights, I utilize discrete-run sensitivity tests relative to the *Fuel Cell Transition* scenario. I opted to use this scenario as a starting point because the scenario conditions more readily encourage a variety of propulsion alternatives.

The first insight is that multiple equilibrium levels are possible for the alternatives. In other words, certain value thresholds must be met for the alternatives to penetrate the market. Figure 5-1 below demonstrates this phenomenon for the FCEV with contours representing $1/gallon increments of gasoline price increase, added to the base gasoline price of $1.22/gallon.

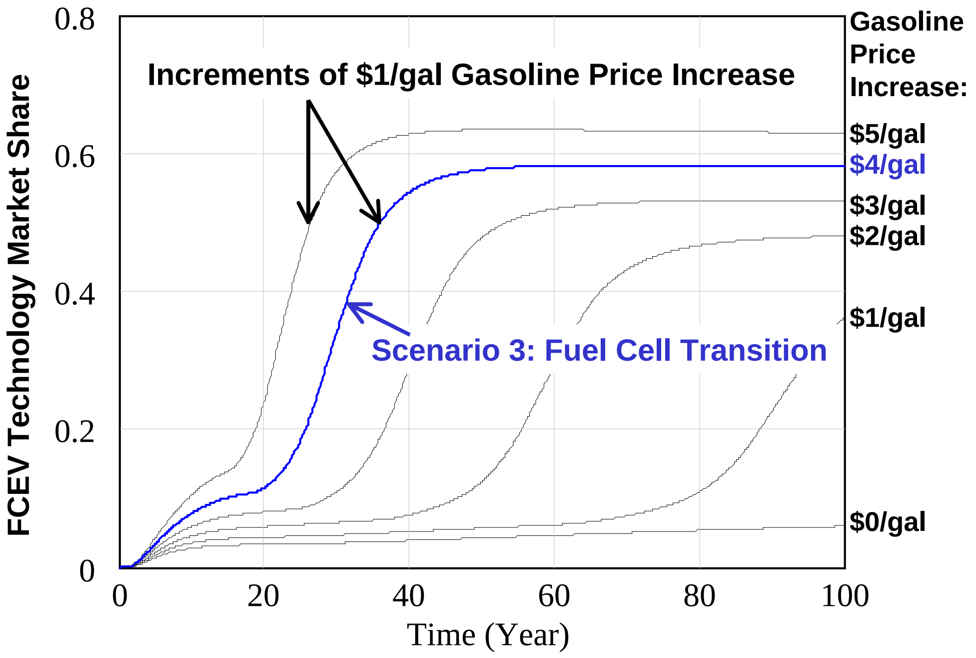

Figure 5-1. Effect of Gasoline Price on FCEV Market Share Level

The plots in Figure 5-1 above extend to the 100-year time horizon to illustrate the equilibrium level as much as possible. The simulation runs illustrated are within the conditions of the *Fuel Cell Transition* scenario for all parameters except gasoline price.

At higher gasoline price, the relative value of the FCEV as an alternative increases, so the equilibrium level increases. More broadly, adjustments that directly impact the consumer value part of the model—be they in fuel price, relative performance, or other sources of value—adjust the ultimate market share that the technology attains. Such multiple equilibrium levels have been observed for other nonlinear systems (e.g., Miller 1998).

Another area of modeling insight regards the infrastructure barrier for the alternatively fueled propulsion systems such as the FCEV and EV. Adjustments in the level of infrastructure coverage enable these alternatives to penetrate the market. As illustrated in Figure 5-2 below, adjustments in increments of 5% initial infrastructure coverage dramatically affect the path that the FCEV takes to penetrate the market.

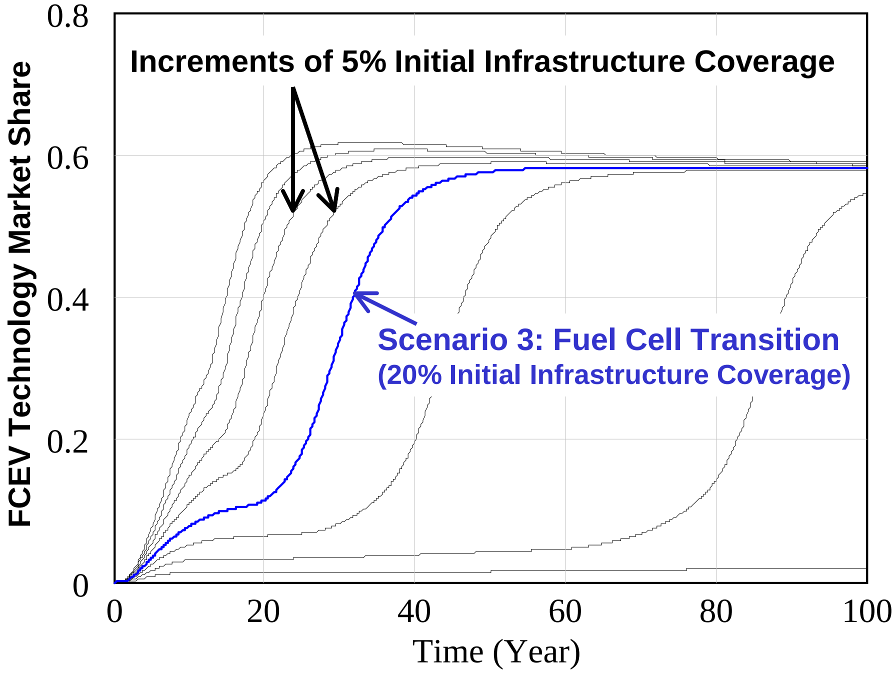

Figure 5-2. Effect of Infrastructure on Timing of FCEV Market Penetration

The simulation runs illustrated in Figure 5-2 above are within the conditions of the *Fuel Cell Transition* scenario for all parameters except infrastructure investment (as set by the *Initial Infrastructure Coverage* parameter). The first plateau for each contour corresponds to the initial infrastructure coverage level set at the start of simulation. As this initial level is increased, the plateau of FCEV market share shortens because the FCEV increases the fleet fraction and thus the desired infrastructure coverage more quickly with a higher initial starting point. Once the desired infrastructure coverage increases, the FCEV market share path embarks on a second stage of s-shaped growth to the ultimate equilibrium level. Adjustments in infrastructure coverage thus do not affect the equilibrium level (excepting the zero coverage state), but rather affect the time in which this level is attained.

The above infrastructure barrier is a formidable threat to hydrogen-fueled fuel cell vehicle success under the assumptions of this model. If gasoline processor fuel cells become viable from a cost perspective, the fuel cell future could progress much more rapidly, alongside the hybrid path exhibited in the *Hybrid Competition* scenario.

5.1.2 Recommendations for Further Exploration

In this section, I offer some recommendations for further exploration from a scenario-modeling standpoint. As a point of reflection, I offer the following quote by Pierre Wack (1985b, p. 140):

> "Scenarios structure the future into predetermined and uncertain elements. The foundation of decision scenarios lies in exploration and expansion of the predetermined elements: events already in the pipeline whose consequences have yet to unfold, interdependencies within the system (surprises often arise from the interconnectedness), breaks in trends, or the 'impossible'."

The recommendations offered for further exploration are an attempt to come closer to what Wack would consider a decision scenario, rather than a first-generation scenario. I focus on several areas of development: robustness of assumptions, model extension, model usage, alternative scenario construction, and finally next-generation or decision scenarios. The latter area of exploration leads naturally to the next section on connecting scenarios to strategy.

Robustness of Assumptions

As always, the usefulness of a model is only as good as the data that enter into it. Here I have tried to include relevant elements rather than limiting the analysis to what is known. Indeed, scenario analysis explicitly welcomes uncertainty to explore diverse futures. Yet much can still be improved on for the basic parametric assumptions underlying the model. I encourage interested readers to explore scenarios using alternative data and assumptions. Technology assessment efforts continue as researchers seek to understand what will be the optimal technology for sustainability, and advise us to consider broad ramifications of a switch in regimes, not just the tailpipe emissions.

Model Extension

For ways of extending the model, I recommend exploring different technologies than those considered here—particularly diesels, compressed natural gas vehicles, gasoline processor fuel cells. While I simplified the list of possibilities to four distinct systems, there are many potential propulsion options that could play a role in the future automotive market.

A global perspective is a much-needed extension for this modeling work. In this analysis, I kept primarily to a U.S. perspective because of the data I used. It would be fascinating to extend the model, even if just to two "regions"—developing and industrialized. Variables such as market size, consumer value of technology attributes, vehicle life and miles traveled would behave differently for emerging markets than for industrialized ones. Infrastructure coverage might be more leveled in emerging markets.

In formulating the model, I utilize a generic market share structure that does not change over time to represent the industry players (us and them). For simplicity, I divide the market evenly between our competitors and us. A more sophisticated approach would be to consider the market share implications of different actions within the model. Market share could be explored such that it can change if a strategy is not followed.

Model Usage

A user interface can be created using the Vensim DSS modeling software to generate a game simulation. This game interface would enable decision-makers to directly interact with the model. Decisions would be simulated as parameter adjustments, enabling real-time feedback on the effect of a chosen path. This form of feedback could greatly accelerate learning and understanding of the model.

Alternative Scenario Construction

Using the same model and basic assumptions, alternative scenarios could be created through the same method of scenario variable identification and adjustment that I used. For example, a scenario could be created that explores what conditions are needed for the market penetration of electric vehicles. Or alternatively, the existing scenarios could be refined through scenario variable adjustment to influence the specific path that is chosen to illustrate the future. For example, the scenario variables in the *Hybrid Competition* scenario could be readily adjusted to create a steeper penetration in the marketplace. The only caution here is to ensure that the assumptions are as internally consistent as possible.

Next Generation Scenarios

Wack (1985a, 1985b) posits that there are multiple generations to scenarios from the first-generation exploratory scenarios to the next-generation decision scenarios. I have created a set of first-generation scenarios using input from interviews and from research. While the modeling exercise can add rigor to the scenario creation process (Paich and Hinton 1998), these scenarios remain "rough" and could thus be further refined. An ideal means of refining the scenarios is through expert dialogue. Such dialogue could readily be combined with decision makers' interaction with the model via a game interface, as recommended earlier.

5.2 Connecting Scenarios to Strategy

Though he acknowledged the importance of the exploratory first-generation scenarios in getting to the next stage of scenario planning, Pierre Wack reflected on the limitations of these scenarios (1985a, p.77) as follows:

> "This [first-generation] set of scenarios seemed reasonably well designed and would fit most definitions of what scenarios should be. It covered a wide span of possible futures, and each scenario was internally consistent." Yet when the scenario set was introduced to decision makers, "no strategic thinking or action could be taken from considering this material."

The above quote emphasizes the importance of connecting scenarios to strategy. If the scenarios are considered in isolation, they can be relegated to the role of interesting fiction. Some of this connection can be attained through scenario refinement, but much of it is attained through scenario usage.

While further refinement of the scenarios is both possible and recommended, the scenarios created in the previous chapter can be utilized to consider alternative strategies. In this section, I discuss how the scenario set could be used for strategic assessment, and what implications could emerge for leadership toward a desired future.

5.2.1 Strategic Assessment

To utilize scenarios as part of an assessment of strategic alternatives, I construct a scenario-strategy matrix (Van der Heijden 1996, p. 234). The matrix outlined in Table 5-1 below demonstrates how alternative strategies might fare in the three scenarios. Rather than simply denoting whether a strategy is successful or not, I provide brief commentary on the likely path of each strategy for a given scenario.

Table 5-1. A Scenario-Strategy Matrix to Explore Options

Strategy	**Scenario 1: ICE Domination**	**Scenario 2: Hybrid Competition**	**Scenario 3: Fuel Cell Transition**
"*Tried and True*": Focus on improving ICE technology. The alternatives are passing fads that lose money.	Bingo! Cash in. Have we now opted to stay with ICE technology in the long term?	The focus on ICE may be successful if it is flexible enough to accommodate a hybrid system.	Most likely a losing bet. Need to keep feelers out for the signs of this transition.
"*Dabbler*": Keep all options open by investing in each. Likely to incur losses in the short term.	May lose quite a bit of money on alternatives, while ready an ultimate transition.	Succeed in hybrid entry. May be able to build on hybrid awareness for other technologies.	The dabbler is ready for anything, so the technology mix that emerges here is welcome.
"*Gambler*": Put all of the "eggs" into a basket that is deemed most attractive, such as the hydrogen fuel cell.	Oops! Maybe we did not invest enough, or we did not form the right alliances.	The gambler could be successful if he develops a gasoline fuel cell akin to a hybrid.	The gambler may help to direct the evolution of this future. Profits uncertain.

The strategies explored in the context of the three scenarios in Table 5-1 elucidate the complexity and subjectivity of this process. A strategy-scenario matrix would be ideally explored as part of a dialogue between knowledgeable experts and decision-makers. Even with clear and quantitative scenarios, the appropriateness of a specific strategy may remain unclear. For example, under the "Tried and True" strategy within the ICE Domination scenario, while profits benefit greatly, the question remains of: what do we intend for the long-term future? These are not superficial strategies, and the answer is not easy. More discussion and “fleshing out” of the scenarios would be needed to fully comprehend the implications of the scenarios on the most effective strategies.

5.2.2 Implications for Stakeholder Leadership

One stakeholder can have a strong influence on the future, based on where investment dollars go, and which alliance partners are chosen. To make wise investment decisions, the stakeholder must work to understand where the real levers are in the marketplace. As mentioned earlier, the stakeholders mentioned in Chapter 1 are involved in shaping the future. In this section, I discuss what actions could be taken by industry, civil society, and government stakeholders to shape the future.

Industry

Industry stakeholders hold the critical role of choosing what propulsion options to develop, and the kind and extent of infrastructure that should support the options. Stakeholders in industry have much to lose if a strategy is misaligned with the future that unfolds. At the same time, the choices that industry makes can also influence the future. The scenario-strategy matrix in the previous section touches on this dilemma. Even so, I conclude with some implications for industry stakeholders.

To make a fundamental shift toward an alternative propulsion system, collaboration both among the varied industry stakeholders, both in automotive and fuel domains, but also with government and civil society where possible. Once an end state is defined, such as reliance on hydrogen fuel generated from renewable resources, then the next step is to figure out what path is most appropriate to get to that state. This transition cannot be overlooked. For instance, if gasoline fuel cells are pursued, how might that affect the transition to a hydrogen economy? Would it be easier, harder, or unaffected by such a path?

Civil Society

In a way, the members of civil society play the most central role in the future of propulsion, in that the consumers make the decision of what to buy. Even if industry makes a technology available as mandated by the government, consumers can choose not to buy such a technology if they do not perceive it to add value to their mobility needs. However, discussing strategic implications for civil society seems nebulous, because such society is after all made up of individuals. Nonetheless, I conclude that there are ways in which members of civil society can intentionally influence the future.

As mentioned previously, civil society includes educators and activists as well as consumers. Not only can education and activism increase awareness of alternatives, such efforts can also begin to affect how civil society values a consumer good. Witness the intensive efforts made in the anti-smoking campaign within the U.S., and its effectiveness at reducing smoking behavior. In addition to influencing regulation to ban smoking in public places, these efforts spawned a sort of social pressure. This pressure shifted the default assumption from one in which smoking was accepted and valued, to one in which it was not accepted.

Admittedly, the implications of smoking are quite different from those of choosing a propulsion system. Indeed, within the United States, personal and collective health drives much of public spending and interest. But if the choice and implications (e.g., the connections between the environmental effects of a propulsion system on human health) are made clear, social pressure can result in dramatic shifts.

Government

Government policy makers play a critical role in shaping the future. A key function of government is to ensure that the needs of society at large are met. For many externalities that are not comprehended in the marketplace, government intervention can ensure that such externalities are taken into account. For example, the environmental externalities of automobiles can be internalized through fee-bates.

Despite their potentially virtuous role, governmental bodies can be plagued by delays in decision-making, special interest biases that overwhelm the common good, and misinformation. To effectively shape the future of automotive propulsion toward one that is sustainable, regulators must work with their counterparts in industry and civil society to better both what is considered to be the ideal future, and to understand the obstacles that must be overcome to achieve such a future. As noted for infrastructure coverage, the level of investment (e.g., in a hydrogen distribution system) can play a critical role in determining whether an attractive alternative ultimately succeeds in the marketplace. Policy makers can influence this level via subsidies or requirements.

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Appendices

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Appendix A: Interview Guide

Future Propulsion Regimes: Scenario Planning Using System Dynamics

Introduction:

Driving forces for shifts in propulsion regimes are highly uncertain. While technology inroads are being made on all types of known propulsion regimes (e.g., hybrids, fuel cells, advanced internal combustion, battery electric), we do not know which will lead the market in years to come.

The purpose of this interview is to better understand the drivers of propulsion shifts, and the dynamics of how they play out. I am hoping that you can provide insight into regulatory, industry, and/or consumer dynamics.

I will probe you to gather qualitative data regarding what you consider to be key uncertainties and concerns. The data from this interview will be used to help structure near-term propulsion scenarios.

General exploratory questions:

What is your title and organizational unit? Can you describe your present position?

What forces (regulatory, competitive, consumer) might drive a shift in propulsion regimes? How might this shift occur?

Suppose you have the opportunity to meet with a time traveler, who has experienced the future ten years from now. You are in charge of developing and implementing the long-term propulsion strategy for your company—you are the “propulsion czar.” You can only ask the time-traveler three questions. What would they be?

If the future in ten years is what you have hoped for, with uncertainties rolling out in the desired direction, how would you answer your own three questions?

If the future in ten years is what you have feared, with uncertainties rolling out in an undesirable direction, how would you answer your own three questions?

If you were to sketch a rough picture of a key concern, what would it look like? What is the hoped-for path into the future? What path(s) do you fear?

Suppose you, as propulsion czar, have to decide RIGHT NOW what strategy to pursue for the next ten years. If this decision had to be made immediately, what would you do?

Additional questions for probing:

Regulators
How might regulatory action impact technology choice—that is, what technologies are made available at a given time?
How might regulatory action impact the adoption of alternative technologies?
What pressures are regulators subject to?

Industry
What pivotal events can you identify from automotive history that should remain in our memories as important lessons for the future?
What competitive actions might lead to a shift in propulsion regimes?

Society
How is consumer awareness of alternative technologies generated?
How might this awareness impact adoption of the technology?
How might consumers decide between propulsion technologies?

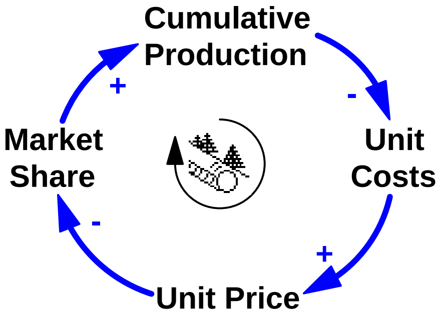
Technology
What attributes of this technology do people value?
How does the technology evolve—that is, how do the attributes change over time? What are the drivers for this change?

Economics
What do you expect the learning curve and economies of scale to be for the technology?
How could this impact the rate of technology development?

Environment
What fuel cycle and infrastructure issues are created with different propulsion technologies? What sort of limits might they run up against?

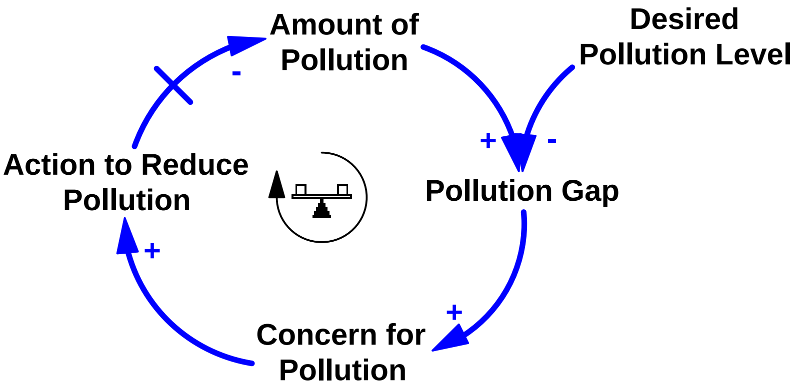
Appendix B: System Dynamics Basics

This appendix outline some of the basics of system dynamics. The "system" part of system dynamics implies a consideration of closed-loop systems, in which feedback mechanisms are of utmost importance. The first type of feedback mechanism is reinforcing feedback (the "vicious" or "virtuous" cycle), implying sustained growth or decline. An example is the learning curve illustrated in Appendix Figure 1 below: as cumulative production increases, unit costs decline, and prices decline accordingly (the + indicates change in the same direction as the preceding variable). Price is inversely related to market share, so as it declines, the market share (demand) will increase. As demand increases, then cumulative production increases. The key here is to multiply the negative(-) connections; if there are an even number of negative connections, the feedback is positive or reinforcing because the connections cancel each other through multiplication. If there are an odd number of negative connections, the feedback is negative or balancing.



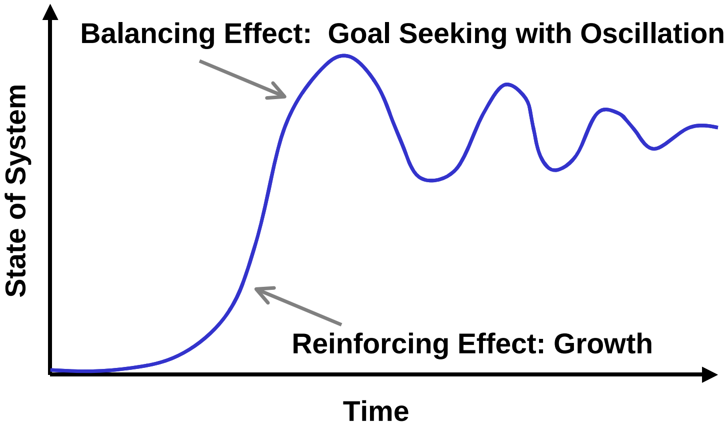
Appendix Figure 1. Example of Reinforcing Feedback Loop

The second type of feedback mechanism is known as a balancing feedback loop. The balancing loop exhibits "goal-seeking" behavior: rather than growth or decline, the balancing feedback seeks to attain equilibrium level. The presence of delays in the system (illustrated by hatchet marks on the arrows) can result in oscillation around the desired state. An example of the reinforcing feedback mechanism could be efforts to mitigate pollution, as illustrated in Appendix Figure 2 below. Suppose there is a desired pollution level that serves as the goal. The difference between this goal and the actual level of pollution results in a pollution gap. The greater the gap, the greater the concern for pollution. And the greater the concern, the greater the action to reduce pollution. This of course takes time, and so the delay is represented by a hatchet, but over that delay the actual pollution level declines. This decline means the gap is smaller so concerns lessen, so actions lessen, and so on.



Appendix Figure 2. Example of Balancing Feedback Loop

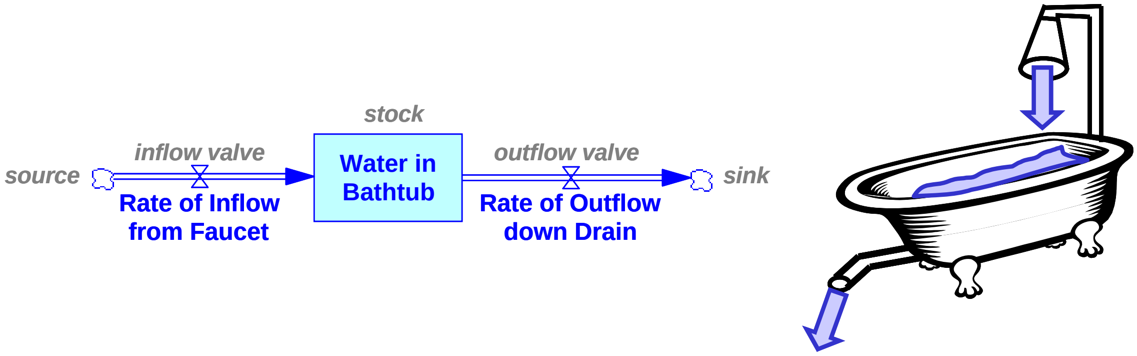
Real-world systems have combinations of balancing and reinforcing loops. You would not see one type of feedback loop acting in isolation. S-shaped growth occurs when reinforcing and balancing loops are present: there is a period of sustained growth followed by a damping of that growth as the system seeks its equilibrium state. Appendix Figure 3 illustrates interacting reinforcing and balancing effects.



Appendix Figure 3. Example of Interaction of Reinforcing and Balancing Effects

If feedback loops are the "system," then stocks and flows are the "dynamics" of system dynamics. The presence of a stock and flow structure means that the system can contain inertia, memory, or delays. The stocks are at the heart of this. They represent accumulation of something (material, energy, or information) and the levels of the stocks characterize the state of the system. Flows represent the rates that enter or leave a stock, and thus represent how the stock changes over time. In a system "snapshot", the flows would be invisible, and the stocks would be apparent.

The classic example is the bathtub, as illustrated in Appendix Figure 4 below. There are two flows: inflow of water from the faucet (controlled by an inflow valve), and flow out of the bathtub down the drain (controlled by an outflow valve). The water in the bathtub is the stock, perhaps quantified in terms of gallons, while the rates of flow would be quantified in terms of gallons per minute. (In mathematical terms, the stock level is determined by integrating the rates of flow.)



Appendix Figure 4. Stock and Flow Representation of Bathtub

Stocks and flows combine with feedback loops to create dynamic systems. Stocks provide information about the system (so the causal arrow would exit a stock), and the stock can only be changed through its flows (so the causal arrows lead to flows, not stocks).

The flow arrows implicitly represent causal arrows leading to the stock variable—for instance, in a causal loop structure, an increase in the rate of outflow would lead to a decrease in the stock and thus be represented by a negative connection.

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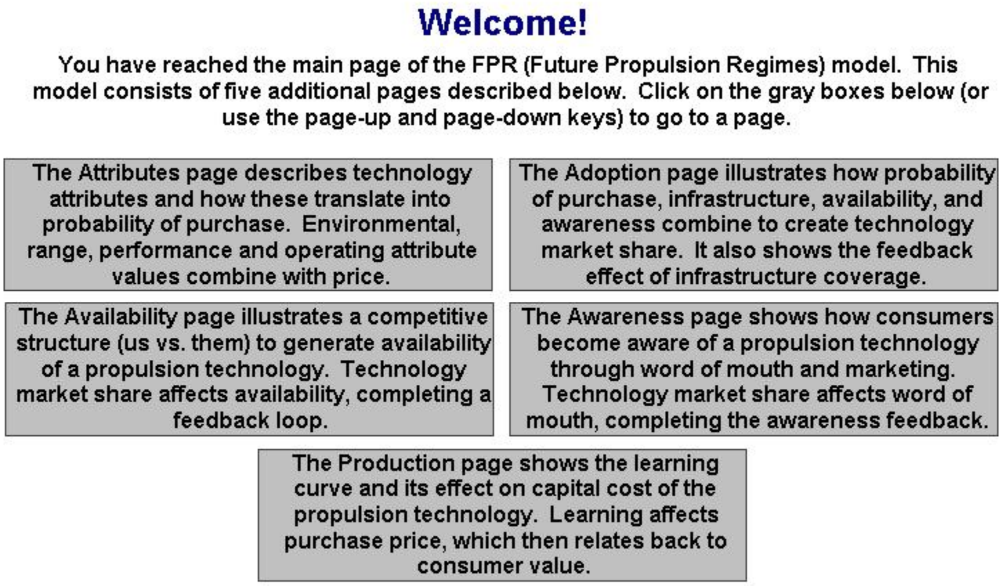


Welcome!

You have reached the main page of the FPR (Future Propulsion Regimes) model. This model consists of five additional pages described below. Click on the gray boxes below (or use the page-up and page-down keys) to go to a page.

The Attributes page describes technology attributes and how these translate into probability of purchase. Environmental, range, performance and operating attribute values combine with price.

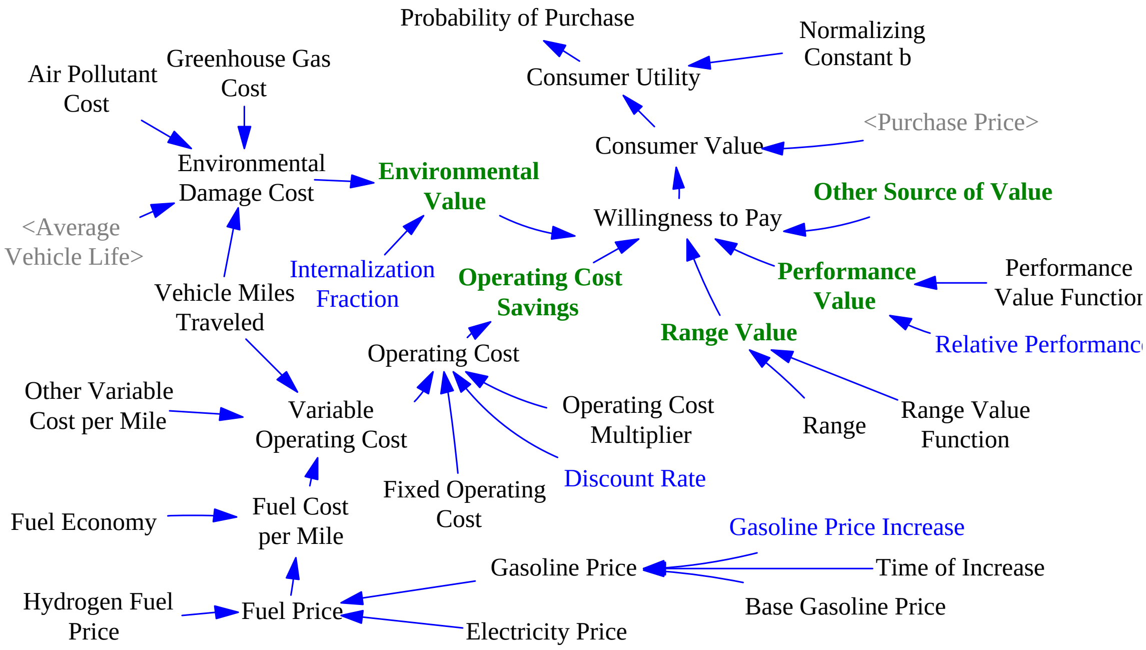
The Adoption page illustrates how probability of purchase, infrastructure, availability, and awareness combine to create technology market share. It also shows the feedback effect of infrastructure coverage.

The Availability page illustrates a competitive structure (us vs. them) to generate availability of a propulsion technology. Technology market share affects availability, completing a feedback loop.

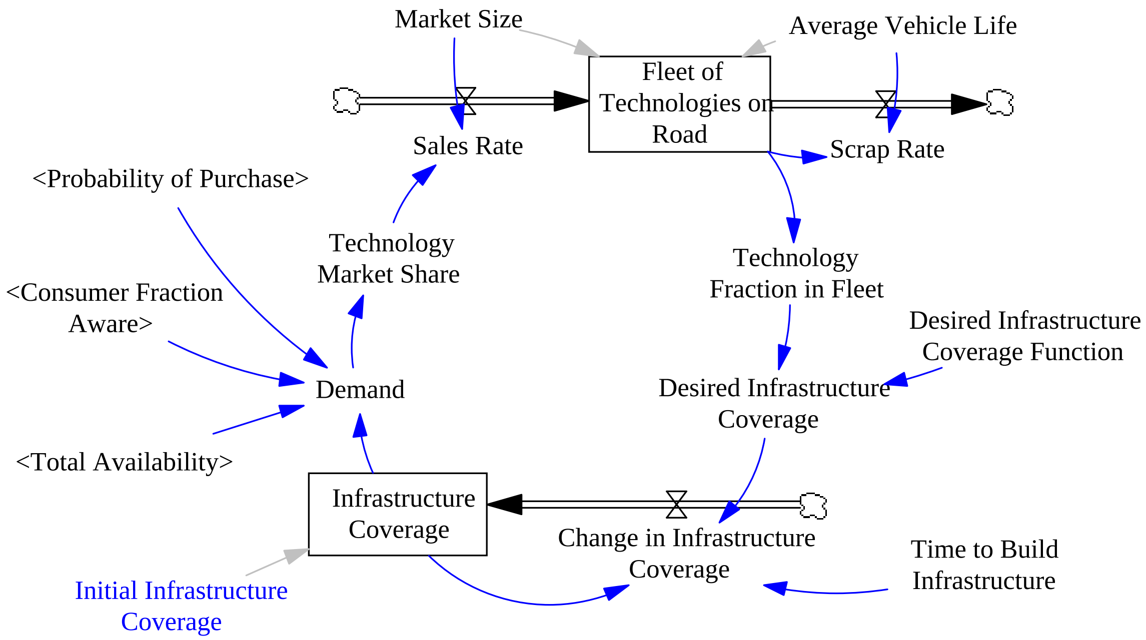
The Awareness page shows how consumers become aware of a propulsion technology through word of mouth and marketing. Technology market share affects word of mouth, completing the awareness feedback.

The Production page shows the learning curve and its effect on capital cost of the propulsion technology. Learning affects purchase price, which then relates back to consumer value.

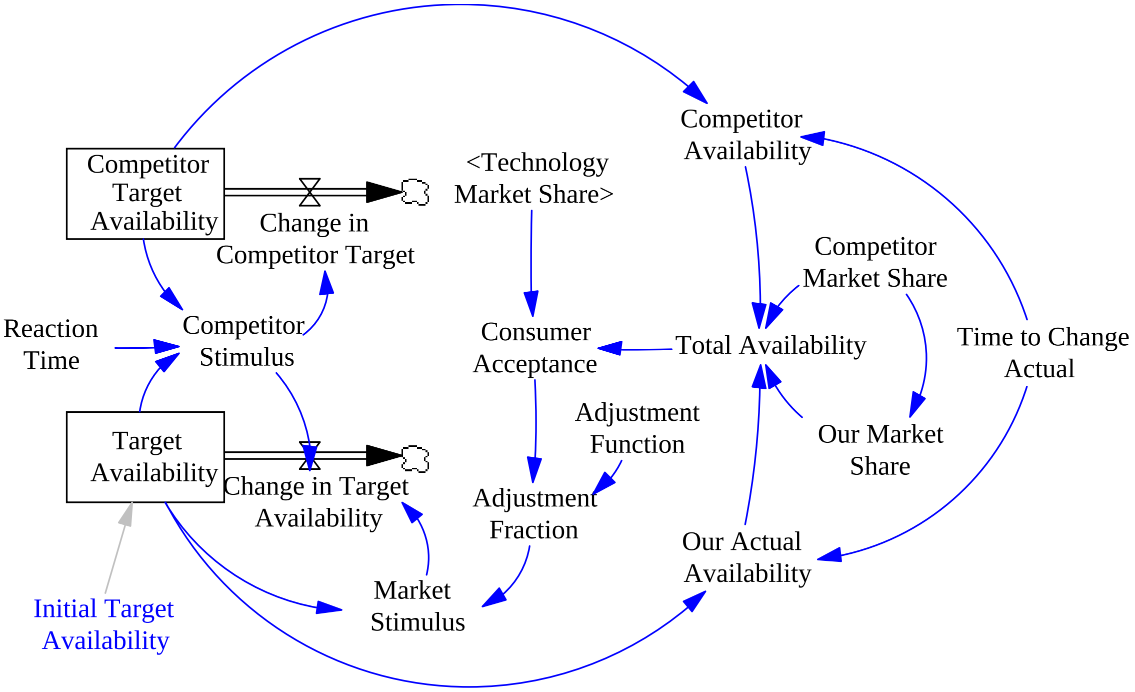
Appendix Figure 5. Main Page of FPR (Future Propulsion Regimes) Model



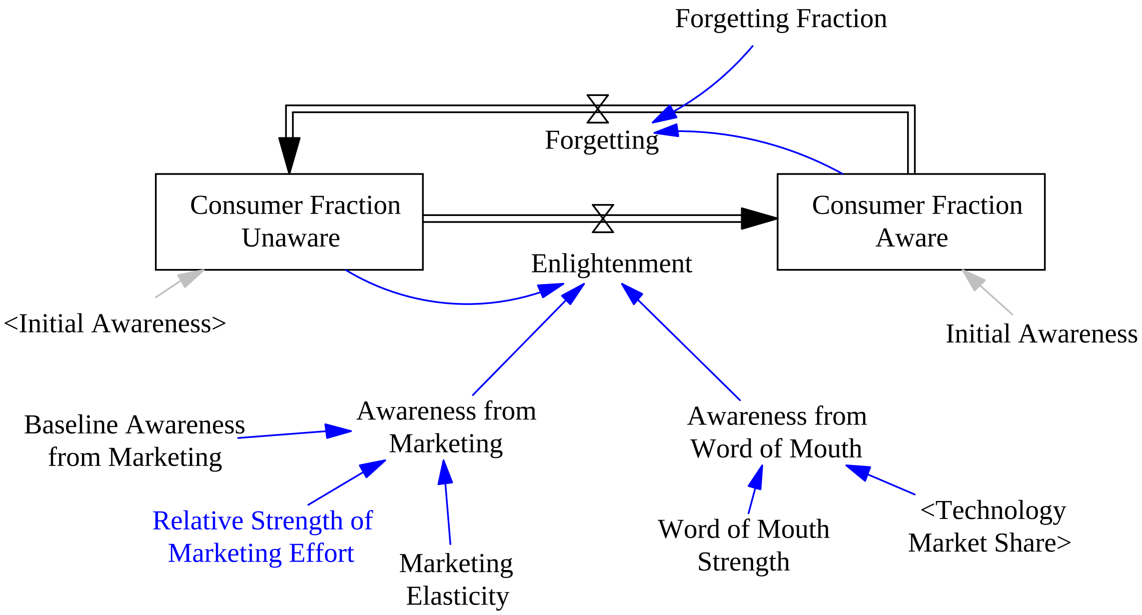
Appendix Figure 6. Sketch Variables in Attributes Page of FPR Model



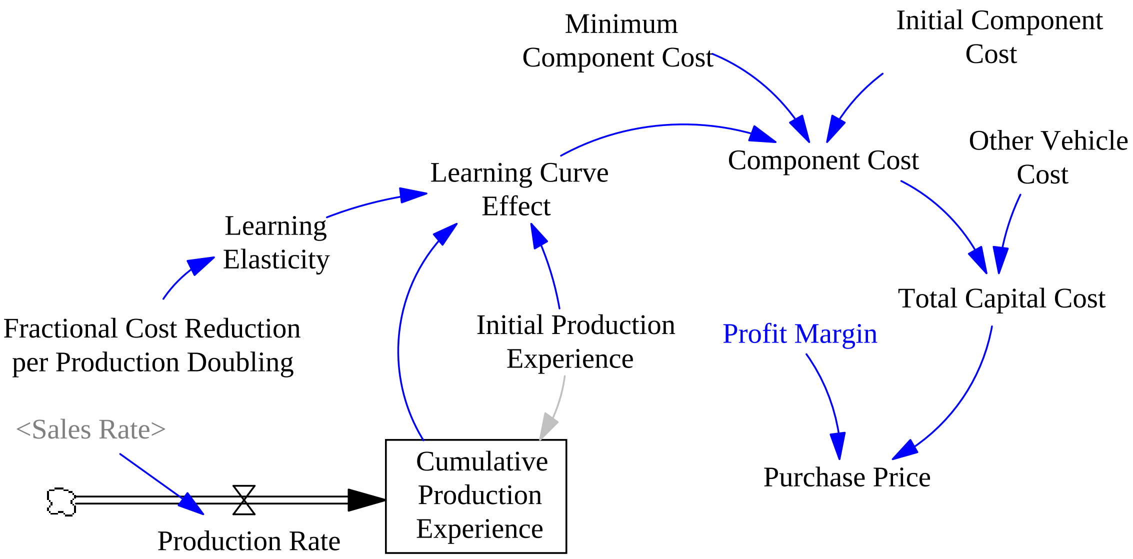
Appendix Figure 7. Sketch Variables in Adoption Page of FPR Model



Appendix Figure 8. Sketch Variables in Availability Page of FPR Model



Appendix Figure 9. Sketch Variables in Awareness View of FPR Model



Appendix Figure 10. Sketch Variables in Production Page of FPR Model

Variable Definitions in Alphabetical Order

(01) Adjustment Fraction[technology]=
Adjustment Function[technology](Consumer Acceptance[technology])
Units: 1/Year

The Adjustment Fraction is represented by the Adjustment Function of Consumer Acceptance for the technology in question. This represents the fraction by which Target Availability is to be adjusted in response to Consumer Acceptance through the Market Stimulus.

(02) Adjustment Function[technology](
[(0,0)-
(1,0.2)],(0,0),(0.134557,0.0105263),(0.2263,0.0263158),(0.302752,0.0429825
),(0.382263,0.0666667),(0.480122,0.102632),(0.584098,0.142105),(0.691131,0.170175
),(0.788991,0.187719),(0.896024,0.198246),(1,0.2))
Units: 1/Year

The Adjustment Function is a gently sloping s-curve that saturates at a 20% adjustment per year when Consumer Acceptance is 100%. (Also shown in Figure 3-9.)

(03) Air Pollutant Cost[technology]=
0.010572, 0.009843, 0.001628, 0.005311
Units: $/mile

The Air Pollutant Cost combines estimates of emissions per mile (Wang 1999) as well as estimates of the cost per unit mass of pollutant (as described in Chapter 2).

(04) Average Vehicle Life=
14
Units: Year

The Average Vehicle Life represents the average number of years a car is used from purchase to scrap. Average Vehicle Life is assumed to be 14 years, consistent with Davis (2000).

(05) Awareness from Marketing[technology]=
Baseline Awareness from Marketing*(Relative Strength of Marketing Effort[
technology])^Marketing Elasticity
Units: 1/Year

Awareness from Marketing is equal to the baseline awareness from marketing, multiplied by the relative strength of marketing effort raised to the marketing elasticity.

(06) Awareness from Word of Mouth[technology]=
Technology Market Share[technology]*Word of Mouth Strength
Units: 1/Year

Awareness from Word of Mouth is equal to the Technology Market Share for the propulsion technology, multiplied by the Word of Mouth Strength.

(07) Base Gasoline Price=
1.22
Units: $/gallon
The Base Gasoline Price is assumed to be $1.22/gallon. This level is consistent with Davis (2000) and Weiss et al (2000).

(08) Baseline Awareness from Marketing=
0.05
Units: 1/Year
Baseline Awareness from Marketing represents the fraction of consumers per year that become aware of a new product through baseline marketing spending.

(09) Change in Competitor Target[technology]=
-Competitor Stimulus[technology]
Units: 1/Year
The Change in Competitor Target availability is equal to the negative of the Competitor Stimulus. This indicates that the competitors are fast-followers, responding to the competitor stimulus but not the market stimulus.

(10) Change in Infrastructure Coverage[technology]=
MAX((Desired Infrastructure Coverage[technology]-Infrastructure Coverage[technology])/Time to Build Infrastructure, 0)
Units: 1/Year
The Change in Infrastructure Coverage is determined by a goal-gap relationship between desired and actual coverage, divided by the time delay for building. This rate has a lower bound of zero, so that it is only responsible for increases. Decreases in infrastructure are assumed to be less constraining than increases, and so are excluded from the scope of this model.

(11) Change in Target Availability[technology]=
MAX(Market Stimulus[technology],Competitor Stimulus[technology])
Units: 1/Year
The Change in Target Availability is equal to the maximum of either the Market Stimulus or the Competitor Stimulus. This MAX formulation indicates that their target availability responds either to the market or to the competition, depending on which is a more positive signal.

(12) Competitor Availability[technology]=
IF THEN ELSE(technology=ICE, 1, DELAY3I(Competitor Target Availability[technology], Time to Change Actual, 0))
Units: Dmnl
Competitor Availability represents the actual availability of a propulsion technology on our competitor's cars. This availability delays the target availability by a third-order delay based on the time it takes to change actual availability. The initial competitor availability is assumed to be zero for all technologies except ICE.

(13) Competitor Market Share=
0.5
Units: Dmnl
Competitor Market Share is assumed to be constant at 50% of the market.

(14) Competitor Stimulus[technology]=
(Competitor Target Availability[technology]-Target Availability[technology
])/Reaction Time
Units: 1/Year
The Competitor Stimulus is the difference between our target availability and their target availability, divided by the time it takes to change the target availability. It impacts Change in Their Target directly, and the negative Competitor Stimulus impacts Change in Our Target.

(15) Competitor Target Availability[technology]= INTEG (
Change in Competitor Target[technology],
IF THEN ELSE(technology=ICE, 1, 0))
Units: Dmnl
Competitor Target Availability represents the goal for the fraction of cars that our competitors offer with a particular propulsion technology. This target is a stock that integrates the Change in Competitor Target availability. The initial target is 0 for all technologies except ICE (which stays at a fraction of 1 throughout).

(16) Component Cost[technology]=
(Initial Component Cost[technology]-Minimum Component
Cost[technology])*Learning Curve Effect
[technology]+Minimum Component Cost[technology]
Units: $/car
The Component Cost of the technology is equal to difference between the Initial Component Cost and the Minimum Component Cost, multiplied by the Learning Curve Effect, then added to the Minimum Technology Cost.

(17) Consumer Acceptance[technology]=
ZIDZ(Technology Market Share[technology],Total Availability[technology])
Units: Dmnl
Consumer Acceptance represents the sales realized for a given technology, divided by the cars made available of that technology. The formula is Technology Market Share (cars sold with technology i/total cars), divided by total availability (cars available with technology i/total cars). Consumer Acceptance must be a fraction between 0 and 1. ZIDZ means "Zero If Divide by Zero".

(18) Consumer Fraction Aware[technology]= INTEG (
+Enlightenment[technology]-Forgetting[technology],
Initial Awareness[technology])
Units: Dmnl

The Consumer Fraction Aware of the technology is represented as a stock that integrates the rate of increase in awareness (Enlightenment) and the rate of Forgetting and begins the accumulation of awareness from the initial awareness level.

(19) Consumer Fraction Unaware[technology]= INTEG (
+Forgetting[technology]-Enlightenment[technology],
1-Initial Awareness[technology])
Units: Dmnl

The Consumer Fraction Unaware of the technology is a stock that integrates the rate of Forgetting and the rate of increase in awareness (Enlightenment) of the particular technology, starting from the initial fraction unaware (represented by 1-Initial Awareness fraction).

(20) Consumer Utility[technology]=
Consumer Value[technology]/Normalizing Constant b[technology]
Units: utils

The Consumer Utility for a technology is the Consumer Value divided by the Normalizing Constant b. The units of Consumer Utility are "utils", or dimensionless representations of relative utility.

(21) Consumer Value[technology]=
(Willingness to Pay[technology]-Purchase Price[technology])
Units: $/car

Consumer Value for a given propulsion technology is equal to the difference between the consumer Willingness to Pay and the vehicle Purchase Price.

(22) Cumulative Production Experience[technology]= INTEG (
Production Rate[technology],
Initial Production Experience[technology])
Units: cars

The Cumulative Production Experience of a technology represents the aggregate experience in number of cars produced for a given technology. This stock provides critical information to the learning curve.

(23) Demand[technology]=
Probability of Purchase[technology]*Infrastructure Coverage[technology]*Consumer Fraction Aware[technology]*Total Availability[technology]
Units: Dmnl

Demand represents the compounded effects of Probability of Purchase, Infrastructure, Awareness, and Availability of a propulsion technology. It is a dimensionless value that has not yet been normalized to assess Technology Market Share.

(24) Desired Infrastructure Coverage[technology]=
Desired Infrastructure Coverage Function[technology](Technology Fraction in Fleet
[technology])
Units: Dmnl

The Desired Infrastructure Coverage represents a the desired fuel and auxiliary serviceability level for the technology. The Desired Infrastructure Coverage depends on the Desired Infrastructure Coverage Function for the particular Technology Fraction in Fleet.

(25) Desired Infrastructure Coverage Function[EV](
[(0,0)-(0.2,1)],(0,0),(0.02,0.04),(0.04,0.1),(0.07,0.3),(0.09,0.5),(0.11, 0.7),(0.14,0.85),(0.17,0.95),(0.2,1))
Desired Infrastructure Coverage Function[FCEV](
[(0,0)-(0.4,1)],(0,0),(0.02,0.04),(0.04,0.1),(0.07,0.3),(0.09,0.5),(0.11, 0.7),(0.14,0.85),(0.17,0.95),(0.2,1))
Desired Infrastructure Coverage Function[hybrid](
[(0,0)-(0.2,1)],(0,1),(0.2,1))
Desired Infrastructure Coverage Function[ICE](
[(0,0.8)-(0.2,1)],(0,1),(0.2,1))
Units: Dmnl

The Desired Infrastructure Coverage Function relates Technology Fractions in Fleet of less than .2 (20% penetration) to the corresponding Desired Infrastructure Coverage; above 20% fleet penetration, coverage is 100%. The table follows an s-shape correlation, indicating that there is a threshold below which there is a disincentive to invest in infrastructure, and above which infrastructure can really grow. For ICE and hybrid, coverage is 100% regardless of fleet fraction. (See Figure 3-6).

(26) Discount Rate=
0.3
Units: Dmnl

The discount rate determines to what extent future operating costs are internalized at the time of purchase. A high discount rate represents that these costs are not internalized very much. The baseline 30% discount rate would be considered high. The discount rate is also a scenario variable, so that it can be lowered to create a future where operating costs are considered more.

(27) Electricity Price=
1.62
Units: $/gallon

The Electricity Price is represented here as $/gallon gasoline equivalent. An electricity price of $1.62/gallon is assumed for the calculations in this model as consistent with Weiss et al (2000).

(28) Enlightenment[technology]=
Consumer Fraction Unaware[technology]*(Awareness from Marketing[technology
]+Awareness from Word of Mouth[technology])
Units: 1/Year

Enlightenment represents the rate of increase in awareness. This rate is equal to the Consumer Fraction Unaware of the technology, multiplied by the sum of awareness effects from Marketing and from Word of Mouth.

(29) Environmental Damage Cost[technology]=
(Greenhouse Gas Cost[technology]+Air Pollutant Cost[technology])*Vehicle Miles Traveled
*Average Vehicle Life
Units: $/car

The Environmental Damage Cost for each propulsion technology is calculated by summing the Greenhouse Gas Cost and Air Pollutant Cost per mile, multiplied by annual Vehicle Miles Traveled and the Average Vehicle Life. No discount rate is applied to the environmental damage costs.

(30) Environmental Value[technology]=
(Environmental Damage Cost[ICE]-Environmental Damage Cost[technology])*Internalization Fraction
Units: $/car

The Environmental Value represents the internalized portion of the environmental benefit that a technology offers relative to the ICE, based both on the Environmental Damage Cost from air pollutants and greenhouse gas emissions, and the fraction of that cost that is internalized.

(31) FINAL TIME = 30
Units: Year

The final time for the simulation.

(32) Fixed Operating Cost[technology]=
1238
Units: $/(car*Year)

The Fixed Operating Cost refers to the insurance and fees that are paid on a yearly basis. The value of $1238/year is taken as common to all technologies, based on data from Davis (2000).

(33) Fleet of Technologies on Road[technology]= INTEG (
Sales Rate[technology]-Scrap Rate[technology],
IF THEN ELSE(technology=ICE, Market Size*Average Vehicle Life,0))
Units: cars

The Fleet of Technologies on Road is a stock vectored by propulsion technology that integrates the Sales Rate inflow and Scrap Rate outflow. The initial fleet consists only of ICE, where the fleet size is equal to the Market Size multiplied by the Average Vehicle Life.

(34) Forgetting[technology]=

Forgetting Fraction[technology]*Consumer Fraction Aware[technology]

Units: 1/Year

The rate of Forgetting is equal to a Forgetting Fraction multiplied by the Consumer Fraction Aware of the technology.

(35) Forgetting Fraction[technology]=

IF THEN ELSE(technology=ICE, 0, 0.08)

Units: 1/Year

The Forgetting Fraction represents the fraction of aware customers that forget about a technology over a year. This fraction is assumed constant, and is 0.08 for all technologies except ICE (which is assumed to have no forgetting).

(36) Fractional Cost Reduction per Production Doubling[technology]=

0.15, 0.3, 0.3, 0.3

Units: Dmnl

The Fractional Cost Reduction per Production doubling of a technology is a critical input into the learning curve. Doubling is considered relative to the initial production level. Base assumptions are 0.15, 0.3, 0.3, and 0.3 for ICE, hybrid, FCEV, and EV respectively. To turn off the learning curve effect, set the Fractional Cost Reduction to zero.

(37) Fuel Cost per Mile[technology]=

(Fuel Price[technology]/Fuel Economy[technology])

Units: $/mile

The Fuel Cost per Mile for a given vehicle represents the fuel price specific to the technology, divided by the fuel economy of the propulsion technology.

(38) Fuel Economy[technology]=

49.1, 70.8, 94.1, 149

Units: miles/gallon

Fuel Economy is represented as miles per gallon gasoline equivalent. Weiss et al (2000)determine fuel economy to be 49.1, 70.8, 94.1, and 149 mpg for ICE, hybrid, fuel cell, and EV respectively

(39) Fuel Price[ICE]=

Gasoline Price

Fuel Price[hybrid]=

Gasoline Price

Fuel Price[FCEV]=

Hydrogen Fuel Price

Fuel Price[EV]=

Electricity Price

Units: $/gallon

Fuel Price represents an array of prices that correspond to the different fuel propulsion regimes. For hybrid and ICE, the fuel price is the gasoline price. The fuel cell electric vehicle and battery electric vehicle fuel prices are those of hydrogen and electricity, respectively.

(40) Gasoline Price=
Base Gasoline Price + STEP(Gasoline Price Increase ,Time of Increase)
Units: $/gallon

The Gasoline Price is equal to the Base Gasoline Price plus any Gasoline Price Increase selected for scenario creation.

(41) Gasoline Price Increase=
0
Units: $/gallon

The Gasoline Price Increase represents the amount by which gasoline prices change, either due to taxes or supply and demand shifts. The baseline assumption is a zero Gasoline Price Increase, but this is also a scenario variable.

(42) Greenhouse Gas Cost[technology]=
0.007186, 0.005133, 0.005817, 0.005646
Units: $/mile

The Greenhouse Gas Cost is determined from the amount of greenhouse gases (CO2 and CH4) emitted per mile of vehicle operation (Weiss et al 2000), as well as the cost per unit mass of greenhouse gas, which is assumed to be $29/10^6 g CO2-equivalent (See Chapter 2).

(43) Hydrogen Fuel Price=
2.2
Units: $/gallon

Hydrogen Fuel Price is expressed as $/gallon gasoline equivalent, and is assumed to be $2.20/gallon, as consistent with Weiss et al (2000).

(44) Infrastructure Coverage[technology]= INTEG (
Change in Infrastructure Coverage[technology],
Initial Infrastructure Coverage[technology])
Units: Dmnl

Infrastructure coverage is a dimensionless fraction of the extent to which technologies are supported by infrastructure for fuel, maintenance, and so forth.

(45) Initial Awareness[ICE]=
1
Initial Awareness[hybrid]=
0
Initial Awareness[FCEV]=
0
Initial Awareness[EV]=
0
Units: Dmnl

Initial Awareness varies with technology, where 1 represents 100% awareness. The initial awareness for ICE is one, while the alternative technologies have zero initial awareness.

(46) Initial Component Cost[technology]=
4770, 6666, 7658, 12822
Units: $/car

The Initial Component Cost represents the starting point for costs of the propulsion technologies. The initial costs presented here are taken from Weiss et al (2000) as 4770, 6666, 7658, and 12822 for ICE, hybrid, FCEV, and EV respectively. While the propulsion costs are already assumed to be appropriate for mass-production levels, I assume additionally that learning can result in further cost reductions to some extent, defined by the Minimum Component Cost.

(47) Initial Infrastructure Coverage[technology]=
1, 1, 0.01, 0.01
Units: Dmnl

Initial infrastructure coverage for a given propulsion technology represents the extent to which fuel and maintenance are available at the start of simulation to seed vehicle demand. For FCEV and EV, this initial coverage is a scenario variable, in that it can be increased to reflect heavy investment in infrastructure prior to demand, which could be induced by regulation. The default values for the FCEV and EV are non-zero at a fraction of 0.01 (1% coverage).

(48) Initial Production Experience[ICE]=
3e+008
Initial Production Experience[hybrid]=
3e+006
Initial Production Experience[FCEV]=
300000
Initial Production Experience[EV]=
300000
Units: car

The Initial Production Experience equals the number of vehicles that have been produced with the given technology prior to start of simulation. This number does not need to correspond literally to reality, but serves as a representative starting point for the experience on a given technology. As such, these initial production levels can affect the steepness of the learning curve (see Sterman 2000).

(49) Initial Target Availability[technology]=
1, 0.01, 0.01, 0.01
Units: Dmnl

Their initial target is represented as a scenario variable, where "they" are the sum of our competitors. The default values for their initial target are 1 for ICE and 0.01 for all other systems.

(50) INITIAL TIME = 0
Units: Year
The initial time for the simulation.

(51) Internalization Fraction=
0
Units: Dmnl
The Internalization Fraction represents the fraction of Environmental Damage Costs that are recognized by the consumer at time of purchase. A fraction of 0 (the default) represents that the environmental cost is not a consideration in the purchase decision. A fraction of 1 indicates that somehow this damage cost is recognized, perhaps through feebates imposed by the government. Internalization Fraction is a scenario variable.

(52) Learning Curve Effect[technology]=
(Cumulative Production Experience[technology]/Initial Production Experience [technology])^Learning Elasticity[technology]
Units: Dmnl
The Learning Curve Effect equals the ratio of Cumulative Production Experience to Initial Production Experience, raised to the Learning Elasticity of the technology. See Sterman (2000).

(53) Learning Elasticity[technology]=
LN(1-Fractional Cost Reduction per Production Doubling[technology])/LN(2)
Units: Dmnl
The Learning Elasticity of a technology for the learning curve is equal to the natural log of the Fractional Cost Reduction per Production Doubling, divided by the natural log of 2 (representing doubling). See Sterman (2000, p. 338) for learning curve formulation.

(54) Market Size=
3.36e+006
Units: cars/Year
Market Size represents the number of cars sold per year, regardless of propulsion technology. The fixed, or constant market size of indicates saturation. Here, the market size of 3,360,000 represents an approximation of the number of sales within the United States for a standard sedan class of vehicles (Davis 2000).

(55) Market Stimulus[technology]=
(1-Target Availability[technology])*Adjustment Fraction[technology]
Units: 1/Year
The Market Stimulus includes the effect of Consumer Acceptance through the Adjustment Fraction, and increases Target Availability accordingly. The Adjustment Fraction serves as a limiter to how much Target Availability can be adjusted at any time.

(56) Marketing Elasticity=
0.7
Units: Dmnl

Marketing elasticity represents the percentage increase in awareness for each percentage increase in spending effort. The default assumption is an elasticity of 0.7.

(57) Minimum Component Cost[technology]=
4000
Units: $/car

The Minimum Component Cost is the minimum cost to build the propulsion technology. This provides a lower boundary for the learning curve.

(58) Normalizing Constant b[technology]=
8625
Units: $/car

The Normalizing Constant b is used to scale consumer value into a normalized consumer value. This constant is selected to result in a 2% decrease in share (not including infrastructure, awareness or availability effects) with a 1% increase in price at the average starting price and an evenly split market (See chapter 3). This corresponds to an elasticity of -2.

(59) Operating Cost[technology]=
(Variable Operating Cost[technology]+Fixed Operating
Cost[technology])*Operating Cost Multiplier
(Discount Rate)
Units: $/car

The operating cost for a technology that is internalized at the time of purchase is equal to the sum of the variable and fixed operating costs, multiplied by the effect of the discount rate on operating cost. This is, in effect, a present-value representation of the yearly operating costs assuming a 10-year horizon.

(60) Operating Cost Multiplier(
[(0,0)-(1,15)],(0,14),(0.05,9.9),(0.08,8.24),(0.1,7.37),(0.15,5.72),(0.2,
4.61),(0.3,3.25),(0.4,2.48),(0.5,1.99),(0.6,1.66),(0.7,1.42),(0.8,1.25),(0.9
,1.11),(1,1))
Units: $/car

The Operating Cost Multiplier correlates the specified Discount Rate to a present value of Operating Cost over the lifetime of the vehicle (14 years). If a different vehicle lifetime is assumed, this table function should be adjusted according to the present value of $1/year over the new lifetime using different discount rates. (See Figure 3-2.)

(61) Operating Cost Savings[technology]=
Operating Cost[ICE]-Operating Cost[technology]
Units: $/car

The Operating Cost Savings represents the present value of the Operating Cost differential between a given technology and the ICE.

(62) Other Sources of Value[technology]=
17000
Units: $/car

Other Sources of Value represents an additional parameter to capture value that is not propulsion-specific, and/or value that is not represented in other attributes. The default value is $17000 for all technologies, specified to generate a positive Consumer Value.

(63) Other Variable Cost per Mile[technology]=
0.0517
Units: $/mile

Other Variable Cost per Mile represents the maintenance and tire service costs incurred at periodic intervals along the vehicle age in mileage. These costs are assumed to be 5.17 cents per mile, based on Davis (2000).

(64) Other Vehicle Cost[technology]=
15730
Units: $/car

Other Vehicle Cost represents the costs of the vehicle that do not vary with propulsion technology. This cost is assumed to be $15,730/vehicle, consistent with Weiss et al (2000).

(65) Our Actual Availability[technology]=
IF THEN ELSE (technology=ICE, 1, DELAY3I(Target Availability[technology], Time to Change Actual, 0))
Units: Dmnl

Our Actual Availability represents the actual fraction of propulsion technologies made available on the sedan platforms that our company offers. This availability lags Target Availability by the Time to Change actual availability in a third-order delay. The initial availability is zero for all technologies except ICE.

(66) Our Market Share=
1-Competitor Market Share
Units: Dmnl

Our Market Share is equal to 1 minus Competitor Market Share, so that the total market is divided between us and them (our competitors).

(67) Performance Value[technology]=
Performance Value Function(Relative Performance[technology])
Units: $/car

The Performance Value as internalized by the customer is represented by the Range Value Function, using Relative Performance as an input.

(68) Performance Value Function(
[(0,0)-(2,11000)],(0,0),(0.318043,192.982),(0.477064,1206.14),(0.58104,2557.02
),(0.654434,4245.61),(0.770642,7140.35),(0.911315,9070.18),(1,10000),(1.15596
,10662.3),(1.38226,10807),(2,11000))
Units: $/car

The Performance Value Function, like that for range, is an s-shaped function relative to the expected performance of an ICE vehicle. Below this expected performance level, the value drops off significantly; above it, value is added marginally. (See Figure 3-4.)

(69) Probability of Purchase[technology]=
Exp(Consumer Utility[technology])/SUM(Exp(Consumer Utility[technology!]))
Units: Dmnl

The Probability of Purchase for a given technology is an exponential function of Consumer Utility. This is based on the logit function, which generates the mean of a logistic distribution using the exponent of utility for a given technology divided by the sum of exponential utilities for all the competing technologies.

(70) Production Rate[technology]=
Sales Rate[technology]
Units: cars/Year

The Production Rate of a technology is determined retroactively from the Sales Rate for each technology.

(71) Profit Margin[technology]=
0.05, 0.05, 0.05, 0
Units: Dmnl

Profit Margin is specified as the fraction of cost that is added to give vehicle price. The Profit Margin can be zero if the vehicle is to be sold at cost, or it can be negative if the vehicle is to be sold at a loss. The default assumption is a 5% profit margin for all technologies except EVs (which are sold at cost because of their high Capital Cost). Profit Margin is a scenario variable.

(72) Purchase Price[technology]=
Total Capital Cost[technology]*(1+Profit Margin[technology])
Units: $/car

The Purchase Price for a given propulsion technology is equal to the Total Capital Cost plus an additional fee appropriate to the specified Profit Margin.

(73) Range[technology]=
396, 407, 375, 250
Units: miles

The Range represents the number of miles that can be traveled between refuelings. The values of 396, 407, 375, and 250 miles are drawn from Weiss et al (2000) for the ICE, hybrid, fuel cell, and electric vehicle, respectively.

(74) Range Value[technology]=
Range Value Function(Range[technology])
Units: $/car

The Range Value as internalized by the consumer is represented by the Range Value Function, using the vehicle Range as an input.

(75) Range Value Function(
[(0,0)-(600,6000)],(0,0),(100,0),(150,100),(200,475),(240,1100),(270,2125),(300,3500),(325,4500),(350,5100),(370,5400),(400,5700),(450,5875),(600,6000))
Units: $/car

The Range Value Function is a table function with an s-shaped threshold. The steep part of the curve represents the penalty that is imposed on vehicles with lower range than the baseline. A $5000 penalty is imposed if the range drops from 350 miles to 150 miles, consistent with Train (2000) findings for electric vehicle preferences. Above 350 miles, the added value of greater range is marginal, illustrated by the flatter slope. (Figure 3-3.)

(76) Reaction Time=
0.5
Units: Year

The Reaction Time is the time to change target availability in response to the Competitor Stimulus. This delay is assumed to be half a year, based on the time to adjust targets based on realization of competitor activity.

(77) Relative Performance[technology]=
1, 1, 1, 1
Units: Dmnl

The Relative Performance of the different technologies is expressed as relative to the baseline ICE vehicle performance. Weiss et al (2000) calculated consistent power-to-weight ratios across technologies, so the default assumption is that Relative Performance is equal across technologies. Other performance parameters that are not encompassed by the power-to-weight ratio can be deemed as other sources of value, an additional variable. Or alternatively, Relative Performance could be utilized as a scenario variable.

(78) Relative Strength of Marketing Effort[technology]=
1, 1, 1, 1
Units: Dmnl
The Relative Strength of Marketing Effort represents the amount of marketing spending for a given technology divided by the baseline marketing spending. The baseline marketing spending (e.g., $30,000,000/year) is sufficient to generate 5% awareness in a year. The default assumption is that all efforts are equal to baseline, but this is a scenario variable that can be adjusted appropriately.

(79) Sales Rate[technology]=
Technology Market Share[technology]*Market Size
Units: cars/Year
The Sales Rate is equal to the Technology Market Share, multiplied by the Market Size.

(80) SAVEPER =
TIME STEP
Units: Year
The frequency with which output is stored.

(81) Scrap Rate[technology]=
Fleet of Technologies on Road[technology]/Average Vehicle Life
Units: cars/Year
The Scrap Rate is equal to the Fleet of Technologies on Road divided by the Average Vehicle Life.

(82) Target Availability[technology]= INTEG (
Change in Target Availability[technology],
Initial Target Availability[technology])
Units: Dmnl
Target Availability represents our availability goal. This target availability integrates the change in their target, and starts with Initial Target Availability.

(83) technology:
ICE, hybrid, FCEV, EV
Four propulsion technology platforms are explored: internal combustion (ICE), hybrid, fuel cell electric (FCEV), and electric (EV).

(84) Technology Fraction in Fleet[technology]=
Fleet of Technologies on Road[technology]/SUM(Fleet of Technologies on Road [technology!])
Units: Dmnl
The Technology Fraction in Fleet represents the fraction that each technology comprises in the total vehicle fleet at a given time. The fraction of an alternative propulsion technology in the fleet lags the Technology Market Share because the fleet is much larger than the number of new cars sold in a year.

(85) Technology Market Share[technology]=
Demand[technology]/SUM(Demand[technology!])
Units: Dmnl

Technology Market Share normalizes Demand so that the sum of all technology market shares is unity. As such, it is equal to demand for the technology divided by the total demand for all technologies. The presence of Demand in both the numerator and denominator creates both reinforcing and balancing feedback components for all feedback mechanisms (see Chapter 3).

(86) Time of Increase=
0
Units: years

The Time of Increase is represents the number of years after simulation starts that a Gasoline Price Increase is imposed. The default assumption is that the higher gasoline price takes place immediately, so time of increase is zero.

(87) TIME STEP = 0.125
Units: Year

The time step for the simulation.

(88) Time to Build Infrastructure=
3
Units: Year

The Time to Build Infrastructure is assumed to be constant at 3 years.

(89) Time to Change Actual=
4
Units: Year

The Time to Change Actual availability is assumed to be 4 years, representing the time to bring the technology through requisite development and production steps to market.

(90) Total Availability[technology]=
Competitor Availability[technology]*Competitor Market Share+Our Actual Availability
[technology]*Our Market Share
Units: Dmnl

Total Availability is the sum of Our Availability and the Competitor Availability, weighted by the respective Market Share of us and our competitor.

(91) Total Capital Cost[technology]=
Other Vehicle Cost[technology]+Component Cost[technology]
Units: $/car

The Total Capital Cost is equal to the sum of Component Cost of the technology and Other Vehicle Cost.

(92) Variable Operating Cost[technology]=
Vehicle Miles Traveled*(Fuel Cost per Mile[technology]+Other Variable Cost per Mile
[technology])
Units: $/(car*Year)
The Variable Operating Cost incurred yearly for vehicle usage is equal to the Vehicle Miles Traveled multiplied by the sum of Fuel Cost per Mile and Other Variable Cost per Mile.

(93) Vehicle Miles Traveled=
12000
Units: miles/(car*Year)
The Vehicle Miles Traveled per vehicle and year is assumed to be constant across propulsion regimes at 12,000 miles per vehicle-year. This is consistent with Davis (2000).

(94) Willingness to Pay[technology]=
Performance Value[technology]+Range Value[technology]+Other Sources of Value
[technology]+Environmental Value
[technology]+Operating Cost Savings[technology]
Units: $/car
Consumer Willingness to Pay for a given vehicle propulsion technology is the sum of the value to the consumer through technology attributes.

(95) Word of Mouth Strength=
0.5
Units: 1/Year
The Word of Mouth Strength represents the fraction of awareness gained through word of mouth for each percentage market share. The default fraction is 0.5 (e.g., one consumer gained for every two owners of the technology per year).

Appendix D: Model Usage Notes

FPR (Future Propulsion Regimes) Model Q & A

How can I view the model structure and relationships?

- First, ensure that you have the right version of software. This model contains “subscripted” (arrayed) variables to represent different technology types, so you may need Vensim DSS just to open it properly. If you want to modify anything, you will definitely need the DSS version of Vensim.
- If you want simply to view the details of a particular scenario, you can download Vensim Model Reader for free (http://www.vensim.com/freedownload.html). To be viewed in Model Reader, the model needs to be in binary format, and its parameters are not adjustable. You can see what the values for different parameters are and how they change over time, but this is limited to one scenario. That means you will need to view different files to see the different scenarios.

How do I run the model to create the scenarios?

- In Vensim DSS 4.1, you have several options for creating the scenarios:
    1. Go to *Model*, select *Simulate*, and then choose the *Changes* tab. Name the run (I have used “ICEDomination”, “HybridCompetition,” and “FuelCellTransition” as run names for the three scenarios). Then choose *Based On*, and select the vdf file that corresponds to that scenario. The vdf files have the same names as the run names.
    2. Alternatively, still on the *Changes* tab, you can select *Change Constants* and then change the parameters yourself consistent with those outlined below and in the thesis. Once you have changed parameters, it is convenient to *Save changes as .cin file* so you can *Load changes from* that file later.

ICE Domination scenario changes:
Relative Performance[hybrid] = 0.8
Relative Performance[FCEV] = 0.8
Relative Performance[EV] = 0.8
Hybrid Competition scenario changes:
Relative Strength of Marketing Spending[hybrid] = 2
Their Initial Target[hybrid] = 0.2
Fuel Cell Transition scenario changes:
Discount Rate = 0.1
Environmental Cost Fraction Internalized = 1
Gasoline Price Increase = 4
Initial Infrastructure Coverage[FCEV] = 0.2
Profit Margin[FCEV] = 0
Relative Strength of Marketing Spending[hybrid] = 2
Relative Strength of Marketing Spending[FCEV] = 6
Their Initial Target[hybrid] = 0.2
Their Initial Target[FCEV] = 0.2

How might I create a different scenario from the ones used in the thesis?

- As described above, you can go to *Model→Simulate→Changes→Change Constants* to create different scenarios. You would probably want to decide in advance what to change.
- Parameters highlighted in blue are ones that are particularly attractive as “scenario variables.” You should be able to rationalize how the scenario is plausible and still internally consistent. For example, you would not want to change “market size” or “average car life” from one scenario to the next. However, you might want to change “gasoline price increase” or “environmental fraction internalized” to reflect a different future while retaining the basic assumptions. There are indeed many “gray zone” parameters, so you will need to use your judgment. By keeping adjustments from the baseline to a minimum, the scenarios are more plausible. You can very easily change the baseline assumptions by using the $Y=x^2$ (equation) button to change a model equation. From this baseline you can create another internally consistent set of scenarios.

How can I learn how sensitive a scenario is to changes in parameters?

- Vensim DSS has powerful sensitivity analysis capability. To harness some of this capability, first choose a scenario by loading that dataset. The dataset can be controlled using the Control Panel (gauge symbol) on the Vensim toolbar, then selecting the *Datasets* tab. By double-clicking on the dataset name, you can control what is loaded and what is not.

Now you are ready for some sensitivity analysis. For the Fuel Cell Transition scenario, try the following:

- Select *Model→Simulate→Sensitivity*, and choose a *Run Name*. Select *Sensitivity Control*, and name a file. Then select *Edit…* to edit the file. Select the *Vector* option from the *Distribution* down arrow. Then press *Parameter*, select *Gasoline Price Increase*, then choose *minimum value* of *0*, *maximum value* of *5*, and *increment* of *0.5*. Then select *Add Editing* to incorporate the changes, and press *OK* to close the window.
- Now choose *Sensitivity Save List* and name a file. Then select *Edit…* to edit the file. Choose the *Select* button at the bottom right of the window to choose the parameter. Scroll to *Technology Market Share*, and select *[FCEV]* from the *subscripts* down arrow. Then choose *OK*. Press *Add Editing* to incorporate this parameter. (You generally want to limit how many parameters you save, because the sensitivity analysis takes a lot of memory.) Press *OK* to close the window.
- Back at the *Sensitivity* tab, press the *Sensitivity* button at the bottom of the window. The model will run a series of simulations. Then select the Sensitivity Graph at the left-hand toolbar (it looks like spaghetti), once you have selected the Technology Market Share parameter in the sketch by double-clicking on it. This will bring up four graphs, one for each technology. The FCEV graph should have lots of spaghetti lines indicating the simulated trajectories above and below the scenario run. By right-clicking on the Sensitivity Graph toolbar, you change select whether you want to view the analysis as discrete runs (spaghetti or contour lines) or as confidence intervals (shaded areas representing different percentage confidence bounds.

You can also optimize a particular variable, such as market share for fuel cell technology.

- Select *Model→Simulate→Advanced*, and then choose the *Payoff Definition* button. Name a file, then select *Ed…* to edit the file. Choose *Policy* (not *Calibration*). For *Variable*, press *Sel* and browse to get *Technology Market Share* (then under the *Subscripts* arrow, select *[FCEV]*). Then press *OK*. Next to *Weight* type the number *1* (if you were minimizing the variable, you would put a –*1* next to *Weight*). Now choose *Add Editing* to incorporate this as a *Payoff Element*. You should see *Technology Market Share[FCEV]/1* in the *Payoff Element* window. Select *OK* to close the *Payoff Definition* window.
- Now choose the *Optimization Control* button. Name a file, then select *Ed…* to edit the file. Next to *Optimizer*, use the down arrow to turn *Powell* to *Off*. Under *Sensitivity*, select *All Constants* using the down arrow. In the window to the right of the equal sign (=), type *10* (This represents a 10% change in all parameters. If a parameter is set at 0, it is changed by .1.). Now select *OK* to close the *Optimization Control* window.
- Back at the *Advanced* tab, choose *Optimize*. This will run a bunch of simulations by changing each parameter, and record the results in a tab-delimited file. The file is called *sortsens.tab* and will be located in the same folder as the model. You can open this file either in Vensim (for viewing only), or in Excel. In Excel, select *Files of Type*: *All Files*, then open *sortsens.tab*. Open the file as *delimited*, then select *tab* as the delimiter.
- In this file, all 93 parameters are shown sorted according to their impact on cumulative technology market share for fuel cells. This list can then be examined for adjustable variables that might be of interest. While *Profit Margin[FCEV]* shows as a major player, it is important to note that it was adjusted from the value of zero to +/- 0.1, indicating that a 10% loss will help technology market share substantially. However, this is not an attractive proposition. Beyond parameters that are held constant for all technologies, we see that *Initial Infrastructure Coverage[FCEV]* and *Gasoline Price Increase[FCEV]* have strong positive effects on fuel cell market share. These have already been adjusted as scenario variables, but we might want to adjust them even more.