

Strategies for the Introduction of Advanced Fuel/Vehicle Systems To The Mass Market

By **Eric C. Cahill**

Bachelor of Science in Aerospace Engineering, University of Southern California, 1993

Submitted to the System Design and Management Program and the Engineering Systems
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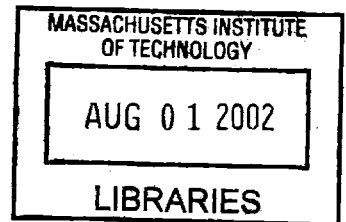
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and

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Eric C. Cahill

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ABSTRACT

The case for proactive market interventions to stimulate accelerated development and adoption of cleaner advanced fuel/vehicle systems continues to gain momentum globally. World population growth, rising national wealth, persistence of auto-centric land development patterns, and the growing popularity of truck-based platforms have reversed the trend toward lighter vehicles, higher fuel efficiencies, and cleaner emissions that began in the 1970's. Since 1984, fuel efficiency has stagnated and even declined as oil prices moved to historically low levels. Lack of consumer demand for fuel economy served to shift investment toward other measures of value such as performance and utility. The convergence of car and truck markets has further impeded progress on the fuel economy front.

Industry continues to come under intensifying pressure from international and domestic concerns regarding adverse vehicle emissions impacts on public health, environmental degradation, global climate change, and national security vulnerabilities stemming from dependence on foreign oil. In response, the world's major auto conglomerates have embarked on a variety of strategies to deliver cleaner vehicles to market. Strategies span in-house and strategic partnering efforts across a range of both available and developing technologies in fuels, batteries, fuel cells, electric hybrids, and improvements to current internal combustion engine (ICE) designs.

This thesis intends to examine a set of representative technological solution pathways that address two key questions for decision-makers: (1) whether market adoption of advanced fuel/vehicle systems can occur under plausible conditions, and (2) what industry strategies and public interventions can best leverage innovation to achieve the accelerated adoption of technologies beneficial to sustainability goals? To answer these questions, the work employs a system dynamics-based model in order to simulate the complex dynamics surrounding this issue. The model provides a useful framework for comprehending the relative directional impacts of varying industry strategies, public interventions, and external market and cultural forces that affect potential outcomes.

The work suggests that plausible adoption scenarios are realizable within a thirty-year time horizon, but that forces deleterious to the innovative capacity of established domestic firms may significantly impede progress. I outline these forces, explain their origins, and recommend industry strategies and public interventions that appropriately address these obstacles.

Thesis Advisor: John D. Sterman, Professor of Management

ACKNOWLEDGEMENTS

I dedicate this work to the memory of my parents, Jim and Joanna Cahill, and to William Oggeri, my late grandfather and “third parent.” My father imbued me with an altruistic desire to affect positive change; my mother taught me to persevere; and my grandfather instilled in me the respect and wonder of lifetime learning. Today, I proudly carry their torch. I know that if they were alive today, they would reflect proudly on their son’s accomplishments and I would take equal pride in knowing I brought them such joy. Their spirit is the divine wind that fills my sails in this wondrous journey.

I also thank the System Design and Management (SDM) program, the Technology & Policy (TPP) program, and the Department of Urban Studies & Planning (DUSP) for believing in my potential and for challenging me on so many levels. I extend the same thanks to my classmates. The richness of diversity, background, experience, and opinion imparted a staggering amount of wisdom that will hopefully obviate any desire of my own to learn the hard way about the realities of the corporate and government world. I also wish to thank those classmates who selflessly gave of their own time to offer a sounding board for my career-based inquiries.

I thank my advisors, John Sterman and Charlie Fine, for their assistance. To John, I appreciate his mentorship and guidance throughout the process. I owe Charlie a debt of gratitude for providing me the opportunity to intern with GM Powertrain and I thank Roger Vardan for his efforts to advance the cause of sustainability on the corporate front. I also wish to thank Nelson Repenning and Jim Lyneis for their masterful teaching of the systems dynamics discipline. And I thank Jim for his ongoing advisement and mentorship during my thesis writing effort.

Finally, I wish to thank my core, but scattered, group of friends – Trent, John, Eric, Robi, Carol, Janet, Rob, Bryan & Rowena, Steve & Michele, Bob & Karin – for their consistent encouragement during very trying times. I consider them all my extended family. I thank my local group of friends – Michele, Susanna, Robin, Clint, and Liz for keeping me insane. I mean sane... Last, but not least, I am grateful for my brother and sister. Their pride in me keeps me going. I also wish to thank Ellis & Marilyn Delameter for their love, support and encouragement.

To me personally, this body of work represents the culmination of a lifetime’s pursuit of truth, and a right-minded determination to envision and realize a better world. In other ways, this work is an attempt to come to grips with the one-dimensional and anarchic mentalities that continue to slap band-aids on symptoms of a much deeper disease. I hope that this work will contribute to the body of knowledge that seeks lasting solutions to the plagues of contemporary society. If not, I can’t say I didn’t try...

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EXECUTIVE SUMMARY

STRATEGIES FOR THE INTRODUCTION OF ADVANCED FUEL/VEHICLE SYSTEMS TO THE MASS MARKET

By Eric C. Cahill

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PROBLEM STATEMENT

Many of the concerns the world faces today with regard to degraded air quality, diminished quality of life, worsening public health, and global climate change find their roots in the highly inefficient factors of production, land development patterns, and transport methods spawned by the Industrial Revolution. Today, virtually two-thirds of all criteria pollutants responsible for urban smog, ground-level ozone, and global warming originate from motor vehicles. These include the poisonous exhaust gases of internal combustion engine processes such as carbon monoxide (CO), a deadly poison, carbon dioxide (CO₂), a known greenhouse gas (GHG), and ozone precursors that consist of oxides of sulfur (SO_x), nitrogen (NO_x), hydrocarbons (HC), and particulate matter with radii of less than ten microns (PM₁₀). EPA estimates that mobile source emissions represent a “significant risk” to human health posing “the greatest potential threat to public health in the largest number of urban areas.” Many of these are either presumed or known human carcinogens (Wang et al, 2000).

Ozone (O₃), a key molecular compound for shielding the Earth’s surface from damaging ultraviolet radiation, exists naturally in the high atmosphere. At ground level, however, ozone poses a dangerous threat to humans and wildlife. According to the American Lung Association (ALA), “Ozone is capable of destroying organic matter, including human lung and airway tissue. It essentially burns through cell walls, and it is capable of doing this at... levels frequently encountered in many U.S. cities” (Doyle 2000). The Centers for Disease Control and Prevention (CDC) estimates that the number of U.S. asthmatics has nearly tripled, from 6.8 million in 1980 to 17.3 million in 1998. Currently,

more than 5 million American children suffer from asthma. In 1999 alone, 200 children under the age of 15 died of this condition (Wang et al, 2000).

RESEARCH OBJECTIVES

I consider this work a study of the dynamics of innovation, applied to the challenge of delivering technological solutions to the problem of automotive emissions in the U.S. marketplace. The greater portion of this effort focuses on the intersection of industry practice and government policy. My objective is to develop and advance a set of product planning strategies and regulatory frameworks for achieving accelerated development, introduction, and adoption of advanced fuel/vehicle system platforms that reach mainstream consumer markets. This objective is predicated on the assertion that informed policy requires a thorough understanding of the dynamics of innovation behind the solutions called upon by social imperatives.

This thesis intends to examine a set of representative technological pathways that address two key questions for decision-makers: (1) *whether market adoption of advanced fuel/vehicle systems can occur under plausible conditions*, and (2) *what industry strategies and public interventions can best leverage innovation to achieve the accelerated adoption of technologies beneficial to sustainability goals?* Part I of the thesis addresses the first question and employs a system dynamics-based model to simulate adoption patterns. Part II focuses on addressing the second question and reaches beyond the limitations of a single model to invoke an additional set of frameworks for analysis. Although the author recognizes that any lasting solution will involve a balance of multiple transportation modes, the work concedes that personal transport will remain the preferred mode of transit in the North American marketplace. Therefore, I limit the scope of analysis to an exploration of the technological solution space for achieving the goals of sustainable mobility.

This work advances the thesis that informed industry strategy and government policy demands a thorough understanding of the role and dynamics of technology innovation in addressing the problem of mobile source vehicle emissions. It does so from a *systemic* perspective based on the participation of multiple and diverse stakeholders and an integrated assessment of available and developing technologies. This analysis is further predicated on the notion of “sustainable mobility” as it pertains to the passenger

vehicle (specifically low occupancy vehicles, i.e. cars and light duty trucks) element of mobile source emissions. In the context of this thesis, sustainability refers to the effort to balance human demand for personal transport with the capacity of our environment to sustain human quality of life. It represents the author's arbitrary translation of the term as interpreted from recognized literature on the subject (i.e. Ashford, Ehrenfeld, Lovins, and Hawkens).

PART I: ASSESSING THE OPPORTUNITY

METHODOLOGY

Central to my research is the extension of a market adoption model based on system dynamics tools to examine potential pathways for the introduction of advanced automotive powertrain technologies to the mass market. To do so, I have borrowed a reference adoption model based on technologies estimated to be available to consumers in the year 2020 (Weiss et al, 2000). The model, as I have revised it, modifies the set of demand attributes to more accurately reflect the consumer purchase decision (see the comparison of model logic flows in Chapter 3) while normalizing the set of potential technologies to a current, rather than an evolved, baseline vehicle – in this case a mid-size ICE-based sedan – supported by the market and energy infrastructure of today (Ogden 2001 & Wang 2000). Thus, the model simulates adoption of competing fuel/vehicle system technologies should automakers choose to bring them to market in their current state of development.

The revised model also incorporates “aging chain” and “co-flow” structures to facilitate the tracking of key metrics of interest over time (see Views 15-20 in the Appendix). Since the model allows the user to simulate a variety of strategies and market conditions, explicit delineation of these critical outputs enables the decision-maker to witness downstream impacts of any particular strategy/policy formulation. The author hopes that the inclusion of these structures in the revised model will improve our ability to predict the consequences of alternative policies, eradicate perverse incentives, and provide a framework for valuing consequences to enable trades that lead to better policy choices.

The revised model incorporates several policy levers to test the impact of various industry strategies and public interventions. These include a fee-bate program that serves to redistribute externality costs by rewarding cleaner vehicles and taxing “dirtier” ones. The user can activate or deactivate the fee-bate program via a built-in switch. Additional levers include the ability to impose a gasoline tax, or pursue a public ad campaign to educate consumers and stimulate awareness of cleaner alternative vehicle technologies. Using these levers, the study establishes a set of scenarios, each representing a deliberate strategy for achieving successful penetration of cleaner vehicles to market relative to today’s dominant propulsion mode, the internal combustion engine (ICE). Although many fuel/vehicle system combinations are possible, I examine four representative technology platforms in the scenarios presented here:

- (1) Gasoline-powered ICE Domination Scenario
- (2) Gasoline-powered Hybrid Electric Vehicle (HEV) Competition Scenario
- (3) Direct hydrogen-powered Fuel Cell Electric Vehicle (FCEV) Scenario
- (4) Grid-dependent Battery Electric Vehicle (BEV) Scenario

FINDINGS

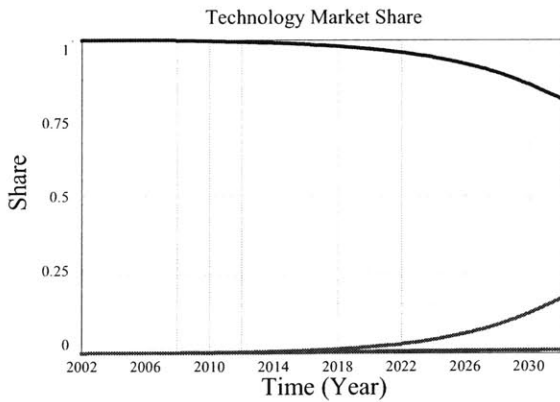
Tables 4.1 and 4.2 in Chapter 4 outline the basic assumptions ascribed to each of the scenarios considered. Inputting these scenario variables into the revised model yields the results illustrated in Summary Tables 1 and 2 and in Summary Figures 5 through 7 on the following pages. These illustrations map scenario results to key sustainability metrics. I refer the reader to Figures 1 through 4 on the following pages for illustrations of the individual adoption patterns witnessed in the simulation of the scenario set. The patterns that emerge provide useful feedback to decision-makers regarding the relative success of strategy and policy regimes in achieving sustainability objectives.

		Scenario 1: ICE Domination				Scenario 2: HEV Competition				Scenario 3: FCEV Transition				Scenario 4: EV Take-off			
		ICE	HEV	FCEV	EV	ICE	HEV	FCEV	EV	ICE	HEV	FCEV	EV	ICE	HEV	FCEV	EV
	Units																
Product Market Share	[%]	81.1	17.3	0.8	0.9	45.4	53.9	0.4	0.4	18.2	32	49.3	0.5	28.1	52.0	0.9	19
Fleet Fraction	[%]	92.7	6.2	0.5	0.6	58.3	41.1	0.3	0.3	43.8	36.6	18.9	0.7	45.6	43.6	0.9	9.9

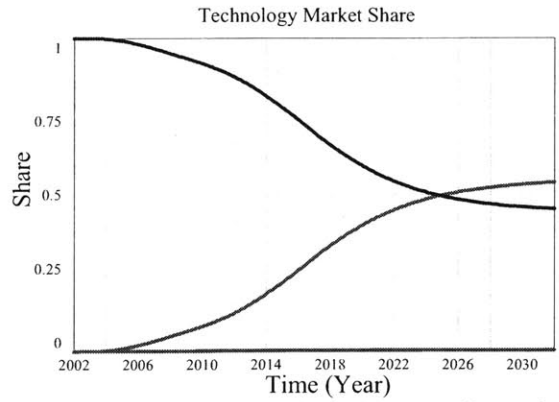
Summary Table 1 – Market Share of New Vehicle Sales and fraction of technologies in the vehicle fleet

		Base	Scenario 1: ICE Domination			Scenario 2: HEV Competition			Scenario 3: FCEV Transition			Scenario 4: EV Take-off		
		2002	2012	2022	2032	2012	2022	2032	2012	2022	2032	2012	2022	2032
	Units													
Total Vehicle Pollutant Emissions	Billions of Kg/yr	16	16.9	36.3	56.3	15.6	26.9	37.5	13.8	18.1	10.6	13.8	19.4	23.8
Total Vehicle GHG Emissions	Billions of Kg/yr	1,234	13.2	24.3	35.2	11.8	15.2	18.6	4.7	-2.4	-8.6	3.6	-4.2	-6.8
Average On-Road Fuel Economy of Gas Vehicles	Miles/gallon	22.4	3.6	11.2	21.0	6.3	26.3	46.4	12.1	44.6	58.5	15.2	46.9	92.9
Aggregate Average Fuel Economy	Miles/gallon	22.4	4.0	12.1	23.2	6.3	27.2	47.3	12.9	45.5	72.8	20.1	65.6	104.5
Fleet Annual Oil Consumption	Billions of gallons/year	107.1	13.1	23.3	31.8	10.6	8.5	9.9	2.1	-11.6	-24.6	-0.7	-17.6	-25.2
Total On-Road Cost of Environmental Damage	Billions of \$US/year	1,223	13.0	28.7	45.4	11.8	19.8	28.4	3.8	4.5	0.3	2.5	4.5	9.6

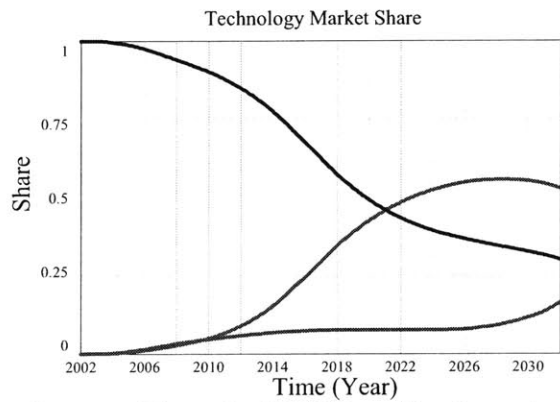
Summary Table 2 – Change in key sustainability metrics by 10-year increments



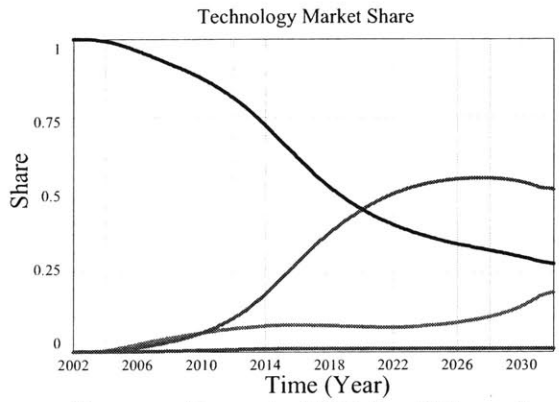
Summary Figure 1 – ICE Domination Scenario



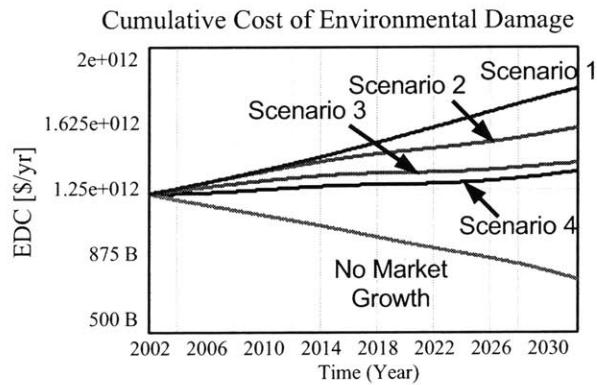
Summary Figure 2 – HEV Displacement Scenario



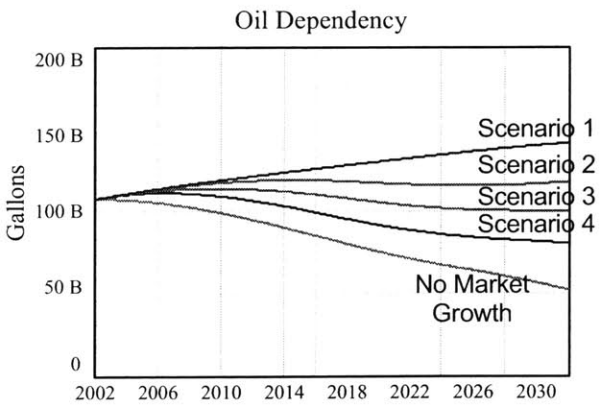
Summary Figure 3 – FCEV Transition Scenario



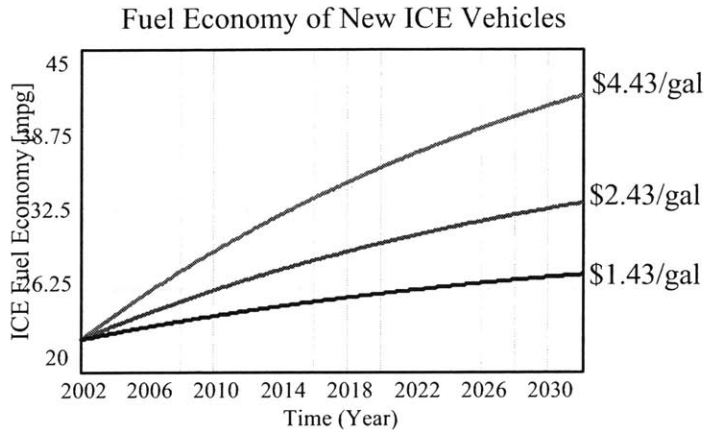
Summary Figure 4 – EV Take-off Scenario



Summary Figure 5 – Cumulative Cost of Environmental Damage by Scenario



Summary Figure 6 – Relative Dependence on Oil by Scenario



Summary Figure 7 – Average Fuel Economy of New Internal Combustion Engine (ICE) Vehicles as a function of gasoline prices.

The model attempts to account for potential ICE development by vested industry interests. It achieves this by establishing a desired fuel cost per mile (3 cents/mile), congruent with consumer expectations for range and fill-up costs based on incumbent ICE platforms. Summary Figure 7 provides a graphic of the relative change in fuel economy for each of the propulsion technologies over the simulation period. I include only those scenarios that reflect different gasoline price thresholds. In the absence of a fuel price increase, ICE-based platforms attain a 22% increase in fuel economy over the thirty-year simulation period. Conversely, as we increase fuel price, automakers are induced to commit greater resources to the goal of achieving greater fuel economy. At \$2.43/gal and \$4.43/gal, automakers increase ICE fuel economy by over 47% and 85%, respectively. The reader may interpret these data as gains derived from improvements in engine efficiency, exhaust after-treatment, fuel pre-treatment (i.e. lean burn), or vehicle light-weighting technologies over the simulation period.

The results from this very simple set of representative scenarios indicate that the adoption of cleaner vehicles is possible under each of the strategies and conditions considered. The author made every effort to keep the scenarios as simple, and as plausible as possible. For example, gasoline price increases were kept to a minimum in achieving the levels of penetration observed. However, there are some important observations to note from the patterns that emerged in the above illustrations:

Scenario 1- Laissez Faire

- In the absence of a concerted industry effort to “push” alternatives to the market place, hybrid electric vehicles nevertheless account for over 6% of the passenger vehicle fleet with over 17% share of new vehicle sales by the year 2032. This is accomplished as well in the absence of government policy interventions or increases in real gasoline prices.
- Despite an average fleet fuel economy increase of 22% over the same period, American dependence on oil and the costs associated with environmental damage continue to grow unchecked.

Scenario 2 – Hybrid Electric Competition

- The combination of a concerted effort by industry and government to introduce HEV products results in a much more significant level of market penetration by 2032 (41% fleet adoption and 54% new vehicle share). This is an extremely plausible scenario, requiring no real increase in gasoline prices and no public ad campaign to stimulate awareness. Rather, modest industry investments in marketing combined with a government fee-bate program enable this market outcome.
- Inclusion of a public ad campaign, however, accelerates the adoption pattern by approximately 7 years.
- In the longer-term (i.e. 10-30 years), however, this scenario fails to check mounting environmental damage costs, despite significant gains in all other key metrics. This result suggests that life-cycle considerations begin to dominate with the emergence of the HEV as the preferred mode of personal transit.

Scenario 3 – Fuel Cell Vehicle Transition

- A transition of the market to fuel cell technologies achieves sustainability as defined previously. The program successfully halts and reverses the growth of costs associated with environmental damage and energy dependency.
- This transition is predicated on a significant commitment of resources by both government and industry stakeholders, potentially coincident with

external market factors (such as a 70% increase in real gasoline prices and/or a gas tax) that benefit the technology's ascendance.

Scenario 4 – Battery Electric Vehicle Take-Off

- A transition of the market to fuel cell technologies achieves sustainability as defined previously. The program successfully halts and reverses the growth of costs associated with environmental damage and energy dependency.
- This scenario is contingent upon significant commitment of resources by industry and government stakeholders to overcome battery-dependent range limitations that handicap widespread adoption in mainstream markets. The scenario also requires coincident external market factors, such as a 300% increase in gasoline prices to stimulate the necessary demand.

PART II: GETTING TO MARKET

The above scenarios establish that the *opportunity* exists for a meaningful level of alternative fuel/vehicle system adoption under plausible conditions. The focus now turns toward the remaining question of the research objective: *What industry strategies and public interventions can best leverage innovation to achieve the accelerated adoption of technologies beneficial to sustainability goals?* Implicit in addressing this question is an examination of the *capacity* and *willingness* of firms to respond to the opportunity. Three crucial impediments to innovation stand to potentially derail efforts by domestic firms to bring alternative solutions to market: (1) the *architectural* challenges implicit in the innovations demanded, (2) the embedded *cultural* resistance to innovation derived from a long history of policy defection, and (3) the temporary advantage conferred by a value proposition centered around a *best-product*, rather than a *customer solutions* strategy for achieving market leadership.

ARCHITECTURAL IMPEDIMENTS TO INNOVATION

The author recognizes that established firms contend with a number of encumbrances that can stymie innovation. A multitude of literature from such industry experts as Abernathy (1978), Utterback (1990), and Christensen (1997) suggest that established firms are the least capable of delivering *disruptive* innovations. Disruptive innovations are distinct from incremental or evolutionary innovations in that they represent radical departures from mainstream products, cater to a fundamentally different consumer value proposition or market, and threaten the existing knowledge, competencies, and dominance of established firms (Christensen, 1997). These authors further contend that organizational rigidities, a product of firm success in delivering established technologies, impede firms from delivering new technologies with initial appeal to niche markets. Niche markets are crucial incubators for establishing a profitable business case for new products, often by appealing to a divergent value proposition that would otherwise languish in mainstream markets where customers expect performance along traditional pathways. However, these early markets typically represent an insignificant fraction of the established firm's normal streams of revenue and thus often fall victim to the impatient and often hostile resource allocation mechanisms of

the established firm. Rather, argues Christensen, the vast majority of “next generation” technologies find their champion via new entrants (Christensen, 1997).

In the auto and energy industries, decades of established process methodology has forged and codified a very rigid set of *communication channels*, *information filters*, and *problem-solving methodologies* necessary for development and delivery of complex products (Henderson & Clark, 1990). But these same competencies make it difficult to transition auto and energy interests to new generations of technologies, especially those that are not only disruptive, but are fundamentally *architectural* in nature. Architectural innovations are unique in that they change the way in which components of a product are linked together, while leaving the core design concepts untouched. By this definition, all of the alternative fuel/vehicle systems considered in Part I involve the reconfiguration of an established system to link together existing components in new ways. The incorporation of off-the-shelf technologies such as the electric motor, battery, or fuel cell will create new linkages and spawn new interactions in the established product. This category of innovation presents subtle challenges to established firms in that it preserves the component knowledge of the organization while destroying the architectural knowledge base (Henderson & Clark, 1990). The new behaviors also present significant liability risks to the incumbent firm.

Where firms often stumble is in their failure to appreciate the systemic change that the new arrangement of sub-systems or components creates. Instead, they tend to rely on their old frameworks – their old architectural knowledge – and consequently miss the real nature of the threat. One of the more revealing examples of this tendency is the attempt by domestic automakers to meet the call for better fuel efficiency and emissions performance via “conversions” rather than by blank sheet, ground up design efforts. To put it another way, the effort is an attempt to shoehorn alternative systems into architectures designed at the outset around the ICE. Their motivation for doing so is based on a misguided effort to control costs and reduce risk. Firms may achieve this in the short term, but the long-term danger implicit in such efforts is two-fold. First, new interactions spawn new system behaviors that ultimately undermine the firm’s established architectural knowledge. Second, the effort fails to recognize or capitalize on the potential to realize an entirely new or *different value proposition* that is either unexplored or unrealized in the mainstream

market. This pitfall is well documented in the disk drive and semiconductor industries (Christensen, 1997). It requires firms to think outside their traditional boundaries and therefore to consider information that the firm has long since screened out as irrelevant to delivering its traditional value proposition (Henderson & Clark, 1990).

The recent consolidation of global automakers, combined with the drive to outsource sub-system development to second- and third-tier suppliers portends an even greater erosion of architectural competencies at the OEM level as technologies evolve. The automakers believe that the combination of industry disintegration and strategic partnering (and other equity sharing relationships) with emerging system development firms will sufficiently manage the risk presented by these technologies. OEM's rightly contend that they can best leverage innovation and align incentives under arrangements that fully segregate development activities from the larger organization. They are further motivated to replicate the success of the mass-customization scheme of the "Dell Model," whereby customers associate value with the total system integrator and provider. This explains the flurry of acquisitions and equity sharing relationships with such fuel cell and electric drive system firms as Ballard, Ecostar, Th!nk, and Excellsis.

But their strategy is misplaced. While the move isolates and protects the activity from the hostile resource allocation mechanisms of the larger organization and aligns incentives by matching the size of early potential revenue streams with the size of the development activity, it also risks undermining the power of the established firm by outsourcing critical competencies. The limited scope of the OEM value proposition – delivering quality car and truck-based products to mainstream markets – precludes the major U.S. automakers from comprehending the potential value of the sub-systems these entities develop. The automakers believe that they are leveraging innovation and outsourcing risk, but they are also outsourcing new architectural competencies. The risk implicit to automakers is analogous to the power shift observed from hardware integrator Compaq to semiconductor provider Intel in the early 90's and is best captured by the famous "Intel Inside" marketing campaign – i.e. new architectural competencies emerge as the dominant source of value in the established product. This vulnerability is further magnified when the product in question is trending toward commoditization, differentiated by price and brand only. The lesson for automakers is that the value of OEM competencies

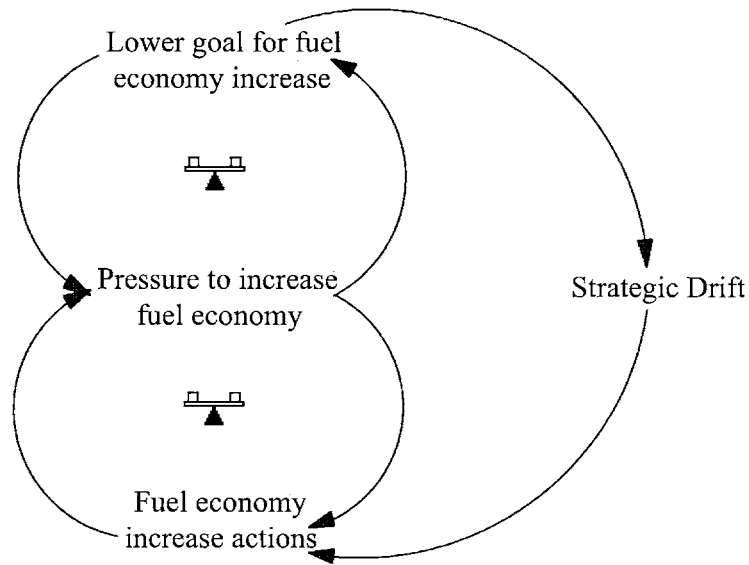
might erode over time in favor of those value chain members that possess the architectural competencies demanded by a new and/or emerging value proposition that went undetected on the “radar screen” of established firms. Ultimately, this portends a scenario where new entrants displace U.S. automakers as the key players in the mobility sector. The second critical impediment sheds some light on the reasons why auto and energy interests might fail to “see” the faint warnings on the radar screen.

POLICY DEFECTION

The second crucial impediment to innovation via established domestic firms stems from a rich industrial history of policy defection that began a half century ago with resistance to the clean air demands of states such as California. Five decades later, the modus operandi of the highly evolved political art form of delay and obfuscation have served to cement an organizational culture averse to pursuing innovation derived from alternative value propositions. This phenomenon is best explained by the “Shifting the Burden” system archetype posited by Senge (1990). Figure 4 presents this archetype as a figure eight. The top loop represents the short-term remedy to a problem faced by the organization; the bottom loop represents the underlying “root-cause” solution. The figure eight explains a wide range of behaviors where well-intended short-term fixes contribute to worsening conditions in the long-term. This is because the tendency to go with the “quick fix” also reduces any perceived need to find more fundamental solutions. Even worse, over time a fundamental solution becomes increasingly difficult to both identify and apply. First, once instigated, people come to rely on the symptomatic solution. This is because the symptomatic solution begins a march down a path requiring still more follow-on decisions that inevitably involve the commitment of expensive resources. This commitment narrows design space and “locks in” downstream decisions to a predetermined set of options. The further downstream into the process, the less likely people are to challenge these assumptions, or to consider divergent solutions (Senge, 1990).

This structural shift, portrayed graphically in Figure 8, initiates “drift” in strategic direction over time and comes at the cost of erosion in market share and competitive position. Furthermore, once a firm embarks down this path it begins to cement and

codify certain organizational structures for problem solving, communication channels, and information filters that handicap the firm from pursuing fundamental solutions. This drift also catalyzes a pattern of “eroding goals,” whereby the gap between the firm’s goals and the current state of progress create two sets of pressures: to improve the situation and to lower the firm’s goals.



Summary Figure 8 – Strategic Drift Effect of the “Shifting the Burden” Archetype

The shifting of the burden dynamic proves insidious in the subtle reinforcing cycle that it fosters, placing increasing dependence on symptomatic solutions (Senge, 1990). In Figure 8 above, the effort by automakers to relieve regulatory pressure via lobbying activities diverts attention and resources from the fundamental problem – product waste and design inefficiencies. And so begins a gradual atrophy of the organization’s ability to identify, focus on, and pursue fundamental solutions to the fuel economy and emissions problem. Consequently, pressures mount to direct resources to further short-term problem solving. In the Corporate Average Fuel Economy (CAFÉ) regulatory regime, automakers “game” fuel economy mandates, allowing them to hold to the letter of the law at the cost of defecting from the *intent* of the law. For example, domestic automakers actually *added* weight to certain medium-duty SUVs to deliberately exceed the gross vehicle weight jurisdiction of CAFÉ truck mandates (Doyle, 2000).

Doing so allowed them to sell an additional SUV and collect on the generous profit margin for each medium-duty truck that successfully skirted the law.

THE BEST PRODUCT FALLACY

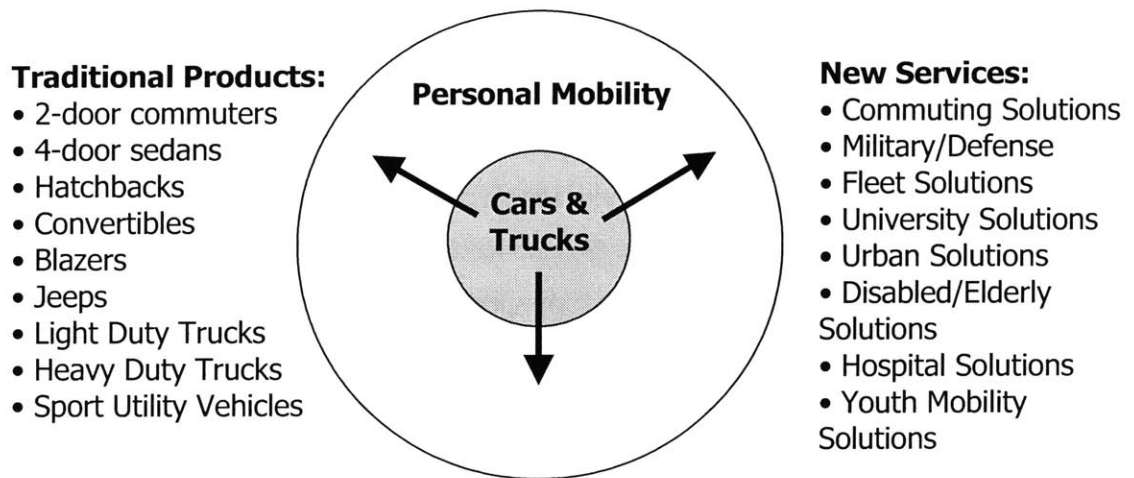
Automakers today face the classic prisoner's dilemma. Simply, the basis for competition is such that they must continue to pursue high margin vehicle segments to sustain profitability. This translates to reliance on luxury segments that exploit flatter price elasticities in order to skim higher margins. It also translates to an unbalanced product portfolio skewed toward low risk projects positioned to chase margins in established segments. Alternatively, a balanced portfolio consists of a fair share of riskier projects aimed at exploring, predicting, and meeting new consumer needs via testing of markets with new product. A balanced portfolio enables firms to grow market share through technology leadership and to capture first-mover advantages while erecting barriers to imitation (Hax, 2001).

U.S. automakers instead find themselves trapped in a highly risk-averse business model characterized by intense competition, thinning margins, and investor demands for short-term returns to shareholder value that offer little financial tolerance for failure. Recently, U.S. automakers have responded to sliding market share with a flood of fresh product distinguished by a concerted revival of classic American design. Design, however, at best conveys temporary advantage to the automaker for two critical reasons. First, the strategy suffers from weak appropriability; competitors can readily imitate it and rapidly bring it to market. A recent study by Merrill Lynch indicates that European and Japanese producers will replace 100% and 91% of their volume with new models, respectively, between now and 2005. U.S. automakers, on the other hand, will renew a mere 67% of their product offerings (*Fortune*, Jan 21, 2002). Second, where complex manufacturing relies upon a matrix organization, delivering superior product comes at the cost of sustaining the functional proficiency of the firm. The symptom emerges in the form of poorer product quality and performance. Consequently, the firm's share slips to design imitators who enter with product of equal or better performance. The early 1990's witnessed the phenomenal revival of Chrysler with industry leading product concepts such as the "cab-forward" and Ram pick-up designs. But the firm ultimately succumbed to

takeover by Daimler when a series of embarrassing performance-based product recalls and competition from rivals mimicking their designs resulted in sagging sales and a vulnerable financial situation. The lesson: best product strategy confers temporary advantage.

RECOMMENDATIONS FOR INDUSTRY STRATEGY

To achieve a system-wide and persisting competitive advantage, a firm must pursue more appropriable strategies. This requires automakers to evolve industry structure around an extended value proposition focused on delivering services rather than pushing product (see Figure 9 below). Automakers can achieve this by forging deep customer relationships, combined with a finer market segmentation that encompasses the broader value proposition. The organization must consider its installed customer base a firm asset that, like the firm’s plant and equipment capital, returns a profit to shareholders. Doing so enables firms to leverage its installed customer base to lower risk-based innovation barriers and “lock-out” competitors who might attempt to imitate (Hax, 2001).



Summary Figure 9 – Expanded Value Proposition: Personal Mobility Solutions

To successfully navigate the introduction of advanced powertrain technologies to wary markets, automakers must concede that the product they are trying to sell will look less like a traditional consumer durables market and more like a high technology market. In other words, automakers should consider the traditional consumer market adoption model (best characterized as “a car for every purpose and purse”) in light of the

Technology Adoption Life Cycle advanced by Geoffrey Moore (1991). To move beyond the important but limited innovator segment – comprised of higher income, technology-savvy environmentalists – to the lucrative mass market, requires delivery of a “compelling application” to the non-technology-savvy early adopter segment. This application would drive its acceptance over other, more established alternatives (for example, the ability of a personal digital assistant to play MP3s). One might envision in-vehicle fuel cell technologies, for example, enabling consumers to power their home or workplace or to sell back power to local utilities. For military applications, one might envision hybrid and fuel cell powered vehicles appealing to stealth and range considerations.

The consumer durable/high-technology hybrid nature of automobiles means that a hybrid approach to marketing is necessary in order to successfully move product up-market from an initial niche to mainstream segments. Incumbent OEMs hold the key to reaching the conservative Early Majority for several reasons. First, this group seeks out references within its own group, creating a Catch-22 chicken-and-egg dilemma for producers. Therefore, the way to reach the group is via a trust-based relationship focused on service and support from proven technologies. To build this trust-based relationship, OEMs should transform the value proposition from the product-centric consumer durables model to a solutions-based consumer services model. For example, automakers could, in concert with the value chain, manage system-of-systems activities that span the spectrum necessary to deliver “total customer solutions.” This includes leveraging extensive OEM distribution and sales networks and core OEM process competencies in vehicle integration with value chain members responsible for customer support. Most importantly, OEM’s should structure joint venture and/or acquisition strategies to pursue development of potentially “discontinuous” product innovations and then leverage the deep customer trust-base of the service strategy to work these higher risk innovations into the market.

RECOMMENDATIONS FOR REGULATORY POLICY

Despite the inherent difficulty for established firms, the barriers to entry in the automotive market are significant. Consequently, industry and government interests must

carefully consider innovation-based impediments in crafting a coherent strategy for bringing advanced vehicle/fuel systems to market via established producers.

Achieving significant air quality improvements requires a multimedia approach to the emissions issue. This means intervening to create economic incentives to enable desired behaviors by affected stakeholders. A two front “war” is necessary. The first front involves stimulating innovation in the most capable of industries and redistributing costs via programs such as fee-bates to lower the entry price of cleaner technologies. The second front involves regulatory interventions that catalyze technological innovation in the longer term to affect more sustainable practices as well as the development of an infrastructure to perpetuate the continued use of those practices.

Although the United States requires the use of state-of-the-art pollution control devices, consistently low gas prices reduce the cost of vehicle ownership and thereby fail to reflect the real cost, or externality cost, to society due to their increased usage. Therefore, little incentive exists for consumers to modify behavior that is aligned with emissions and energy dependence reduction goals. A good deal of the potential for vehicle emissions reductions involves removing the fleet of “dirtier” vehicles from the road earlier. Unfortunately, the costs imposed by the requirement for more fuel efficient vehicles has, in concert with factors such as vehicle safety and crash worthiness, increased the real price of new cars, with consequences that work counter to emissions goals. Higher purchase prices translate to lower turnover, as consumers must amortize the higher cost over a longer period of ownership. Lower turnover means the worse polluting vehicles stay on the road longer. To contend with this perverse incentive, policies should work to increase the *operating* cost of the worst polluting vehicles, including trucks, SUVs, and minivans, while simultaneously redistributing vehicle purchase prices to reflect implicit externality costs. This can be achieved by levying an “emissions tax” with annual vehicle registration and renewal. Authorities can then target these moneys, in concert with point of sale fees, toward point of sale and registration-based rebates for relatively cleaner vehicles.

In addition to policies that encourage diffusion of cleaner technologies, authorities must incentivize behaviors beneficial to air quality in the longer term. Considerable air quality gains can be achieved via the encouragement of higher-occupancy modes of transport. But municipalities must provide transport mode choice to the public. This entails modification of

zoning laws and permitting procedures to incentivize transit-oriented development. Moneys collected from low-occupancy transit can then be redistributed to expand local metro and light rail networks. Such efforts can go far toward mitigating the air quality impacts of urban sprawl in the longer term.

Another key enabler for public intervention is education and awareness.

Contemporary acceptance of harmful motor vehicle emissions bears striking similarities with early efforts to understand and eventually curb tobacco use. As evidence from the medical community implicated tobacco products and exposure to second-hand smoke with increased incidence of lung disease and cancer, organizations such as the American Lung Association and the American Cancer Society unleashed a sustained blitz of media campaigns to alert and educate consumers to the hazards of smoking. Grass roots lobbying efforts further succeeded in enacting laws and local statutes prohibiting smoking in public places. The recent shift in research focus to understanding the adverse health impacts of motor vehicle emissions may portend similar developments. With mounting epidemiological evidence coming to the public's attention, awareness campaigns that warn of the hazards of motor vehicle use may emerge to educate consumers and stimulate demand for cleaner propulsion technologies.

In summary, policies should use a multimedia approach to both enabling innovative capacity and to modify consumer and industry behavior over time. Authorities should target interventions that co-optimize economic growth with tangential benefits to air quality. Establishing a fee-bate policy regime that redistributes costs to reflect externality impacts away from high emission vehicle use and toward the combination of low emissions vehicles and infrastructure-building activities that support higher-occupancy modes can achieve this. For example, federal support for expansion of light rail networks, combined with tax incentives and development waivers that favor transit-oriented development, works on two fronts. First, it can enable technological innovation that serves to "lock-in" a more desired future by laying the mass-transit infrastructure network. Second, in so doing the inherent architecture of the network encourages and shapes future behavioral patterns of the consuming public in a direction beneficial to air quality.

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1 **INTRODUCTION**

“How stupid are we, the most technologically advanced culture in the history of mankind, to live without an ozone layer??? We’ve got men, we’ve got rockets, we’ve got Saran wrap. Fix it!!!” – Lewis Black, Comedian

The intent of the research that follows is to adapt a model to simulate potential adoption futures for a set of vehicles whose propulsion systems represent three distinct and radical departures from today’s dominant internal combustion engine (ICE)-based design. This chapter will begin by presenting the problem scope and the main conceptual frameworks for analysis. Part I consists of those chapters that attempt to determine the extent of the *opportunity* for bringing cleaner advanced fuel/vehicle systems to market. This section of the thesis leverages a system dynamics model for doing so. Chapter 2 provides a background of the reference market adoption model, Chapter 3 details the revisions and extensions applied, and Chapter 4 describes the methodologies for selecting a set of representative scenarios and presents the findings of these scenarios. I also critically examine the results of this chapter to determine the degree to which the scenarios achieve the objectives of sustainability.

Part II consists of those chapters dedicated to an assessment of the innovative *capacity* and *willingness* of established domestic automakers to bring advanced fuel/vehicle systems to market. Chapter 5 outlines the events and forces that created the complex and intractable crisis that the problem of vehicle emissions represents today. The chapter also attempts to outline the key industry forces, dynamics, and trends that will provide some of the greatest challenges to stakeholders in their efforts to achieve meaningful policy outcomes. To conclude, Chapter 6 invokes a set of relevant critical frameworks to recommend a preferred strategy to industry and government stakeholders for achieving the goal of sustainable mobility.

I consider this work a study of the dynamics of innovation, applied to the problem of delivering technological solutions to the problem of automotive emissions to the U.S. marketplace. Unlike many traditional studies of industry innovation in the high-tech arena, this particular application involves unique complexities of much higher order for two principal reasons. First, the solution need not depend solely on a technological fix. Rather,

the provision of alternative transit modes, representing current state of the art, might contribute a substantial portion of the requisite steps necessary for mitigating some of the deleterious impacts of increased automobile usage. Thus, the emissions conundrum presents a problem of individual consumer choice on the demand side of the equation. The second distinguishing characteristic also falls under the demand side of the equation and concerns individual consumer willingness to pay for advances that benefit the commons. Later sections discuss this concept in further depth.

To summarize, this study attempts to identify, and offer strategies to control for, the economic, cultural, and political risks associated with attempts to deliver innovations to market that are uniquely characterized by (1) reliance on a purely technological fix, and (2) an initial gulf between cost and the consumer's willingness-to-pay. I will also attempt to suggest a policy framework that relies on high-leverage entry-points for public interventions that can serve to narrow the gulf, seed demand, and grow the requisite market. The analysis relies in large part on a systems dynamics-based model designed to simulate the market adoption characteristics of a set of representative propulsion technologies, should producers choose to make them available to American consumers today. I rely on relevant scientific, economic, political, institutional, and technological aspects of the problem to attempt to identify the key market adoption criteria, energy consumption and emissions consequences, and to recommend product planning strategies and policy intervention options for their mitigation. These are this work's ultimate deliverables.

Of greatest concern to stakeholders is how the pollutant emissions of motor vehicles contribute to the concentrations of ozone, particulate matter (PM), carbon monoxide (CO), sulfur dioxide (SO₂), hydrocarbons (HC), and oxides of nitrogen (NO_x). To address these concerns, the following sections cite two key studies, the American Cancer Society (ACS) study of over 150 U.S. cities (Pope et al 1995) and the Harvard Six Cities Study (Dockery et al 1993), to characterize the nature, sources, and associated impacts of criteria pollutants to human health. I distinguish between criteria pollutants and secondary pollutants in that the former are known to have direct impacts to human health. It is hoped that a multi-disciplinary approach to the complex problem of vehicle-related emissions and energy dependence will yield greater insight to the dynamics involved. This

insight will enable decision-makers to execute effective strategies and high-leverage market interventions with the goal of improving public health and quality of life.

1.1 PROBLEM SCOPE

Many of the concerns the world faces today with regard to degraded air quality, diminished quality of life, worsening public health, and global climate change find their roots in the highly inefficient factors of production, land development patterns, and transport methods spawned by the Industrial Revolution. Today, virtually two-thirds of all criteria pollutants responsible for urban smog, ground-level ozone, and global warming originate from motor vehicles. These include the poisonous exhaust gases of internal combustion engine processes such as carbon monoxide (CO), a deadly poison, carbon dioxide (CO₂), a known greenhouse gas (GHG) contributor, and ozone precursors that consist of oxides of sulfur (SO_x), nitrogen (NO_x), hydrocarbons (HC), and particulate matter with radii of less than ten microns (PM₁₀).

Ozone (O₃), a key molecular compound for shielding the Earth's surface from damaging ultraviolet radiation, exists naturally in the high atmosphere. At ground level, however, ozone poses a dangerous threat to humans and wildlife. According to the American Lung Association (ALA), "Ozone is capable of destroying organic matter, including human lung and airway tissue. It essentially burns through cell walls, and it is capable of doing this at... levels frequently encountered in many U.S. cities" (Doyle 2000). The Environmental Protection Agency (EPA) argues that repeated exposure to ozone pollution for several months "may cause permanent structural damage to the lungs." Furthermore, anyone who spends time outdoors during the summertime is at risk, because, as EPA contends, "Even when inhaled at very low levels, ozone can trigger a variety of health problems, including aggravated asthma, reduced lung capacity, and increased susceptibility to respiratory illnesses like pneumonia and bronchitis" (Doyle, 2000).

Just within the United States the problem has reached epidemic proportions. Along the belt of cities running along the Eastern seaboard region from Miami to Atlanta to Baltimore to New York and Boston, many counties continue to fall short of the National Ambient Air Quality Standard (NAAQS) for ozone. At least 100 million Americans reside in areas that fail to meet EPA's eight-hour air quality standard for ozone. Contrary to early

industry arguments that the problems are of a localized nature, evidence clearly indicates that the deleterious impacts of pollution favor no state, coast, or region of this or any other country. During the summers of 1998 and 1999, ozone-limit violations occurred regularly along the East Coast in cities such as Delaware, Maryland, New Jersey, Pennsylvania, New York, North Carolina, Washington, DC, West Virginia, and Virginia. They also occurred in Southern cities such as Atlanta, Austin, Dallas, and Houston, West Coast cities such as Los Angeles and the majority of Southern California, and in Midwest cities such as Cincinnati, Dayton, Milwaukee, and Toledo (Doyle, 2000).

1.1.1 EMISSIONS IMPACTS TO PUBLIC HEALTH

What are the costs of this invisible by-product of motor travel? Research Atlanta estimates that about 1,000 additional persons each year will develop chronic bronchitis and emphysema. The Centers for Disease Control and Prevention (CDC) estimates that the number of U.S. asthmatics has nearly tripled, from 6.8 million in 1980 to 17.3 million in 1998. Currently, more than 5 million American children suffer from asthma. In 1999 alone, 200 children under the age of 15 died of this condition (Wang et al, 2000).

EPA estimates that mobile source emissions are responsible for 42% of the production of 188 hazardous air pollutants (HAPS) that Section 112 of the Clean Air Act Amendments of 1990 requires the agency to monitor. EPA has labeled these pollutants a “significant risk” to human health posing “the greatest potential threat to public health in the largest number of urban areas.” Many of these are either presumed or known human carcinogens (Wang et al, 2000). Table 1.1 lists Cancer Unit Risk Estimate (CURE) values. These data reflect the increased lifetime cancer risk caused by a continuous lifetime exposure to a 1.0 microgram per cubic meter ($\mu\text{g}/\text{m}^3$) increase in a given pollutant’s concentration.

		Pollutant (mg/mi)					4 Air Toxics Combined (mg/mi)	
Vehicle	Stage	VOC	Formaldehyde	Acetaldehyde	Butadiene	Benzene	EPA CUREs	CARB CUREs
ICE (CG)	Feedstock	17.11	0.244	0.05	0.004	0.212	0.75	0.292
	Fuel	71.64	0.753	0.177	0.073	1.515	5.198	2.114
	Vehicle	207	1.000	0.384	0.496	5.947	24.348	9.097
	Total	295.76	1.996	0.611	0.573	7.674	30.296	11.503
HEV (FRFG2)	Feedstock	9.01	0.128	0.026	0.002	0.111	0.395	0.154
	Fuel	37.62	0.431	0.098	0.038	0.585	2.559	0.905
	Vehicle	148.2	1.246	0.367	0.482	3.559	21.881	6.678
	Total	194.82	1.805	0.491	0.522	4.256	24.834	7.737
EV (US Mix)	Feedstock	27.61	0.653	0.072	0.046	0.124	2,720	0.536
	Fuel	5.79	0.061	0.056	0.002	0.092	0.275	0.123
	Vehicle	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Total	33.4	0.713	0.128	0.048	0.217	2.995	0.659

Source: Wang et al (2000)

Table 1.1 – EPA and CARB Cancer Unit Risk Estimate (CURE) values for ICE, HEV, and EV-based platforms

1.1.2 IDENTIFICATION OF EMISSIONS REDUCTIONS

In order to achieve the goal of improving public health and quality of life it is necessary to aggressively target those pollutants that provide the highest leverage for doing so. Of the five criteria pollutants cited earlier, PM₁₀ and the ozone precursors pose the greatest threat to human health. The most consistent findings of the ACS and Six Cities Study suggest that particulates with a diameter of less than 10 microns (PM₁₀) are most harmful to human health, resulting in elevated hospital and emergency room admissions for respiratory problems related to chronic bronchitis, asthma attacks, and restricted activity days. These studies demonstrate evidence that for each 10- $\mu\text{g}/\text{m}^3$ increase in PM₁₀ levels, an increase in daily mortality on the order of 1% is expected. An independent reassessment of these results by the Health Effects Institute's (HEI) US-wide National Morbidity, Mortality and Air Pollution Study (NMMAPS) confirmed a 0.5% increase in mortality. These data are consistent with a similar European APHEA study publicizing a 0.6% increase. Most susceptible are those with pre-existing cardiovascular conditions, namely the elderly. Although unconfirmed, recent evidence implicates PM₁₀ as a contributor to the premature death of infants. These studies also implicate long-term exposure to PM₁₀ to relative increases in chronic mortality caused by

respiratory or cardiovascular diseases. If confirmed to hold true, health impacts on the U.S. population could be several orders of magnitude more severe than suggested by the acute mortality figures illustrated here. The distribution of these health costs also raises significant questions regarding environmental justice. The NMMAP Study also found that the less educated segments of the population suffered disproportionately higher incidence of cardiopulmonary disease and lung cancer (HEI, 2001).

More recently, scientists suspect that fine particulates of less than 2.5 microns diameter (PM_{2.5}) may also impact human mortality. The ACS and Six Cities Study found that long-term average mortality rates were 17% to 26% higher among individuals living in communities with higher levels of fine particulates, PM_{2.5}, even after accounting for the effects of risk factors such as cigarette smoking and medical history. Public health authorities have used these data to quantify the shortening of the average American and European lifespan associated with air pollution (US EPA 1999). Tables 1.2 and 1.3 provide a basis for monetizing the avoidance of adverse health incidence. The result suggests that benefits on the order of a hundred billion dollars are possible. Although these data are sensitive to the value ascribed to adverse health impacts, the evidence overwhelmingly supports interventions necessary to achieve such gains.

Value of Selected Health Effects in the U.S.	
Per person Annual Mortality	\$4,800,000
Per person Annual Chronic Bronchitis	\$260,000
Work-loss Day	\$83
Minor Restricted Activity Day	\$38

(Source: Harvard Six Cities Study)

Table 1.2 – Value of Selected Health Effects in the U.S

	Cost Range	
Accident Costs not paid by Responsible Party	13	49
Congestion Costs	34	146
Mortality & Morbidity from Mobile-source Emissions	19	284
Other Externality Costs	34	421
Total Externality Costs (Billions of Dollars)	100	900

(Source: Delucchi, 1997)

Table 1.3 – Range of potential externality costs imposed by motor vehicle travel

Although its impact on mortality is less clear than PM₁₀, studies have linked ozone (itself a secondary pollutant), with decreased respiratory function and increased eye irritation,

cough, asthma, and respiratory-related hospital and emergency room visits. NO_x, a greenhouse gas, and Volatile Organic Compounds (VOCs) such as HC, react in the atmosphere to form ground-level ozone. VOCs are typically less costly to control, but ozone formation is NO_x sensitive. Furthermore, these pollutants affect the formation of secondary PM_{2.5} (formed in the atmosphere via chemical transformations rather than directly as a product of combustion). Since roughly half of PM_{2.5} is secondary in nature, policies should focus on the mitigation of NO_x emissions to leverage reduction in both ozone and secondary PM_{2.5} formation.

The transportation sector is the single greatest source of particulates and the ozone precursors NO_x and HC. Within this sector, primary contributors include diesel tractor-trailers, heavy-duty diesel trucks, and private autos. Outside this sector, point sources such as electricity generation also contribute heavily to NO_x formation; area sources involved in the production, storage, and use of solvents and fuels also contribute significantly to HC emissions.

Several global trends portend to worsen an already critical state of affairs. China, India, and Latin America represent massive potential markets for the big automakers. With the rising tide of global wealth, whole-scale adoption of current ICE-based technologies would suffocate the planet's carrying capacity, i.e. its ability to cleanse our environment through the natural processes of surrounding ecosystems. Even worse, Americans have grown fond of larger, more polluting truck-based platforms such as SUVs, Minivans, and trucks. Table 1.4 illustrates that as of two years ago, trucks actually surpassed cars in annual market share of fleet sales.

	1975	1988	1996	2000
New Cars	80%	70%	60%	50%
New Light Trucks	20%	30%	40%	50%

(Source: Delucchi, 1997)

Table 1.4 – Market Share of New Cars and Light-duty Trucks by year

This trend is characteristic of a nation-wide shift from higher to lower efficiency modes of transport. Poor coordination of land use development and infrastructure planning at the metropolitan level as well as the exodus of city populations to suburbia, have contributed to the unabated rise in practices that perpetuate and exacerbate air pollution mitigation efforts.

In many western cities where the ascendance of the automobile predated land development patterns, for example, rail transit simply doesn't exist. Thus, policy interventions should target modes, behavior, and supporting infrastructure to affect desired air quality outcomes.

1.2 CONCEPTUAL FRAMEWORK

1.2.1 SYSTEMS THINKING

“When a [great] problem arises... the safest policy is to delay dealing with it rather than trying to do away with it, because those who try to do away with it almost always increase its strength and accelerate the harm which they feared might come from it.” (Machiavelli 1979)

Machiavelli grasped the erosive nature of perverse incentives; that is, behavior spawned by misaligned incentives that results in outcomes counter to that which the intervener sought upon the outset. Preventing this behavior demands a systems-based approach to complex problems. Throughout this analysis, I will approach the emissions conundrum from a “systems” perspective. That is, not as an expert in any one field such as economics, history, industrial science or engineering, but from a multi-disciplinary context that brings the tools of all of these disciplines to bear on the problem. True, for the purpose of this thesis I have limited my scope to examining the technology-based solution pathways for vehicle emissions; I have already argued that other non-technology options exist. Therefore, my recommendations will remind the reader that the options suggested here, while hopefully salient, must be accompanied by complementary and coordinated actions encompassing a spectrum of pathways on behalf of the set of key stakeholders.

The beauty of systems thinking is that it recognizes the importance of forces that lie beyond the control, and often reason, of man. Since youth, man is trained to break apart very complex problems and analyze the manageable chunks (Senge, 1990). History has witnessed some of mankind's greatest achievements from this simple, engineering-based approach: construction of the Panama Canal, Victory over the Axis Powers in WWII, and the Apollo Space Program. Unfortunately, the approach has also yielded undesired and often terrible results: Thalidomide, Nuclear Proliferation, Global Warming, and a host of others. Some persistent problems such as poverty continue to elude solution.

We often witness these undesired effects when our endeavors necessitate our involvement with what Sussman (2001) refers to as very Complex, Large-Scale, Integrated

Open Systems, or CLIOS for short. Complex in that the problem involves multiple stakeholders with divergent interests, multiple levels of decomposition, and first- and second-order, nonlinear behavior that defies the limits of human prediction or comprehension. *Large-Scale* in that the problem is characterized by multiple boundary layers representing interfaces with human, ecological, or technical systems of varying size and scope, from the macro to the micro. *Integrated* in that that the problem is characterized by multiple points of connectivity, i.e. nothing acts in isolation but rather “everything is connected to everything else” (Sterman, 2000). Most importantly, the problem is an *open system*. It defies bounding and is subject to external manipulation and influence by forces both within and beyond the control of man. What man often fails to appreciate is that problem solving, by definition, involves intervention in open systems. The intervention is equivalent to a force that, like dipping a toe into a pool of water, initiates waves, or a series of processes that may, or may not be, visible, predictable, or quantifiable by human reason. Worse still, these problems involve delays that often obscure the causal links and hide the true sources of the adverse behavior witnessed. Thus, continued intervention often only exacerbates the problem, targeting only the symptoms of a deeper illness.

The problems posed by the pollutant emissions of motor vehicles qualify under this definition. Systems dynamics provides a tool for learning in such complex systems (Sterman 2000). I invoke the method throughout this work to facilitate a better understanding of the sources of, and behaviors witnessed by, the complex interplay of the multiple and diverse forces and dependencies involved in the emissions problem. The method enables the construction of a cohesive picture, or “shared vision” amongst stakeholders with divergent interests. In this sense, the tool provides value by bridging the disparate mental models, problem-solving methodologies, and channels of communication that impede the cooperation necessary to achieve meaningful progress. By doing so, I hope to facilitate high-leverage interventions (i.e. interventions that affect the desired “systemic” behavior rather than isolated areas) that avoid the pitfalls of policy resistance to achieve desired ends.

1.2.2 THE FALLACY OF ACCOUNTING PRACTICES

Under a hypothetical business accounting regime, we might expect businesses to debit deductions from the natural stock of capital and to factor in the “costs” of adverse product emissions. Under such a regime, we would expect producers to include these factors as part of the “cost of production” and to price passenger vehicles, and the energy that fuels them, accordingly. Thus, goods and services would be priced according to their “true” cost. That is, the cost that the individual consumer pays for the factors of production required to produce, distribute, and sell the vehicle and its fuel *in addition to* the cost borne by society as measured by the adverse ecological and health impacts actualized by the good’s production, operation, and disposal.

But lo, this is not the case. Rather, it is an implicit rule in business that what you do not *measure* does not *matter*. Our current business paradigm operates on tenets long-held since the inception of the Industrial Revolution that natural capital exists as a right to all entities that might endeavor to “improve” upon it for the purpose of man and that such stock is essentially inexhaustible in supply. From the perspective of the late Eighteenth Century, such an assertion might well have seemed perfectly plausible. But the unavoidably exponential pattern of growth in the population and wealth of the world’s human inhabitants over the past two centuries has served to undermine this fallacious assumption. Nevertheless, long-standing accounting practices continue to treat natural resources as non-existent until extracted for productive purposes (Hawken, 1993).

Now, more than ever, the ascendance and prosperity of man on this planet has initiated not gradual degradation of precious natural resources, but rather the disintegration of every natural system on Earth. These systems sustain life and provide the factors necessary for the growth and sustenance of whole economies. Most disturbingly, they do so via mechanisms as complex and arcane to human understanding as the weather. Thus is the moral imperative for acting now to stem what might already be irreversible forces at play.

1.2.3 THE TRAGEDY OF THE COMMONS

Assuming stakeholders wish to preserve the current consumer desire for personal modes of transport, and presuming industry can “close the loop” on the emissions

problem via a technological fix, the customer may prove unwilling to pay for the fix. I do not attempt to argue that previous studies of innovation in industries such as personal computing lacked these risk characteristics. Rather, I assert that this particular problem provides a unique challenge to firms and society in that it invokes the *tragedy of the commons*; that is, even in the presence of a technological fix, the individual consumer may prove unwilling to pay for the initial high costs associated with providing benefits appropriated more by society than by the individual. To better explain this phenomenon, I provide the simplified situation outlined by Table 1.5 below. Suppose market research provides the following data on two features under consideration for inclusion in their next generation vehicle platform.

Innovation	Producer		Consumer	
	Account	Value	Account	Value
<i>Cup Holder</i>	Price	\$20	Individual	\$20
	WTP	\$20	1-1	\$18
	Cost	\$5	Network	\$2
	Profit	\$15	Communal	\$1
			Internalized	\$0
			Total Value	\$21
		Tot Consumer WTP	\$20	
<i>Cleaner Engine</i>	Account	Value	Account	Value
	Price	\$4,000	Individual	\$2,000
	WTP	\$2,000	1-1	\$1,800
	Cost	\$3,800	Network	\$200
	Profit	(\$1,800)	Communal	\$2,000
			Internalized	\$0
		Total Value	\$4,000	
		Tot Consumer WTP	\$2,000	

Table 1.5 – Simplified cost accounting for producer-to-consumer transactions

The transaction involves no intermediaries between the producer and the consumer. The producer has a cup holder design that it believes it can sell to the consumer at the price point of \$20. Since the cup only cost the firm \$5 to make, the company pockets \$15 in profit. The firm arrived at a price of \$20 by a close examination of how the consumer imputes a value to the added benefit delivered by the cup holder. In the “Consumer” column of Table 1.5, I segment the consumer’s decision between (1) the value internalized

from benefits derived by the individual consumer, and (2) the value internalized from benefits derived by the community. Note that two values comprise the individual's direct benefit from the invention. One-to-One ("1-1") benefits represent the monetary worth of the feature's benefit derived via the consumer's direct interaction with that feature. In the cup holder example, the consumer directly benefits from the convenience of having a place to set his cup down while driving. Network benefits consist of the set of benefits the consumer gains from the interaction of others with the feature the consumer has paid for. Again, in the cup holder example, the consumer ascribes a value of \$2 from the convenience that say, his passenger gains from having a convenient place to set his cup so that it doesn't spill and damage the car's interior.

Also note that the cup holder has a "communal" value equal to \$1. This is an arbitrary value that represents the benefits realized by society. In this particular example, the cup holder provides a convenient holding location for an empty soda can so that the driver can locate a receptacle for disposal rather than ejecting the item from the car. This is a benefit to society because it indirectly prevents litter that imposes a cost on society in that its presence reduces quality of life, lowers real estate values, and requires costly public intervention to clean up. Yet in Table 1.5, observe that the consumer does not impute this value in their willingness to pay calculus. Perhaps the consumer only drives cross-country and therefore does not internalize the costs his litter imparts on other communities. Nevertheless, the sum of the value to all parties is \$21, but the customer is only willing to pay \$20 because the consumer internalizes only 20 of the total \$21 of value. This is of little concern from the producer's point of view. Since the cost to society did not represent a factor in the cup holder's production, the cost is not reflected in the price of the feature. On individual value alone, the cup holder has a profitable business case.

Not so for the cleaner engine feature. The sum of the *internalized* values derived from individual and communal considerations equals the consumer's total willingness to pay (WTP) for that product. Observe that in the case of the cup holder, the firm turns a substantial profit because the consumer's total WTP is much greater than the cost to produce and deliver the attribute to the customer. In the cleaner engine example, however, although individual and communal values sum to a total value that could substantiate a profitable business case, the consumer only internalizes the benefits derived to the

individual. Therefore, individual consumers will pay only \$2000 for the benefit, an amount that falls far short of a profitable business case for the producer. Despite the fact that the act of making the product imparts a cost on society, this value is absent from the cost calculus. Furthermore, the act of operating the product imparts additional costs on society, but the cost is not represented in the consumer's value calculus.

But why should action rest on a moral imperative rather than a market imperative? The answer lies with the consumer. Because price rarely imputes the real, or the collective, cost of goods and services, the consumer behaves just as ignorantly as price. That is, why should a single consumer be expected to bear the cost of cleaner products if his share of the benefits is a fraction of the price paid. This is the classic "tragedy of the commons" dilemma. Furthermore, there often exists significant disparity in the distribution of costs and benefits across the pool of consumers. For example, why should consumers in the Midwest pay a premium on a product for benefits disproportionately distributed to consumers in Northeastern states, as is the case with the U.S. Acid Rain Program? To contend with this cost/benefit asymmetry, the program employs an emissions trading scheme that establishes an artificial market for the trading of emissions credits. The success of emissions trading is attributed to the "enabling myth" that location doesn't exist as far as emissions credits are concerned (Ellerman, 2002). I will discuss the potential for such a regulatory scheme in later sections.

The problem is rich with irony after irony. First, because price has historically ignored "true" costs, customers have come to develop certain expectations with regard to vehicle and fuel prices. Thus, to transition to a regime that includes such costs risks a negative reaction by both producers and consumers. Producers are quick to highlight market studies that underscore the reluctance of consumers to pay for the costs such improvements would entail. Consequently, any increase in price for these attributes risks significant revenue streams on already thin margins. All else equal, an increase in price results in reduced demand and reduced revenues.

But the premium is greatest only during the initial introduction of the technology, where economies of scale haven't yet coalesced. As manufacturers reach higher levels of production, scale economies reduce the price penalty, thereby making the technology accessible to broader market segments. But these improvements require significant up-

front investments in plant and equipment. To amortize these fixed costs, firms must sell in considerable volume. The paradox is such: if mainstream customers are the key to turning a profit, how can a business attain the scale necessary to reach a market-clearing price point for the mass market if mainstream consumers cannot afford the pre-scale cost of the technology?

1.2.4 LIFE CYCLE ANALYSIS (LCA)

The data presented in the following chapters reflect metrics that consider the entire product life cycle. That is, the factors required to extract, transport, process, manufacture, distribute, operate, and dispose and/or recycle the product. The vast majority of data, from which the conclusions of this study are drawn, are based on life cycle-based assessments performed via Argonne National Lab's (ANL) GREET Model (Wang et al, 2001). These results also draw from life cycle figures presented by Princeton's Center for Environmental and Energy Studies (CEES) (Ogden, 2002) and MIT's Energy Lab (Weiss et al, 2000). In all cases, the sources determine lifetime vehicle emissions based on upstream process such as fuel extraction, storage, and distribution as well as downstream processes such as vehicle refueling and combustion from operation. The figures also consider the factors of production required to manufacture, deliver, and dispose and/or recycle the vehicle product. Table 1.6 provides a summary of the fuel and propulsion technology packages considered as well as the processes accounted for in the data provided. Tables 1.7 through 1.10 list cost per mile data for each of the scenarios considered with respect to the five criteria pollutants and greenhouse gases.

Fuel/Vehicle Technology	Process Analyzed
Conventional Gasoline (CG)	<i>Upstream</i> Process fuel combustion
Federal RFG Phase 2 (FRFG2)	
Direct Hydrogen, decentralized Natural Gas	Fuel Production
Grid-independent HEV (HEV)	Fuel transportation, storage, & distribution
PEM Fuel Cell-powered electric vehicle (FCEV)	<i>Downstream</i> Vehicle refueling
Battery-powered electric vehicle (EV)	
	Vehicular fuel combustion
	Vehicular fuel evaporation
	Brake and tire wear

Source: Wang et al (2001)

Table 1.6 – Model Basis for Life Cycle Analysis (LCA) of fuel/vehicle technologies

Emissions of Baseline Gasoline ICE Vehicle

Emissions (g/mile)	Upstream	Operation	Total LCA	Cost[cents]/mile
VOC	0.10	0.21	0.30	0.11
CO	0.14	5.52	5.66	1.59
NOx	0.20	0.28	0.47	0.36
PM10	0.02	0.03	0.05	0.02
SOx	0.12	0.05	0.17	0.06
Total Pollutant	0.57	6.08	6.65	2.15
CO2-equivalent	113	401	514	5.14

Table 1.7 – Baseline Life-Cycle Gasoline ICE Vehicle Emissions

Emissions of Gasoline HEV (ICE) Vehicle

Emissions (g/mile)	Upstream	Operation	Total LCA	Cost[cents]/mile
VOC	0.05	0.15	0.20	0.07
CO	0.09	3.53	3.62	1.02
NOx	0.11	0.28	0.39	0.30
PM10	0.01	0.04	0.04	0.02
SOx	0.06	0.00	0.06	0.02
Total Pollutant	0.32	3.99	4.31	1.43
CO2-equivalent	64	216	280	2.80

Table 1.8 – Life-Cycle Gasoline HEV (ICE) Emissions

Emissions of Direct Hydrogen FCEV Vehicle

Emissions (g/mile)	Upstream	Operation	Total LCA	Cost[cents]/mile
VOC	0.01	0.00	0.01	0.00
CO	0.12	0.00	0.12	0.03
NOx	0.15	0.00	0.15	0.11
PM10	0.00	0.02	0.03	0.01
SOx	0.01	0.00	0.01	0.00
Total Pollutant	0.29	0.02	0.31	0.16
CO2-equivalent	171	0	171	1.71

Table 1.9 – Life-Cycle Direct-Hydrogen FCEV Emissions

Emissions of Grid Dependent Battery Electric (EV) Vehicle

Emissions (g/mile)	Upstream	Operation	Total LCA	Cost[cents]/mile
VOC	0.04	0.00	0.04	0.01
CO	0.11	0.00	0.11	0.03
NOx	0.78	0.00	0.78	0.60
PM10	0.06	0.02	0.08	0.03
SOx	0.93	0.00	0.93	0.34
Total Pollutant	1.91	0.02	1.93	1.01
CO2-equivalent	384	0	384	3.84

Table 1.10 – Life-Cycle BEV Emissions

1.2.5 INNOVATIVE CAPACITY

Innovative capacity at the firm, or industry level, refers to the propensity of organizations to innovate. The literature also speaks of innovative capacity in terms of *innovative capability* and *adsorptive capacity*. Regardless of the moniker, the science recognizes that firms, industries, and entire nations exhibit disparate levels of invention as measured by such criteria as patent filings.

There is little question that auto and energy interests have the capacity to innovate. There is, however, the considerable question of whether or not they possess the capacity to innovate down alternative propulsion pathways. The willingness of firms to do so depends not entirely on the presentation or emergence of a profitable business case, but also on the cultural and business systems required to stimulate, reward, and realize such innovations. Chapter 2 delves into an examination of this complex and qualitative part of the adoption dynamic.

PART I: ASSESSING THE OPPORTUNITY

2 SYSTEM DYNAMICS DEVELOPMENT OF THE REFERENCE MODEL

Central to my research is the extension of a market adoption model based on System Dynamics tools to examine potential pathways for the introduction of advanced automotive powertrain technologies to the mass market. To do so, I have borrowed an adoption model, heretofore referred to as the reference model, constructed by an LFM student based on technologies estimated to be available to consumers in the year 2020. Many of the conclusions drawn in this thesis are derived or verified from the application of this model, specifically tailored for the purpose of addressing the problem of achieving the goals of a sustainable automotive sector as highlighted in Chapter 1. In order to do so, the author adopted an existing model as a reference framework. From this reference model, the author set out to revise its structure in a number of aspects to appropriately address the subject of the study.

Prior to any discussion of these modifications, it is first necessary to outline the structural approach of the reference model. For a more explicit description or for detailed documentation of this model, I refer the reader to Metcalf 2001. A brief overview should suffice here.

2.1 STRUCTURE

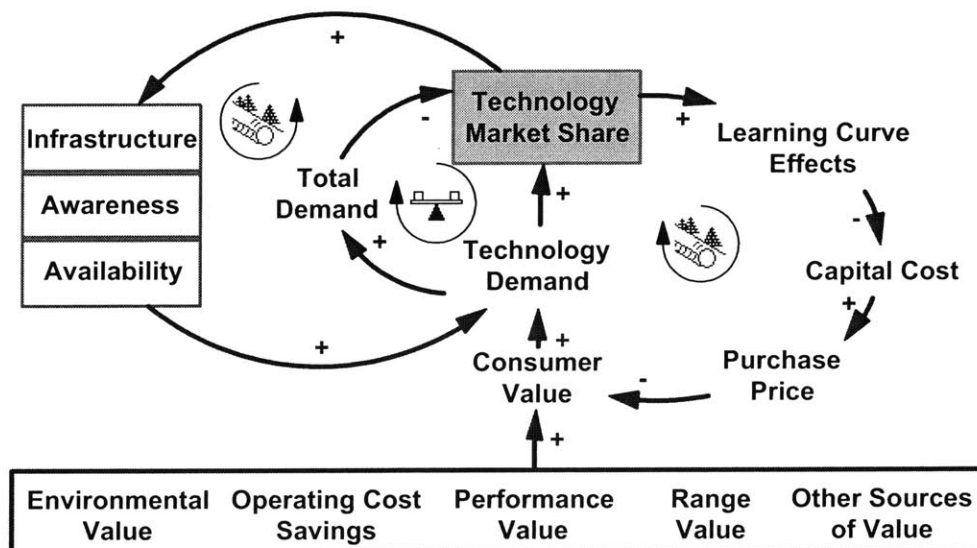


Figure 2.1– Overview of the System Dynamics structure of the reference model

The reference model consisted of 95 sketch variables, 68 of these representing variables containing distinct values for each of the propulsion regimes considered. The model comprised 298 elements in total, with 195 endogenous relationships and 103 exogenous parameters. The left-hand side of the diagram illustrates the key feedback mechanisms: infrastructure [coverage], [technology] availability, and [consumer] awareness.

Infrastructure Coverage represents the complementary service infrastructure required to support a given propulsion system. Support includes not only the provision of fuel service stations in adequate numbers to satisfy the convenience demands of customers, but also the establishment of a trained community of service technicians, specifically educated to service, repair, and maintain the fleet of vehicles on the road. Thus, Infrastructure Coverage encompasses a broad spectrum of activities beyond the mere construction or retrofit of the nation's gas stations. Rather, it could include the creation of new, or adaptation of existing, value networks required to explore, extract, store, and distribute the appropriate fuel or energy carrier to the vehicle.

For the relatively less radical propulsion architectures such as the gasoline-powered HEV, the fueling infrastructure side of the equation is negligible when compared to the need to establish the necessary certification regimen to license and train a cadre of service technicians to support the newer technologies of the advanced powertrain. On the other hand, the more radical propulsion architectures such as the FCEV, using direct hydrogen as its energy carrier, could entail significant capital investment in a fueling infrastructure in addition to the licensing and certification of a service community. Table 2.1 offers a comparison of the level of investment required for a representative set of potential propulsion architectures.

<i>Propulsion Architecture</i>	<i>Fueling/Energy Carrier Infrastructure</i>	<i>Service & Repair Infrastructure</i>
Gasoline ICE	Negligible	Negligible
Gasoline HEV	Negligible	Moderate
Diesel HEV	Moderate	Moderate
Gasoline OBR FCEV	Negligible	Very High
Methanol OBR FCEV	High	Very High
Direct Hydrogen FCEV	Very High	Very High
BEV	Moderate-High	High

Table 2.1 – Relative investment hurdles for representative propulsion architectures

Technology Availability refers to the extent to which automakers make advanced propulsion technologies available to the consumer market. In order to manage risk, manufacturers will often introduce technologies on a limited basis to tease out the market and attempt to gain valuable insights regarding product performance in the operating environment. As a result, automakers may opt to deliberately undersupply the market. Executing such a strategy also serves to stimulate demand for the product, prop up price, and limit exposure to excess capacity or oversupply. Thus, consumers may have a legitimate demand for the technology, but their access to the product is restricted by the supply of product available for consumption.

Finally, Consumer Awareness plays a crucial role in technology adoption for reasons that are self-explanatory. Consumers may be unaware of the existence of alternative technologies or the attendant benefits they potentially offer over established products. Without adequate marketing and advertising campaigns, consumers may remain uneducated and unaware of these benefits despite the level of infrastructure coverage or product availability on the market. Media coverage can also serve to seed public awareness, knowledge, and interest in the costs and benefits of alternative technologies so that consumers can factor these considerations in the purchase decision.

Infrastructure Coverage, Technology Availability, and Consumer Awareness represent the characteristics of a given technology exogenous to the consumer's purchase decision. These are combined with a *Probability of Purchase* derived from product

attributes endogenous to the consumer's purchase decision. Together, they yield aggregate demand for a particular technology. They are multiplicative. Thus, demand is predicated on some level of existence for each of these considerations. This makes sense implicitly. If no one is aware of the technology, if no infrastructure exists to support the technology, and if the automakers fail to make any technologies available to consumers, then it is reasonable to assume that Demand would be non-existent in such cases. There is, however, a potential fault in this logic, which the author intends to broche when discussing the revised model.

Each of these four dynamics contributes both reinforcing (as represented by the snowball in Figure 2.1) and balancing (as represented by the scale) behaviors in the system due to the interrelated effects of *Technology Demand* on *Technology Market Share*. The relationship of these effects to technology Demand resembles the "chicken-and-egg" dilemma. In other words, a precondition for the existence of one is the existence of the other; which comes first is uncertain. In the absence of the three exogenous conditions, market demand fails to materialize. Yet, in the absence of demand the key players have little incentive to invest scarce resources in supporting infrastructure, product availability, or consumer awareness.

It is useful for the author to point out a key observation for discussion in later chapters. The mass-market model is predicated on the assumption that automaker and energy concerns will be willing to supply new technologies to the market and that consumers in the mainstream market will be willing to adopt them. Thus, automakers perceive that they must ensure new products either approach or exceed the performance characteristics of existing products. Secondly, suppliers must also be sufficiently motivated by the potential for growing revenue streams where large, risk-laden capital commitments are required.

In the reference model, Technology Demand for each propulsion type increases the Total Demand for all propulsion options, which is then used to normalize Technology Market Share. Competition between propulsion technologies for Technology Market Share creates a balancing feedback. Conversely, as technologies penetrate the market to capture increasing share, costs decline with scale, thereby enabling a more attractive Purchase Price that stimulates increased demand. This reinforcing behavior results from the "learning

curve” effect typically exhibited by new technologies as the innovation evolves. The reference model provides the means to adjust the relative strength of these feedback mechanisms.

Again referring to Figure 2.1, we see that the demand for a given propulsion architecture is derived from the calculation of cumulative Consumer Value from the sum value of a set of criteria product attributes. These attributes include Operating Cost, Performance, Range, Environmental Cost, and Other Sources of Value. In order to grasp the structural differences between the reference and revision models, a general discussion of each attribute follows. Again, for a more detailed treatment, I refer the reader to Metcalf 2001.

2.1.1 TREATMENT OF ATTRIBUTE VALUE IN STIMULATING CONSUMER DEMAND

Environmental Value

The reference model determines cost per mile of air pollution and greenhouse gas (GHG) emissions and then translates these into annual costs based on the assumption of 12,000 vehicle miles traveled per year and a vehicle lifetime equal to 14 years. The author chose not to apply a discount rate to these figures, arguing instead that the absence of a discount rate is justified in order to appropriately account for costs that reflect environmental and societal externalities. I concur with the author’s assessment here. The reference model thus calculates the total cost of environmental damage created by a particular propulsion technology and then converts the cost to a relative value by comparison to incumbent technology, i.e. the ICE.

Notably, Metcalf translates the full cost of environmental damage to a cost realized at the point of sale by the customer via an Internalization Fraction. This fraction represents the degree to which the consumer at the point of sale internalizes costs stemming from environmental damage. Metcalf includes this parameter as a scenario variable.

To summarize, the reference model computes a monetary value in terms of \$/vehicle for environmental benefit associated with the environmental damage cost differential of cleaner propulsion technologies and incumbent, ICE-based systems. This value is returned, along with the set of additional attributes discussed, to calculate product demand for a given technology. This is expressed as

Equation 2.1 – Environmental Value

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

where

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

EDC_i = *Environmental Damage Cost*, \$/vehicle

$f_{internal}$ = *Internalization Fraction*, dimnl

Operating Cost Savings Value

The reference model seeks to capture the value ascribed to the consumer from the cost differential of owning and operating a vehicle relative to the incumbent ICE product. This is accomplished by calculating the annual operating cost as a function of both variable and fixed costs. Variable costs are those dependent on fuel cost and fuel economy. Fixed costs are those associated with insuring, maintaining, and servicing the vehicle.

Metcalf then adjusts the annual cash flows by a discount rate of 30% to reflect the opportunity cost (annual rate of return) considered by consumers at the time of purchase. Metcalf rightfully notes that consumers typically associate much higher discount rates than what might be considered reasonable when making purchase decisions. The discount rate, however, is a scenario variable and can be adjusted to reflect greater consumer internalization, i.e. sensitivity, to operating costs. Metcalf uses a table function to convert the user specified discount rate into an appropriate multiplier that is applied to annual cash flows over the 14-year vehicle life. Again, refer to Metcalf 2001 for the specifics of this multiplier.

Again, Metcalf translates the internalized cost of operating the vehicle into a relative monetized value via the cost differential between a given propulsion technology and the ICE operating cost as expressed by Equation 2.2.

Equation 2.2 – Operating Cost Savings

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

where

$OpSavings_i$ = *Operating Cost Savings* (Figure 2.1), \$/vehicle

Range Value

In translating vehicle range to consumer value, Metcalf rightly cites survey data and analysis by Train (2000), suggesting that consumers place a strong negative value on range below a certain expected threshold. Furthermore, the negative impact of ranges short of this threshold is far greater than the positive value associated with a corresponding increase in range. Metcalf dubs this phenomenon a “convenience threshold,” representing the consumer’s expectation regarding the frequency with which he/she must fill the tank. An s-shaped table function translates this behavior to a monetized value. The model employs a number of such s-curves rather than “if...then” constructs to capture similar consumer behavior or technical system patterns.

Performance Value

The reference model estimates performance value on a relative scale, where ICE performance is unity. Performance captures a number of both quantitatively measurable vehicle characteristics such as acceleration, horsepower, top speed and more qualitative ones such as handling, towing capacity, or hill-climbing ability. Metcalf again employs an s-curve function table to translate relative performance to a monetized value. The s-curve function simulates the diminishing marginal returns of increased performance and the substantial penalty incurred for falling short of the benchmark ICE. In this model, relative performance for the set of advanced powertrains is a static scenario variable, determined by the user at the outset. It remains fixed for the life of the run and despite the subjective nature of the curve, it maintains consistency of relative performance differentials across the set of technologies. The user can, however, adjust this function to reflect a new set of scenarios.

Other Sources of Value

Metcalf uses this attribute for two purposes. First, in her words “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.” Secondly, it is used as “filler” to ensure that the consumer’s Willingness to Pay (equal to the sum total of all attributes)

exceeds the purchase price of the vehicle to yield positive value. The difference between Willingness to Pay and Purchase Price thus equates a positive value to the consumer that can be compared in relative terms amongst the set of technologies. The default value to achieve this is \$17000/vehicle for all technologies. This is an arbitrary and subjective figure. It attempts to incorporate the value of all other product features that operating savings, performance, range, or environmental impact attributes fail to capture.

2.1.2 DEMAND

The reference model sums the five individual values derived from the five endogenous product attributes discussed in 2.1.1 to establish the consumer's Willingness to Pay. Subtracting the actual Purchase Cost of the vehicle from this quantity yields the relative value to the consumer as illustrated in Equations 2.3 and 2.4 below.

Equation 2.3 – 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 , \$/vehicle
- $OpSavings_i$ = Operating Cost Savings of technology i , \$/vehicle
- $RangeValue_i$ = Range Value of technology i , \$/vehicle
- $PerfValue_i$ = Performance Value of technology i , \$/vehicle
- $OtherValue_i$ = Other Sources of Value of technology i , \$/vehicle

Equation 2.4 – Consumer Value

$$Value_i = WTP_i - P_i$$

where

- $Value_i$ = Consumer Value of technology i , \$/vehicle
- WTP_i = Willingness to Pay for technology i , \$/vehicle
- $P_i(t)$ = Purchase Price of technology i , \$/vehicle

Metcalf then translates consumer value into a probability of purchase via the use of a normalizing constant. The author uses this constant to convert Consumer Value to a dimensionless form of Consumer Utility appropriate for exponentiation to yield Probability of Purchase. To do this, the model uses a form of the multinomial logit model common in marketing research. The logit formulation serves to integrate out error terms across the technologies (Lilien et al 1992).

The author selected a normalizing constant by manipulation of the price elasticity equation for a technology at a certain price. The price elasticity represents the reduction in market share observed from a one percent price increase. The market share, however, is that share that might exist in the absence of the feedback effects represented by infrastructure, availability, and consumer awareness. These feedback effects are considered external to the logit formulation for probability of purchase, and are thus excluded from computation of the normalizing constant.

Equation 2.5 – Formulation of the Normalizing Constant from the Price Elasticity Equation

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

where

e_{price} = Price elasticity, dimensionless

$share$ = Share of technology independent of feedback effects, dimensionless

The model uses the Probability of Purchase to estimate starting market share and the initial price level to solve for the normalizing constant, b , for each of the representative technologies assuming an elasticity of -2. But because price elasticity changes at different levels of market share, the author applies a single constant across all technologies to eliminate bias of one technology over another under changing external conditions. This ensures that the probability of purchase is based on the endogenous technology attributes. The use of a normalizing constant is circumspect, however, raising a number of concerns with regard to the validity of its application. These concerns will be addressed in detail upon description of the revised model.

2.2 FEEDBACK EFFECTS ON CONSUMER DEMAND

The probability of purchase, derived from the multinomial logit function described previously, combines with the three exogenous factors (Infrastructure Coverage, Technology Availability, and Consumer Awareness) to determine aggregate demand for a given technology as illustrated in Equation 2.6.

Equation 2.6 – 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 , 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 multiplicative nature of the demand equation indicates that demand will be zero in the absence of any one of these elements.

Infrastructure Feedback

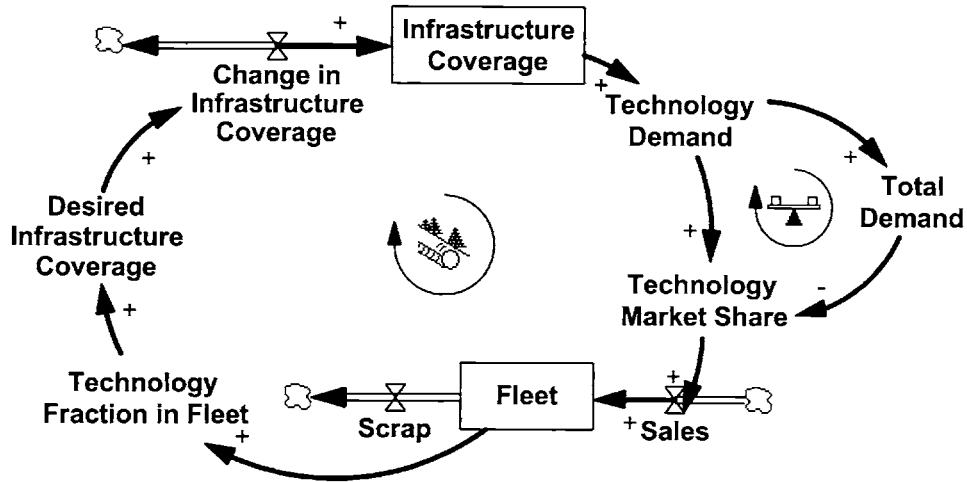


Figure 2.2 – Structure of Infrastructure Coverage Feedback in the Reference Model

The above diagram outlines the feedback mechanisms of infrastructure coverage, tracing the relationship between coverage and demand for a given technology. The provision of infrastructure is a prerequisite for demand. Increasing demand increases market share of new vehicle sales, displacing other technologies, thereby increasing the fraction of a particular propulsion technology in the fleet at any given time. Note that the provision of infrastructure is dependent on this fraction, rather than the market share of new sales. This implies, for example, that fuel service providers base their supply decisions on the pool of vehicles on the road rather than on shorter-term sales trends.

Infrastructure Coverage is presented as a stock in the reference model and is assumed 100%, or unity, for gasoline-fueled architectures, i.e. ICE and HEV. Conversely, the more radical technologies have near zero supporting infrastructures initially. All else equal, as demand for a technology increases, desired infrastructure coverage increases as well. This increase is represented by an s-shaped function that translates the Technology Fraction in Fleet to Desired Infrastructure Coverage. The function implicitly simulates a “decision rule,” on which fuel suppliers base their supply decision. A delay in bringing infrastructure on line, however, reflects the time to implement such change. The increase in coverage translates to increased demand, increased Technology Market Share, which

increases the total fraction of the technology fleet on the road at any given time. The infrastructure feedback mechanism simulates the “chicken-and-egg” dilemma. This mechanism is one of the principle barriers to market for the alternatively fueled propulsion architectures.

Awareness Feedback

The second of the three key exogenous feedback mechanisms relates to consumer awareness for reasons that are self-explanatory. Producers cannot expect purchase activity in the absence of consumer awareness of the technology’s existence or attendant benefits relative to the mainstream product that currently suffices their needs. Thus, the lack of consumer awareness constrains the actualization of consumer demand via technology market share. Figure 2.3 illustrates the logic of the reference model.

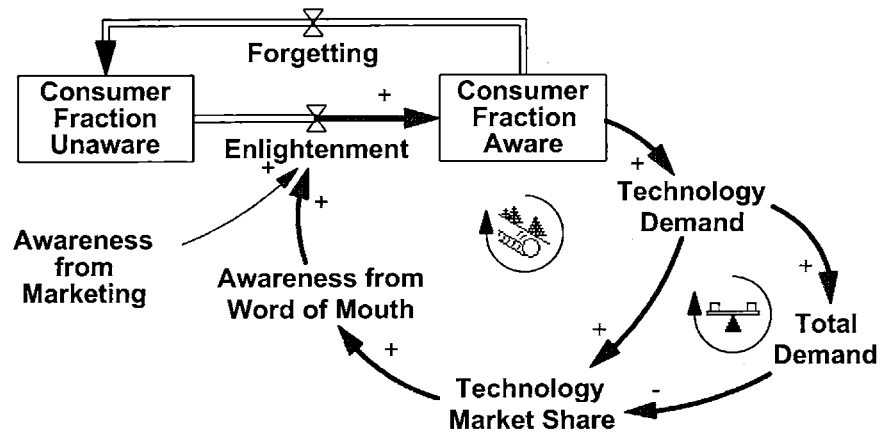


Figure 2.3 – Consumer Awareness Feedback Structure of the Reference Model

The diagram above presents two stock (or state) variables that disaggregate the total consumer population into a pool of consumers aware of the existence of a given technology and a pool of consumers that are unaware of the technology. Two activities serve to “enlighten” consumers, converting them from the unaware pool to the aware pool. The first is via marketing campaigns that use media resources to educate consumers. The second stems from word of mouth effects as technologies make inroads to the market. With more owners of new technologies comes increased spreading of the word. The word of

mouth effect translates the number of people made aware per new vehicle owner. The user can specify the strength of this effect as a fraction between zero and unity where a fraction of 0.5 translates to one person enlightened for every two new owners) as expressed in Equation 2.7.

Equation 2.7 – Awareness through Word of Mouth and Marketing

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

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

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

Conversely, lack of consumer demand for a technology relative to other alternatives would translate into decreased market share and hence decreased word of mouth. A negative word of mouth effect initiates a balancing feedback mechanism that would serve as a drag on demand for that product, all else being equal. The elasticity in the above equation refers to the increase in consumer awareness for a percentage increase in marketing spending or an equivalent media effort.

Even aware consumers will “forget” over time in the absence of stimulation, thereby returning consumers to the unaware pool. This reinforcing feedback structure, by which awareness diffuses through a population, is congruent with the Bass diffusion model presented by Sterman (2000).

Availability Feedback

Availability refers to the fraction of vehicles made available to the public by automakers and serves as a surrogate to the notion of access to a given propulsion

technology. It implicitly represents the range of activities necessary to bring a given technology to market such as research and development. Purchase activity cannot take place in the absence of product availability. Thus, anything less than 100% availability implies that despite all other factors in demand, not all consumers will have access to the technology in order to execute a sale.

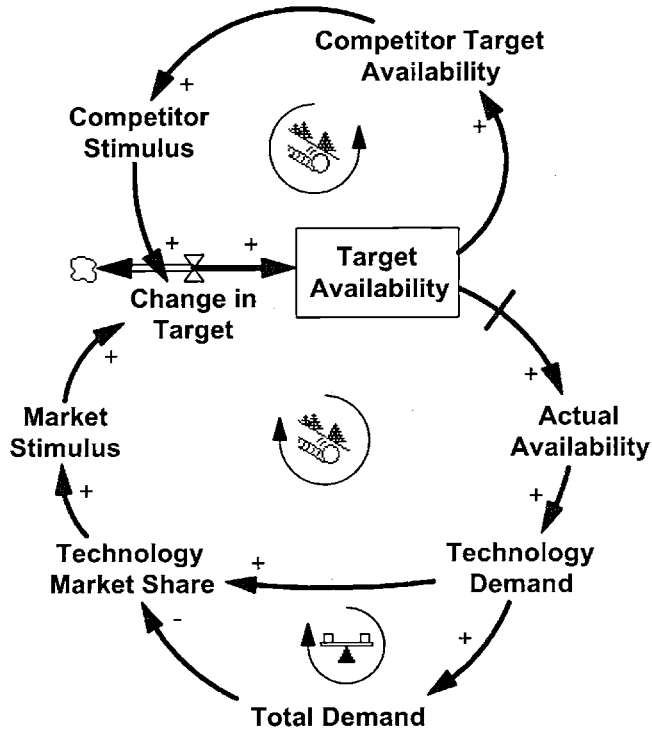


Figure 2.4 – Technology Availability Feedback Structure of the Reference Model

Figure 2.4 illustrates the two major reinforcing feedback mechanisms derived from this dynamic. The automaker’s target for availability translates to an Actual Availability over a delay equal to the average time required to bring the technology through development phases to the required production levels (the delay is indicated by a hatchet mark between Target Availability and Actual Availability in Figure 2.4). The sum of Actual Availability and Competitor Availability generates total availability. It is total availability that enables the increase of Technology Market Share, as consumers must choose between the set of alternatives actually available to them.

Competitor Stimulus and Market Stimulus effects converge to affect the Change in Target Availability. In the reference model, a single firm responds to both, and the other firm responds only to competitor activity. This would be representative of a “fast-follower” strategy.

The reference model uses Consumer Acceptance, expressed as a ratio of the technology’s market share relative to its availability as indicated in Equation 3.8, as a surrogate for the Market Stimulus effect. The formula serves as a kind of metric for “market pull,” dubbed Market Stimulus, and defines an Adjustment Fraction via an s-curve that peaks at 20% adjustment of the target availability per year at peak Consumer Acceptance.

Equation 2.8 – Consumer Acceptance of Technology

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

where

$Accept_i$ = Consumer Acceptance of technology i , dmnl

The Adjustment Fraction combines with Target Availability to create Market Stimulus as in Equation 2.9 below.

Equation 2.9 – Impact of Market Stimulus on the rate of Chang in Target Availability

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

where

$MktStim_i$ = Market Stimuls for technology i , 1/year

Tgt_i = Target Availability for technology i , dmnl

f_{adj} = Adjustment Fraction, 1/year

The Market Stimulus thus responds to Technology Market Share by multiplying the maximum increase in Target Availability by the Adjustment Fraction. But Change in Target Availability also responds to Competitor Stimulus as indicated in Equation 2.10.

Equation 2.10 – Impact of Competitor Stimulus on the rate of Change in Target Availability

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

where

- $CompStim_i$ = Competitor Stimulus for technology i , 1/year
 $CompTgt_i$ = Competitor Target Availability for i , dmnl
 t_{react} = Reaction Time required to adjust Target Availability, years

Competitor Stimulus emulates competitive intelligence activities of the firm. The firm can then adjust its target as it learns of its competitor's intentions. Similarly, the competitor stimulus from the perspective of the competing firm is equal in magnitude and opposite in sign to Equation 2.10 above. The model then considers these stimuli and selects the greater of the two, as the Change in Target Availability as in Equation 2.11.

Equation 2.11 – Change in Target and Actual Availability Based on Market and Competitor Stimuli

$$\Delta Tgt_i = \text{MAX}(MktStim_i, CompStim_i)$$

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

$$Actual_i = \text{DELAY3}(Tgt_i, t_{react})$$

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

The decision rule implicit in the above set of equations is that, all else equal, via competitive intelligence, competition will increase their own target availability in response to the initiating firm.

2.3 GOVERNING INTERACTIONS & STRUCTURAL LOGIC

I conclude this section by retracing Figures 2.1 – 2.4 to convey the full sense of the reference model. Figure 2.5 captures the logic flow in a single graphic.

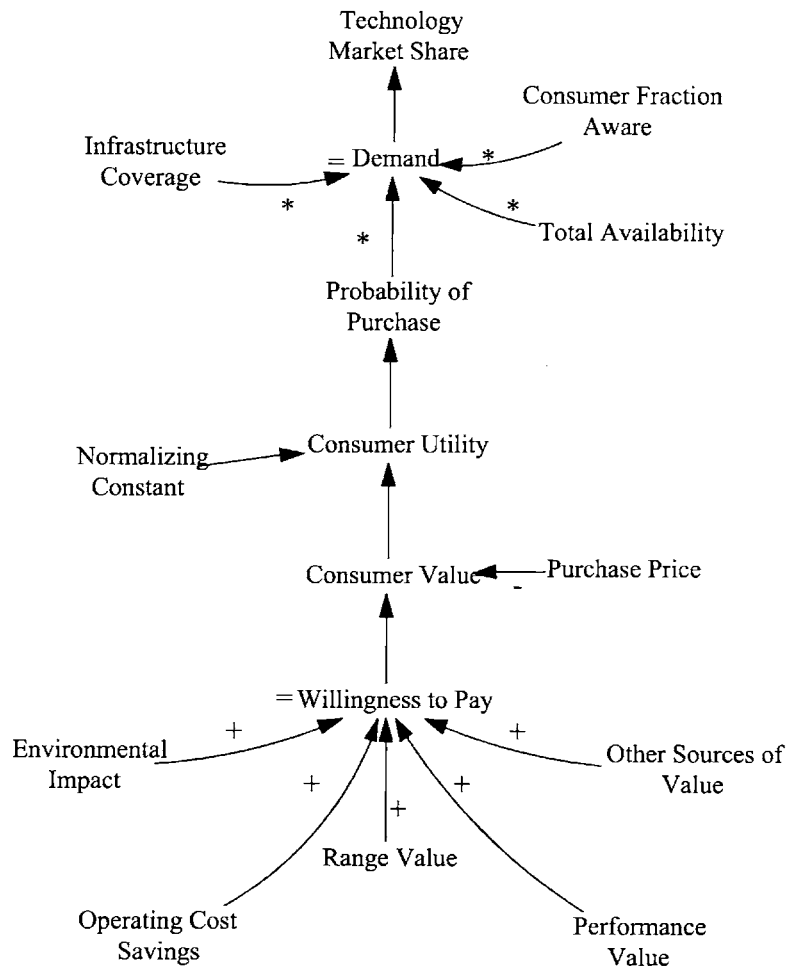


Figure 2.5 – Structural Logic of the Reference Model

The reference model monetizes five criteria values and sums them to equal willingness to pay. Subtracting price yields value that is then divided by a normalizing constant to yield utility. A logit function translates utility to a probability of purchase that is then multiplied against infrastructure coverage, availability, and consumer awareness to yield demand from which market share can then be determined.

Referring back to Figure 2.1, we begin the process with a set of five endogenous and static vehicle performance attributes. These values yield a Probability of Purchase that distributes market share amongst the set of technology alternatives based on their relative

benefit. Considered alone, demand would remain static based on this distribution. However, consideration of exogenous market conditions to include infrastructure coverage, technology availability, and consumer awareness initiates a number of dynamic processes that shift demand over time. First, a Learning Curve effect enables generic technology buy-down dynamics that serve to narrow the cost differential between alternative technologies and the ICE with increasing scale.

The Awareness Feedback serves to “open up” the potential market for alternatives by stimulating demand via awareness campaigns such as marketing spending and media coverage. The initial state of the incumbent ICE architecture is 100% consumer awareness. Infrastructure Feedback adds to the Awareness and Learning Curve effects. Infrastructure Coverage, again equal to 100% for the ICE, serves as an entry barrier to the set of alternative technologies. Table 2.1 attempts to convey the degree of the barrier that each technology must overcome to penetrate the market. Finally, Availability feedback completes the model. Again, the ICE begins with 100% availability; automakers must dedicate the resources to bring alternative technologies to market, bringing with it delays that alternatives must overcome to penetrate the ICE-dominated market.

2.4 REFERENCE MODEL SIMULATIONS & CONCLUSIONS

Metcalf executes a number of simulations to determine the conditions and stakeholder activities necessary to achieve three alternative futures. These include ICE Domination, Hybrid Competition, and FCEV Transition scenarios. The model employs eight “scenario variables” to enable the user to generate distinct scenarios. They are defined as the following:

- (1) *Relative Performance* – A user defined, static variable between zero and one, where the performance of the ICE is unity and the set of alternatives to the ICE are less than, or equal to, unity. The variable is a surrogate for vehicle characteristics such as acceleration, torque, and horsepower. The model uses a default assumption that all vehicle architectures have equal performance based on Power-to-Weight Ratio (PWR) as indicated by the study performed by the MIT Energy Lab (Weiss et al, 2000). The study explicitly normalized

performance when it projected technology development out twenty years so as to compare other vehicle characteristics.

- (2) *Relative Strength of the Marketing Effort* – A user defined, static variable representing a ratio of the targeted spending for a given technology divided by the baseline marketing spending for the vehicle platform (a mid-size sedan). Thus, a ratio of 1 indicates that automakers make equivalent commitment of marketing and media efforts to the technology in consideration when compared to the baseline. Automakers must increase this ratio to promote an alternative technology.
- (3) *Initial Target Availability* – A user defined, static variable with a default value near zero (1%) for all but the ICE (100%). This scenario variable serves to execute a firm’s internal strategy with regard to the set of potential vehicle architectures. It can also capture “technology-forcing,” external regulatory policy such as ZEV mandates that require automakers to bring solutions to market as a surrogate for demand.
- (4) *Initial Infrastructure Coverage* – Fixed at 100% for the incumbent ICE technology, the user can specify the initial level of fuel and service support that precedes an alternative technology’s introduction to market. This variable serves as a lever for the user to execute a co-operative partnership arrangement whereby joint investment by key stakeholders (auto, energy, and public concerns) pre-empt the chicken-and-egg hurdle by supplying infrastructure to market prior to demand.

Interestingly, DoE and the California Fuel Cell Partnership are working to deploy an alternative-fueling infrastructure that will be initially supported by complementary energy-based revenue streams such as distributed power prior to the arrival of demand in passenger vehicles sufficient to support the station alone. DoE’s Hydrogen Technology Advisory Panel has proposed deployment of an energy station at a location with significant natural gas availability. Prior to the arrival of sufficient vehicle demand, the station would benefit from stationary production of electrical power via fuel cell technologies for distributed power generation. This proposal entails establishment of a natural

gas reformer facility for the production of hydrogen that feeds a fuel cell of varying size and power to produce electricity. The station also could derive additional sources of revenue from serving natural gas, compressed natural gas (CNG), and compressed hydrogen customers.

At such time that alternatively fueled vehicles become available and penetrate the market, the station might require at best a retrofit to enable transfer of fuel onboard the vehicle. Such a strategy is predicated on the adoption of adaptive/flexible infrastructure deployment based on modular architectural principles that seek to control for the risk associated with uncertainty in market conditions and technological evolution by “designing in” characteristics and interfaces for accommodating these changes downstream. Doing so offers the potential of avoiding significant cost penalties should the market and/or technologies depart down a divergent path. In the context of DoE’s proposed energy station, the strategy aims to create an alternative fuel infrastructure “in wait” with the ability to service an emerging market should one materialize. However, failing this, the facility is capable of profitability should this market fail to materialize.

- (5) *Profit Margin* – A static, user-defined scenario variable with a default value of 5% over the capital cost. The user can adjust this value lower to seed demand.
- (6) *Internalization Fraction* – A static, user-defined scenario variable with a default value of zero. It represents the fraction of environmental damage costs considered by the consumer at the time of purchase.
- (7) *Discount Rate* – A static scenario variable that determines the extent to which consumers internalize future operating costs at the time of purchase. The author uses a relatively high baseline rate of 30% to more accurately reflect typical consumer purchase behavior rather than discount rates reflective of opportunity costs used in financial analysis.
- (8) *Gasoline Price Increase* – Also a static, user-defined scenario variable that allows the user to simulate a change in gasoline prices due to market supply/demand dynamics or due to the imposition of a gasoline tax. The

increase is a discreet step function at the model outset rather than a gradual price shift.

Upon defining the set of scenario variables to reflect varying initial conditions and strategies, Metcalf (2000) then determines the conditions necessary to achieve a representative set of alternative “future propulsion regimes.” She finds that in the baseline scenario, using the default assumptions that best reflect current market conditions, the ICE easily dominates in the short-term. In the long-term, however, HEVs make gradual, but limited, inroads to the market due to the inherent delays of commercializing the technology. This emergence occurs in the absence of a concerted stakeholder push due to the assumption that the gasoline HEV, like it’s ICE counterpart, benefit from full infrastructure coverage at the outset and through the reinforcing feedback mechanisms discussed previously. Conversely, FCEV and EV technologies remain stymied of any significant market penetration due to the considerable infrastructure barriers facing them.

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

Table 2.2 – Reference Model Scenario Variable Adjustments

The second scenario, “Hybrid Competition,” seeks to determine the conditions necessary for the HEV to make significant penetration to the passenger vehicle market.

Metcalf (2000) concludes that the HEV requires three prerequisites for adoption in significant numbers: equivalent performance to the ICE, marketing spending equal to a factor of two over the baseline, and 20% initial target availability. Doing so reduces the delays required to seed consumer awareness while committing to development and commercialization of the hybrid product (*Initial Target Availability*). The infrastructure barriers again prevent the more radical FCEV and EV designs from achieving any significant level of market penetration.

The third and final scenario attempts to establish the conditions necessary for an “FCEV Transition” to occur in the marketplace. These conditions are summarized in Table 2.2 above and enable the FCEV architecture to achieve penetration of around 10% in just over 10 years. The technology then “takes off” via an inflection in its market share between the 20 and 25-year points. Initial infrastructure seeds demand for the FCEV and could represent the coordinated commitments of energy, auto, and government concerns. Note that gas prices are exceedingly high. This is accounted for by adjusting the discount rate downward to reflect greater consideration of vehicle operating costs by the consumer at the point of purchase. Metcalf (2000) notes that this could correspond with tighter macroeconomic conditions.

Summary of Reference Model Assumptions

Before continuing, the following represents a synopsis of some of the core assumptions of the reference model:

- (1) Costs are in constant dollars.
- (2) Analysis beginning in the year 2000 and ending in the year 2030.
- (3) All technology parameters begin in the year 2000 with values derived from projections to the year 2020 (see Weiss et al).
- (4) One aggregate consumer market segment.
- (5) All technologies are normalized to equivalent performance as projected by Weiss et al (2000).
- (6) One benchmark product segment representing the aggregate market for all passenger vehicles. In this case, a mid-size sedan comparable to a Toyota Camry or Ford Taurus.

- (7) Two competing firms – “Ours” and “Theirs”
- (8) Parameterized to the North American market.
- (9) Average Vehicle Miles Traveled of 12,000 miles per year per car
- (10) Average Vehicle Life of 14 years
- (11) Vehicle Purchase Price equals the sum of the component (or technology-specific) costs,
- (12) Other Vehicle Cost is assumed constant across technologies, and a profit margin as specified by the user.

From these core model assumptions, we now turn to the development of the revised model.

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3 SYSTEM DYNAMICS DEVELOPMENT OF THE REVISED MODEL

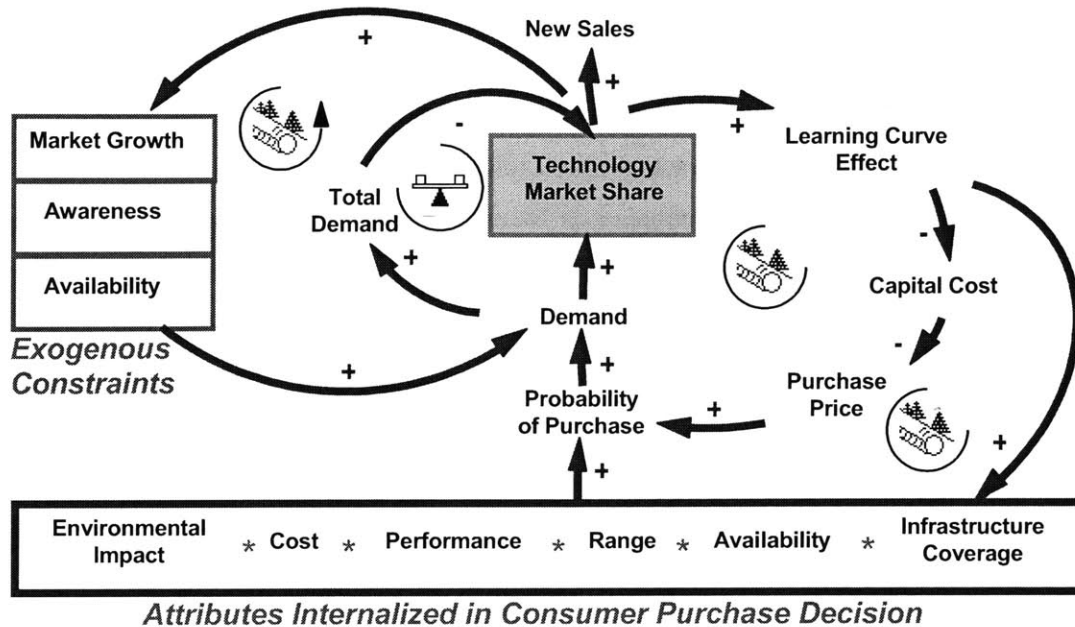


Figure 3.1 – Overview of the System Dynamics structure of the revised model

The diagram illustrates the major elements and feedback effects. Note the boxed elements considered exogenous to the consumer purchase decision; elements considered endogenous to the purchase decision are noted in red.

3.1 TECHNOLOGICAL EVOLUTION

A primary basis for revising the reference model rests on the fact that it relies on data derived primarily from the projections provided by Weiss et al (2000). This report normalizes all technology parameters to equivalent performance based on a single path of evolution to the year 2020. For a more detailed description of this methodology, I refer the reader to this MIT Energy Lab publication. The document evolves the energy infrastructure in parallel with evolving vehicle technologies based on an EIA assessment of the future distribution of energy sources feeding the nation’s electricity grid and service stations. In doing so, the authors of the report establish a single scenario-based “most likely” path of development for an aggregate mass market existing twenty years hence.

Metcalf (2001) uses the Energy Lab data for two critical reasons. First, the assumptions underlying the results are explicitly stated and therefore transparent to third-party scrutiny and reproduction. Second, the report considers a comprehensive set of potential technologies and normalizes them to provide a fair basis for comparison of the relative attributes and feedback dynamics we wish to examine.

This distinction warrants further explanation. To better understand the logic of the reference model, one might equate it to “stepping into the future” roughly two decades from today and observing the fleet of vehicles on the road and the differences amongst them at that point of development. We then “reset” the clock as “current day” and run the model based on scenario variables under the control of the modeler. In sum, the reference model normalizes the set of potential technologies relative to an “evolved baseline” vehicle – in this case a mid-size advanced body sedan – supported by the aggregate market and energy infrastructure projected for the year 2020. The purpose, however, is not to “fast-forward” to a future that might better support alternative technologies, but rather to provide a reference point from which to base relative differences amongst technologies as objectively as possible (Metcalf 2000).

Another key distinction deserves attention here. Upon leveling the playing field and winding the clock back twenty years, the user fixes the scenario variables. These include the initial *endogenous* vehicle attributes from which the model derives a probability of purchase and ultimately demand for a given propulsion architecture. These attributes are noted in red in Figure 3.1. Upon initiation of a simulation, the model starts the clock, allowing the set of propulsion technologies to compete for market share subject to the *exogenous* feedback effects of [population-based] *new market growth, technology availability, and consumer awareness*. These are the boxed variables in Figure 3.1. Although *infrastructure coverage* is the result of activities exogenous to the purchase decision, we do not include it as an exogenous restraint because the consumer still has the option to purchase the technology, even if little infrastructure exists. Conversely, the consumer will not have the option to purchase if he is unaware the technology exists in the first place, or if the technology is simply not for sale (i.e. available).

Note, however, that both *infrastructure coverage* and *technology availability* are included as attributes endogenous to the purchase decision. This is because the consumer

internalizes these considerations at the point of purchase. Alternatively, a consumer cannot internalize whether or not he is aware of the technology's existence. Thus, awareness remains purely an exogenous restraint on the potential sale of new propulsion architectures. In sum, we can say that the consumer will consider the relative level of infrastructure coverage and the availability of a desired propulsion architecture when choosing amongst a set of options. A consumer cannot, however, consider a purchase if he is unaware the technology exists.

Returning to the reference model's frame of reference, the reader essentially witnesses a scenario play out from current day with data derived from a hypothetical visit to an alternative future twenty years ahead. The modeler's motive is to establish relative, rather than absolute, differences in attributes amongst competing technologies. Thus, the model never claims to provide absolute results in the form of specific figures for sales, emissions, or fuel economy. Rather, the model conveys directionally useful information to the decision-maker.

3.2 "LEARNING ENGINES"

Alternatively, the model as this author has revised it establishes relative differences amongst the set of technologies as they exist *currently*. The model draws from data on both criteria air pollutant and greenhouse gas emissions provided by the most recent GREET model simulations supplied by alternative propulsion research efforts at Argonne National Labs (Wang 2001). Unlike Weiss et al (2000), the data supplied by ANL represents the set of technologies, as they exist in their current state of development. Furthermore, the revised model replaces the attribute-based endogenous scenario variables that remain static throughout the simulation with a set of dynamic variables that employ "learning engines" to more accurately simulate their potential evolution over time.

3.2.1 THE LEARNING ENGINE CONSTRUCT

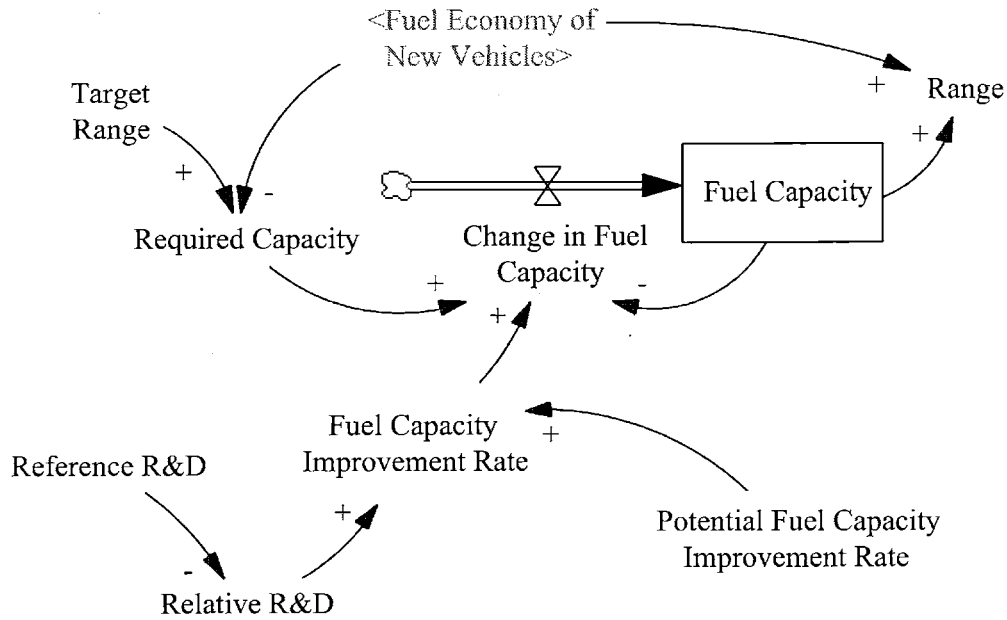


Figure 3.2 – Capacity as a representative “learning engine” for simulating the evolutionary path of technology development

The learning engine is a fairly simple System Dynamics construct that employs a state variable to represent the level of development of the attribute we wish to model at any given time. Figure 3.2 provides a representative learning engine from the actual revised model to better illustrate the concept.

The learning dynamic sketched above relies upon a decision rule that establishes a desired target level for a given attribute. In the fuel capacity example above, the customer’s expectation of a particular vehicle range establishes the target capacity required to deliver this range to the mass market, based on the fuel economy of the propulsion technology in question. Note, however, that fuel economy is also a dynamic, evolving vehicle property with a similar learning engine, which will be discussed shortly. Thus, the technologies involved in increasing range, i.e. on-board fuel storage capacity and system fuel economy, combine to close the differential between actual and desired state properties.

Changes in external conditions, deliberate investment, or commitment of stakeholder resources all serve to close the gap between the actual vehicle performance

level and the target vehicle performance metric at a rate determined by the severity of external catalysts or the degree of resource commitment. This rate is arbitrarily capped at a maximum to limit the pace of evolution to levels characteristic of industry-wide trends. Table 3.1 explicitly lists the rates applied for each of the learning dynamics employed in the model. These rates represent the maximum potential rate of change. The actual rate of change is determined by the actual commitment of resources toward the full development potential, relative to the baseline levels. Baseline levels are those that would apply in the absence of R&D investment guided by strategic directives. For example, to enable a strategy predicated on bringing fuel cell technologies to market, an automaker might choose an R&D investment target 50% above current, baseline spending to hasten the availability of the technology to the market place as well as to boost the performance of the attributes crucial for market adoption.

For convenience, the “Learning Curve” dynamic for production experience is included in the last row of the table. The Learning Curve simulates technology-specific economies of scale by specifying a fractional reduction in cost, per doubling of cumulative production. Unlike the product-specific performance attributes that trend toward a target based on the resource commitments of stakeholders, the Learning Curve implicitly trends toward a market-clearing cost at a pace dependent on market demand. The author applied relatively lower rates for scale economies for the less radical propulsion architectures; arguably a reasonable approximation, given the maturity of ICE technological development and the greater level of system and component level commonality shared between the ICE and HEV platforms.

Technology Rate of Change	ICE	HEV	FCEV	EV
Fuel Capacity	0	0	0.2	0.1
Fuel Economy	0.08	0.15	0.15	0.15
Performance	0.10	0.25	0.25	0.25
Infrastructure Coverage	0	0.30	0.25	0.25
Fractional Reduction in Cost per Production Doubling	0	0.10	0.15	0.15

Table 3.1 – Maximum Potential Rates of Improvement for the Learning Curve Mechanisms

In sum, the learning engine construct attempts to capture the evolving dynamics of stakeholder efforts to close the gap between a vehicle attribute's current performance and the ideal performance desired by *mainstream market* consumers. This is analogous to dynamically tracing the technological trajectory of vehicle attributes considered essential to delivering the levels of performance desired by the mass market (Christensen 2000, Sterman 2000).

One can imagine a fairly limitless set of learning engines at finer levels of system decomposition. For example, we could construct similar "engines" to replicate riding down the learning curve for key vehicle components or sub-systems such as vehicular fuel cells, battery trains, or hybrid drive systems. This is outside the scope of this thesis, however. Rather, the author surmises that the more generic learning engines applied in Table 3.1 captures improvements along these lines. For example, fuel capacity evolution could account for the emergence of more radical technologies such as nanostructures or the diffusion of off-the-shelf technologies such as advanced materials for lighter, stronger storage tanks for alternative propulsion applications.

3.2.2 LIMITATIONS OF THE LEARNING CONSTRUCT

As implied by the above statement, the modeler must be aware of three key limitations of the learning construct. First, the curve does not model the potential emergence of breakthrough technologies (one can imagine that doing so would involve the incorporation of a step function at some arbitrary point in time). Despite the plausibility of such a scenario, the author chose to refrain from attempts to model discreet events of such random and unpredictable nature so as to devolve the model of potential bias toward a given technology. Second, the model does not capture efforts to close the performance gap relative to the demands of niche market consumers. Thus, the revision model implicitly assumes that auto and energy stakeholders are attempting to reach mainstream consumer segments from the outset.

Conversely, Christensen (2000) provides evidence that the history of industry innovation suggests that firms have traditionally enjoyed greater success in bringing new technologies to the mass market by initially introducing the technology to niche markets. Doing so allows firms to downplay the technology's relative weaknesses while leveraging

it's relative strengths to a market willing to pay a premium for those features. This dynamic will be discussed in greater depth later in the chapter.

The second observation concerns the distinction between commitments of resources toward product, versus process-based innovation. The first four entries in Table 3.1 approximate the learning dynamic of product-focused technological evolution. A firm typically gleans these improvements during the early development phases of the product life cycle. Conversely, the last entry in Table 3.1 represents cost reductions gained from the commitment of resources toward process-oriented activities such as standardization, repeatability, and scale. A considerable array of industry research supports the assertion that innovations evolve in this manner. Utterback (1998), for example, notes the tendency of firms to commit resources in the earlier phases of development toward product-based activities in order to achieve the desired level of performance required of the target market.

Over time, however, as the product approaches levels appropriate for commercialization, the firm chooses to “freeze” the design. Doing so allows the firm to focus resources away from further improvements to product and toward the plant, equipment, and training required to mass-produce it. These process-based initiatives enable the standardization, repeatability, and scale required to coalesce a value chain capable of supplying the needed materials at reduced cost. Thus, the strength of the learning dynamic shifts over time from product-based improvements that drives attribute performance toward commercialization, to cost reductions enabled by process-based improvements and value chain emergence (Utterback, 1998). This can be characterized as a shift from performance to cost-based learning dominance as illustrated in Figure 3.3.

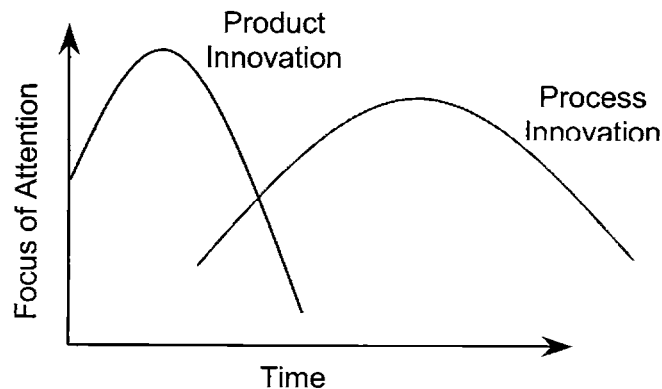


Figure 3.3 – The Evolution of Learning Dominance in the Product Life Cycle

I distinguish radical innovation between product and process evolution via these curves. As discussed in previous chapters, the earlier stages of innovation are characterized by product-oriented improvements that seek to commercialize an innovation by achieving the performance thresholds deemed necessary for the market. These early stages of development are marked by significant achievements along the performance trajectory. Once the technology reaches the threshold performance level required of the market, however, prohibitive cost often becomes the greater barrier to commercialization. Although R&D activities typically manage to achieve cost reductions by seeking out cheaper materials during development, realizing a market clearing cost target often requires the kind of process-based cost reductions attainable only by economies of scale. Economies of scale happen only when a market for the product emerges. Thus, the classic chicken-and-egg dilemma rears its ugly head yet again. Producers are loath to commit the considerable resources required when the market is uncertain. Regulatory intervention can facilitate cost reductions from scale by creating an initial market for high-risk alternative technologies. One method for doing so is fleet purchase mandates.

To summarize the learning curve dynamic, automakers or other stakeholders attempt to close the gap between current and ideal range, fuel capacity, fuel economy, and infrastructure coverage by targeted R&D investments over time. In the reference model, the scenario variables governing the vehicle attributes endogenous to the vehicle remain static throughout the run. Only the exogenous scenario variables, i.e. *infrastructure coverage, product availability, and consumer awareness*, adjust dynamically as the model steps through time. The user initiates these variables prior to the run, thereby establishing the “starting point” from which the vehicles will compete. The user also exercises control over other scenario variables such as changes in the price of gasoline and the level of marketing investment for stimulating the reinforcing effects of the awareness feedback dynamic.

3.3 MODEL STRUCTURE AND LOGIC FLOW

Another of the fundamental departures from the reference model resides in the treatment of exogenous market and transportation infrastructure system considerations and endogenous vehicle system considerations. This distinction provides the guiding framework for the construction of the revised model and the equations and decision rules that govern consumer, vehicle, market, and infrastructure system behaviors.

3.3.1 LOGIC FLOW

The reader should carefully note the distinctions between the logic flow of the reference model as illustrated in Figure 3.4 and the logic flow of the Revision Model represented in Figure 3.5 on the following page.

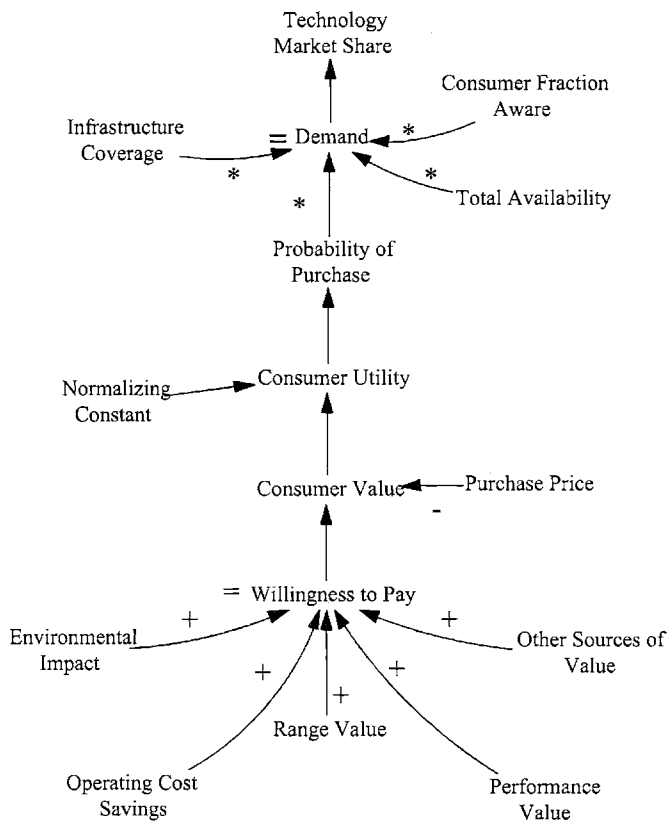


Figure 3.4 – Structural Logic of the Reference Model

The reference model monetizes five criteria values and sums them to equal willingness to pay. Subtracting price yields value that is then divided by a normalizing constant to yield utility. A logit function translates utility to a probability of purchase that is then multiplied against infrastructure coverage, availability, and consumer awareness to yield demand from which market share can then be determined.

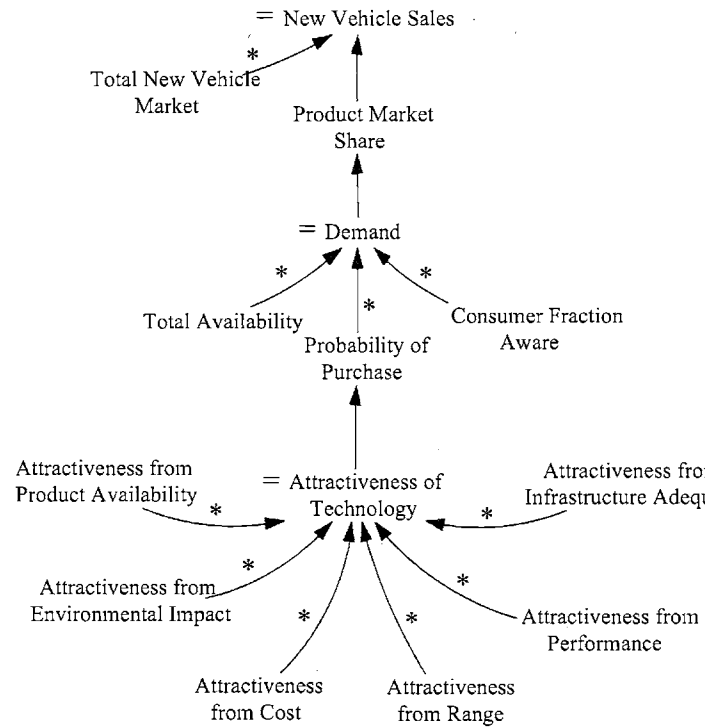


Figure 3.5 – Structural Logic of the Revised Model

The revised model obviates the need for a normalizing constant by comparing a set of product attributes to a reference value equal to unity (represented by the baseline ICE product). The attributes are multiplicative rather than additive to reflect zero demand in the absence of an attribute. The logit function returns a probability of purchase for a given technology. Demand for a given technology is then a function of the product of the probability of purchase, consumer awareness, and product availability. Technology Demand is then normalized by the sum of the demand for all technologies to yield Product Market Share. Multiplying this by the market size yields New Sales for a given technology.

Key differences to note from Figures 3.4 and 3.5 include:

- (1) The variables *Willingness to Pay*, *Consumer Value*, *Consumer Utility*, and the *Normalizing Constant* have been removed.
- (2) The variable “Attractiveness of Technology” has been created and is equal to the product, vice the sum, of the attractiveness of each of the technology attributes.
- (3) The attractiveness of a given technology is equal to the product, rather than the summation, of the attractiveness of each independent attribute to the customer.
- (4) *Infrastructure Coverage* has been decoupled from the computation of Technology Market Share; instead, this condition is now considered an attribute that impacts the overall attractiveness of a given technology. The author contends that this variable is a condition external to the vehicle itself; the consumer factors this condition into his purchase decision, but the condition does not restrict the sale of vehicles to anyone willing to purchase. Conversely, awareness and availability do restrict the sale of vehicles even if the consumer is willing to buy; the consumer cannot purchase if he’s unaware of the product’s existence and he cannot buy if the product is unavailable.
- (5) In accordance with (4), the variable *Infrastructure Coverage* has been removed from the computation of *Demand* for a given technology. The reference model computes Demand as the product of Probability of Purchase, Infrastructure Coverage, Consumer Fraction Aware, and Total Availability.
- (6) *New Vehicle Sales* is calculated as the product of *Product Market Share* and the annual *Total New Vehicle Market*.
- (7) *Product Market Share* is determined by normalizing *Demand* for a given technology product against the sum of the individual demands for each technology product.

Three concerns with the reference model motivated these changes. First, the treatment of *Demand* in the reference appears to separate *Infrastructure Coverage* and *Product Availability* from the consumer’s purchase decision. The reader can note from

Figure 3.4 that these attributes are considered exogenous to the *Probability of Purchase*. The revised model, on the other hand, treats these attributes as both exogenous, and endogenous, considerations that the consumer factors into the purchase decision (see Figure 3.5); they are therefore key attributes affecting the *Probability of Purchase*.

The model ultimately returns the *Product Market Share* as the fraction of Demand for a given technology product relative to the total demand of all technology products considered. Moving up the logic flow diagram in Figure 3.5, the product of *Total New Vehicle Market* and *Product Market Share* yields *New Vehicle Sales* for a given technology. The reader should note the difference between *Product Market Share* and the variable *Technology Fraction in the Fleet*. The former represents a given product's share of new sales in the current period, while the latter represents a given product's share of the aggregate fleet of vehicles on the road. Consequently, *Technology Fraction in the Fleet* is equivalent to the snapshot of the mix of vehicles on the road at any given time and reflects the lag between current sales and historical purchasing trends. Section 3.4.1 discusses this variable in further detail.

Secondly, note from Figure 3.4 that the reference model derives purchase probability from the summation of consumer *Willingness to Pay* for a representative set of product attributes. The *additive* nature of this computation could present a logic fault when considered under extreme conditions. For example, suppose that a given propulsion architecture has no range at all. Implicitly, we know that a passenger vehicle with no range would have absolutely zero value to a customer. But because the computation is additive, the model would still return a positive value for the *Probability of Purchase*, assuming that any one of the other four attributes have a non-zero value. In light of these concerns, the revised model considers the *product* of all technology attributes endogenous to the consumer's purchase decision – that is, the model computes purchase probability of a given propulsion architecture as the total product of the values returned for each attribute affecting the purchase decision.

Finally, the revised model departs from the use of a “*Normalizing Constant*” by considering the attractiveness of each attribute against a reference, or baseline, value. The reference value reflects the consumer's current expectation for attribute performance based on the level of performance delivered currently by products employing dominant

propulsion technologies (i.e. the gasoline ICE). The ratio of current performance to reference performance provides the input to a “function for attractiveness” for each product attribute. This function translates the input determinant to a dimensionless output value representing the attractiveness of the product to the consumer at the point of purchase. In sum, the revised model treats the computation of purchase probability as multiplicative, rather than additive. Thus, if an attribute returns a zero attractiveness value, the *Probability of Purchase* will be zero as well.

3.4 SCENARIO VARIABLES

The revised model leverages much of the reference model structure and therefore uses many of the original scenario variables. The model modifies a number of these variables to account for subtle differences in logic and structure. The model also goes further to include a set of additional scenario variables, or “switches,” whereby the user can “turn on” particular policy/strategy levers to witness the influence of such interventions on the simulation. Table 3.2 compares the set of scenario variables provided by the reference and revised models.

Scenario Variable	Reference Model	Revised Model
Relative Performance	X	X
Relative Strength of the Marketing Effort	X	X
Initial Infrastructure Coverage	X	X
Initial Target Availability	X	X
Gasoline Price Increase	X	X
Profit Margin	X	X
Discount Rate	X	*
Internalization Fraction	X	*
Initial Sensitivity to Environmental Impact	*	X
Relative Strength of Public Ad Campaign		X
Initial Target Product Investment		X
Feebate Program		X

Table 3.2 – Scenario Variables in the reference and revised models

3.4.1 ASSESSING ATTRIBUTE VALUES

In contrast to the reference model, which derives a probability of purchase for a particular platform by considering vehicle attributes endogenous to the *vehicle system*, the revised model considers vehicle attributes from the perspective of the consumer's *purchase decision*. That is, the calculation of the *Probability of Purchase* for a given technology is based on whether these attributes are endogenous to the consumer's purchase decision.

The contribution of each attribute to the total purchase probability is calculated by considering the attractiveness of each technology's attributes relative to the ICE benchmark. This is accomplished by comparing the actual value to the reference value. For the endogenous attributes, the reference is equal to unity and is equivalent to customer expectations for the mass market as predetermined by the incumbent ICE architecture. The ratio of actual to reference is then translated to a dimensionless attractiveness measure by a look-up function. The look-up function attempts to convert the magnitude of the ratio to a dimensionless value representative of consumer behavior. Equation 3.1 calculates the total Attractiveness for a given technology as the product of the set of values returned by the respective attribute functions. Equation 3.2 converts the attractiveness metric to a technology-specific probability of purchase using the logit function.

Equation 3.1 – Total Attractiveness for a given propulsion architecture

$$TotAttract_i = A_{Perf} * A_{Range} * A_{Cost} * A_{Env} * A_{Avb} * A_{Infra}$$

where

$TotAttract_i$	= Total Attractiveness of technology i , dmn1
A_{Perf}	= Attractiveness from performance of technology i , dmn1
A_{Range}	= Attractiveness from range of technology i , dmn1
A_{Cost}	= Attractiveness from environmental impact of technology i , dmn1
A_{Avb}	= Attractiveness from product availability of technology i , dmn1
A_{Infra}	= Attractiveness from infrastructure adequacy of technology i , dmn1

Equation 3.2 – Probability of Purchase Logit Formulation

$$Utility = \sum_{j=1}^4 \exp(TotAttract_j)$$

$$Pr_i = \frac{TotAttract_i}{Utility}$$

where

$Utility$ = Total Utility to the customer of all platforms, dmnl
 Pr_i = Probability of Purchase for technology i , dmnl

Performance

The level of performance of each vehicle attribute is considered relative to a benchmark. Because the ICE has long been the dominant propulsion mode, customers have developed expectations for performance based on their experience with this technology. For this reason, the model designates performance of ICE-based vehicle technologies as reference and assigns it the value of unity. In this context, Performance refers to the set of vehicle attributes relating to such considerations as power, torque, acceleration, top speed, and handling. Performance is a scenario variable, although default values are set to reflect the standing of each technology relative to the benchmark if they were to hypothetically go to market today. Equation 3.3 calculates the attractiveness of a given technology relative to the ICE.

Equation 3.3 – Performance

$$A_{Perf} = f_{Perf} \left(\frac{Perf_i}{Perf_{ICE}} \right)$$

where

$Perf_i$ = Performance of New Vehicles of technology i , dmnl
 $Perf_{ICE}$ = Reference performance of ICE technology, dmnl
 f_{Perf} = Function for attractiveness from performance, dmnl

Equation 3.3 returns the attractiveness from performance metric for a given technology to Equation 3.2. Performance is a dynamic scenario variable. The user establishes the initial performance parameter relative to the ICE as well as the level of R&D investment targeted toward closing the performance gap between a new alternative technology and the

incumbent ICE. Thus, all performance values less than one will approach unity over time at a rate determined by relative technology investment.

Range

The revised model departs significantly from the reference model with regard to the treatment of the range attribute. In establishing relative differences in vehicle range, the reference model relied on data provided by Weiss et al (2000). This MIT Energy Lab report chose to normalize vehicle attributes according to their power-to-weight ratio. To do so, the report essentially shores up the performance shortfall of alternative propulsion platforms such as the HEV and FCEV by partially “borrowing” from the positive range differential associated with them. With the exception of the EV, the result is an almost uniform range of approximately 400 miles across the breadth of propulsion systems. Because the EV suffers from inherent range limitations, the Weiss data penalize EV platforms by borrowing from other vehicle attributes.

Alternatively, the revised model treats range as a dynamic vehicle attribute. The initial range is a scenario variable, as are the investment levers associated with R&D investment targeted toward closing the gap between the range demanded by the mass market and the actual range at any point in time. These investments are, however, limited by inherent delays in the system. Equation 3.4 describes the calculation that delivers the value for attractiveness derived from vehicle range to Equation 3.1.

Equation 3.4 – Vehicle Range

$$A_{Range} = f_{Range} \left(\frac{Range_i}{Range_{ICE}} \right)$$

where

- $Range_i$ = Range of New Vehicles of technology i , dmnl
- $Range_{ICE}$ = Reference range of ICE technology, dmnl
- f_{Range} = Function for attractiveness from range, dmnl

The function for attractiveness from range follows an arbitrary S-shaped curve that attempts to simulate the inherent disparity in valuation associated with vehicles limited by

range to less than 250 miles on a single fill-up or charge. Market data indicates that consumers discount the technology to a much greater extent than the equivalent premium that might be paid for ranges above 400 miles. The S-curve attempts to capture this purchase behavior.

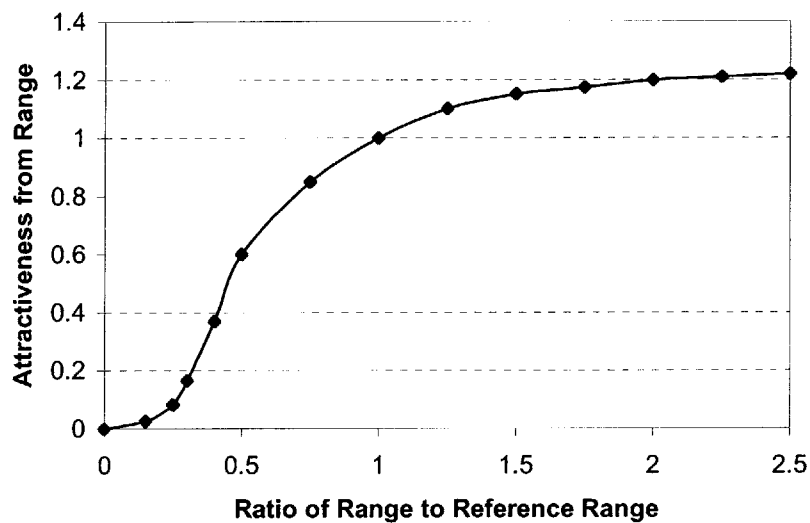


Figure 3.6 – Attractiveness from Range as a function of the ratio of range for a given technology to the range of the benchmark ICE platform.

Cost

The reference model compares the operating cost of different technologies, with variability dependent upon fuel cost and fuel economy. The revised model departs little from this basic construct. We continue to assume a fixed VMT of 12,000 miles per vehicle annually. The model returns total operating cost per year by combining both fixed and variable costs. The model departs from the original only in the application of a discount rate that adjusts dynamically with shifts in fuel cost. For further explanation of the methodology for computing and applying this discount rate to the stream of variable costs, please see Section 3.5.3. Figure 3.7 illustrates the methodology behind the calculation of the total lifecycle vehicle cost considered in the consumer purchase decision.

The construct first attempts to determine the total variable costs involved as derived from two sources: fuel cost and other variable costs such as service and maintenance. 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). Predictably, these depend upon VMT and a fuel cost assumed static over the period of ownership by the consumer and are summed to yield total Variable Operating Cost. The model then applies the Discount Rate detailed in Section 3.5.3 to the total Variable Operating Cost and adds this to the total Fixed Operating Cost to yield the total Lifecycle Operating Cost of the vehicle. It should be noted that the Discount Rate is first transformed into an Operating Cost Multiplier via a table function that is then applied to a yearly cash flow over a period equal to the average vehicle life of 14 years. I refer the reader to Metcalf 2001 for the equations governing calculation and application of this multiplier. Suffice it to say here that the multiplier is simply a factor that when multiplied against a stream of annual payments, converts those payments to the operating cost internalized by the consumer at the time of purchase. It is equivalent to a Net Present Value calculation in financial analysis.

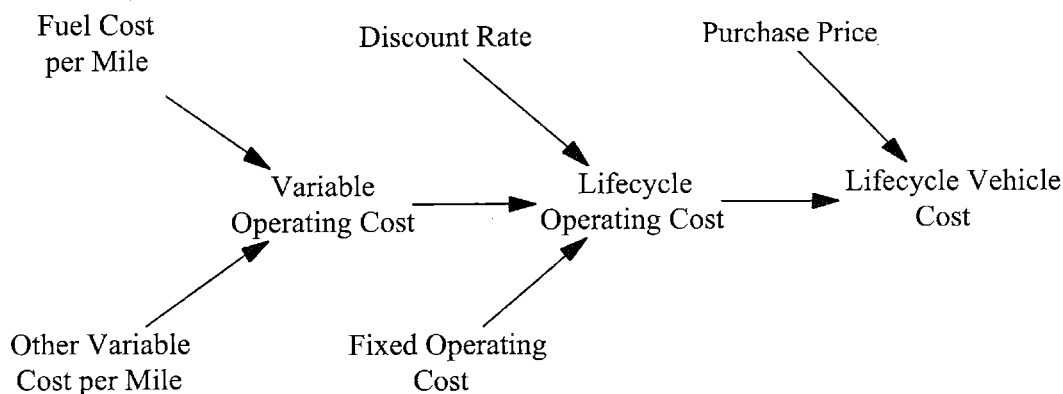


Figure 3.7 – Fishbone diagram of Lifecycle Vehicle Cost to the consumer

This construct then adds Purchase Price to the Lifecycle Vehicle Cost to yield a total cost to the consumer. This value returns to Equation 3.5 where it is compared against the benchmark ICE platform. The function depicted in Figure 3.8 then converts this ratio to a value representing the level of attractiveness imputed by the consumer for this vehicle attribute.

Equation 3.5 – Attractiveness from Cost

$$A_{Cost} = f_{Cost} \left(\frac{Cost_i}{Cost_{ICE}} \right)$$

where

$Cost_i$ = Lifecycle Vehicle Cost of technology i , dmnl

$Cost_{ICE}$ = Reference Lifecycle Vehicle Cost of ICE technology, dmnl

f_{Cost} = Function for Attractiveness from Cost, dmnl

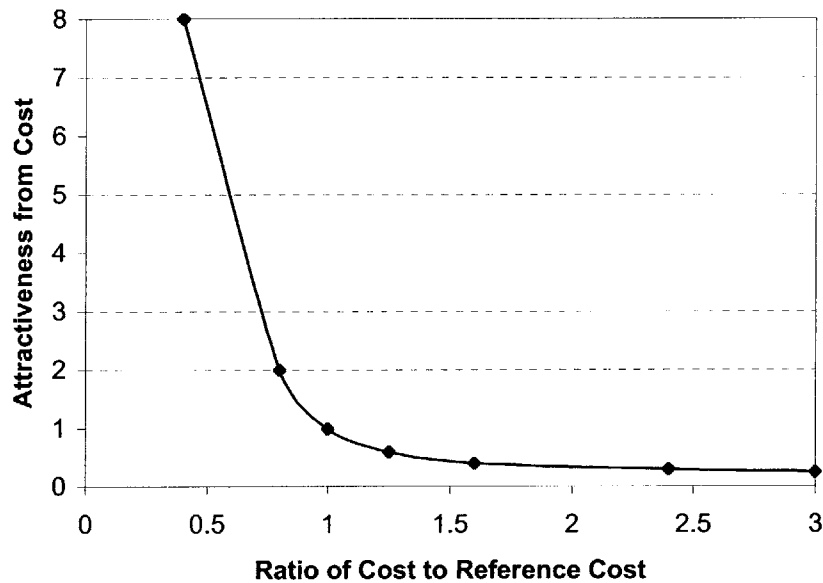


Figure 3.8 – Attractiveness from Cost

(As a function of the ratio of the cost for a given technology relative to the benchmark ICE platform)

Environmental Factors

Currently, this vehicle attribute plays a minor role in the consumer's purchase decision. I argue that this is a consequence of two forces. First, that only a small segment of the consumer population demonstrates any sensitivity to environmental factors. Therefore, the majority of potential buyers fail to internalize such considerations when deciding on a vehicle purchase. Second, producers must respect consumer expectations, but behaviors are malleable; that is to say that behaviors are evolvable and governable. Behaviors evolve over time, but external forces in the form of laws, norms, media, and design of the world around us shape them (Lessig, 2001). Thus, although only a small fraction of the

consumer population might factor environmental consequences into their purchase decision currently, much can be done to modify this behavior in the years ahead. Such an argument is analogous to the emergence of a value system antithetical to smoking. It is directly the result of media efforts to educate consumers to the hazards they face.

The model computes an Environmental Damage Cost based on the methodology described in Chapter 1. It determines a value for the Attractiveness of Environmental Factors as illustrated in Equation 3.6 by comparing the Environmental Damage Cost of a given technology with that of the dirtiest benchmark, once again the ICE. The ratio is then converted to an attractiveness measure via the function displayed in Figure 3.9.

Equation 3.6 – Attractiveness from Environmental Factors

$$A_{Env} = f_{Env} \left(\frac{EDC_i}{EDC_{ICE}} \right)$$

where

- EDC_i = Environmental Damage Cost of technology i , dmnl
- EDC_{ICE} = Reference Environmental Damage Cost of ICE technology, dmnl
- f_{Env} = Function for Attractiveness from Environmental Factors, dmnl

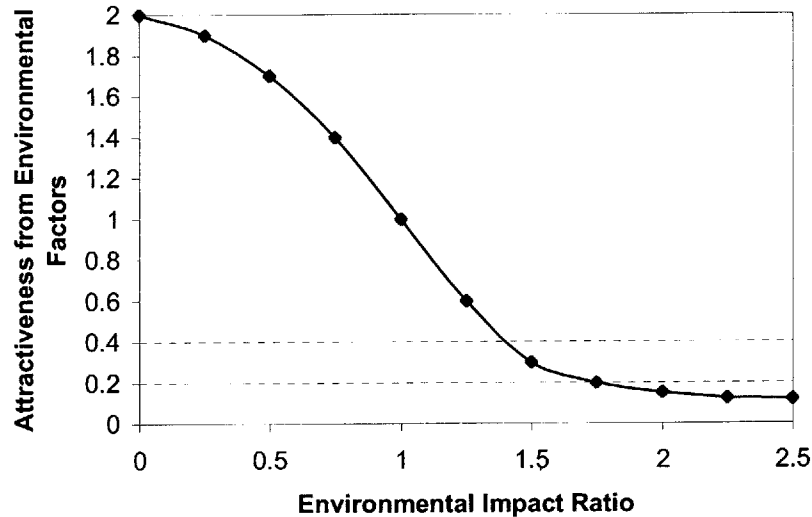


Figure 3.9 – Attractiveness from Environmental Factors

(Derived as a function of the ratio of Environmental damage created by a given technology relative to the damage created by the benchmark ICE technology)

Product Availability

The revised model treats the availability of alternative technologies to the public as endogenous to the consumer purchase decision and is included here for that reason. The author contends that demand may exist for such alternative technology, but that the inaccessibility, inconvenience, or sheer absence of the available product on new car lots penalizes the new technology in the form of a decreased probability of purchase. In other words, consumers may be more likely to take their business elsewhere. The construct is analogous to all other vehicle-specific attributes in that it compares the availability of a given alternative with the incumbent benchmark, returning a ratio that is then converted to an attractiveness measure determined by an arbitrary function as in Equation 3.7 and Figure 3.10.

Equation 3.7 – Attractiveness from Technology Availability

$$A_{Avb} = f_{Avb} \left(\frac{Avb_i}{Avb_{ICE}} \right)$$

where

- Avb_i = Availability of technology i , dmnl
- Avb_{ICE} = Reference Availability of ICE technology, dmnl
- f_{Avb} = Function for Attractiveness from Availability, dmnl

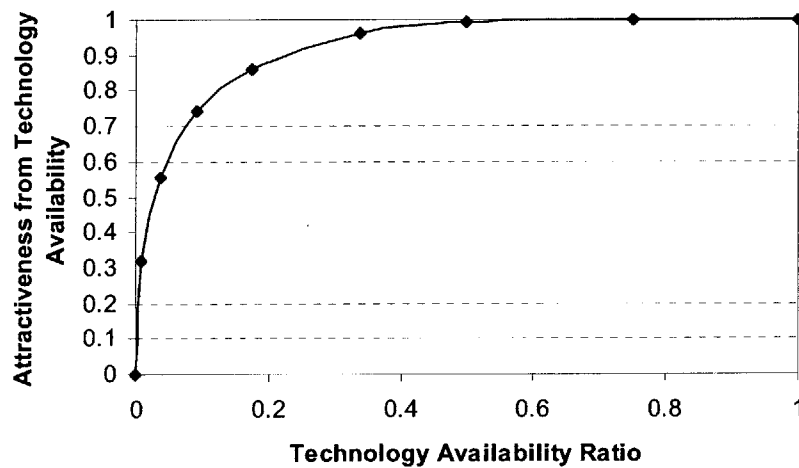


Figure 3.10 – Function for Attractiveness from Availability of a given propulsion system

Infrastructure Coverage

By analogy to technology availability above, the author contends that the consumer considers the infrastructure coverage supporting a given propulsion system a key criterion of purchase. 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 HEV, FCEV and EV technologies, this initial coverage is a scenario variable, in that it can be increased to reflect heavy investment in infrastructure prior to the technology's introduction to the market and prior to demand, which could be induced by regulatory intervention. The default values for the FCEV and EV are non-zero at a fraction of the potential (1% coverage). The model defaults ICE to unity and HEV to 0.9, reflecting the pre-existence of a necessary fuel service infrastructure for this technology. Equation 3.8 and Figure 3.11 illustrate the formulation of an attractiveness figure of merit.

Equation 3.8 – Attractiveness from Infrastructure Coverage

$$A_{Infra} = f_{Infra} \left(\frac{InCov_i}{InCOV_{ICE}} \right)$$

where

- $InCov_i$ = Infrastructure Coverage of technology i , dmnl
- $InCOV_{ICE}$ = Reference Infrastructure Coverage of ICE technology, dmnl
- f_{Infra} = Function for Attractiveness from Infrastructure Coverage, dmnl

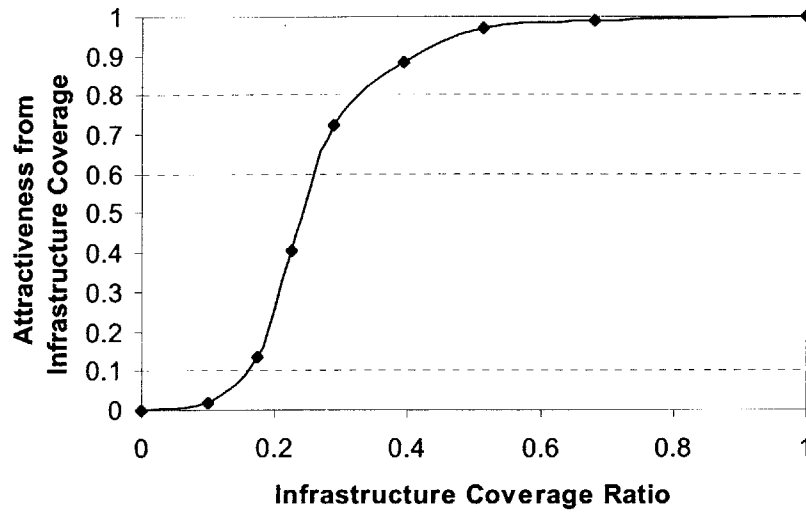


Figure 3.11 – Effect of Relative Infrastructure Coverage on Vehicle Attractiveness

3.5 TRACKING KEY METRICS

The revised model includes useful mechanisms for capturing the state of various attributes of the market adoption “system” at any point in time. This tool enables decision-makers to pre-run policy scenarios to determine, in advance, the relative success of alternative strategy options. We accomplish this by establishing the key metrics by which stakeholders wish to gauge the systemic impact of a given strategy. System Dynamics uses stock and flow structures to track quantities flowing through various stages of a system (Sterman, 2000). Structures referred to as “Co-flows” and “Aging Chains” allow us to track a set of key attributes and metrics of consequence. These mechanisms relay the state of attributes at any given time and are described in detail in the following section.

3.5.1 CO-FLOWS AND AGING CHAINS

Seven new views were created, each using aging chains and co-flows to facilitate the tracking of the following key metrics of interest over time:

- (1) Average Fleet Fuel Economy
- (2) Average Fleet Performance
- (3) Average Fleet Range

- (4) Average Fleet Air Pollution
- (5) Average Fleet Greenhouse Gas (GHG) Emissions
- (6) Average Fleet Vehicle Price
- (7) Fleet Annual Oil Consumption
- (8) Technology Fraction in the Fleet
- (9) Total Vehicle Pollutant Emissions
- (10) Total Vehicle Greenhouse Gas (GHG) Emissions
- (11) Total Environmental Damage Cost

Each of these metrics provides critical data to stakeholders regarding the outcomes of particular strategies. To track these variables, we first construct an aging chain. An aging chain consists of any number of stocks called cohorts. Each cohort can have any number of inflows and outflows as illustrated in the generic aging chain and co-flow structure of Figure 3.12.

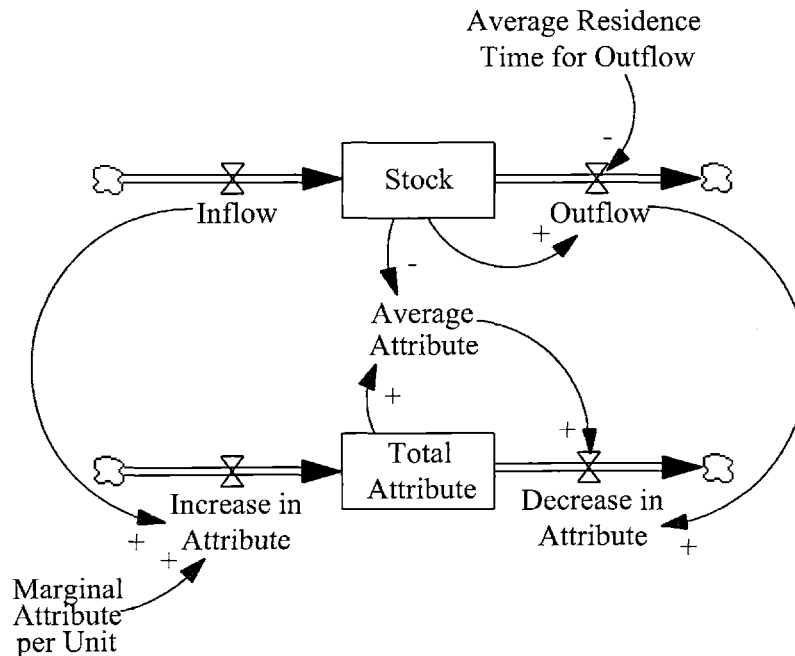


Figure 3.12 – A Generic Co-flow structure for tracking attributes of a stock

To yield the attribute *Average Fleet Fuel Economy*, the aging chain constructed in the revised model disaggregates the vehicle fleet stock into two separate cohorts called

“Late Model Vehicles” and “Older Vehicles.” Each cohort has an inflow and an outflow as illustrated in Figure 3.13.

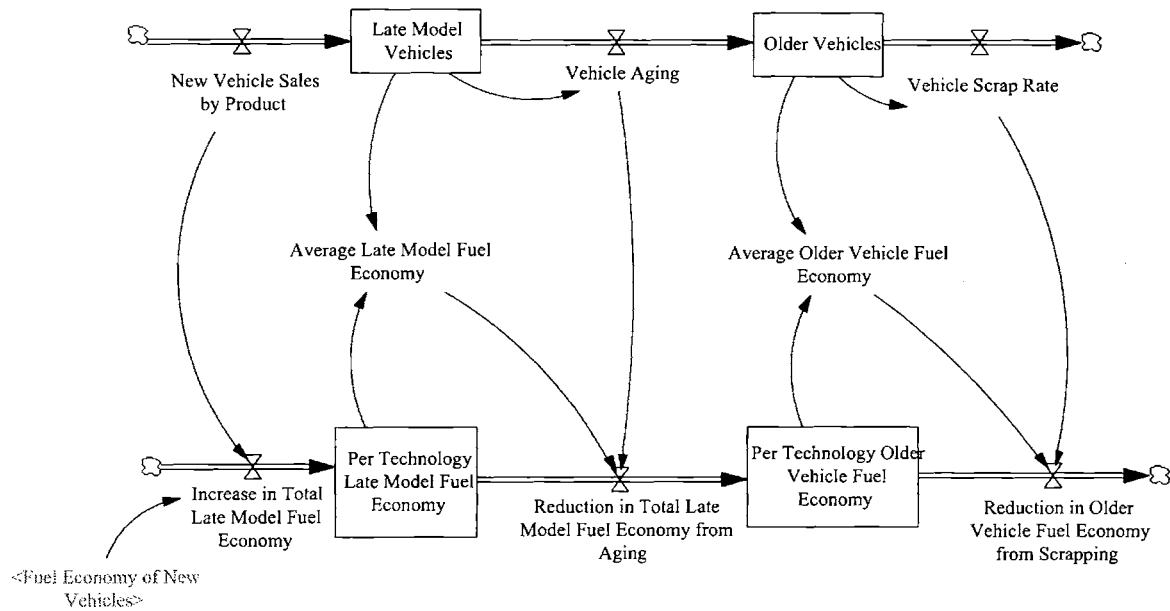


Figure 3.13 – Representative Aging Chain/Co-flow for tracking fuel economy in the revised model

The inflow to “Late Model Vehicles” is *New Vehicle Sales* and the outflow is *Vehicle Aging*. The inflow to the stock of *Older Vehicles* is *Vehicle Aging* and the outflow is the *Vehicle Scrap Rate*. Equation 3.9 describes the behavior of the aging chain formulation.

Equation 3.9 – Aging Chain Formulation

$$LMVehicles_i(t) = \int_{t_0}^t (Sales_i(s) - Aging_i(s)) ds + LMVehicles_i(t_0)$$

$$Sales_i = TMS_i * MktSize$$

$$Aging_i = \frac{LMVehicles_i}{NVLife}$$

where

$LMVehicles_i$	= Late Model Vehicles of technology i , vehicles
$Sales_i$	= New Vehicle Sales of technology i , vehicles/year
TMS_i	= Technology Market Share of technology i , dmnl
$MktSize$	= Size of the New Vehicle Market, vehicles/year
$Aging_i$	= Aging rate of technology i , vehicles/year
$NVLife$	= New Vehicle Life, years

The co-flow structure mirrors the structure of the main aging chain while providing the key information necessary to yield the metric of interest (Sterman, 2000). In the Fuel Economy example illustrated in Figure 3.13, I construct the stocks *Total Late Model Fuel Economy* and *Total Older Vehicle Fuel Economy*. These stocks form an aging chain similar, and parallel to, the first. Both flows contribute the necessary data for the metric we wish to capture – in this case *Average Late Model Fuel Economy* and *Average Older Vehicle Fuel Economy* per Equations 3.10 through 3.13. Equation 3.14 yields the metric of interest, *Average Fuel Economy* for the fleet at any given time, by summing the two fuel economy stocks over the entire vehicle fleet. Metrics 2 through 6 were constructed by analogy. Equations 3.10 through 3.12 yield the remaining figures of merit.

Equation 3.10 – Average Late Model Fuel Economy

$$AvgLMFE_i = \frac{LMFE_i}{LMVehicles_i}$$

where

$AvgLMFE_i$	= Average Late Model Fuel Economy of technology i , mpg*cars
$LMFE_i$	= Late Model Fuel Economy of technology i , mpg
$LMVehicles_i$	= Late Model Vehicles of technology i , cars

Equation 3.11 – Average Older Vehicle Fuel Economy

$$AvgOVFE_i = \frac{OVFE_i}{OVehicles_i}$$

where

$AvgOVFE_i$ = Average Older Vehicle Fuel Economy of technology i , mpg*cars
 $OVFE_i$ = Older Vehicle Fuel Economy of technology i , mpg
 $OVehicles_i$ = Older Vehicles of technology i , cars

Equation 3.12 – Total Average Fleet Fuel Economy

$$FleetAvgFE_i = \frac{AvgLMFE_i + AvgOVFE_i}{LMVF + OVF}$$

where

$FleetAvgFE$ = Fleet Average Fuel Economy of technology i , mpg
 $LMVF$ = Late Model Vehicle Fleet, vehicles
 OVF = Older Vehicle Fleet, vehicles

Equation 3.13 – Average Vehicle Performance

$$FleetAvgPerf_i = \frac{AvgLMVPerf_i + AvgOVPerf_i}{LMVF + OVF}$$

where

$FleetAvgPerf_i$ = Fleet Average Vehicle Performance of technology i , dnmil
 $AvgLMVPerf_i$ = Average Late Model Vehicle Performance of technology i , dnmil
 $AvgOVPerf_i$ = Average Older Vehicle Performance of technology i , dnmil

Equation 3.14 – Average Vehicle Range

$$FleetAvgR_i = \frac{AvgLMVR_i + AvgOVR_i}{LMVF + OVF}$$

where

$FleetAvgR_i$ = Fleet Average Vehicle Range of technology i , miles
 $AvgLMVR_i$ = Average Late Model Vehicle Range of technology i , miles
 $AvgOVR_i$ = Average Older Vehicle Range of technology i , miles

underpinning any forthcoming policy recommendations in the larger thesis research effort. The author hopes that the inclusion of these structures in the Revision Model will improve our ability to predict the consequences of alternative policies and provide a framework for valuing those consequences to make better decisions.

3.6 MODEL EXTENSIONS AND ADDITIONAL STRUCTURES

The following sections detail the construct of several key extensions to the reference model. This includes the logic and structures used, the equations governing system parameters and behaviors, and any decision rules used to simulate decision-making activities.

3.6.1 CONSUMER SENSITIVITY TO ENVIRONMENTAL IMPACT

The reference model employs a simple switch construct to account for consumer sensitivity to environmental considerations in the purchase decision. That is, the consumer is fully sensitive to environmental impacts, i.e. the switch is “on,” or the consumer is entirely negligent of such consequences, i.e. the switch is “off.” In contrast, the revised model treats environmental sensitivity as a dynamic, rather than discrete, parameter of the consuming public that can be influenced over time. In the construct illustrated in Figure 3.15 below, consumers migrate from the stock of “environmentally insensitive” to the stock of “environmentally conscious” as a function of the impact of the Public Awareness Campaign lever. This lever is discussed in greater detail in the following section. For now, it suffices to say that the model begins with the assumption that only 5% of the market factors environmental impacts into their purchase decision. The Public Advertising Campaign lever serves to educate consumers of the health and environmental consequences of vehicle emissions. Thus, it enables the outflow of consumers from the “insensitive” pool to the environmentally conscious pool.

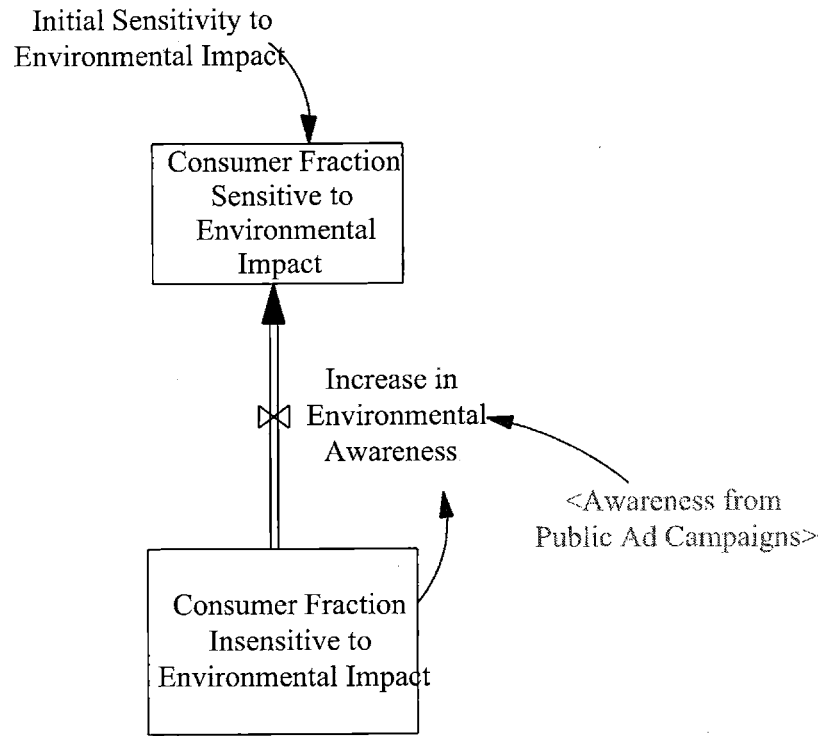


Figure 3.15 – Consumer Sensitivity to Environmental Considerations in the purchase decision

The dynamic is distinguished from private marketing efforts, which raises consumer awareness of the existence of product alternatives. Private marketing campaigns may serve to simultaneously educate consumers regarding the health and environmental benefits of their products, but I have chosen not to include this here to avoid potential double counting. For simplicity, I have also chosen to exclude a “forgetting fraction” in this basic construct. The author feels justified in doing so in that the attribute reflects the evolutionary emergence of an environmentally responsible value system. Equation 3.15 outlines the formulation of these parameters.

Equation 3.15 – Formulation for Consumer Fraction Sensitive to Environmental Impact

$$CF_{Insensitive} = \int_{t_0}^t (-Increase(s)) ds + (1 - Initial(t_0))$$

$$Increase = CF_{Insensitive} * PACampaign$$

$$CFSensitive = \int_{t_0}^t (+Increase(s))ds + Initial(t_0)$$

where

- Increase* = Rate of increase in consumer environmental consciousness, 1/year
PACampaign = Awareness generation from public advertising, 1/year
CFInsensitive = Consumer Fraction Insensitive to Environmental Impact, dmnl
CFSensitive = Consumer Fraction Sensitive to Environmental Impact, dmnl
Initial = Initial fraction of consumers sensitive to environmental impact, dmnl

The Sensitivity construct forwards the fraction of consumers sensitive to environmental impact to the Attractiveness from Environmental Impact formulation for a given technology. Equation 4.16 illustrates.

Equation 3.16 – Attractiveness of Environmental Impact

$$f_{Env} = f_{adj} \left(\frac{EDC_i}{EDC_{ICE}} \right) - 1$$

$$AttractEnv_i = (1 + CFSensitive) * f_{Env}$$

where

- f_{Env}* = Function for Attractiveness from Environmental Impact, dmnl
f_{Adj} = Environmental Adjustment Function, dmnl
EDC_i = Environmental Damage Cost of technology *i*, \$/vehicle
EDC_{ICE} = Environmental Damage Cost of technology *i*, \$/vehicle
AttractEnv = Attractiveness from Environmental Impact of technology *i*, dmnl
CFSensitive = Consumer Fraction Sensitive to Environmental Impact, dmnl

The above equations enable us to simulate the emergence of a stronger environmental value system in the representative market, should we choose to do so.

3.6.2 MARKET GROWTH

A key difference from the reference model is the inclusion of a simple market growth “engine” that attempts to simulate the effect of population and vehicle market growth on the feedback mechanisms discussed earlier. Figure 3.16 portrays the growth engine construct for the North American vehicle market.

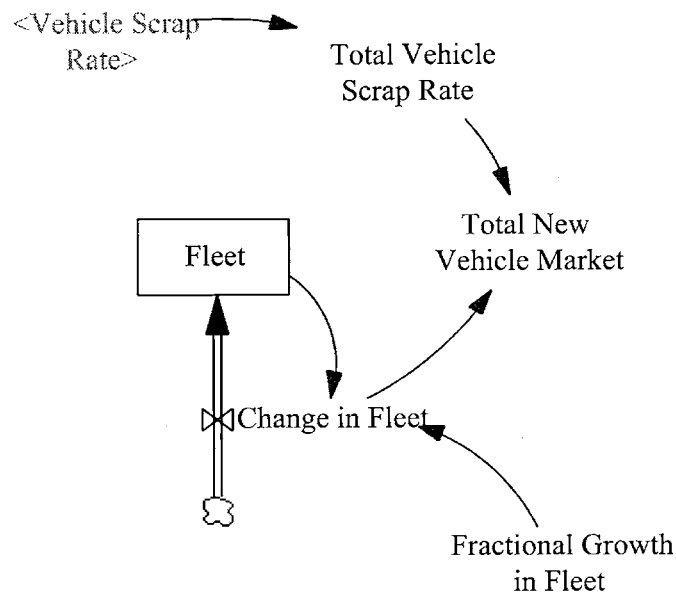


Figure 3.16 – Market Growth Construct of the revised model

The construct begins with the state variable *Fleet* initialized at 200 million vehicles, an approximation representative of the number of light duty vehicles on the road in the U.S. market in 2002 (Ward’s, 2000). The Fractional Growth in Fleet determines the rate of vehicle fleet growth. The default value is 1.6% per year and is representative of the historical rate of sales growth in the U.S. over the past thirty years (U.S. Census, 2000). Equation 3.17 tallies the Total New Vehicle Market as the sum of both new vehicle *market growth* resulting from historical increases in sales, and increasing vehicle *turnover*, derived from the increasing segment of vehicles reaching the end of their 14-year service life.

Equation 3.17 – Total New Vehicle Market

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

$$Scrap_i = \frac{OldFleet_i}{OVL}$$

$$TotScrap = \sum_{j=1}^4 Scrap_j$$

$$\Delta Fleet = Growth * Fleet$$

$$MarketGro = TotScrap + \Delta Fleet$$

where

<i>Fleet</i>	= Size of the Total Vehicle Fleet, vehicles
<i>Scrap_i</i>	= Scrap Rate of technology <i>i</i> , vehicles/year
<i>TotScrap</i>	= Total scrap rate of all vehicles, vehicles/year
<i>ΔFleet</i>	= Change in Fleet size, vehicles/year
MarketGro	= Total New Vehicle Market, vehicles/year
<i>t₀, t</i>	= Initial time and current time, respectively, years
<i>s</i>	= Point in time between initial and current time, years
<i>ds</i>	= Time period for integration, years

As will be discussed in Chapter 4, the inclusion of a market growth dynamic serves both balancing and reinforcing roles in the actual marketplace.

3.6.3 DISCOUNT RATE

In contrast to the reference model, the revised model brings the discount rate applied to variable costs endogenous to the model. The discount rate equates the annual rate of return applied by the consumer to future cash flows at the time of purchase. Typical discount rates used in financial analysis range from 5-10% per year, representing the opportunity cost of foregone interest payments from short-term debt instruments (Brealey and Myers 2000). But consumers often exhibit quite different behavior when weighing variable costs in their purchase decision. Studies of the home appliance market indicate

that consumers often implicitly apply a much higher discount rate to savings derived from energy efficiency, sometimes as high as 50% per year. This means the customer fails to internalize much of this cost and therefore significantly discounts the importance of this cost savings when considering their purchase. This may result from consumer expectations of continued low variable cost, ambivalence over payments that are not current, or the simple lack of consideration to this particular cost element.

For the purpose of this thesis, the author has dynamically linked fuel prices with the discount rate to more accurately reflect consumer behavior patterns at the point of purchase. Essentially, this involves a function that creates an inverse relationship between gas prices and the discount rate. In other words, the discount rate dynamically decreases as gas prices increase relative to historical expectations. Simply translated, as fuel costs increase, the consumer implicitly applies more weight to future fuel costs when considering the purchase of a vehicle. This function returns a discount rate ranging from 12.5% to 36%, based on increasing fuel cost as indicated by relative gas prices. Figure 3.17 below illustrates the function for the discount rate with increasing relative gas prices translating to decreasing discount rates.

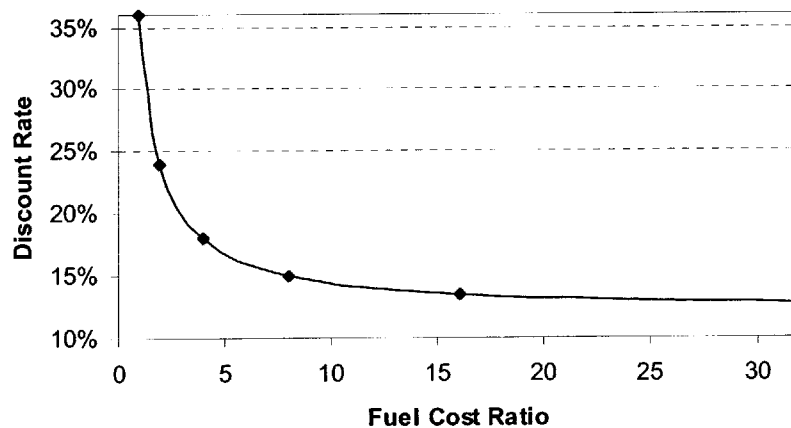


Figure 3.17 – Effect of Relative Gas Prices on Discount Rate

3.6.4 FEE-BATE PROGRAM

The Fee-bate Program represents a form of regulatory intervention that attempts to redistribute externality costs to those consumers responsible for generating those costs. Retail vehicle prices, nor fuel prices, accurately reflect the "true" cost of the vehicle to

consumers because they ignore costs borne by society in the form of reduced quality of life. The “Fee-bate” construct in the revised model uses a redistribution scheme based on the differential between the environmental damage cost of a given technology and the benchmark cost created by the incumbent propulsion mode – the ICE. Purchasers of a cleaner propulsion mode relative to the ICE will receive an incentive rebate equal to some function of the environmental damage cost differential. Conversely, purchasers of dirtier modes will be subject to a fee equal to some function of the cost differential.

The fee-bate attempts to achieve two goals. First, it lowers the cost barrier of new and cleaner technologies to consumers by subsidizing them with funds drawn from fees assigned to dirtier technologies. By closing the cost gap, consumers can focus on other performance-based purchase criteria. Second, by lowering the cost hurdle at the introductory phase, technologies capable of competing with dominant modes can rapidly achieve market penetration, enabling producers to quickly achieve scale economies to drive down manufacturing costs. Third, because fees are initially drawn from a significant pool of vehicles and transferred to a much smaller pool of new vehicles, the per-vehicle charge is a fraction of the actual damage cost differential. Thus, fees phase in incrementally, grow with successful adoption of alternatives, and then phase out as scale economies drive down the real cost of alternatives and obviate the need for subsidies.

The revised model applies a formula based on the fraction of late model technologies in the vehicle fleet. Equation 3.18 describes the calculation of the Feebate Fraction. This fraction is then applied to the differential in environmental damage cost to yield the fee that will be levied against the ICE or the rebate provided the cleaner alternative. These amounts are added or subtracted against the vehicle purchase price.

Equation 3.18 – Feebate formulation

$$FeebateFrnx_{ICE} = 1.2 - (LMTFFleet)_{ICE}$$

$$FeebateFrnx_i = 1 - (LMTFFleet)_i$$

$$FeebatePgm_i = (EDC_{ICE} - EDC_i) * FeebateFrnx_i$$

where

$FeebateFrxn_{ICE}$	= Fee fraction charged to the ICE retail price, dmnl
$FeebateFrxn_i$	= Rebate fraction deducted from the retail price of alternative technologies, dmnl
$FeebatePgm_i$	= Total fee/rebate applied, \$/vehicle

The fee-bate construct is a scenario variable that includes a basic switch, allowing the user to turn this particular policy intervention on or off, based upon the desired scenario.

3.6.5 PUBLIC AWARENESS CAMPAIGN

The Public Awareness Campaign construct serves to stimulate awareness of the adverse quality of life and health impacts of mobile source air pollution as well as to seed awareness of the availability of alternative products on the market. In the role of the former, media campaigns analogous to anti-tobacco advertisements serve to educate the public of the potential hazards to individuals and society posed by emissions of criteria air pollutants. In this sense, the effort parallels a grass roots effort to instill more environmentally responsible behavior by the consuming public.

Concurrently, the investment would complement privately funded industry marketing campaigns, thereby serving to accelerate the awareness and word-of-mouth dynamics in the model. In this role, publicly funded advertisements essentially expand the pool of potential consumers in the awareness stimuli *exogenous* to the purchase decision. At the same time, the campaign works to strengthen environmentally responsible consumer behavior that would result in consumers ascribing greater value to environmental considerations during the vehicle purchase decision process. In this sense, the campaign works to influence decision variables *endogenous* to the consumer purchase decision. Equation 3.19 lists the formulas applied.

Equation 3.19 – Public Advertising Campaign

$$PACAware = MktgNorm * (PACRel)^e$$

$$PACRel = \frac{PACExpend}{Baseline}$$

where

- PACAware* = Awareness generation from Public Ad Campaign, 1/year
- MktgNorm* = Normal awareness generation from marketing, 0.05/year
- PACRel* = Relative strength of Public Ad Campaign, dmnl
- e* = Marketing elasticity, dmnl
- PACExpend* = Expenditure on Public Ad Campaign, dmnl/year
- Baseline* = Baseline private spending on marketing, equal to unity, dmnl/year

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4 TECHNOLOGY ADOPTION SCENARIOS

I open this chapter with a discussion of how the formulations in the previous chapter interact under the baseline assumptions of the revised model. I outline four scenarios, the criteria for their selection, and the assumptions underlying each. I then present the results of each simulation and close with a brief interpretation of their basic meaning. Each scenario illustrates a potential adoption pathway for the representative propulsion architecture. For simplicity, I have chosen to “fix” each major technology with a specific energy carrier, even though one could experiment with a variety of energy carriers for each of the technologies represented.

Second, the reader should bear in mind that the model does not attempt to “evolve” the energy infrastructure as with the vehicle-specific attributes deemed crucial to the customer purchase decision. Thus, some key metrics such as fleet annual fuel consumption and Environmental Damage Cost may appear worse than might actually occur, should a greater fraction of the U.S. power grid derive energy from renewable resources. The model as presented should be considered a work in progress, subject to continued refinement and extension. The purpose of providing these metrics is to lend the reader a sense of the scale of the problem and the patterns that might emerge under a variety of possible conditions. Thus, the reader is cautioned to consider the results presented in relative, vice absolute terms.

4.1 BASELINE ASSUMPTIONS

For the purpose of this thesis, the baseline scenario is equivalent to the scenario that yields continued ICE domination of the vehicle market. It is presented as Scenario 1, and represents simulation under the default values assigned to the set of Scenario Variables to be discussed shortly. These values represent the state of technologies, markets, and value systems, as they exist today. I use actual and verifiable data where possible. However, due to the proprietary nature of some figures, I have chosen to infer generic or arbitrary values where appropriate. The author derived these approximations via his best educated guess, based on discussions with industry representatives or gleaned from available literature.

Static Assumptions

The set of scenarios that follow were selected to represent their respective class of propulsion architectures. That is to say that the fundamental propulsion technologies stem from four primary and discernible architectures, each designed to leverage the potential benefits derived from their respective power generation and delivery methods. The architectures chosen consist of the grid-independent variants of the internal combustion engine (ICE), the hybrid electric vehicle (HEV), the fuel cell electric vehicle (FCEV), and the grid-dependent battery electric vehicle (BEV).

Table 4.1 on the following page lists the crucial design assumptions of each of the propulsion architectures selected. ICE-based platforms, to include the HEV, employ a spark-ignition direct-injection (SIDI) engine. For the purpose of this thesis, compression-ignition engines (i.e. diesel) have been omitted primarily due to Tier 2 regulatory requirements that effectively outlaw the levels of NO_x and particulate emissions associated with diesel engines. The author should note, however, that industry continues to develop technologies such as plasma-based lean burn and plasma NO_x trap after-treatment that may enable automakers to achieve order-of-magnitude reductions in these emissions. The allure of diesel is its superior energy density, roughly 10% higher than the gasoline equivalent. This characteristic gives diesel its 25-30% edge in fuel economy over gasoline-powered vehicles. Assuming automakers are able to reduce emissions (or dilute mandates) to comply with forthcoming law, diesels will still face the relative lack of sufficient fueling infrastructure to support significant adoption in the marketplace.

For the reasons above, all ICE-based technologies are assumed to run on gasoline. The FCEV, on the other hand, draws from direct, on-board storage of compressed hydrogen and therefore requires no on-board reformer to convert conventional fuels to a hydrogen carrier. Alternatively, the BEV draws power directly from the U.S. electricity grid; it is therefore the only platform represented that does not operate independent of the power grid. The default base gas price is \$1.43/gallon and is consistent within the range of retail gas prices observed historically (EIA, 2001). Although CEES projects hydrogen costs of \$1.70 per gasoline-equivalent gallon (Ogden, 2002), to maintain maximum plausibility the model assumes a per gallon gasoline-equivalent cost of hydrogen of \$2.20, consistent with the more conservative estimates provided by Weiss et al (2000). This

Static Assumptions	ICE	HEV	FCEV	BEV	Source
Powerplant	-SIDI ICE	-SIDI ICE -Electric Motor	-Fuel Cell Stack -Electric Motor	-Electric Motor	Wang 2001
Fuel	Gasoline	Gasoline	Direct Hydrogen	Power Grid	Wang 2001
Energy Carrier	Gasoline	Gasoline	Hydrogen	Electric Potential	Wang 2001
Fuel/Energy Cost [Per GEG]	\$1.43	\$1.43	\$2.20	\$1.62	Weiss 2000
Initial Gasoline- Equivalent Fuel Economy, [miles/gal]	22.4	42.6	72.0	67.2	Wang 2001
Initial Powertrain System Cost	\$4,770	\$9,000*	\$100,000*	\$18,000*	Weiss 2000 + Industry Est.*
Initial Production Experience [units]	300,000,000	40,000	100	10,000	Estimate**
On-Board Fuel Processing	No	No	No	No	Wang 2001
Dependence	Grid Independent	Grid Independent	Grid Independent	Grid Dependent	Wang 2001

*Cost indicated includes total powertrain system costs for the propulsion architecture and are derived from industry estimates.

**Initial cumulative production experience figures are “order-of-magnitude” approximations intended to calibrate learning curve dynamics.

Table 4.1 – Basic Design Assumptions for the Scenario Set

report also provides the initial cost of the ICE propulsion system. The author has approximated the generic current cost of the set of alternative systems based on industry interviews that provide order-of-magnitude accuracy only. Initial fuel economies for the set of technologies are consistent with calculations provided by the GREET model (Wang, 2001). The author estimated cumulative production experience figures as order-of-magnitude approximations derived from historical industry production volumes for the purpose of calibrating learning curve effects with observed industry patterns.

4.2 SCENARIO VARIABLES

In keeping with the intent to establish maximum plausibility of the scenarios and to ensure that model variables are fairly straightforward, the author has attempted to keep user-based changes to a minimum. Doing so enables the user to generate distinct scenarios based on a minimum of parameter adjustments. The following set of variables comprises the scenario variables explicitly delineated for user adjustment to generate the scenarios discussed in the remaining sections of the thesis.

1. *Initial Relative Performance*

The model establishes the performance of the set of alternative technologies relative to the propulsion architecture dominant in the existing market. Thus, the model fixes the ICE at unity for the entirety of the simulation period and initializes all other architectures as some fraction of unity. This fraction represents the current state of development of the performance attribute for a given technology relative to the benchmark ICE. Here, performance is measured in terms of the power-to-weight ratio (PWR) based on the study provided by Weiss et al (2000). In contrast to this report, however, the default assumption of the revised model does not explicitly normalize this attribute to compare other vehicle characteristics. Thus, performance varies initially, and throughout the simulation period. Furthermore, the user can adjust the initializing parameters only. Unlike the static performance assumption of the reference model, upon simulation, the relative state of performance for a given technology may evolve from the initial, user-defined, reference point.

2. Relative Strength of the Marketing Effort

This variable represents one of the private-sector levers from which management may use to execute a particular product strategy. The model simulates this lever as a ratio of the spending on marketing for the given technology relative to the baseline marketing spending for the vehicle platform. The default assumption is set to unity. Thus, a user-defined strength of “2” equates to a doubling of marketing and media-based efforts to promote the alternative technology relative to the baseline.

3. Initial Infrastructure Coverage

As per the reference model, this user-defined variable provides an additional lever for product strategy and represents the availability of a supporting fuel, maintenance, and service infrastructure necessary to seed vehicle demand at the start of the simulation. Again, the model benchmarks the set of alternative technologies relative to the dominant technology, setting the ICE at unity for the duration of the simulation. Alternatives are initialized as some fraction of unity. The default value of the HEV is set to 0.9, reflecting the pre-existence of a necessary fueling infrastructure, but the initial lack of skilled technicians required for service and maintenance. The default values of the FCEV and EV technologies are set at 0.01 (1% coverage) reflecting the lack of both the necessary fueling infrastructure and adequate service and maintenance support. The user may adjust the FCEV and EV values to reflect intensive investment by private and/or public entities prior to introduction in order to circumvent the chicken-and-egg dilemma and seed initial demand.

4. Initial Target Availability

The default initial target availability for the set of alternative propulsion technologies at near zero (1%). This lever could represent a deliberate, internally driven industry effort to advance an alternative technology as part of a cohesive strategy to market alternative vehicles. Alternatively, it could reflect external intervention in the form of zero tailpipe emissions vehicle (ZEV) mandates or near-zero emissions mandates. Such mandates require that automakers meet certain threshold sales targets for cleaner vehicles as a minimum percentage of total vehicles sold annually.

5. Initial Target Product Investment

The initial target product investment for a given propulsion architecture represents the deliberate infusion of funds to accelerate product-based performance improvements by management. Product-based improvements refer to the set of vehicle attributes, such as range, fuel economy, and performance, considered most relevant by consumers in making their purchase decision. This scenario variable provides the key lever by which management can attempt to close the performance gap between actual and desired vehicle attributes. The reader should note that this scenario variable is static in that it does not adjust dynamically as market adoption patterns emerge over time. The default value for all technologies except the ICE (benchmarked at unity) is 0.01 (1%).

The model also factors in “spillover” effects from technology investment. That is, investments targeted toward advancing one propulsion technology concurrently benefits development of other technologies that share common systems and components. For example, investments targeted at HEV system development might spawn technologies applicable for use in FCEV platforms if, for example, the two systems rely on similar electric motors, generators, or other common componentry.

6. Profit Margin

The default value for the profit margin applied to a given technology is 5%. Profit margin is an exogenous scenario variable; once the user defines this variable, it remains fixed for the duration of the simulation regardless of demand and adoption patterns. The user may adjust the profit margin for a particular technology downward in order to lower the purchase price and seed demand as part of a targeted strategy to gain market penetration and scale economies, to learn from the early market, or to promote a public image of environmental responsibility. Both Toyota and Honda have chosen to price their Prius and Insight HEV models well below cost in the North American market. The user could simulate this strategy by indicating a negative profit margin for the HEV technology.

7. Initial Sensitivity to Environmental Factors

The initial sensitivity to environmental factors represents the initial assumption regarding the portion of the population considered environmentally aware enough to factor

environmental considerations into their purchase decision. The default value is 5%, meaning that roughly one-in-twenty consumers will weigh this factor when buying their next car.

Again, the user can choose to seed environmental awareness of the consumer market prior to the launch of product by indicating a higher initial sensitivity. Alternatively, the user could grow sensitivity by choosing to fund a public advertising campaign targeted at making the public aware of the adverse health and environmental impacts of pollutant emissions.

8. Relative Strength of the Public Ad Campaign

This variable represents one of the public-sector levers from which non-profit or government entities may attempt to modify the purchasing behavior of consumers. The model simulates this lever via a construct analogous to the relative strength of the marketing effort. It is a ratio of the spending on a public advertising campaign relative to the baseline marketing spending for the vehicle platform. The default assumption is zero, indicating that no such campaign is active. Thus, a user-defined strength of “1” is equivalent to the level of effort expended by industry marketing activities to promote a particular model. The model assumes it achieves the equivalent impact of private-sector marketing and media-based efforts to promote the alternative technology relative to the baseline. The Public Ad Campaign affects two consumer dynamics: awareness of cleaner alternatives and sensitivity to environmental factors.

9. Gasoline Price Increase & Time of Gasoline Price Increase

The user can specify an increase in the price of gasoline and the time at which the increase takes effect. Doing so enables the user to simulate either exogenous market supply and demand forces at work or a government-imposed gasoline tax. Thus, the user can witness the potential downstream impacts of these external forces on market adoption patterns. The baseline assumption is zero, indicating that gasoline prices remain fixed at the base price of \$1.43/gallon for the duration of the simulation.

10. Fee-bate Program

The fee-bate program, described in detail in Chapter 4, represents a public sector intervention to account for externality costs in vehicle price. This scenario variable employs a

switch construct with a default value of zero, allowing the user to turn this particular intervention “on” by assigning the switch a value of 1. The user can thus simulate the impact of this public intervention congruent with other scenario adjustments.

4.3 SCENARIO DEVELOPMENT

With the static assumptions and scenario variables defined, we now turn to the specific characteristics of the scenario set. Table 4.2 on the following page summarizes all assumptions and notes adjustments to the default values in bold. These adjustments define the scenarios discussed in this section.

Note that Scenario 1 involves no adjustment to the default parameters, and thus represents the ICE domination future, the baseline for all other scenarios. To create an alternative to the status quo, it is necessary to adjust key scenario variables. For the HEV competition scenario, we adjust five parameters from the default assumptions. These consist of a combination of both private sector strategy and public sector policy intervention. The FCEV and BEV scenarios, on the other hand, entail nine adjustments each, corresponding with the higher level of stakeholder activities, contributions, and cooperation required to realize these futures.

Given these conditions, Table 4.3 lists figures for the market share of a given propulsion architecture and the fraction of that technology comprising the fleet of all vehicles on the road after thirty years. Table 4.4 lists values for the key progress metrics we wish to track for each scenario in ten-year increments. Table 4.5 presents this same data as a percent change over the baseline year (2002). I now turn to a discussion of the findings provided by each scenario simulation.

Scenario Variable	Scenario 1: ICE Domination				Scenario 2: Hybrid Competition				Scenario 3: Fuel Cell Transition				Scenario 4: EV Take-Off			
	ICE	HEV	FCEV	EV	ICE	HEV	FCEV	EV	ICE	HEV	FCEV	EV	ICE	HEV	FCEV	EV
Propulsion Architecture																
Initial Performance	1	0.7	0.6	0.6	1	0.7	0.6	0.6	1	0.7	0.6	0.6	1	0.7	0.6	0.6
Relative Strength of the Marketing Effort	1	1	1	1	1	2	1	1	1	1	3	1	1	1	1	4
Initial Infrastructure Coverage	1.0	0.9	0.01	0.01	1.0	0.9	0.01	0.01	1.0	0.9	0.2	0.01	1.0	0.9	0.01	0.2
Initial Target Availability	1.0	0.01	0.01	0.01	1.0	0.2	0.01	0.01	1.0	0.2	0.2	0.01	1.0	0.2	0.01	0.2
Initial Target Product Investment	1.0	0.01	0.01	0.01	1.0	0.4	0.01	0.01	1.0	0.2	0.4	0.01	1.0	0.2	0.01	0.4
Profit Margin	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Initial Sensitivity to Environment	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Relative Strength of Public Ad Campaign	0				1				1				1			
Gasoline Price Increase	0				0				+\$1				+\$3			
Feebate Program	OFF				ON				ON				ON			

(Changes to default values are noted in bold)

Table 4.2 – Scenario Variable assumptions for the Scenario Set

	Units	Scenario 1: ICE Domination				Scenario 2: HEV Competition				Scenario 3: FCEV Transition				Scenario 4: EV Take-off			
		ICE	HEV	FCEV	EV	ICE	HEV	FCEV	EV	ICE	HEV	FCEV	EV	ICE	HEV	FCEV	EV
Product Market Share	[%]	81.1	17.3	0.8	0.9	45.4	53.9	0.4	0.4	18.2	32	49.3	0.5	28.1	52.0	0.9	19
Technology Fraction in the Fleet	[%]	92.7	6.2	0.5	0.6	58.3	41.1	0.3	0.3	43.8	36.6	18.9	0.7	45.6	43.6	0.9	9.9

Table 4.3 - Year 2032 Product Market Share & Technology Fraction in the Fleet Projections

Progress Metric	Units	Base Year	Scenario 1: ICE Domination			Scenario 2: HEV Competition			Scenario 3: FCEV Transition			Scenario 4: EV Take-off		
		2002	2012	2022	2032	2012	2022	2032	2012	2022	2032	2012	2022	2032
Total Vehicle Pollutant Emissions	Billions of Kg/yr	16	18.7	21.8	25	18.5	20.3	22	18.2	18.9	17.7	18.2	19.1	19.8
Total Vehicle GHG Emissions	Billions of Kg/yr	1,234	1,397	1,534	1,668	1,380	1,421	1,464	1,292	1,205	1,128	1,278	1,182	1,150
Average Fuel Economy of Gas Vehicles	Miles/gallon	22.4	23.2	24.9	27.1	23.8	28.3	32.8	25.1	32.4	35.5	25.8	32.9	43.2
Aggregate Average Fuel Economy	Miles/gallon	22.4	23.3	25.1	27.6	23.8	28.5	33	25.3	32.6	38.7	26.9	37.1	45.8
Fleet Annual Oil Consumption	Billions of gallons/year	107.1	121.1	132.1	141.2	118.4	116.2	117.7	109.4	94.7	80.7	106.3	88.2	80.1
Total On-Road Cost of Environmental Damage	Billions of \$US/year	1,223	1,382	1,574	1,778	1,367	1,465	1,570	1,269	1,278	1,227	1,254	1,278	1,341

Table 4.4 – Key Progress Indicators by Scenario at 10-year Increments

	Units	Base	Scenario 1: ICE Domination			Scenario 2: HEV Competition			Scenario 3: FCEV Transition			Scenario 4: EV Take-off		
		2002	2012	2022	2032	2012	2022	2032	2012	2022	2032	2012	2022	2032
Total Vehicle Pollutant Emissions	Billions of Kg/yr	16	16.9	36.3	56.3	15.6	26.9	37.5	13.8	18.1	10.6	13.8	19.4	23.8
Total Vehicle GHG Emissions	Billions of Kg/yr	1,234	13.2	24.3	35.2	11.8	15.2	18.6	4.7	-2.4	-8.6	3.6	-4.2	-6.8
Average On-Road Fuel Economy of Gas Vehicles	Miles/gallon	22.4	3.6	11.2	21.0	6.3	26.3	46.4	12.1	44.6	58.5	15.2	46.9	92.9
Aggregate Average Fuel Economy	Miles/gallon	22.4	4.0	12.1	23.2	6.3	27.2	47.3	12.9	45.5	72.8	20.1	65.6	104.5
Fleet Annual Oil Consumption	Billions of gallons/year	107.1	13.1	23.3	31.8	10.6	8.5	9.9	2.1	-11.6	-24.6	-0.7	-17.6	-25.2
Total On-Road Cost of Environmental Damage	Billions of \$US/year	1,223	13.0	28.7	45.4	11.8	19.8	28.4	3.8	4.5	0.3	2.5	4.5	9.6

Table 4.5 – Percent change in Key Progress Indicators by Scenario at 10-year Increments

4.3.1 SCENARIO 1 (BASELINE): ICE DOMINATION

Scenario Basis

In the ICE Domination scenario, gasoline prices remain unchanged at levels considered relatively affordable to consumers. Because gas prices are low, consumers fail to internalize fuel costs, implicitly discounting the costs of refueling by 36%, a figure congruent with energy studies in the appliance sector. Only 5% of consumers internalize environmental considerations in their purchase decision and this figure remains static through the course of the simulation period. This scenario is equivalent to a “laissez faire” approach to vehicle development, in which stakeholders accept the status quo and make little effort to actively intervene in the marketplace.

Findings

Figure 4.1 below illustrates the market adoption pattern for the baseline scenario. In the absence of targeted industry investment in product development or marketing, public policy intervention, or external market shocks such as a gasoline increase, ICE architectures easily dominate the market over the thirty-year scenario period. HEV platforms do eventually establish a minimally respectable level of market penetration, comprising over 17% of sales by 2032, and over 6% penetration of the total fleet of vehicles on the road.

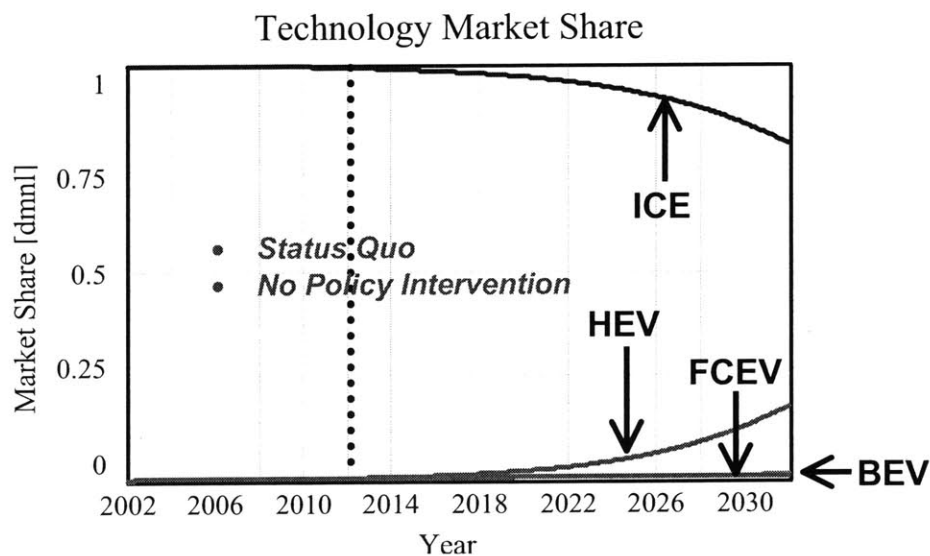


Figure 4.1 – Technology Market Share in the ICE Domination Scenario

In contrast, FCEV and BEV propulsion architectures achieve negligible (<1%) market penetration over the same period. This can be attributed to the more severe infrastructure support hurdles facing these technologies. HEVs on the other hand, benefit from a pre-existing gasoline fueling infrastructure.

The reader should note that the adoption of HEV platforms is highly dependent on model assumptions and inputs. Although the default level of investment in marketing is equal to one, automakers could constrain HEV demand significantly through the awareness feedback mechanism by refusing to invest in HEV product marketing. More importantly, the model does not attempt to distinguish between foreign and domestic auto interests. Thus, if domestic automakers deliberately suppressed efforts to stimulate HEV awareness through marketing channels, foreign automakers may choose to do so anyway.

One of the most fascinating aspects of this “race” amongst a set of potential technologies, is the jockeying of firms over time, each with their own strategy for technology leadership, in order to position themselves to capture value should a particular technology “take-off.” The disparity amongst firms in their relative core competencies and competitive position with regard to leadership across the spectrum of potential propulsion technologies spawns a number of conflicts of interests. These conflicts represent misalignments in incentive structures that can result in significant impediments to innovation and progress.

For example, consider Firm A: a domestic firm that holds a key leadership position in electric vehicle technologies, but suffers relative to its competitors in hybrid-based platforms. We could expect this firm to exert its market power to lobby government representatives and influence value networks in order to create a market environment nurturing of its own technology and hostile to Firm B, a foreign firm with a technological lead in HEV architectures. In order for Firm A to protect its potential EV market from possible losses that might be incurred should HEVs enter at more affordable prices, Firm A might choose to lobby against a proposed revision of state mandates that would allow a more liberal interpretation of “Zero-Emission Vehicles” to include “Near Zero-Emission” technologies such as the HEV.

4.3.2 SCENARIO 2: HYBRID COMPETITION

Scenario Basis

Referring back to Table 4.2, the HEV Competition scenario again assumes zero increase in gasoline price over the thirty-year simulation period. As a result, the scenario basis remains equivalent to the conditions specified in the baseline ICE Domination scenario. In contrast to Scenario 1, I adjusted five scenario variables to create the behavior observed. Fundamentally, this involved a coordinated stakeholder effort to prepare the market for the successful entry of HEV technologies. Industry strategy includes a 40% targeted investment in product development above the baseline combined with a marketing effort double the baseline. Public sector interventions include the public advertising campaign to seed awareness and environmental sensitivity and the fee-bate program to fold externality costs into the purchase decision, thereby stimulating demand for cleaner technologies. The scenario initializes target availability of the HEV platform at 20%. The reader may interpret this as a function of internal industry strategy to reduce risk exposure, test demand, and provide or react to a competitive stimulus. Alternatively, the target might also represent near-zero emissions mandates required by law.

Findings

Figure 4.2 below illustrates the market share of annual fleet sales by propulsion type. In contrast to Scenario 1, we witness a much earlier and significant penetration of HEV technologies, with an inflection point signifying take-off and denoted by the dotted line around year ten (2012), vice year 26 (2028) in the baseline scenario.

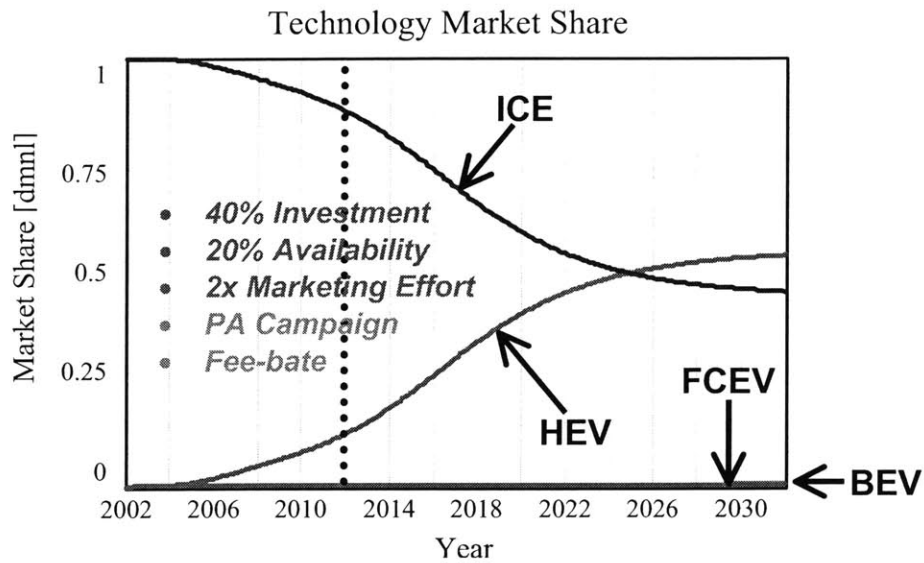


Figure 4.2 – Technology Market Share as a fraction of total sales for the HEV Competition scenario

There are several implications suggested by the adoption pattern that emerges in this scenario. I caution the reader that each should be interpreted in terms of the directional relationship suggested rather than any absolute points of data. First, stakeholders may interpret the activities required by both private and public sector entities as a plausible potential future. One might argue, however, that auto and energy interests might contest the imposition of fee-bate structures that create undo advantage to competition. For example, a firm with a leadership position in HEV-based development might lobby against a fee-bate regime that provides incentive to fuel cell or battery electric technologies. Avoiding this particular perverse incentive – the exercise of market power to influence standard-setting bodies, regulatory entities, value chain members, or other stakeholders – requires a context-based fee-bate regime that dictates the desired health and environmental outcomes only while avoiding dictates that directly specify or favor a particular technology solution. Second, note that the coordination of both private and public sector activities accelerates the “take-off” inflection in the market by roughly 16 years, with attendant benefits to environmental, public health, and energy security impacts that will be discussed in the following chapter.

4.3.3 SCENARIO 3: FUEL CELL TRANSITION

Scenario Basis

The third scenario poses the question: what conditions are necessary to achieve market penetration and take-off of fuel cell-based propulsion systems in the mass market? Table 4.2 indicates that for this particular scenario, the author adjusted nine scenario variables vice the five under Scenario 2. Clearly, for fuel cell-based technologies to emerge as a respectable competitor in the mass market, it will have to reach a state of maturity capable of competing on vehicle attribute terms with HEV platforms. The FCEV propulsion scenario envisions entry to the market in its current state of development, assumed by default to be 60% that of the ICE.

It will also take concerted coordination amongst auto, energy, government, and institutional stakeholders to overcome the chicken-and-egg dilemma and lower the barriers that impede fuel cell entry into the mainstream transportation market. Industry actions include a more concerted marketing effort than was the case in Scenario 2. More importantly, in contrast to the HEV Competition future envisaged in Scenario 2, FCEV technologies require the parallel development of a supporting infrastructure. Thus, I have adjusted this scenario variable to reflect emplacement of such infrastructure, equivalent to 20% relative to the ICE. The model assumes that this coverage is achieved prior to the introduction of fuel cell-based platforms to the mass market. Furthermore, the model does not distinguish the sources of this coverage; it could reflect the investment of a single stakeholder, or it could result from the combined investment of auto, energy, government, and other institutional entities.

In addition to the variable adjustments made to the HEV Competition scenario, the FCEV propulsion platform requires four additional interventions. External market conditions and public sector interventions must combine to a \$1 real increase in gasoline price (equivalent to a 70% increase). This 70% increase in could reflect supply or demand-based market condition futures and/or the imposition of a gasoline tax by government. Consequently, the discount rate associated with fuel cost decreases from the 36% level of the previous two scenarios, to 28%, reflecting greater consideration of fuel cost to the consumer at the point of purchase. The fee-bate program is active. Finally, this scenario operates from the supposition that HEV development continues in parallel with fuel cell

development efforts during the same period. The model, however, does not factor in the maturing of the technology via complementary market segments, such as distributed power. Many of the leading firms in fuel cell power have targeted the commercial and residential distributed power markets as prerequisites to achieve the early revenue streams necessary to support continued development for future transportation applications. Figure 4.3 illustrates the results of this scenario.

Findings

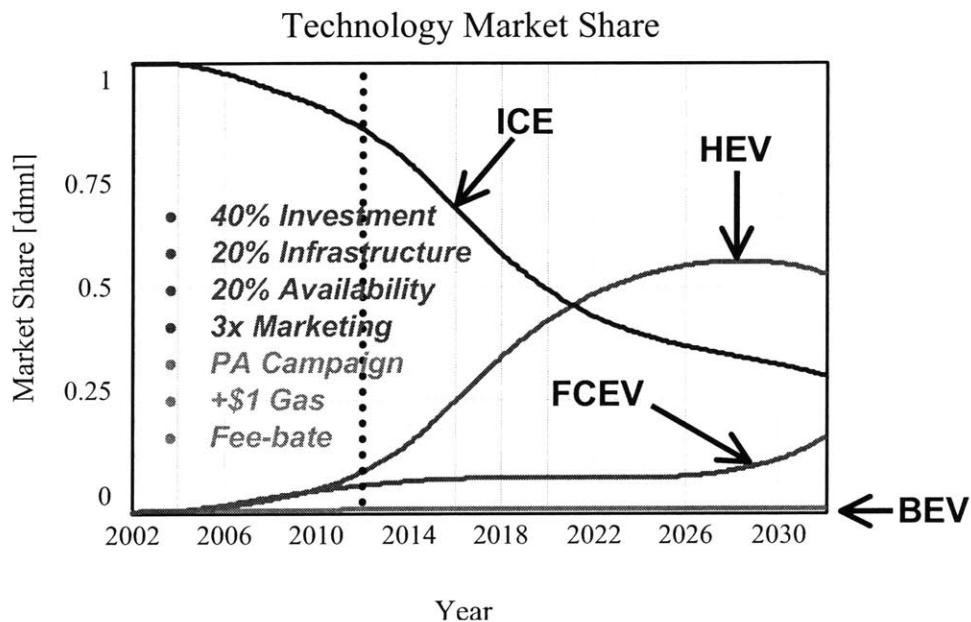


Figure 4.3 – Technology Market Share as a fraction of total sales for the FCEV Transition scenario

The adoption pattern of Scenario 3 suggests some notable characteristics. First, note that HEV and FCEV-based platforms compete for market share early on. This is attributable to the impact of the fee-bate on reducing the purchase cost of FCEV platforms to a level competitive with alternatives. Within the decade, hybrids take-off (inflection point at year 2011, approximately), moving quickly into the marketplace. Fuel cells, however, reach a plateau at about 7% market share and languish for a decade before achieving an inflection point signifying take-off. We can attribute this pattern to the non-linear nature of infrastructure coverage desired by industry interests. Industry stakeholders require that FCEV platforms achieve a certain threshold of penetration into the fleet before

they will more fully commit to infrastructure development. This pattern corresponds with the findings of Metcalf (2000) and indicates that a number of years pass before FCEV-based platforms breach the threshold required for energy companies to gain the incentive to invest in greater infrastructure coverage.

Another intriguing pattern analogous to the findings of Metcalf (2000) is the “hybrid hump” phenomenon. That is, FCEV propulsion architectures achieve take-off at the cost of ICE *and* hybrid technologies. We can surmise that the strength of the market growth dynamic is insufficient to satiate increasing demand for FCEV-based product. Therefore, adoption behavior is more characteristics of a saturated market in that the balancing dynamic of competition amongst technology platforms reflects a “zero-sum” game: one technology’s gain comes at a competing technology’s loss.

Examining Figure 5.5 yields another interesting pattern of behavior in that we witness two technological disruptions that change the basis for competition amongst propulsion architectures. ICE platforms dominate the market at the outset, but HEV technologies displace them within two decades’ time. The simulation period concludes at the thirty-year point, just as FCEV-based platforms achieve take-off. If were to extend the simulation period out an additional twenty years to 2052, we would witness the decline of HEV platforms and the emergence of FCEV technologies in less than twenty years’ time. In sum, we witness an acceleration of the propulsion technology life cycle through all phases of development. This stands in stark contrast to industry history, considering that ICE-based designs have dominated the automotive market for over 70 years. I leave a more detailed discussion of this observation for the following chapter.

4.3.4 SCENARIO 4: BATTERY ELECTRIC TAKE-OFF

The final scenario considers the conditions necessary for grid-dependent battery electric-based propulsion systems to take off in the mainstream market.

Scenario Basis

Table 4.2 indicates that for this particular scenario, the author adjusted nine scenario variables in a manner analogous to Scenario 3. Exceptions include the necessity to quadruple marketing strength over the baseline and to increase gas prices by \$3 per

gallon, representing an over 300% increase in this parameter. The increase in real cost translates to a consumer perceived discount rate applied to fuel cost of just under 21%, a conservative figure under the circumstances. Although less plausible than Scenario 3, this increase could consist of external market supply and demand forces and/or it could stem from the imposition of a gasoline tax. In either case, the reader should note that the increase approximates the real cost of petrol to consumers in foreign markets such as Europe.

The BEV faces many of the same infrastructure-based barriers that face the FCEV. However, despite its affordability relative to its FCEV counterpart, the BEV platform suffers additionally from diminished range in its current state of technological development. As in Scenario 3, FCEV technologies require the parallel development of a supporting infrastructure. Thus, I have adjusted this scenario variable to reflect emplacement of such infrastructure equivalent to 20% relative to the ICE. The model assumes that this coverage is achieved prior to the introduction of BEV-based platforms to the mass market. As previously indicated, the model does not distinguish the sources of this coverage; it could reflect the investment of a single stakeholder, or it could result from the combined investment of auto, energy, and government entities.

Findings

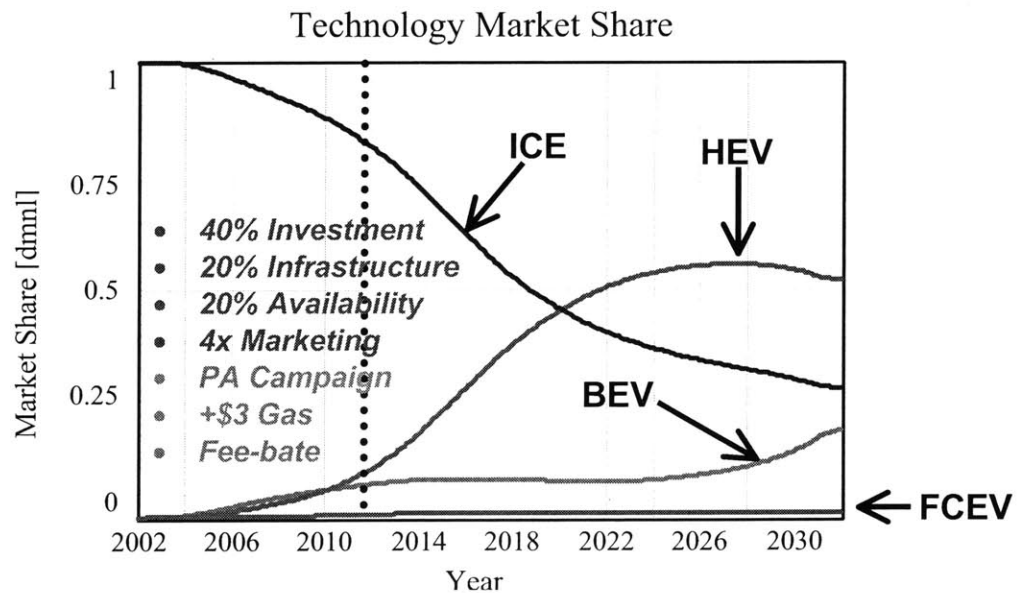


Figure 4.4 – Technology Market Share as a fraction of total sales for the EV Take-Off scenario

Analogous to Scenario 3, the BEV achieves a market “beachhead” early on due to the equalizing effect of the fee-bate regime on vehicle purchase price. We can surmise from Figure 4.4 that HEV platforms, once again, achieve take-off within a decade whereas comparable BEV platforms hit a plateau by 2014 and actually shed a fractional amount of share before achieving the critical fleet fraction necessary for the provision of infrastructure by energy stakeholders. Once infrastructure comes on line to support the technology, combined with evolutionary advances in battery technology that extend range, BEV propulsion architectures achieve take-off in the mainstream market as indicated by the inflection point in the final decade of the simulation period. In order to avoid bias, the model does not factor in breakthroughs in battery or energy provision technologies.

Note, however, that at the tail end of the simulation, BEV-platforms appear to reach another inflection point. This signifies that the technology might have reached the limit of its penetration, given the performance constraint of the range attribute and the relative improvement of the environmental factors attribute of its HEV cousin. Thus, it appears that the two technologies coexist in that they divide and maintain their respective share of the market.

The next section will attempt to recommend a preferred strategy to stakeholders by re-examining each of these scenarios in the context of the key sustainability metrics discussed in Chapter 4.

4.4 ENVIRONMENTAL, PUBLIC HEALTH, & ENERGY SECURITY

The four scenarios discussed in the previous sections of this chapter represent potential futures based on the dynamics and parameters considered by a single model. The purpose of employing such a model is to gain insight to certain market dynamics in order to ascertain risk, manage that risk, and ensure that potential outcomes achieve desired objectives. Upon setting out, the goal of employing a system dynamics-based model were three-fold: (1) to examine the conditions necessary for the adoption of cleaner propulsion technologies by the mass market, (2) to observe the system-wide impacts of adoption patterns in the North American market, and (3) to determine how well the combination of industry strategy, regulatory policy, and market conditions achieved desired social

objectives. What the model could not lend us, however, is insight into the methods for successfully delivering advanced propulsion platforms to mainstream consumer markets. I leave this discussion for the remaining chapters.

4.4.1 SOLUTION PATHWAYS

To date, federal and state governments have attempted to promote research and development of technologies that hold the promise of achieving environmental, health, and national security objectives.

USABC

In the early 1990's, the federal government helped forge the U.S. Advanced Battery Consortium (USABC), a partnership amongst key auto industry OEMs and battery suppliers to allow cooperation that could speed the development of an advanced battery capable of achieving the performance requirements demanded of transportation applications. During this time, GM came to market with its *EVI*, the first production electric vehicle in 70 years. Unfortunately, although the USABC achieved significant progress, it ultimately failed to attain the order-of-magnitude gains in range, life, and cost reduction necessary to reach mainstream market requirements and appease the players involved.

PNGV

Alternatively, the Partnership for a New Generation of Vehicles (PNGV), inaugurated by the Clinton Administration in September of 1993, set as its goal the building of a five-passenger sedan capable of accelerating to 55 mph in less than 12 seconds while achieving three times the then-current average of 27.5 mpg (Shnayerson, 1996). The proclamation favored no single technological solution such as EVs, but required results within a decade's time. Like USABC, the federal government would share costs with industry while allowing collaboration amongst the major OEMs and suppliers to define standards and speed solutions to market. But also like USABC, while demonstration vehicles such as GM's Precept, Ford's P2000, and DaimlerChrysler's NECAR series proved out the potential for advanced fuel/vehicle systems in passenger

vehicles, the effort failed to spawn a production vehicle from the domestic automakers. U.S. firms still consider cost-effective platforms generations away from mass-market commercialization.

Freedom Car

Most recently, the Bush Administration cut substantial funding to PNGV in favor of the “Freedom Car” proposal. “Freedom Car” would yet again represent an industry/government partnership to speed the development of cleaner technologies, this time based on fuel cells, to market. While a promising technology for weaning the American public away from fossil fuels and toward hydrogen, a much more ubiquitous energy carrier available through vast reservoirs of natural gas, fuel cells remain in a relatively immature state of development for the rigors of transportation-based applications. But, this does not preclude realizing the potential the technology offers for achieving long-term industry and social imperatives at some point in a very uncertain future. Currently, fuel cell suppliers such as Ballard, Plug Power, and UTCFC are cautiously venturing into niche market applications such as outdoor portable power, and auxiliary and distributed power, where the strengths of fuel cells outweigh their weakness in the current state of the art. For automakers, fuel cells offer the promise of transitioning away from open-system engine designs to closed-loop processes that would obviate the vast resources spent by industry each year to thwart efforts to impose ever-stricter emissions laws.

The ICE Again???

Most interestingly, however, are claims from industry that ICE-based solutions exist to the nation’s environmental, health, and national security objectives. Arguably, automakers may have a point. From a business perspective, automakers have targeted engine development resources toward improvements promising the highest margin and thus the highest return on invested capital. Irrespective of competitive pressure, automakers will provide improvements along pathways the consumer is willing to pay the greatest for. This is no more than simple business sense. Consequently, we have observed significant advances in horsepower, torque, acceleration, and towing capacity. Along each of these pathways, the consumer has demonstrated its willingness to pay. Largely due to low gas

prices, the market has witnessed little analogous demand for fuel economy or fuel efficiency. Consequently, automakers have dedicated a minimum of resources toward improving product along these lines, committing only to keep up with evolving emissions mandates. In fact, wherever possible, automakers have taken advantage of market trends and legal loopholes that allow them to skirt mandates and chase the high margin segments of the market. For example, domestic automakers have classified sport utility and cross-over vehicles as trucks whenever possible, in some cases even *adding* weight via beefed-up suspension systems to push these platforms over the threshold of regulatory jurisdiction (Doyle, 2000).

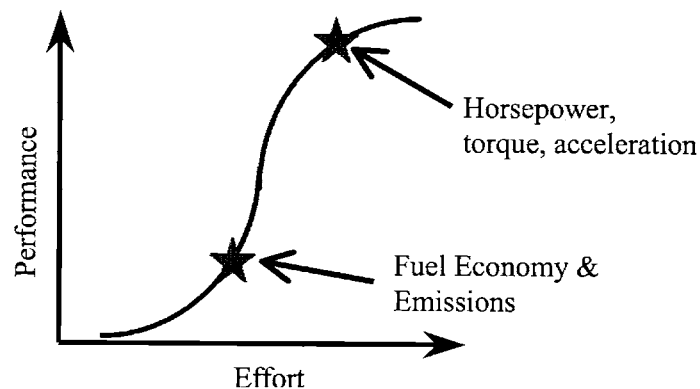


Figure 4.5 – Relative state of ICE development as a function of individual performance characteristics

But can automakers really achieve factor-ten improvements in fuel economy and emissions via ICE technology as some suggest? To answer this question, I apply the Christensen framework of analysis. First, if we were to segment ICE development along its performance characteristics, we might observe the S-shaped curve of technological development indicated in Figures 4.5. It is possible to argue that market demand has stimulated development of engine attributes such as horsepower and towing capacity up the technology s-curve to a higher state of maturity. Conversely, lack of demand has produced little development along fuel economy modes of improvement. We can therefore argue that this particular engine attribute resides at a more immature point on the technology s-curve.

The importance of this observation lies in the level of effort required to yield gains along the attribute pathway. It implies that automakers could achieve significant

improvement if management chose to commit the resources to develop the necessary technologies and processes. Traditional modes of problem solving recognized the inherent trades involved between fuel economy and emissions performance, and other more desired powertrain attributes such as horsepower, torque, and acceleration. Less traditional modes, however, involving emerging electronic and plasma technologies, hold the promise of improving yields in fuel economy and emissions with little degradation of other key engine performance characteristics.

Current cooperation between auto and energy interests to reduce sulfur content in diesel fuel, for example, could open the door to 25-30% gains in fuel efficiency from this switch alone. Further developments in ultra-capacitors, selective on/off (allowing automatic shut down and start up of the engine during start/stop), advanced NO_x traps, lean burn, and exhaust after-treatment made possible by plasma science offer the potential of providing cost-effective solutions to the problem of high NO_x and particulate content in diesel exhaust. Combining an electric motor to create a “mild hybrid” can add to these economy gains should their cost achieve market clearing levels in time.

The model attempts to account for potential ICE development along these lines. It achieves this by establishing a desired fuel cost per mile (3 cents/mile), congruent with consumer expectations for range and fill-up costs based on incumbent ICE platforms. Figure 4.6 provides a graphic of the relative change in fuel economy for each of the propulsion technologies over the simulation period. Note that I include only three scenarios representing the different fuel price levels. In the absence of a fuel price increase, ICE-based platforms attain a 22% increase in fuel economy over the thirty-year simulation period. Conversely, as we increase fuel price, automakers are induced to commit greater resources to the goal of achieving greater fuel economy. At \$2.43/gal and \$4.43/gal, automakers increase ICE fuel economy by over 47% and 85%, respectively. These improvements may be derived from improvements in engine efficiency, exhaust after-treatment, fuel pre-treatment, or vehicle light-weighting technologies.

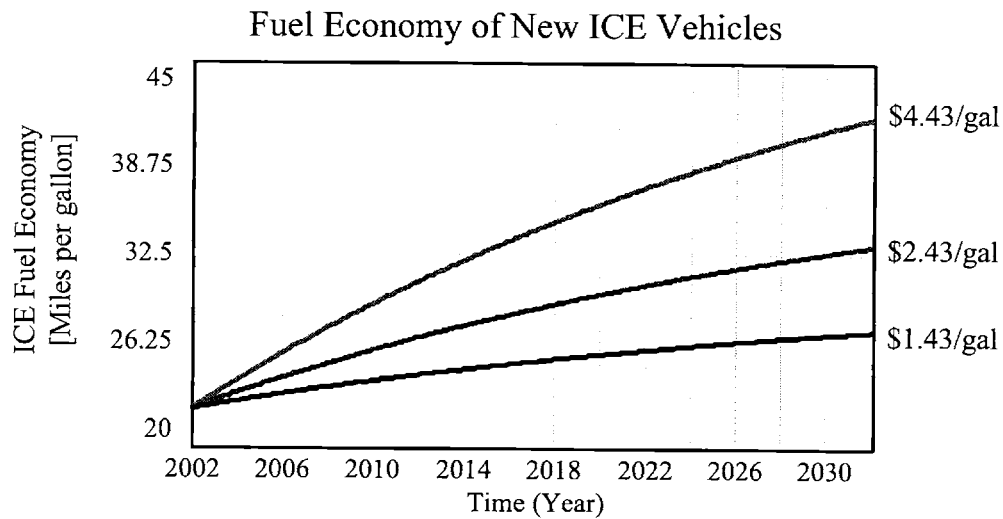


Figure 4.6 – Fleet Average Fuel Economy of ICE-based platforms for Scenarios 1-4

4.4.2 SUSTAINABILITY GOALS

Based on the previous discussion, stakeholders argue the case for a number of potential pathways for keeping pace with stricter emissions and fuel economy requirements. From an industry perspective, doing so should require a minimum of cost. The difficulty resides in determining which is the desired future. And here is where a system dynamics-based model can serve as an aid to decision-makers in the face of large uncertainties and complex, 2nd-order, non-linear system behaviors.

Each of the four adoption scenarios discussed previously spawns system-wide consequences. I have revised the model to account for some of the key metrics of import to decision-makers and stakeholders. Therefore, I return to these metrics for the express purpose of rendering a preferred course based on desired outcomes.

Energy Security

Figure 4.7 below provides an illustration of the magnitude of the differential in energy dependence amongst potential futures in light of national security objectives.

Oil Dependency

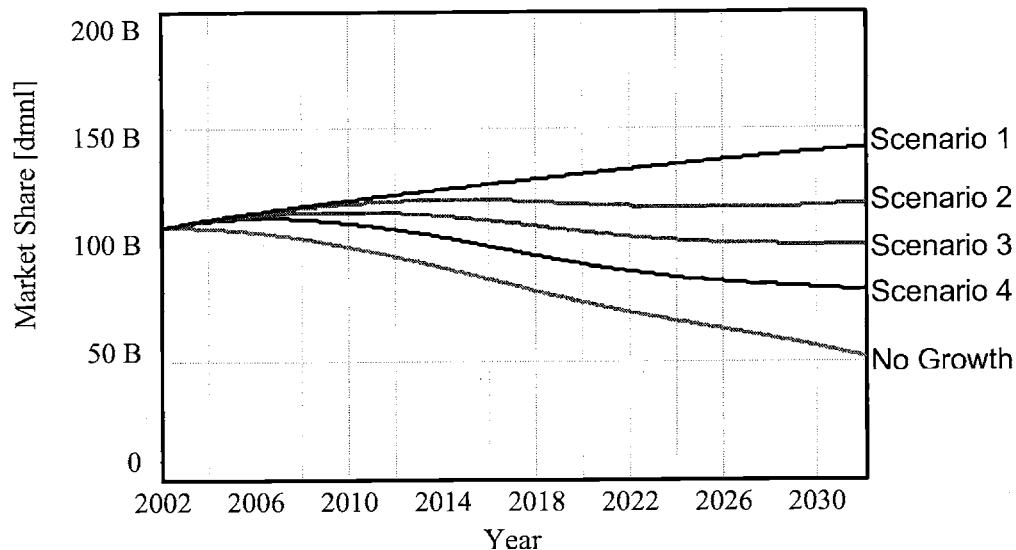


Figure 4.7 – Annual Fleet Average Oil Consumption with “No Market Growth”

The bottom line represents Scenario 3 under a “no market growth” assumption. I provide this graphic to convey a sense of the influence of the market growth dynamic on this particular metric. The differential between Scenario 3 and Scenario 3 with “No Growth” is on the order of 50 billion gallons of fuel per year. In other words, by 2032, our very conservative figure for market growth is responsible for 50% of the total annual dependence on oil. Failing to consider this dynamic might certainly lead decision-makers astray.

Under Scenario 1, the combination of incremental improvements to fuel economy and limited market penetration of HEV-based platforms fails to keep pace with the deleterious effects of market growth. Consequently, oil dependency increases by 32% over the thirty-year period from approximately 107 billion gallons per year to 141 billion gallons per year. The trend shows little sign of abating in the out years. Under the HEV future envisioned in Scenario 2, the market growth dynamic dominates in the early years, but within a decade the penetration of cleaner HEV-based technologies reverses the trend in oil dependency. Note, however, that the market growth dynamic eventually regains dominance toward the latter half of the final decade. Thus, even the HEV dominated future fails to check market growth. Only Scenarios 3 and 4 achieve the goal of reduced energy

dependence within the simulation period. Both scenarios experience increasing dependence in the early years, but soon overcome the market growth dynamic as the respective technologies achieve initial adoption levels and displace dirtier, less efficient propulsion platforms. By the end of the run, FCEV- and BEV-based strategies achieve overall reductions in oil dependence of 7% and 25%, respectively. The disparity in these figures reflects the different adoption patterns that emerge in these two scenarios, given the gap in fuel price. If we were to adjust the FCEV-based adoption scenario to reflect an equivalent increase in fuel cost, we could expect wider adoption of alternative platforms and thus less dependence on oil.

Environmental Damage Cost

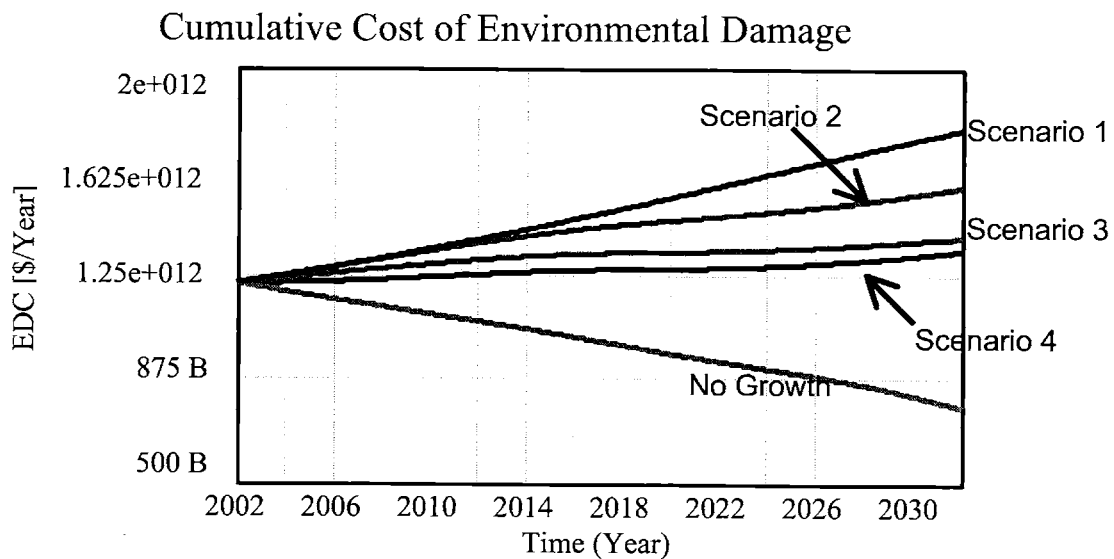


Figure 4.8 – Cumulative Environmental Damage Cost for all scenarios relative to a “No Market Growth” trajectory

Figure 4.8 lends insight to the relative costs of environmental and health-related damages over the simulation period. The grayed bottom line represents the “no market growth” version of Scenario 3 described earlier to highlight the degree to which demand growth works counter to public health and environmental goals.

In light of sustainability goals, the adoption patterns witnessed under Scenarios 1 and 2 clearly fail to keep pace with the market growth dynamic. In contrast, Scenarios 3 and 4 appear to curtail growth until about the latter third of the simulation period, where we

once again witness increasing EDC as the adoption of cleaner propulsion alternatives fails to keep pace with market growth. Unlike Figure 4.7, the graphic appears to indicate that regardless of public or industry strategy, the costs of environmental damage continue to mount. But it serves our purpose here to remind the reader that these figures provide directional significance only. Again, the model does not attempt to evolve the energy infrastructure to account for shifts in the relative level of dependence on fossil fuel, renewable, and non-renewable resources. Should we consider these forces, we may ultimately observe an overall decrease in EDC within the thirty-year study period.

With respect to energy dependence and the costs to public health and the environment, the data presented here clearly support the case for a combination of industry strategies and public policy analogous to Scenarios 3 and 4. All else equal and barring reliance on external economic shocks, Scenario 3 proves the more plausible future, given the political distaste for measures that call for increases in the gasoline tax. It serves to note, however, that I advance this recommendation under the assumption that the goal is to directly deliver propulsion-based innovations to mainstream consumers in the mass market. The next chapter contends with some of the potential pitfalls facing such a strategy. History proves that disruptive innovations – those that threaten the existing business paradigm – often face significant industry resistance. Consequently, new entrants are most consistently credited with ushering in new waves of innovation, often by displacing established firms. Thus, government leaders should resist strategies that rely on a single solution pathway. Rather, the realization of desired outcomes rests on a solid comprehension of the dynamics of innovation and the countervailing forces that threaten to derail even the most ingenious policy frameworks.

PART II – GETTING TO MARKET

5 INDUSTRY HISTORY, CHARACTERISTICS AND TRENDS

There exists a wide spectrum of potential solution pathways for the problem of vehicle efficiency. Industry leaders have known and even pursued, pathways that included alternative propulsion designs such as electric and steam motors for decades. Yet while industry dedicated assets to their development, few have ever pursued their subsequent production. This research suggests a number of reasons for this apparent lack of motivation. Such industry characteristics as reliance on rigid, largely static manufacturing processes and tooling with high fixed capital costs, the highly integrated nature of automotive engineering, a value proposition/business case dependent upon scale, persistence of low gas prices, lack of demand, and a 70-year culture wedded to the ICE and the regime that preserves it prove the greatest impediment to progress on the efficiency front. But technological barriers aside, the problem persists currently due to the misalignment of business interests with social imperatives. The most important assertion of this research, however, is that even in the presence of real market demand, the business system is simply not attuned to justify and stimulate investment along these pathways.

5.1 IMPEDIMENTS TO INNOVATIVE CAPACITY

In no uncertain terms, unless significant process and product change occurs with haste, these trends will pose the greatest threat to human health and quality of life within the next few decades on a scale far worse than smoking. Worse still, it threatens the health and maintenance of the omnipresent life support system called Earth that sustains our livelihood and the commerce that enriches it. This research presupposes that the advancement of technological solutions rests squarely on public policies and industry strategies that align business interests with this vital social imperative. This means constructing a business system and regulatory regime that creates a profitable business case for the accelerated adoption of clean vehicle technologies.

Detroit's Big Three automakers have in their history, when called upon, delivered magnanimous feats of technological prowess. During World War II, Ford, GM, and Chrysler converted in record time over 85% of their total capacity to wartime production of

munitions, jeeps, tanks, and aircraft to equip America's vaunted "Arsenal of Democracy." Following the war, the Big Three returned full swing into commercial production, eager to provide a new car to every GI returning home from the war. After all, the GI would need a car to commute to work from his new home secured with a VA Loan in one of the many housing tracts in the new suburban America.

Fast forward now to the year 2002, where over 600 million motor vehicles, each powered by an internal combustion engine, operate on the planet. Every single one of these vehicles spews thousands of tons of known greenhouse gasses and carcinogenic toxins into the air we breathe every day. Every piece of evidence suggests that this number will double to over a billion vehicles by the year 2020 (Doyle, 2000). Government regulation and industry efforts have made great strides in reducing a handful of emissions such as lead on a per car basis by nearly 95%. But rising automotive usage, urban sprawl, and the displacement of fuel efficient cars with SUV, minivan, and other truck-based platforms have combined to double the number of vehicle miles traveled, reduce weighted average fleet fuel economy, and virtually eliminate per vehicle gains on a net fleet emissions basis. Even worse, only in the past decade has the world's scientific, government, and industrial communities accepted the phenomenon of global warming as fact, and that rising wealth and growing motor vehicle usage, and the carbon dioxide emissions associated with it, are the single greatest contributor.

Unfortunately, despite evidence of industry evolution in directions that hold the potential of stemming these adverse impacts, the current business paradigm – the value proposition by which auto interests make money – will continue to delay and impede necessary progress on this front. Although this research substantiates the potential for achieving great strides within three decades' time, it calls into question the capacity of established interests to deliver. Chapter 5 presents conclusive data supporting the argument that meaningful market adoption can happen. The objective of this research is to consider not only whether (1) Can meaningful market adoption of cleaner technologies happen and under what conditions, but equally as important (2) Who is more likely to deliver them, domestic incumbents, foreign competitors, or new entrants? The following sections consider the architectural and cultural forces that offer insight into these important questions.

5.1.1 ARCHITECTURAL PERSISTENCE

The Role of Architecture in Shaping Norms, Laws, and Values

Two key developments of the 20th century left our generation saddled with the costly and necessary endeavor of attempting to mitigate the ecological and health damage passed on to us by the generation that came before. The first development was the emergence of the internal combustion engine as the dominant industry design, rather than the steam or electric alternatives that were common during the technology's formative years. The ICE is an open system based on the thermodynamic properties of the Carnot Cycle. At best, the gasoline-powered version achieves a peak efficiency of only 25%. In reality, because the ICE is based on static compression volumes, it operates outside the engine's peak efficiency band during the majority of its operation, realizing on average a mere 17% efficiency rating. The rest is exhausted in the form of poisonous waste gases into the ambient environment where it is presumed to diffuse to non-toxic levels. The important take-away from this development is the general industry, and consumer-wide acceptance, of an *open-system* propulsion design for motorized travel. Thus, not only would the technology define all future architectures, in so doing it would also acculturate entire industry value chains and generations of consumers to a set of behaviors, expectations, norms, and values that any alternative paradigm suggested by 21st century society would have to contend with (Lessig, 2000).

The second key development of the 20th century that exacerbates current emissions-reduction efforts is the pattern of land use development that emerged in the post-WWII era. In cities whose development followed the emergence of the automobile, the advent of zoning laws, highway funding regimes, and transportation engineering practice codified wide avenues, vast artery-and-collector road networks, and separation of uses that embedded personal vehicle-dependence deep into the fabric of American society. These infrastructures required vast capital to emplace, and contrary to espoused notions of modular design, reflects the most rigid and persisting objects of mankind's construct. Decades, even centuries might pass before obsolescence, war, natural disaster, or economic imperative might clean the slate for an alternative infrastructure.

Real estate development economies emerged from this architecture; creating economies where consumers place value on proximity to places of home and work in terms of commute time, rather than physical distance. Previous generations had measured proximity in terms of transportation by foot or rail; now, they would measure by time of travel via personal automobile. The difference is one of scale and the consequence to human quality of life. The car enabled the dispersion of society to suburbia and “edge cities” while simultaneously eroding any business case for more efficient forms of transit such as light rail. Automotive travel requires a certain degree of wealth to afford, thereby stranding the less wealthy in the metropolitan centers, further spurring the exodus of the relatively wealthy to the suburbs. Since the 70’s, such dispersion has led to the emergence of “edge cities” along circumferential business routes outside the metropolitan center. Like the auto-centric planned cities that sprung up in the American west, edge cities fell pray to planning with many of the same auto-centric precepts, offering little if any transportation mode choice to its inhabitants.

The key take-away from this development is the persistence of erected infrastructure and the modes of social behavior and interaction that it enables or disables (Lessig, 2000). I argue that this infrastructure is the physical manifestation of a more coherent architecture that reflects the economic, political, social, and legal values that enabled it. The architecture is a two-way channel of communication. Human values and the tools and technologies of human hand help us envision an architectural construct from which to plan our cities, locate our places of work, and organize our neighborhoods; at some critical threshold, the persistence of that architecture’s infrastructure affects behavior that ultimately serves to sustain it (Lessig, 2000). It does so by lowering the cost of evolution within the current paradigm while erecting cost barriers for substitutes. The following industry example offers a case in point.

At the conclusion of WWII, the auto and energy interests of the time envisioned an architecture that would lay down a path of development mutually beneficial to firms and societies. To enable this future, they acted to remove the barriers to automotive prosperity and to ensure infrastructures that would nurture a healthy and sustained period of demand growth for their motorized innovation. From the automotive perspective, these barriers included the existence of substitutes such as non-motor vehicle mass-transit and on-street

railways that restricted motor vehicle movement. When it came to the ICE, the automakers pulled out all the stops to ensure a supportive infrastructure to spur demand.

Despite the existence of extensive electric railways in major American cities such as Los Angeles, San Francisco, New York, and Philadelphia, auto interests saw an alternative mass transit future for America's cities: motorized bus lines. Through a complex network of subsidiaries that included National, American, and Pacific City Lines, General Motors and a host of industry partners that included stalwarts Standard Oil, Phillips Petroleum, Hertz, Mack Truck, Greyhound, and Firestone Tire & Rubber executed one of the most well-conceived and quietly executed acts of market power of the 20th century. In no uncertain terms, this collaboration systematically acquired, and then dismantled, the streetcar, trolley, and "light rail" transit operations of virtually every major metropolitan city in the United States. By slowly starving the transit systems of funds for maintenance and new purchases to keep up with demand growth, GM's subsidiaries successfully eliminated electric rail transit, replacing it with a much less efficient, less profitable, and universally unpopular fleet of ICE-powered busses (Doyle, 2000).

In 1949, a federal court found General Motors guilty of criminal conspiracy, fining the company a laughable \$5,000 and its treasurer \$1. National City Lines continued for 6 more years before it sold off its motorized operations. Through contract provisions, the firm explicitly prohibited buyers from engaging in the purchase of any new equipment using any fuel or means of propulsion other than gasoline (St. Clair, 1986). The result: a complete stagnation of competition. By that time, GM's subsidiaries had removed 88% of the nation's streetcar network; of the 40,000 streetcars that existed in 1936, only 5,000 remained (St. Clair, 1986).

Today, many cities such as Los Angeles, San Diego, Phoenix, Chicago, Detroit, and Atlanta struggle with the political unpopularity and cost of retrofitting their metropolitan communities with subway or other light rail alternatives. Debates rage over asphalt versus rail. Rail detractors argue that the cost per mile of track relative to ridership simply cannot compete alongside the relatively more affordable option of additional traffic lanes. Although this wasn't always so, their argument is well founded. The GM-led coalition achieved its objective: Emplace an infrastructure that sustains demand growth while stimulating further infrastructure growth that erects barriers to substitutes by making them

more costly. Auto-centric zoning laws, city plans, and land development patterns emerged that dispersed populations, separated uses, and reduced densities. Consequently, this deliberately installed architecture today disables a competitive business case for density-dependent rail lines. These developments provide a critical case study of how persisting architectures shape laws, norms, values, and consumer expectations. Those behaviors that emerged from dependence on the automobile as the principle focus of organization, serve today to preserve automobile dependence and suppress implementation of alternative solutions. Ironically, however, this key episode in U.S. industrial history serves to demonstrate that concerted stakeholder action can, when combined with hospitable market conditions and the promise of large potential profits, realize the emplacement of the necessary infrastructure to support demand for a chosen propulsion technology.

Architectural persistence defies near-term solution and works counter to social values such as equity, public health, access to and preservation of natural resources, and national security objectives. Wholesale dependence on motorized transit equates with dependence on foreign oil, a gaping vulnerability that invites exploitation and manipulation by foreign powers as witnessed by the oil shocks and recessions of the 1970's and early 80's. It compels our elected officials to fund regional baby-sitting efforts that cost the American public dearly. The presence of a single U.S. aircraft carrier in the Arabian Gulf, for example, comes with a price tag of over one million dollars per day, not to mention the lives and livelihoods it endangers. Finally, from the perspective of the inhabitants of these regions, our visible physical presence smacks of 19th century imperialism, providing fodder for propaganda that enables backward and corrupt governments to continue to control and oppress their populations by propping up the U.S. as a scapegoat for the starvation and misery of their people. If there is one thing that we have learned, one-dimensional solutions often yield multi-dimensional punishments...

The role of architecture is ubiquitous in our society. It exists at all levels – in our cities, our homes, our roads, our places of work – and defines the physical world around us; design determines our interaction with the physical world; it frees and constrains our activities. Until leaders from all sides recognize the magnitude of the impact of architectures on society, we will continue to find ourselves a prisoner of entrenched systems and behaviors that work counter to our most valued ideals. This research advances

the notion that leaders must craft policies and strategies that consider architecture as an avenue of opportunity, and leverage it to enable behaviors that yield desired social outcomes.

5.1.2 POLICY DEFECTION

“If the human race can send a man to the moon, surely it can clear up smog.” – a California state senator, 1969

In October 1997, William Clay Ford, Jr., now chairman and CEO of Ford Motor Company and a graduate of the Sloan School of Management, spoke to the Detroit chapter of the Society of Automotive Engineers.

“The love affair with the automobile might not be over yet, but the honeymoon is. Environmental Stewardship is a heartfelt concern of our customers and of policy-makers around the world. It should be a top priority for the auto industry in the twenty-first century. The challenge is clear: we must lead the green revolution.”

Since the 1970's, automakers doubled the fuel efficiency of their automobiles, reduced emissions more than 96 percent nationally, and now recycle more than 75 percent of automotive content. These represent significant achievements in their own right, but came about more as a result of the force of law and by the determined efforts of legislators like Senator Edwin Muskie, than by any voluntary program of industry's invention. In fact, Ford's challenge to automakers stands in stark contrast to nearly half a century of determined resistance to calls by governments, institutions and environmentalists to clean up their act.

The following is a representative sample of the record:

- Automakers delayed installing Positive Crankcase Ventilation (PCV) on new cars bound for California until 1966. The technology involved a simple, inexpensive metal tube and had been around since the 1930's.
- In 1969, the US Dept of Justice (DOJ) filed suit against the Automobile Manufacturer's Association (AMA), accusing the Big Three automakers of a 16-year industrial conspiracy to willfully obstruct and delay the research, development, manufacturing, and installation of pollution control devices. The automakers settled by consent decree.

- Ford publicly announces an early catalytic converter in 1957 and a blowby device in 1962, but is “silenced” by the Public Relations Committee of the AMA.
- In a blatant exercise of market power, Chrysler cancels Engelhard Industry’s contract to supply catalysts to the OEM for being “too aggressive in its testimony” at EPA hearings regarding the effectiveness of pollution control devices.
- In a 1970 Ralph Nader study of foot-dragging by automakers on emissions solutions, a GM engineer states that management “already had the conclusion [that the steam engine was not a feasible alternative] and we were told to prove it.”

Over the past five decades, the major US automakers have forged a predictable modus operandi in their almost universal treatment of emissions and fuel economy efforts. It might look something like this:

1. *Do whatever it takes to kill any pollution control, fuel economy, or emissions related requirement or mandate that legislation might impose.*
2. *If killing the measure proves infeasible, pursue actions to dilute the requirements or delay its enactment as long as possible.*
3. *Dedicate a minimum of resources to emissions control efforts, but enough to demonstrate the firm’s commitment to a potential solution.*
4. *Insist, and continually demonstrate that while the firm is making progress, the technology remains unfit for commercialization due to performance problems and cost.*
5. *If engineers provide a range of estimates for cost and time to market, publicize only the highest figures.*
6. *If a legislature is nearing a decision that may prove harmful to the industry, release a public statement indicating the firm’s intent to deliver ahead of the would-be deadline of the proposed regulation.*
7. *Whenever possible, commit the firm to government-sponsored partnerships to shore up appearances that the firm is doing everything it can to bring cleaner technologies to market and to buy time for a change in external conditions, such as a more industry-friendly administration, to materialize.*

5.1.3 INDUSTRY SCENARIOS AS A PLANNING TOOL

The record, and this established modus operandi, begs the question: Should we really expect innovation on the fuel efficiency front to come from domestic industry stalwarts? If history is any proof, the answer is unequivocally no. Rather, a more predictable scenario involves the emergence of overwhelming external forces, market or competitive, that forces the hand of industry for the sake of their own survival.

Michael Porter (1985) defines a scenario as “an internally consistent view of what the future might turn out to be.” *Industry* scenarios enable the firm to translate uncertainty about the future into the strategic implications for competition within an industry. It is not meant as a forecasting tool; rather, the method enables management to make implicit assumptions about the future explicit, and to consider the range of possible and credible industry structures that may result (Porter, 1985). Because the purpose of this research is to identify high-leverage public interventions and to inform firm strategic planning, the author believes that the exploration of some simple future industry structures may prove instructive to decision-makers. The following represent the set of relevant scenario development considerations:

- Gas price volatility
- Consumer sensitivity to environmental, public health, & national security considerations
- Shifting regulatory regimes
- Competitive stimulus/Competitor behavior
 - Market cultivation versus demand pull
 - Market leadership versus fast-follower

In light of the above, consider a set of potential scenarios from the government’s perspective, regarding the conditions that might emerge resulting in the desired emissions outcome:

1. *Gas Increase Scenario* – Gas prices move higher due to movements in supply and demand and remain high for long enough time for an engineering-based industry response. Industry exerts market power to push gas prices down without success. Incumbent foreign competitors come to market with HEV- and EV-based options in popular vehicle segments.
2. *Laissez Faire Scenario* – Nothing happens. Status quo prevails, but energy industries slowly migrate to cleaner, but still traditional, gasoline and diesel fuels.

Gas prices continue at relatively low levels and incumbents successfully stifle competitive entry via market power. Firms manage to make evolutionary emissions and fuel economy improvements to the ICE.

3. *U.S. Market Leadership Scenario* – Through a concerted marketing strategy, incumbent automakers aggressively (<10 years) phase in cleaner, more fuel-efficient platforms. Beginning first with demonstration vehicles and following with launches into the most popular vehicle segments. Foreign producers follow suit.
4. *Foreign Market Leadership Scenario* – Incumbent foreign competitors, executing a deliberate strategy, successfully phase in cleaner, more fuel-efficient platforms to popular vehicle segments. Domestic firms follow within two years with similar, variant, or alternative designs of their own.
5. *Us versus Them Scenario* – Incumbent foreign competitors act, but incumbent domestics resist, hoping that foreign efforts will prove futile. U.S. firms accelerate development of alternatives, but publicly fight for regulatory obstacles to imports.
6. *New Entrant Scenario* – Through a concerted strategy, a non-OEM moves up-market from a niche. They are able to wrest share from incumbents via a different value proposition. Technology begins at a performance disadvantage to mainstream market requirements, but the steeper technological trajectory carries it to mainstream markets. Entrant builds a value network base from which to challenge incumbents, but needs brand recognition of incumbent auto firms. New entrant firms forge strategic partnering arrangements whereby entrant provides system solution and automaker provides brand, distribution channel, and systems integration.

The purpose of examining this set of potential future industry scenarios is two-fold: (1) to identify those futures most preferential for achieving desired *performance*-based outcomes, (2) to identify those with preferential (or at least neutral) *competitive* outcomes, and (3) to steer government policy regimes toward frameworks that achieve both desired *performance* and *competitive* outcomes. While a scenario may achieve (1), it is an entirely more difficult endeavor to achieve both (1) and (2). Yet history is replete with examples where the pursuit of (1) at the expense of (2) proved politically untenable due to the significant margin of economic, media, and political influence established firms could marshal on behalf of preserving their interests. Thus, a crucial requirement of a successful policy framework must effectively address competitive outcomes. Failure to do so will only translate to fierce and counterproductive policy resistance efforts by key industry stakeholders.

The first scenario relies on a sustained increase in gas prices to stimulate the necessary demand for alternatives. However, given the historically low level of prices in the U.S. and industry estimates suggesting 40 years of remaining oil reserves to support our fossil-fuel dependent world economy, I assign a fairly low probability to this outcome. The second scenario implies little, if any public intervention or targeted industry strategy. Rather, it asserts that continued progress in ICE technology is enough to achieve the requisite levels of emissions for sustainability. Based on the results of the system dynamics model in the following chapters, this scenario too bears little resemblance to reality. The remaining scenarios suggest U.S., foreign, and new entrant market leadership in emissions progress. The discussion that follows focuses on resolving the relative likelihood of this set of potential futures.

In attempting to identify the more likely scenarios, history serves as a potential barometer. Today's debate regarding the efficacy of bringing alternative propulsion technologies to the market mirrors a similar debate that occurred four decades ago in late '60's California. During that decade, Washington began proposing actions that would bring the federal government into alternative engine research and purchase of alternative vehicles for government fleets. In 1969, the Nixon Administration inaugurated a program of R&D "to marshal both government and private research with the goal of producing an unconventionally powered virtually pollution free automobile within five years" (Doyle, 2000). The program, a clear forerunner of a series of similar efforts such as USABC and PNGV (see Section 5.4.1 for a more detailed description of these partnerships), never received the funding it was promised. Rather, it drifted back toward efforts aimed to improve the ICE before dying a quiet death under follow-on administrations.

The decade also saw the appearance of ICE alternatives such as the electric car, the steam-based Rankine Cycle engine, gas turbines, and even gasoline-electric hybrids. GM showed off a cavalcade of 26 such vehicles in its "Progress of Power" show in 1969, the same year America saw a man walk on the moon. Unfortunately, most of these cars had "problem areas" – which the manufacturer ensured were highlighted. Others, such as William Lear of Lear Enterprises charged into the controversy with plans to develop and prove the efficacy of a production ready "clean" engine. His company successfully developed an engineering prototype of a cleaner car based on the vapor turbine steam

engine used in a production bus of the firm's make that could meet or exceed the 1976 Clean Air Act requirements. But the project died when financial assistance from government and auto interests failed to materialize (Doyle, 2000).

Disgusted by the lack of industry response to California's severe smog problem, state senator Nicholas Petris introduced bill SB 778 to the California Senate in early '69. The bill would prohibit the sale of all diesel- and gasoline-powered internal combustion engines in the state by 1975. Industry lobbyists scoffed, but the bill passed 26-5 before the Automobile Manufacturer's Association (AMA), now taking the bill a bit more seriously, brought their weight to bear to kill the fledgling bill in the Assembly. Up until that point, state and federal regulators followed the approach of setting performance standards rather than dictating technological solutions.

Other similarities with today's alternative engine debate abound. For example, one of the crucial hurdles to the effectiveness of catalytic converters involved the lead content in gasoline. With pressure coming from the auto industry and the Nixon Administration, and with the threat of upcoming legislation, Big Oil conceded to voluntarily phase out leaded gasoline (Doyle 2000). The episode mirrors today's bid to entice oil interests to phase out sulfur content in diesel. For the automakers, the diesel-powered ICE holds the key to achieving 25-30 percent greater efficiencies in fuel economy, and thus reduced carbon dioxide emissions. Unfortunately, like lead, sulfur poisons the catalyst in diesel engines, reducing catalyst life and degrading its performance. California, long averse to diesel due to its high NO_x and particulate content, will effectively ban diesel when Tier II requirements go into effect in 2004, unless Big Oil can make significant reductions in sulfur content.

Yet another analog to the Clean Air decade involved the effort of automakers to develop devices such as a thermal reactor that could burn off excess gases at high temperature. The effort mirrors today's effort by exhaust system manufacturers to bring promising advances in plasma science to bear on the problem of gasoline and diesel emissions. By subjecting poisonous exhaust gases to an intense hot flame, the plasma device reduces the compounds to inert constituents while eliminating most particulates and reducing NO_x by orders of magnitude over today's catalytic technologies (Cohn et al, 2001).

The striking lessons from the events of four decades' time are clear. In hindsight, we know that a series of external forces came to bear on U.S. automakers. The passing of watershed legislation such as the National Environmental Policy Act (NEPA) of 1969 and the Clean Air Act of 1970 established environmental due process, instantiated the EPA and armed it with sweeping regulatory authority over industry. Shortly thereafter came the first of two oil shocks that sent the U.S. economy into a tailspin with an Energy Crisis that begged for the kind of technological leadership automakers had demonstrated in WWII. Instead, while corporate lobbyists and industry leaders delayed, obfuscated, and equivocated, foreign competitors rushed to fill the burgeoning demand for clean and fuel-efficient cars with advanced technologies such as Honda's CVCC engine.

For nearly two decades, domestic automakers claimed that technologies for achieving the 1975 requirements of the Clean Air Act did not exist. Yet Honda came to market with a stratified-charge engine that could meet 1975 emissions requirements *without a catalytic converter*. By 1980, market research indicated that the portion of the purchase decision weighted toward fuel economy reached 40% (Plotkin, 1996). In that crucial window of opportunity, U.S. firms had little to offer the American public. Imports, however, gained a crucial beachhead on American soil. Consequently for the Big Three, the 1970's would mark the beginning of an inexorable slide in market share that shows no sign of abating to this very day. Furthermore, the quality movement spawned by Japanese entry revamped production processes to achieve efficiencies, but failed to recognize or capture value from similar efficiencies to be had in closing open-system product designs.

Then, as today, the domestic auto firms continue to struggle in their effort to maintain share. We have witnessed the bold move of GM to come to market with a production electric vehicle, the *EVI*, in 1996. Yet even during this period, GM and its Big Three cousins Ford and Chrysler continued to lobby against emissions-related regulatory regimes such as California's ZEV mandate, requiring that vehicles with zero tailpipe emissions comprise a minimum percentage of new car sales by 1998. These efforts proved successful in delaying the requirement to the year 2003. To date, GM's *EVI* remains the only production vehicle designed from the ground up around an electric motor that can meet this mandate, albeit in an unpopular two-door commuter consumer segment. Ford and Chrysler (now DaimlerChrysler) intend to offer conversions. Japanese producer

Toyota will offer a conversion as well, but in one of its more popular vehicle segments, the compact 4-door SUV known as the *RAV4*.

Both Honda and Toyota boast first to market rights on production hybrids, Toyota with its 5-passenger *Prius* model, and Honda with its 2-passenger commuter *Insight*. Next month, Honda will offer the *Insight*'s gasoline hybrid-electric engine in its popular 5-passenger *Civic* line of compact sedans. The move marks a first for the industry, and is being complemented by parallel marketing efforts that attempt to appeal to the environmental concerns of consumers. The marketing campaign relies as well on efforts to create an association via eco-labels, between consumers and the company's cleaner product offerings. Meanwhile, only in 1999 did the members of the Big Three, led by the prodding of Ford chairman William Clay Ford, Jr., dissolve their membership with the Global Climate Coalition (GCC), an industry-funded lobbying group that contested the existence, and sources of, global climate change phenomena. Although Ford withdrew plans it announced earlier to release a production version hybrid of its most popular Explorer SUV, as of this date the firm still plans to come to market with a hybrid version of its compact SUV, the *Escape*.

In sum, while the stage for alternative propulsion technologies in the first decade of the 21st century smacks of *de ja vu*, the competitive pressures of modern day, combined with technological advances, may yield accelerated progress on this front. Of the six scenarios listed earlier, this author is inclined to let history, and the culture entrenched by it, judge. Doing so clearly points to scenarios involving either foreign incumbent or new entrant leadership in delivering emissions-based innovations to market.

5.2 INDUSTRY MATURATION – THE CAR COMES OF AGE

In the last section, we discussed the history, and resulting culture, of industry resistance to emissions and fuel economy imperatives. This section examines another industry trend with implications for market leadership in the emissions arena, the maturing of the technology life cycle. Marketing experts contend that the auto industry is in the midst of a transition typical of products in a mature phase of the product life cycle. Figure

5.1 depicts these phases as a function of the product attribute most crucial to product differentiation.

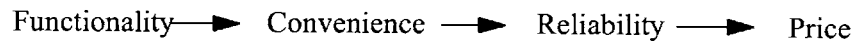


Figure 5.1 - Primary basis for differentiation during the product life cycle

There are a number of indications that the auto industry is currently migrating toward a phase of maturity whereby price is the primary differentiator. Price pressures spawned by global competition have spawned an industry-wide move toward consolidation, with the largest players executing acquisition strategies predicated upon staking out brand across product segments and securing distribution networks in key, potentially high-growth market segments. Cost reduction efforts have also impacted the make/buy decisions of the six major OEMs. Firms have emphasized core competencies such as system integration and have chosen to outsource those elements of the value chain deemed either outside their core expertise, or characterized by declining growth rates or margins, to second- and third-tier suppliers.

Instead, firms are seeking out related businesses where the firm can leverage core expertise to capture potentially higher margins in higher growth segments such as in-vehicle communication services. Consolidation also conforms with the industry move toward platform commonality as a means to reduce the number of base platforms while simultaneously broadening product offerings across the full spectrum of traditional market segments (i.e. fewer platforms, more models). Finally, the recent industry consolidation around brand across the product line only confirms management's belief that price has become the most critical differentiator. Commanding brand across the spectrum of product offerings enables firms to leverage higher margins from segments with flatter price elasticity of demand.

If the above indicators are correct, the move of the industry's bread and butter product toward commoditization only portends an extremely tenuous business proposition for domestic automakers. With declining overall margins, any externally imposed price pressure outside of competitive or demand stimulus will threaten already thin revenue

streams. We could therefore expect regulatory efforts such as CAFE to meet fierce resistance from industry management. Even worse, emissions mandates, fees, or other instruments of regulatory intervention would specifically target the highest margin profit segments of the domestic automakers, namely trucks, crossover vehicles, and SUVs. Figures 5.2 and 5.3 highlight the significance of the growth in light-duty truck platforms as compared to the relative decline in car sales in terms of units sold as well as the value of sales in this segment.

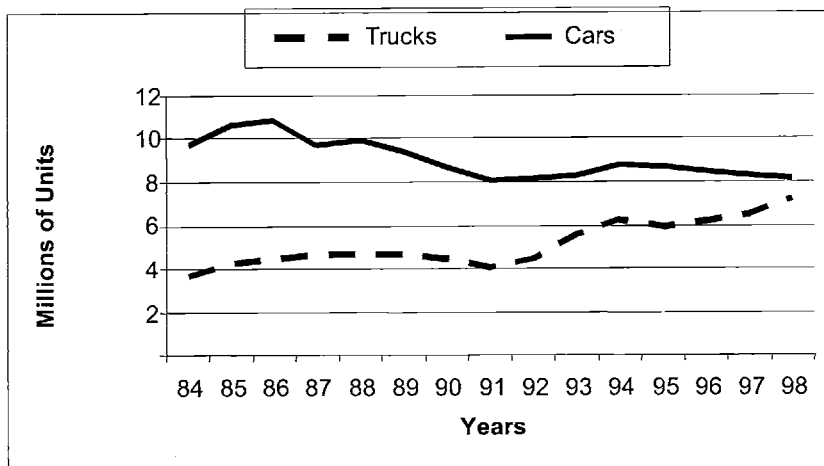


Figure 5.2 – Unit sales of cars and trucks, 1984-1998

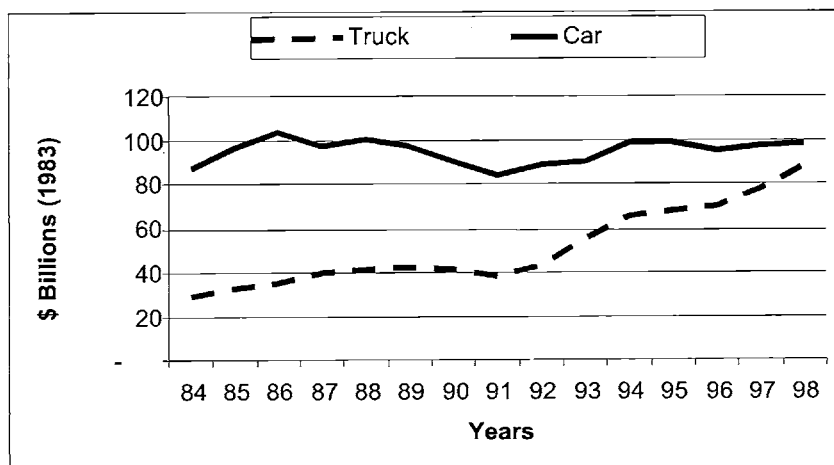


Figure 5.3 – Value of U.S. car and truck sales, 1984-1998

From the perspective of the domestic automakers, it is a simple equation. Regulation forces automakers to take measures that will impose costs that the mainstream consumer is not willing, or able, to pay for. If, however, the consumer desired greater fuel efficiency or reduced emissions, he would seek out a producer offering such a vehicle at a price that the market would bear. But because for the past two decades gasoline prices in North America have remained some of the lowest in the world, fuel efficiency is of little concern to consumers relative to other considerations such as utility and performance. Indeed, statistics gathered by the author while contributing to an auto industry study at MIT bear out this relationship as illustrated in Figures 5.4 and 5.5.

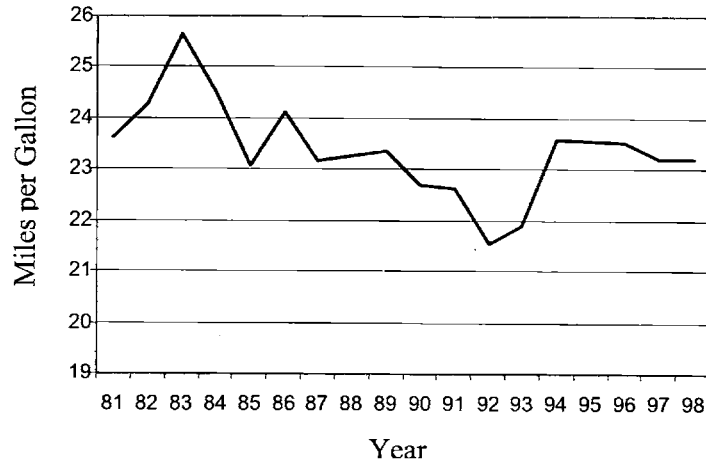


Figure 5.4– Average fuel economy of all passenger vehicles from 1981-1998

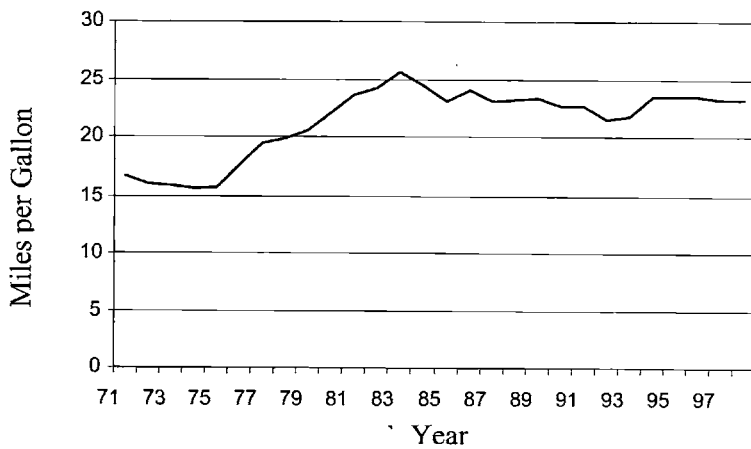


Figure 5.5 – Average fuel economy of all passenger vehicles, 1971-1998
 (Sources: Barry, Levisohn, and Pakes (1995); *Wards, Automotive News*)

Figure 5.5 provides a longer-term view of fuel economy trends by expanding the sample backwards to 1971 using data provided by Barry, Levisohn, and Pakes (1995). In the expanded series, we can observe overall increases in the fuel efficiency of vehicles from just 16 mpg at the beginning of the 1970's decade to a high of 25.6 mpg by the early 1980s. We can speculate that the provision of more fuel-efficient product stemmed from three external forces that fundamentally shifted the character of market demand in favor of attributes enabling higher fuel economy. These forces included the twin oil shocks in '71 and '79, competitive entry of Japanese makes, and the establishment of fuel economy mandates under CAFÉ (for Corporate Average Fuel Economy) in the wake of the Clean Air Act of 1970.

Despite inception of the CAFÉ regulatory regime, the combination of the energy crisis with the timely arrival of small, fuel-efficient Japanese imports provided enough of the economic and competitive stimulus for domestic automakers to act. Ironically, the arrival of these foreign imports would also signal a shift toward the next evolutionary phase in product differentiation away from *convenience* and toward *reliability* as previously illustrated in Figure 5.1. This is evidenced by the quality movement of the 1980's, initiated by the Big Three as a consequence of their struggle for survival against the onslaught of cheaper, more reliable, high-quality Japanese imports.

After 1983, the industry adjusted, and fleet fuel efficiency decreased again to a low of about 21.5 mpg in 1992, after which, it recovered for the remainder of the 1990s to slightly over 23 mpg. But fuel efficiency remained below the 1983 peak, eventually stabilizing around 23 miles to the gallon until the latter half of the 1990's, where it began yet another downward trend, this time initiated by America's nascent love affair with utility vehicles.

While fuel economy has slipped from a high of nearly 26 miles to the gallon in 1983, vehicle performance and utility have trended upward. Light duty, truck-based platforms have enabled domestic automakers to meet this demand with new product that has displaced car-based platforms over the same period. By 1998, truck-based models surpassed cars, grabbing over 50% of the new vehicle market. It is interesting to note,

however, that even before trucks, minivans, and SUV's gained popularity in significant numbers, by 1992 fuel economy had slipped to just 21.6 miles to the gallon.

This statistic belies a deliberate shift in emphasis away from fuel economy toward the other more valued attributes of utility and performance. Truck-based platforms could not only meet this demand at less cost than comparable car-based models, they could do so unencumbered by the higher CAFÉ mandates associated with their car-based cousin. In 1984, the Big Three boasted 84% and 78% market share of the domestic light-duty truck and car markets, respectively. By 1998, the Big Three's share of the domestic car market slid to 58%, while they maintained market share in domestic trucks. Asian auto firms, however, threaten to penetrate this share with a glut of new truck-based product in the near term. Thus, American firms face assaults on their highest margin vehicle segments on two fronts. In addition to potential regulatory moves that threaten to erode these profit streams, domestic automakers concomitantly face the more ominous prospect of declining market share in their most profitable vehicle segments.

5.3 THE CAR: CONSUMER DURABLE OR HIGH TECHNOLOGY PRODUCT?

But does the problem rest squarely with the customer? If the customer does not demand and is not willing to pay for cleaner, more fuel efficient vehicles, then requiring automakers to sell them such products is doomed to be a losing business proposition. And in an industry where profitability rests on mature products with thinning margins and a high fixed cost of investment is de rigueur, the potential for loss is such that no self-respecting manager could justify his job over it. Especially when the organization views the potential revenue stream as an insignificant fraction of its bread and butter product.

But the problem of absent customer demand for potentially superior product is one that is not unique to the auto industry. Rather, the high-tech industry is flush with examples of superior products that struggle in the marketplace, only to stagnate or withdraw unceremoniously (example: Apple's Newton). The problem depends on one's perspective. Automakers continue to treat their customers as a traditional consumer market rather than a high-tech market, when every indication is that today, and tomorrow's, automobiles contain more high-tech gadgetry than ever before. Witness the emergence of in-vehicle communications systems (i.e. telematics), more advanced E-PROM chips that

provide real-time On-Board Diagnostics (OBD), or ever more sophisticated materials and assembly techniques. The average automobile currently carries twenty computer processors and over sixty on-board sensors. This number is expected to increase dramatically in the coming decades as vehicles adopt telematics for communications, geolocation, and intelligent transportation applications.

Automakers are also experimenting with the idea of platform commonality and sub-system modularity. In concert with the evolution of vehicles from dependence on mechanical interfaces to electronic or electromechanical ones (i.e. “drive by wire”), automakers may to some extent enable “plug and play” capability. Aside from the challenge of defining standards for interface protocols, doing so means contending with (1) widening disparity in the technology life cycles of the sub-systems that comprise the vehicle and (2) displacement of vehicle turnover by higher sub-system turnover. This portends a potential shift of value in the supply chain to the second and third tier suppliers of electronic and electromechanical systems. The risk to automakers is the “Intel Inside” phenomenon where the higher margin value of the vehicle may shift from the OEM’s brand to the supplier of the vehicle’s subsystems (Fine, 1998).

But car firms seem to have a difficult time accepting the idea that they are selling a high-tech product, rather than a traditional consumer durable. The distinction between the two is even greater when one considers the fact that a vehicle is typically the second most expensive purchase an average consumer will make in his lifetime. Each requires a very different marketing approach to gain successful entry of new product. Failing to comprehend the difference in the type of market one is selling to, combined with the sheer magnitude of the purchase decision, only worsens the predicament; it will hinder success while further justifying the supposition that consumers cannot be made to pay for what they don’t want.

But today’s car purchase resembles less a pure *consumer durable* and more a *high technology* product. In previous decades, a consumer could buy a car and expect the vehicle to deliver its value proposition equipped with relatively static technology over the course of its life. Today, however, a car is taking on a host of new value propositions that depend upon technologies with much shorter product life cycles than the vehicle itself. But because today’s cars lack adaptability at the user interface, consumers will consider good

design *and* technology obsolescence in their purchase decision. Thus, a vehicle purchase today looks more like a high technology purchase than ever before. Consider a purchase of a laptop computer or even a PDA. Because of the high price point of these purchases, the average consumer will buy with the expectation that the product will deliver about three years of useful life before the technology is surpassed by newer innovation. But imagine if the laptop cost a mere \$100, rather than \$3,000. All else equal, we might expect that at hypothetical, and unrealistic price point, the more tech-savvy consumer segments would upgrade to a laptop of superior technology as that technology became available in the market. In other words, no delay would exist between the consumer's desire to "upgrade" and the act of upgrading. It is therefore the magnitude of the cost that dictates the consumer's expectation regarding the useful life of the product.

Furthermore, at higher price points the purchase begins to take on the character of a business investment in plant and equipment, the key difference being that a business can write-off depreciation of capital equipment and a private car consumer cannot. Thus, the consumer holds the property longer to amortize the high fixed cost of the vehicle purchase. This spawns two additional behaviors. First, we can expect product turnover to decrease. Automakers have long since been aware of the inverse relationship between vehicle price and vehicle turnover. Second, we would expect good design to play a larger role in the consumer's purchase decision. After all, the longer one must own the product, the more we would expect the consumer to base the purchase decision on how well he can live with the design over the expected period of ownership. Automakers have also long understood the importance of the car as a fashion statement to the purchaser.

So how does this translate to the new car market and what does it mean for automakers? I can answer this question with another question. What if cars hypothetically cost \$2,000 instead of \$20,000? First, we would expect the game to fundamentally change. The used car market might slip to a mere fraction of today's, for example. But two other key behaviors might emerge. First, product turnover should increase markedly. Second, good design might take on less importance than previously. After all, if a customer grows tired of a design after six months, he would be more inclined to purchase another one rather than hold out in order to recoup the original cost of purchase.

What this observation portends for the auto industry is this: as vehicles trend toward high technology, consumers will become more concerned with the potential for obsolescence. In the absence of built-in modularity, many will choose to “wait and see” in the short-term. Fundamentally, mainstream consumers do not want to bear the risk of technology obsolescence. Removing this concern from the purchase equation is the first step toward breaching the early majority segment of the technology adoption curve.

6 OVERCOMING IMPEDIMENTS TO INNOVATION

The previous chapters explored a representative set of potential pathways for the adoption of a statistically meaningful proportion of “cleaner” advanced fuel/vehicle technologies. Excepting GM’s foray into the California market with its *EVI*, as of this writing, only the two largest Japanese automakers have entered the U.S. market with production advanced propulsion platforms. The 5-passenger Toyota Prius and the 2-passenger Honda Insight commuter were designed from the ground up around hybrid gasoline/electric powertrains. These vehicles represented “first of their kind” forays into the alternative powertrain market. Both envisioned modest demand targets, but success at this experimental level appears to have emboldened these automakers. Both manufacturers have announced intentions to release subsequent HEV and BEV models. Toyota will offer an EV version of its popular RAV-4 SUV and Honda will offer a hybrid gasoline/electric version of its popular Civic line next month as a 2003 model. It marks the first time an automaker will offer an already popular model as a hybrid for sale in the U.S. market. Although Ford has indicated its intention to come to market with a hybrid version of its Escape SUV in the 2003 model year, to date not a single domestic automaker has countered the moves of their Japanese competitors.

These events suggest that the major Japanese players are executing according to a larger strategic vision. Their short-term goal: test the market with a couple of introductory production models, learn from failures, but build on success. Deliberately design interfaces that evoke desired modes of behavior from consumers, educating them to value the emergent benefits of the new technology. In the mid-term, release alternative power trains as an option package in popular, existing production models. Continue to drive costs down via scale and scope. In the long-term, the price differential erodes, and if the market is cooperative, fuel prices increase relative to today’s prices, and the larger adoption segments “buy in.” Sound simple? Far from it, and the path is riddled with risk that firms must manage carefully along the way.

In this chapter, I turn to the more thorny issues confronting efforts by domestic automakers to successfully bring advanced powertrain technologies to market.

6.1 PITFALLS OF ARCHITECTURAL INNOVATION

In order to formulate and target high-leverage public interventions that achieve desired outcomes, regulatory authorities must grasp the dynamics of the innovative forces they wish to marshal in the public and private sectors. Innovations originate from many potential sources, including government labs, the R&D wings of established firms, and academic institutions. This body of research focuses solely on the technological solution space and presupposes that established automakers will deliver the innovation demanded. Therefore, comprehending the sources and nature of innovation will enable decision-makers to construct policy regimes that harness the capacity of those entities most capable of delivering innovations to market.

First, regulatory entities must understand that performance-based requirements, by definition, place a burden on firms. The degree of difficulty that firms face in achieving the requirement is largely determined by the nature and type of innovation the requirement invokes. The requirement may necessitate simple diffusion of off-the-shelf technologies; such solutions often lie within the technological know-how of the source firm, or may involve the diffusion of existing technologies from adjacent industries. Conversely, the outcome desired by regulators may require a much more complex solution that challenges the firm outside its traditional core competencies.

Different types of innovation yield very different competitive consequences because they require very different organizational capabilities to deliver them (Henderson & Clark, 1990). In attempting to ascertain whether established firms are best positioned to produce innovation in advanced fuel/vehicle systems, it is useful to examine the nature and type of innovation required to deliver a successful solution to market. William Abernathy (1978) and Clay Christensen (1997) differentiated between fundamental types of innovation. *Incremental* innovations represent minor and continuous product improvements that are evolutionary in nature, cater to existing markets, and reinforce the organizational capabilities and market dominance of established firms. Discontinuous or *disruptive* innovations, on the other hand, represent innovation that is radical in nature, caters to a fundamentally different consumer value proposition or market, and threatens the existing knowledge, competencies, and dominance of established firms. I contend that the efforts to realize clean propulsion technologies will more closely approximate the latter.

As a consequence, this will prove one of the more considerable obstacles threatening the successful introduction of cleaner technologies to the mainstream consumer markets.

The potential solution scenarios discussed in this research rely on the adoption of a set of alternative propulsion systems couched in established ICE-based automotive designs. I suggest that as a result, stakeholders invoke another more insidious derivative of the disruptive class of innovation referred to as “architectural” by management literature. Henderson & Clark (1990) define architectural innovations as those that change the way in which components of a product are linked together, while leaving the core design concepts untouched. This category of innovation preserves the component knowledge of the organization while destroying the architectural knowledge base. But because architectural knowledge is deeply embedded in the structure and information processing procedures of established firms, it is often difficult for firms to recognize and hard for them to correct. Figure 6.1 attempts to map the distinction between radical, incremental, and architectural innovations based on the degree of change demanded of the product’s (1) architecture, and (2) components and core design concepts.

		Degree of Change Demanded in Components & Core Competencies	
		Negligible	Significant
Degree of Change Demanded in Product Architecture	Negligible	Incremental	Modular
	Significant	Architectural	Radical

Figure 6.1 – Innovation Types as a function of change demanded

Successful product development demands two competency bases: (1) component knowledge, or knowledge about each of the core design concepts and their implementation, and (2) architectural knowledge, or knowledge surrounding the linking of components and

sub-systems to create an integrated and coherent whole (Henderson & Clark, 1990). Innovation is often characterized by periods of experimentation followed by the emergence of a dominant design (Utterback, 1994). The dominant design “freezes” the product architecture, defines the interaction of systems and components, and emerges in order to take advantage of scale economies. The dominant design, in essence, stabilizes the product architecture by incorporating a range of basic design choices that are not revisited in subsequent designs (Henderson & Clark, 1990). Often, with the emergence of a dominant architecture, firms cease investment in learning about alternative configurations and instead focus their efforts on achieving process efficiencies.

A full seventy years have passed since the emergence of the ICE as the dominant propulsion design in the auto industry. The focus of competition has long since shifted away from the exploration of design space and toward the perfection of repeatable and predictable processes for delivering the dominant design at scale. Today, the ICE remains the central organizing principal of modern vehicle design, production, and firm organization. By necessity, the successful engineering, production, and sale of complex manufactured products such as automobiles entails highly defined structures and routines. These structures and routines help the firm deal with complexity, but embed certain implicit *communication channels*, *information filters*, and *problem-solving strategies* that enable the firm to execute its mission (Henderson & Clark, 1990).

This research has discussed a representative set of advanced fuel/vehicle systems that automakers have either produced, or are currently under development for potential production. The majority of these technologies involve predominantly architectural design changes for several reasons. First, with minor exceptions the proposed alternatives deliver a virtually identical set of attributes exhibited by current ICE-based platforms. Customers will observe many of the same components, and arrangement of components, they have come to expect in customary ICE-based vehicles: four wheels, four seats, four doors, and a steering wheel. Second, the core design concept behind each of these components, and the science and engineering associated with them, remain undisturbed. Technologies such as the electric motor, battery, and fuel cell are new only in their application to automobiles. Finally, and most importantly, the alternatives involve the reconfiguration of an established system to link together existing components in new ways. Many of these reconfigurations

will occur “under the hood,” outside the visual field of the customer. Nevertheless, the incorporation of existing technologies such as electric motors, generators, and ultracapacitors will create new linkages and spawn new interactions in the established product.

The inherent complexities and unpredictability of these interactions create significant obstacles for firms with long entrenched, deeply embedded architectural knowledge. Much of what the firm knows will prove useful in climbing the steep learning curve involved. But the firm’s greatest assets can also become its greatest liability. Henderson & Clark (1990) argue that the subtlety of this challenge – recognizing what is useful and what is a liability, and acquiring and applying new knowledge – often proves difficult for established firms because of the way architectural knowledge is organized and managed. Organizations build knowledge and capability around the recurrent tasks they perform.

Where firms often stumble is in their failure to appreciate the systemic change that the new arrangement of sub-systems or components creates. Instead, they tend to rely on their old frameworks – their old architectural knowledge – and consequently miss the real nature of the threat. For example, in a potentially misplaced effort to save money and reduce risk, many automakers are attempting to meet the call for better fuel efficiency and emissions performance via “conversions” rather than by blank sheet, ground up design efforts. To put it another way, these firms are attempting to shoehorn alternative systems into architectures designed at the outset around the ICE. The danger implicit in such efforts is two-fold. First, new interactions spawn new system behaviors that ultimately undermine the firm’s established architectural knowledge. Second, the effort fails to recognize or capitalize on the potential to realize an entirely new or different value proposition that is either unexplored or unrealized in the mainstream market. This requires firms to think outside their traditional boundaries and therefore to consider information that the firm has long since screened out as irrelevant to delivering its traditional value proposition.

The development of the jet aircraft industry provides a useful analog. With the arrival of jet engine technology, established aircraft providers understood that they had to develop jet engine expertise, but only those that recognized the significance of the subtle changes that the new technology would impart on the aircraft “system” survived the

subsequent shake-out as the industry transitioned from turboprops to jets. This architectural innovation permanently tilted the competitive landscape and witnessed the ascendance of Boeing and the decline of de Havilland and Douglas Corporation as the industry leader. The episode proves ample warning to domestic automakers that choose to defer market leadership in advanced powertrains to foreign competitors in favor of a “fast-follower” strategy. Such a strategy is predicated on the fallacious notion that new architectures can be easily acquired, absorbed, or adapted to the organization’s old frameworks.

In summary, this research contends that aside from a deeply embedded culture averse to realizing innovations on the emissions front, the architectural implications of the innovation demanded stands as one of the greatest obstacles to the realization of emissions progress by established automakers. The problem is further compounded by the recent industry shift toward sourcing a greater portion of sub-system and component design to 2nd and 3rd tier suppliers, while focusing core OEM competencies on systems integration activities. Thus, OEM efforts to reduce product development risk may ultimately tilt the firm toward increasing dependence on its architectural competence base, thereby exposing the firm to greater architectural risk. The deeply embedded nature of this knowledge, the considerable delay in recognizing its presence, and the time and resources required for management to develop and institute mechanisms to effectively counter its adverse effects translates to a long-term handicap of the firm. Such developments may yield significant competitive consequences when considering the formulation of policy regimes that aim to yield desired performance- and competitive-based outcomes.

6.2 POLICY RESISTANCE

In order to understand the intransigence of domestic auto firms with regard to fuel economy and emissions, one must return to the formative years of the federal Clean Air Act of 1970. In the late 1960’s and well into the 70’s, U.S. automakers unequivocally protested, lobbied, and successfully delayed and diluted federal and state efforts that mandated drastic reductions in vehicle pollutant emissions. Their primary arguments routinely centered on the localized nature of the problem (to urban centers such as Los Angeles, Boston, and New York), the inherent trade off between emissions and fuel

economy, and the reduced demand and subsequent loss of jobs that would follow from the inevitable increase in car prices. Despite two oil shocks that created overnight markets for fuel-efficient vehicles, only the Japanese automakers stood ready with product to seize the opportunity. Sadly, even today the major U.S. automakers still fail to see the irony of this event in industrial history; for it was on the basis of fuel economy that the Japanese automakers were first able to establish a beachhead on U.S. soil. Later, as gas prices stabilized, the famed reliability of their products would wrest double-digit market share from Detroit's Big Three.

Today, the situation has seen little change. The effort of domestic automakers to systematically delay and dilute measures to improve emissions and fuel economy performance reflect nearly four decades of a highly evolved political art form. The nation's automakers continue to practice this art form today, throwing hundreds of millions of dollars a year and vast company resources at lobbies that endeavor to quietly smother efforts in Congress to increase corporate average fuel economy (CAFÉ) standards. Due to the delay of fleet composition to reflect the current market share of new vehicle sales, every year of delay effectively impedes the realization of results a decade's time.

Despite the arguably optimistic scenarios depicted by our adoption model, deeply embedded cultural and institutional mindsets preclude market leadership by domestic firms. Rather, as I will argue shortly, the Japanese, and possibly even the Europeans, will beat the Americans to the high-growth, high-margin segments of the market yet again. I attribute this first to the architectural nature of innovation that auto firms must contend with as discussed previously, and second to the cultural and organizational barriers that constrain solution space and limit innovative capacity along these pathways.

6.2.1 THE "SHIFTING THE BURDEN" SYSTEM ARCHETYPE

The "Shifting the Burden" system archetype detailed by Peter Senge is one of nine representative patterns of individual and organizational behavior noted in *The Fifth Discipline* (1990). In basic form, this dynamic is composed of two balancing processes. Both attempt to correct the same problem. The top process represents the symptomatic intervention, commonly understood as the "quick fix" solution. While available immediately for application, this method frequently yields benefits quickly in the short-

term, but only temporarily. The bottom loop in Figure 6.2 below represents the fundamental response to the problem. Although this response addresses the root cause of the issue at hand, it typically involves considerable delay to implement and bear fruit. Despite this delay, the fundamental response offers a much more permanent solution to the initiating problem condition.

Senge explains that in shifting the burden structures there is an additional reinforcing, or amplifying, loop created by a number of side effects instigated by implementation of symptomatic solutions. He cites as an example the administering of drugs to correct a health problem. If an unhealthy lifestyle initiated the problem, then the fundamental solution lies in a change of lifestyle. The drugs represent the symptomatic solution. Although they treat the symptoms effectively, they can lessen the pressure of making the difficult changes of habit required to restore full health. A patient with a heart condition might come to rely on the medication rather than altering his dietary intake or exercise regimen, for example.

6.2.2 APPLYING THE SYSTEM ARCHETYPE TO U.S. AUTOMAKERS

The shifting the burden structure explains a wide range of behaviors where well-intended short-term fixes contribute to worsening conditions in the long-term. This is easy to imagine when the symptomatic solution is typically the most obvious and available remedy. It offers the seductive qualities of demonstrating initiative to one's superiors that the problem is being addressed and of achieving measurable progress within one's own tenure. But Senge points out that addressing a problem in this "quick and easy" way also reduces any perceived need to find more fundamental solutions. Even worse, over time a fundamental solution becomes increasingly difficult to both identify and apply. First, once instigated, people come to rely on the symptomatic solution. This is because the symptomatic solution begins a march down a path requiring still more follow-on decisions that inevitably involve the commitment of expensive resources that narrow design space and "lock in" downstream decisions to a predetermined set of options. The further downstream into the process, the less likely people are to challenge these assumptions, or to consider divergent solutions. Thus, design space narrows over time as the firm commits resources. Second, these solutions typically reward the manager with a feeling of having

solved the problem. Ultimately, however, it diverts attention from the fundamental problem and the burden shifts to increasing reliance on symptomatic solutions.

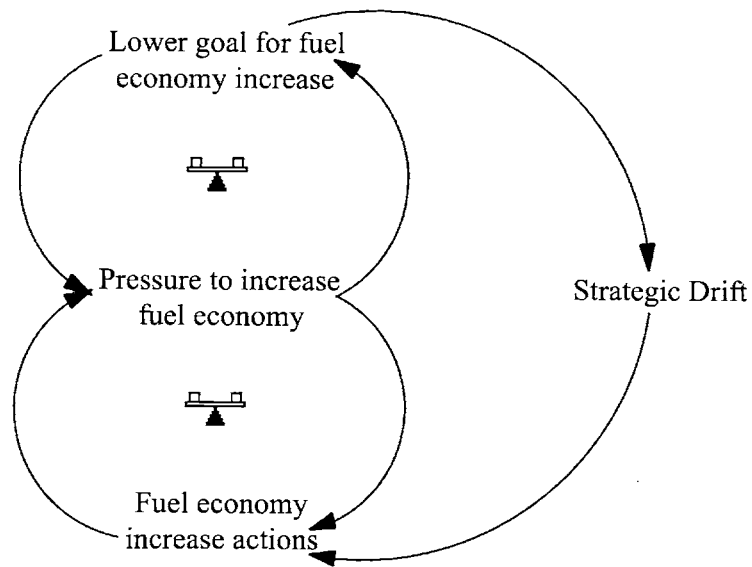


Figure 6.2 – The “Figure 8” and Strategic Drift

This structural shift, portrayed graphically by Figure 6.2, initiates “drift” in strategic direction over time and comes at the cost of erosion in market share and competitive position. Furthermore, once a firm embarks down this path it begins to cement and codify certain mental models, organizational structures for problem solving, and channels of communication. Furthermore, Senge cites the frequent appearance of the phenomenon of “eroding goals” whereby the gap between the firm’s goals and the current situation create two sets of pressures: to improve the situation and to lower the firm’s goals. Eroding goal dynamics are a fundamental tenet of societies and are not only played out within firms but amongst firms and amongst public and private entities (Senge, 1990).

Since the early 1960’s domestic automakers lobbied against increases in fuel economy or reductions in emissions. Frequently, their lobbying efforts succeeded in diluting and delaying emissions standards and fuel economy targets. In some instances, automakers successfully convinced Congress to “roll back” targets to the less stringent terms of earlier model years. Typical arguments included the projected cost, increasing

competition from foreign automakers, compromising of the nation's security posture [citing the decline of American manufacturing and the importance of self-sustainability in armaments production], and the widespread displacement of labor that would result from these measures. Since the industry provided data that correlated automaking with roughly one out of every seven jobs in the U.S., congressional representatives often cowed to the implicit threat of layoffs conveyed by such arguments (Doyle, 2000).

Most fascinating is Peter Senge's comparison of these tendencies with the generic dynamics of addiction. Almost all forms of addiction involve the shifting of burden to other elements of the system. "All involve opting for symptomatic solutions, the gradual atrophy of the ability to focus on fundamental solutions, and the increasing reliance on symptomatic solutions." He correctly observes that by this definition, organizations and entire societies are just as vulnerable to addiction as individuals. Insidiously, the symptoms of this kind of addiction-like behavior tend to lie beneath the immediate surface, evolving slowly over long periods of time. They surface occasionally in the form of periodic crises. What persists, however, is a slow descent to lower levels of financial health for the firm or the industry. The longer the deterioration, the more difficult it becomes for people to challenge the fundamental causes and the more costly it becomes to alter the course. Thus, the fundamental response loses steam while the symptomatic response gains in strength.

"Strategic Drift" consists of a number of patterns of behavior indicative of the shifting of the burden system archetype. First is the "figure eight" effect, whereby in the fuel economy game the tendency to lower the target serves to ease the pressure of achieving a reduction in the fuel economy gap. This reduces the actions required of the firm to increase fuel economy but in turn slows any progress toward closing the gap. Slower progress toward closing the gap increases the pressure on the automaker to reduce it. This pressure fuels further effort by the automaker to lower the bar for performance, and thereby perpetuates the cycle indefinitely.

The shifting of the burden dynamic insidious is the subtle reinforcing cycle that it fosters, placing increasing dependence on symptomatic solutions (Senge, 1990). Second, the assault on CAFÉ via scores of Washington lobbyists diverts attention and resources from the fundamental problem – product waste and design inefficiencies. And so begins a gradual atrophy of the organization's ability to identify, focus on, and pursue fundamental

solutions to the fuel economy and emissions problem. Consequently, pressures mount to direct resources to further short-term problem solving. Automakers “game” CAFÉ mandates, allowing them to hold to the letter of the law at the cost of defecting from the *intent* of the law. For example, domestic automakers actually *added* weight to certain medium-duty SUVs to deliberately exceed the gross vehicle weight jurisdiction of CAFÉ truck mandates (Doyle, 2000). Doing so allowed them to sell an additional SUV and collect on the generous profit margin it provided for each medium-duty truck that successfully skirted the law.

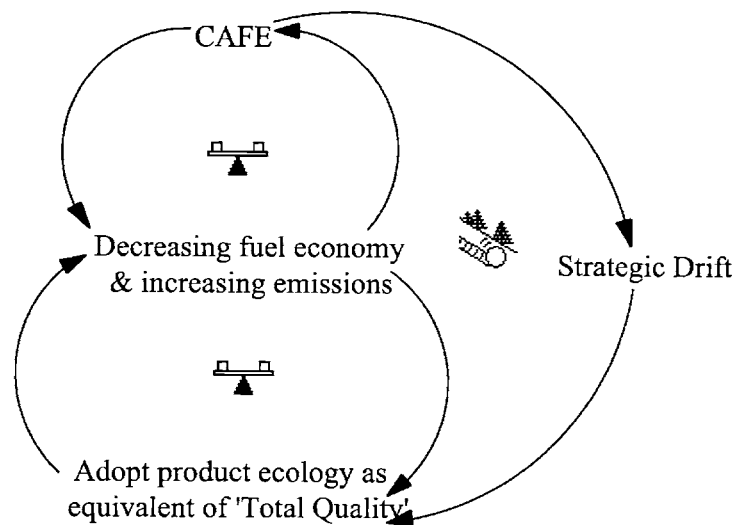


Figure 6.3 – Strategic Drift and Emissions Regimes

As the auto firms embarked on a path of defecting from the intent and spirit of CAFÉ law as depicted in Figure 6.3, the ability to alter course and revert to a more fundamental approach to the problem grew in difficulty. As the average consumer’s appetite for increasing utility and vehicle size grew, American automakers invested heavily in the skill and capital needed to deliver this performance attribute. They sought to cash in on the enormous margins that such products promised but did so with a strategy completely decoupled from the fuel economy and emissions conundrum. Rather, domestic firms became ever more diligent in their lobbying efforts and more creative in ways to circumvent CAFÉ restrictions. Consequently, one of the most promising technological

solutions for achieving fuel economy targets – employment of advanced composites and lightweight materials such as aluminum to reduce vehicle mass – faces a significant roadblock in the form of trade-offs in vehicle safety. As trucks have risen in popularity and grown to represent over 50% of the new vehicle market share, the average gross vehicle weight of the fleet has risen as well. Thus, auto industry advocates have essentially closed off, or have at least compromised, a potential avenue of solution space to the fuel economy and emissions dilemma. Furthermore, earlier strategic decisions to defect from CAFÉ have actually served to provide additional ammunition against advocates for regulatory intervention. After all, federal fuel economy mandates could potentially compromise vehicle safety, a sensitive subject to a legislator’s constituency. The automakers know this, and exploit it to their advantage by linking the two seemingly disparate subjects.

A final pattern of behavior indicative of strategic drift is the tendency of firms to cite previous related failures as justification for the delay in committing resources toward improving fuel economy and emissions performance. Oft-heard are the cries of automakers having been stung once by investments in improving fuel economy at the expense of investing in attributes the customer is willing to pay for. The past three decades indicate that future movement in gas prices may prove volatile, but they will be temporary and short-lived. Consequently, decision-makers will be inclined to delay investment in improving fuel economy, preferring to defer instead to time to allow fuel prices to settle on a stable equilibrium indicative of past decades. This is the preferred course for two reasons. First, why commit when the past indicates that the spike will be temporary? Secondly, why should the auto manufacturer bear the risk of future fuel price volatility when that risk can be deferred to the customer? Notably, GM’s unsuccessful introduction of the first production electric vehicle, the *EVI*, has proved a useful tool to justify the claims of automakers that externally imposed mandates cannot deliver a market where one doesn’t exist. In essence, the *EVI* experiment offers a convenient “I told you so” argument to regulators and is frequently cited in statements to the media.

The development the *EVI*, a significant engineering feat in its own right, provides an interesting case study of both perverse incentives and strategic drift acting in concert to counter the more benevolent intent of GM’s Advanced Technology Vehicles (ATV) Group to deliver a profitable vehicle program to Corporate GM. In the mid-90’s, even as ATV’s

engineers toiled away to meet cost, mass, and range targets, GM's corporate lobbyists were hard at work in California and the Northeast. What were they doing? First, they attempted to stall and derail efforts by the Northeastern states to adopt California's stricter emissions mandates, most importantly the part mandating that ZEV sales comprise 2% by 1998, and then 10% by 2003, of all new car sales. Second, with the deep pockets of Big Oil, they threw all of their weight at CARB to convince the regulatory body to scrap, or at the very least delay, the ZEV mandate. Now this begs the question: Why would an automaker, who otherwise stood as the sole source provider of the only technology at hand to meet the ZEV mandate, with the promise of capturing an uncontested share of the market, fight a law that by fiat created the market for this product? Clearly, perverse incentives were at play. Should California's mandate come to fruition unabated, GM stood ready to deliver the product. Should the product prove successful, however, the Northeastern states would jump on the ZEV bandwagon and this is what GM feared most. Simply stated, the technology was not suited for the harsh climate of the Northeast. In fact, if the states pressed and GM gave, the automaker believed the product would ultimately fail, opening the firm to a torrent of product liability litigation. As GM corporate saw it, the only course of action that could prevent this inevitability was to kill the ZEV mandate in California (Shnayerson, 1996).

GM proved successful in its effort to forestall enactment of the ZEV mandate. In the summer of 1996, as GM announced its launch of the *EVI* to consumer markets in California, CARB announced that it would suspend the 2% mandate for 1998, but that the 10% mandate for 2003 would stand unperturbed. Consistent with the history of U.S. auto strategy, one could surmise that the 10% mandate would come under pressure next. Important to note in this case are the countervailing forces involved. At one extreme, GM granted the green light to one of the most far-sighted technological efforts ever embarked on by the firm. At the other extreme, is that same firm's effort to derail its own trailblazing project in the midst of a booming post-recession economic recovery. I argue that this "two-faced" strategy is the product of strategic drift and is indicative of the insidious effect of several decades of policy resistance. After all, could not have GM directed its lobbying efforts toward convincing the regulatory bodies of the Northeastern states that their

technological solution was not fungible and that the firm would have to pursue other avenues to meet the unique demands of that market?

6.2.3 THE PRINCIPLE OF LEVERAGE

The hard lesson learned of the *EVI* episode, tips automakers to think twice before investing. Burned once, firms resurrect the martyred failure to justify delay and to opt for a more risk-averse competitive posture. Auto manufacturers argue that they have spent hundreds of millions of dollars on fuel economy and emissions research largely in response to government mandates rather than real consumer demand. They argue that these regulations have tacked on hundreds of dollars to the cost of a car, weakened their competitive standing with foreign imports, and cost them market share with little or no return on their investment. And to add insult to injury, after nearly four decades gas prices remain cheap and available while consumers clamor for increased performance, utility, and size. If gas prices reflected the actual cost of supply, they argue, perhaps then consumers would demand improvements to fuel economy and might actually prove willing to pay for it when delivered.

Senge, however, argues that it is just this kind of behavior – a tendency to shift the burden to other stakeholders – that underpins the mindset of a firm that has long since departed from seeking fundamental solutions to the core problem. As fleet fuel economy stagnated during the eighties and early nineties (prior to beginning its downturn in the mid-nineties), the domestic automaker's customer base evolved toward those who were less sensitive to poor fuel economy. This in turn meant that customers became more sensitive to price and other vehicle attributes. But price-conscious customers typically prove less loyal and more amenable to competitors offering lower prices. Furthermore, increased price sensitivity meant that designers fell under increased pressure to control costs so as to capture customers that might otherwise defect to the competition. Consequently, American automakers risked drifting into the vulnerable position of being a low-quality, low-price supplier of low margin vehicles.

In response, U.S. automakers pressed ahead with two strategies. First, they pushed responsibility for the development of whole subsystems onto the supply chain. In so doing, they hoped to shift the role of product innovation to the supply chain while focusing

resources on their own core competency as vehicle systems integrators. Second, automakers moved en masse away from “car” production to “truck” production. The consuming public’s insatiable appetite for bigger, tougher, utility-based vehicles was indicative of growing real wealth in the boom of the mid- to late-90’s. This growing segment of affluent, less price sensitive, investment-savvy Americans provided a huge boon of opportunity for capture of large rent margins by U.S. firms. Most domestic automakers eagerly closed car plants across the world or converted them to truck shops to gain the capacity to cash in on the SUV craze. But foreign competitors soon followed and at the precipice of a new worldwide manufacturing recession, domestic automaker stand poised and ready with new and fresh product to push to a confident consumer market. Post 9/11, and post 0 percent financing programs that artificially and temporarily propped up capacity utilization figures for the industry, the future looks much more bleak. Despite a wealth of new product, competitors will roll out more. Where can the domestics find new horizons for competitive differentiation in such a tight market?

6.3 RECOMMENDATIONS FOR INDUSTRY STRATEGY

6.3.1 A NEW VALUE PROPOSITION

In Chapter 5, we witnessed the progressive diminution of the propulsion platform life cycle as technologies transitioned from ICE- to HEV and finally to FCEV- or EV-based phases of technology dominance. In this section, I hypothesize that the acceleration of propulsion technology life cycle stems from the accelerating pace of innovation in complementary “ITEC” technologies: i.e. those derived from information, telecommunications, electronic and energy sectors. To date, automakers have captured only a small fraction of the potential of these technologies to improve manufacturing processes, with the latest movement toward “lean” and the notion of “mass-customization.” Only in recent years, have automakers begun to consider the implications of incorporating the breadth of ITEC innovations throughout the entirety of vehicle design, not only in improving the process of design and vehicle development, but also to incorporate ITEC technologies into vehicle design. Doing so offers the promise of realizing added value for the customer while achieving competitive differentiation in the market. Although we have witnessed the advent of telematics as a viable business opportunity, few other

complementary technologies have trickled through. With the exception of more advanced on-board electronics to monitor vehicle activities, vehicles today remain “dumb” relative to other high-technology cousins such as aircraft. Rather, industry continues to view their product as consumer durables vice high technology products and therefore design, manufacture, distribute, and support their product as such.

The shortening of propulsion system life cycles portends a number of uncertainties and risks for industry stakeholders and consumers. I have argued throughout this thesis that the provision of personal mobility will continue to trend away from patterns consistent with consumer durables markets and will take on an increasing flavor of high-technology ones. If true, automakers must remain ever vigilant of such trends and nurture core competencies in directions that allow them to capture value in the supply chain and value in the consumer market from a system-wide perspective. Hax (2001) argues that to do so, firms must reject imitation of competitors and a product-centric mentality that steers the industry toward commoditization. Instead, Hax suggests that firms erect significant barriers around the customer through “a unique customer value proposition based on deep customer segmentation, and customer and consumer understanding.” Rather than benchmarking competitors as the central organizing principle for product strategy, firms should concentrate on leveraging B2B and B2C technologies to nurture the integrated value chain consisting of key suppliers, consumers, and complementors.

The end-goal of such a strategy for the OEM is system “lock-in,” whereby customers and suppliers operate from a base of trust and comfort to effectively “fold in” the more radical and disruptive technologies abhorred by the sales and marketing arm of the firm. It is instead crucial that sales and marketing take on a much more proactive and involved relationship with the customer in the after-market. Today, these arms continue to operate from a traditional consumer durables perspective: know your customer, push product that the customer demands, and wait for them to come back to buy more product. The long-view goal in this model is to achieve “best product” via aesthetic design, all else being equal in an increasingly commoditized market.

But history bears out that since the entry of foreign competition and the emergence of global markets, best product in the auto industry is a fleeting achievement at best. It is window dressing with a 5-year lifespan in a business with the markings of the fashion

industry, but with a four-year delay in product delivery. The complexity, scale, and rigors of global manufacturing necessitate standardization and repeatability. To do so, automakers rely on a matrix organization divided into functional and product/program units of interaction. Industrial science bears out the phenomenon of the swinging pendulum, with firms involved in such complex manufacturing endeavors shifting in dominance from one to the other. Few firms have discovered a means to avoid this tendency. Thus, product-based excellence is a difficult, and tenuous goal to attain, and even more so to maintain for a length of time that yields the level of return on investment necessary to sustain the firm during leaner, functionally driven periods. The industry is ripe with examples of firms that achieved temporary best product advantage only to find themselves teetering on the brink of bankruptcy, or financially vulnerable to hostile acquisition. Such examples include General Motors circa 1980, Chrysler (now Daimler Chrysler) circa 1997, and Ford Motor Company circa 2002.

Christensen (2000) proclaims, “Advantage is Temporary.” If so, is it more risky to pursue advantage down a path with a proven track record of short-term temporary advantage within your industry, with diminishing returns to invested assets? Or does it make more sense to pursue strategies untried in the domestic market, but that have a proven track record of success in adjacent high-tech industries such as business copiers or operating systems? These case studies illustrate the potential of achieving more sustained advantage derived from pursuing Total Customer Solutions as the key enabler for achieving “System Lock-In” as a strategic goal of the firm? The latter offers a number of benefits. First, because the strategy involves forging a close and deeply segmented relationship with the customer, the customer becomes an asset to the firm in creating additional value. More importantly, it offers the potential for firms to gain critical feedback earlier in the design process, to test out early markets to gain insight, and to ensure that new technologies breach the natural divide between adoption segments in the Technology Adoption Life Cycle (Moore, 1999). Customers are less averse to the “shocks” of disruptive change, when they trust the provider from the perspective that the vendor will ensure the customer continues to receive uninterrupted transportation service that meets or exceeds his expectations.

Another key advantage of the Total Customer Solutions strategy is the relatively high appropriability of the value created. Deep customer, supplier, and complementor networks are not forged overnight. Rather, these value chains require a gestation period before firms can capture the potential fruits of their efforts. Since the success of a BEV, for example, hinges on the provision of energy to sustain a range acceptable to the customer, the OEM must work with complementors to align interests and nurture adjacent and niche markets that promise to lower the barriers to entry. The removal of barriers, and the establishment of an entrenched complementary asset such as vehicle charging stations offer the potential to create significant, long-term value to the firms best positioned with product to take advantage of this infrastructure.

In sum, a much more advantageous and achievable goal for auto and energy firms is to accept the changing nature of their industry. This entails a shift from the mindset that the firm is operating in a purely consumer durables market and toward an acceptance that the product is trending toward a market that will place higher value on high technology-based systems with shorter product life cycles. Thus, the market will exhibit patterns of behavior more representative of high tech markets than consumer durables. In order to thrive in the high tech market, firms must abandon the notion that “best product” will achieve lasting advantage in favor of an organizing principle that places “Total Customer Solutions” at the fore of industry strategy. Doing so enables the firm to extend this unique value proposition to new segments and to leverage adjacent technologies via complementors. Thus, customers, suppliers, and complementors become part of a total, systems-based, solutions package enabling complementor lock-in, competitor lockout, and ultimately, “System Lock-In” (Hax, 2001).

6.3.2 EMPLOYING THE TECHNOLOGY ADOPTION LIFE CYCLE MODEL

Automakers today face the classic prisoner’s dilemma. Simply, the basis for competition is such that they must continue to pursue high margin vehicle segments to sustain profitability. This translates to reliance on luxury segments that exploit flatter price elasticities in order to skim higher margins. It also means that the firm’s product portfolio becomes skewed toward products positioned to chase margins in established segments

rather than committing a balanced portion of the firm's product portfolio to the riskier endeavor of seeding new markets.

Yet seeding new markets is a necessary ingredient for market leadership in innovation that might enable the firm to capture first-mover advantages and lead market rents. Rather, domestic automakers find themselves trapped in a highly risk-averse business model with intense competitive pressures and thinning margins that offer little financial tolerance for failure. U.S. automakers have responded with efforts to recapture lost market share via a concerted revival of classic American automobile design. GM's recent hiring of Bob Lutz as their Chief Designer attests to the firm strategy of beating the competition on the basis of superior aesthetic design. Design, however, at best conveys temporary advantage to the automaker for two critical reasons. First, design suffers from weak appropriability; competitors can readily imitate it and rapidly bring it to market. Thus, any increased rents from aesthetic superiority will be cannibalized by imitation product in adjacent segments. Second, where complex manufacturing relies upon a matrix organization, delivering superior product comes at the cost of sustaining the functional proficiency of the firm. Like a pendulum that swings between product and functional competence, at some threshold, a product-focused organization witnesses the dilution of the functional depth of its engineers. The symptom emerges in the form of poorer product quality and performance. Consequently, the firm's share slips to design imitators who enter with product derived from a more functionally competent period. The early 1990's witnessed the fabulous revival of Chrysler, thanks in large part to industry leading product concepts such as "cab-forward" and Ram pick-up designs. But Chrysler succumbed to a series of embarrassing product performance-based recalls and competitive entry by its rivals who adopted similar design enhancements. In 1998, Chrysler's sagging sales and poor financial position left it ripe for takeover. Shortly thereafter, German conglomerate Daimler-Benz acquired the struggling firm. The lesson: a best product focus conveys temporary advantage only.

To achieve a system-wide and persisting edge on competitors, a firm must pursue more appropriable strategies. This section argues that building a deep customer relationship, combined with finer segmentation that encompasses a broader value proposition as depicted in Figure 6.4 is a necessary part of the equation. The firm must

consider its installed customer base as an asset that, like the firm’s plant and equipment capital, must be employed toward providing a return to shareholders. Doing so enables firms to leverage its installed customer base to lower risk-based innovation barriers and “lock-out” competitors who might attempt to imitate (Hax, 2001).

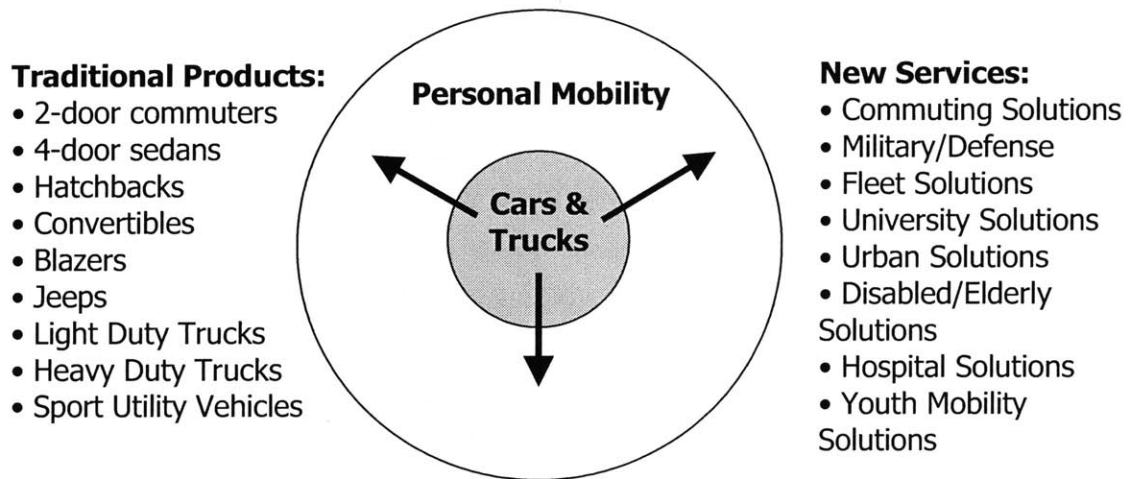


Figure 6.4 – Expanded Value Proposition: Personal Mobility Solutions

To successfully navigate the introduction of advanced powertrain technologies to wary markets, automakers must concede that the product they are trying to sell will look less like a traditional consumer durables market, and more like a high technology market. In other words, automakers should consider the traditional consumer market adoption model (best characterized as “a car for every purpose and purse”) in light of the Technology Adoption Life Cycle advanced by Geoffrey Moore (1991). Unlike the Sloan model, in which the automaker “owns” the consumer over the course of his life, providing a car for every major life phase, the Technology Adoption Life Cycle paints a very different portrait of adoption behavior. Both entail a relationship with the customer. The latter, however, is rife with pitfalls that belie the complex and risk-laden characteristics of high cost, higher turnover, high technology products.

Again, automobile history provides a useful starting point. Sloan understood that people want things that are new, and only need a good reason to buy the new thing. So Sloan introduced a wonderful new concept: the annual model changeover. The idea was to provide different kinds of cars for different kinds of customers. Customers always bought

more than just basic transportation – they bought style, performance, convenience and the driving *experience*. Sloan recognized the necessity of capturing customer lifetime value and building brand loyalty, offering a product for every price-range and life-stage. Today, customers look to cars to provide much of the same, except that technology plays a much greater role in delivering them.

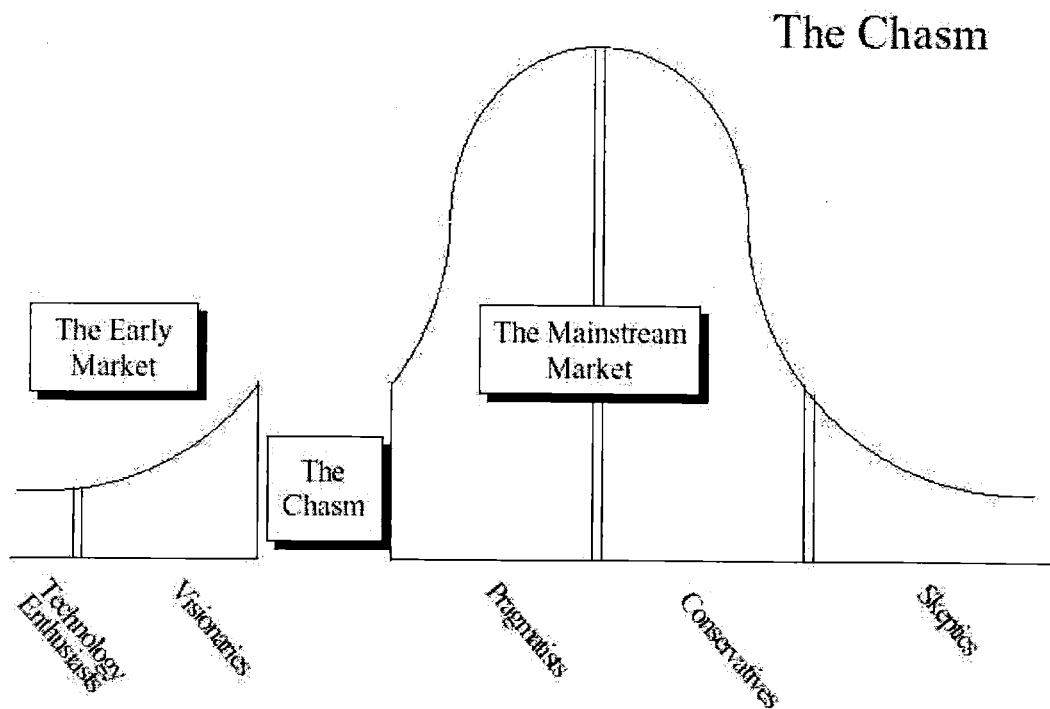


Figure 6.5 – Moore's Technology Adoption Life Cycle

Figure 6.5 portrays the Technology Adoption Life Cycle as a normal curve, segmented by the psychographic adoption groups that comprise it. Gaps exist between psychographic groups; therefore, every group will resist accepting a new product if it is presented to them in the same way it was to the group to the immediate left. Each gap presents the risk of loss of momentum and potential stagnation or death. To reach the Early Adopters, the firm must present the customer with a “compelling application” that would drive its acceptance over other, more established alternatives (e.g. the ability of a personal digital assistant to play MP3s). According to Moore, the key to winning over this segment is to demonstrate that the new technology “enables some strategic leap forward, something

never before possible, which has an intrinsic value and appeal to the non-technologist.” Therefore, what are the “killer apps” provided by advanced powertrains and who is positioned to best derive value from them: fleets, consumers, or some other segment?

To transfer technology from the Early Adopters in the fleet market to the Early Majority, the firm must evolve the technology to be progressively easier to use. In contrast to Moore’s assumption that this divide rests between the Early and Late Majorities, I argue that in the mainstream consumer automotive market, this divide comes much earlier in the adoption life cycle and that the Early Adopters represent a much smaller population than in the pure Technology Adoption Life Cycle Model. I equate this to two crucial differences in the vehicle market. First, cars are evolving from a pure consumer durable to a hybrid between a high-technology product and a consumer durable product. Secondly, individual purchasers lack the kind of compelling business application that the promise of scale and scope enable in industry. Thus, the Early Majority occupies a much larger area under the normal curve, perhaps 1.5 – 2 standard deviations from the mean.

In order to bridge the gap between Early Adopters and the Early Majority (or from fleet to consumer markets), the marketing arm of the firm should share responsibility for the user interface with engineering in order to ensure that product design achieves the desired consumer behavior and user experience. The design of the instrument cluster in Toyota’s Prius HEV model provides a perfect example of this effort in action. The center of the cluster displays LED readout of the basic energy conversion pathways, and the associated fuel economy, of the vehicle in real time. The user can thus visualize the effect of his driving pattern on the efficiency of the vehicle. In many ways, the design attempts to “lead the horse to water;” that is, to show the consumer the compelling application for the vehicle technology. Secondly, the design creates an interactive experience between the user and the vehicle, such that the user modifies his behavior to optimize the potential of the technology.

The consumer durable/high-technology hybrid nature of automobiles means that a hybrid approach to marketing is necessary in order to successfully move product up-market from an initial niche to mainstream segments. Incumbent OEMs hold the key to reaching the conservative Early Majority for several reasons. First, this group seeks out references within its own group, creating a Catch-22 chicken-and-egg dilemma for producers.

Therefore, the way to reach the group is via a trust-based relationship focused on service and support from proven technologies. The Early Majority psychographic group is much more price-sensitive and risk-averse. It would be a mistake to approach this group with a risk-laden, strategic leap forward proposition. Secondly, in order to build this trust-based relationship, OEMs should organize around a “total solutions,” service-based value proposition rather than one based on “best product” (Hax, 2001). Firms can thus focus on their strategic core competencies. For example, automakers could, in concert with the value chain, manage system-of-systems activities that span the spectrum necessary to deliver “total customer solutions.” This includes leveraging core OEM process competencies in vehicle integration with value chain members responsible for customer support. OEM’s also bring their extensive distribution and sales networks to the partnership in the effort to deliver “total” customer solutions.

Third, OEM’s should structure joint venture and/or acquisition strategies to pursue development of potentially “discontinuous” product innovations and then leverage the deep customer trust-base of the service strategy to work these higher risk innovations into the market. OEM’s can achieve this via careful and deliberate strategies for growing innovation. For example, firms can employ a range of strategic partnering relationships that leverage the innovative capacity inherent of smaller firms. This outsourcing strategy avoids the pitfall of in-house efforts that subject such projects to the scrutiny of corporate resource allocation mechanisms. Such decision gates typically prove unreceptive to high-risk projects that absorb company resources to pursue undefined markets with the promise of fractional returns relative to the firm’s mainstream product lines (Christensen, 1997). The strategy also has a downside, however. Firms risk outsourcing those portions of the supply chain that hold the greatest value (Fine, 1998). This again, is the “Intel Inside” risk of the strategy. To hedge this risk, OEM’s can take a variety of equity positions in these firms.

Finally, the total customer solutions focus could enable traditionally risk-averse OEMs to balance out their product portfolios as suggested in the generic Aggregate Product Portfolio illustrated in Figure 2.7. Currently, the product portfolio of domestic automakers is “bottom-right” heavy. This is a consequence of the current product-based paradigm that

relies on the traditional financial levers of turnover and margins. Ideally, firm portfolios should comprise a set of projects balanced along the diagonal from bottom-right to top-left.

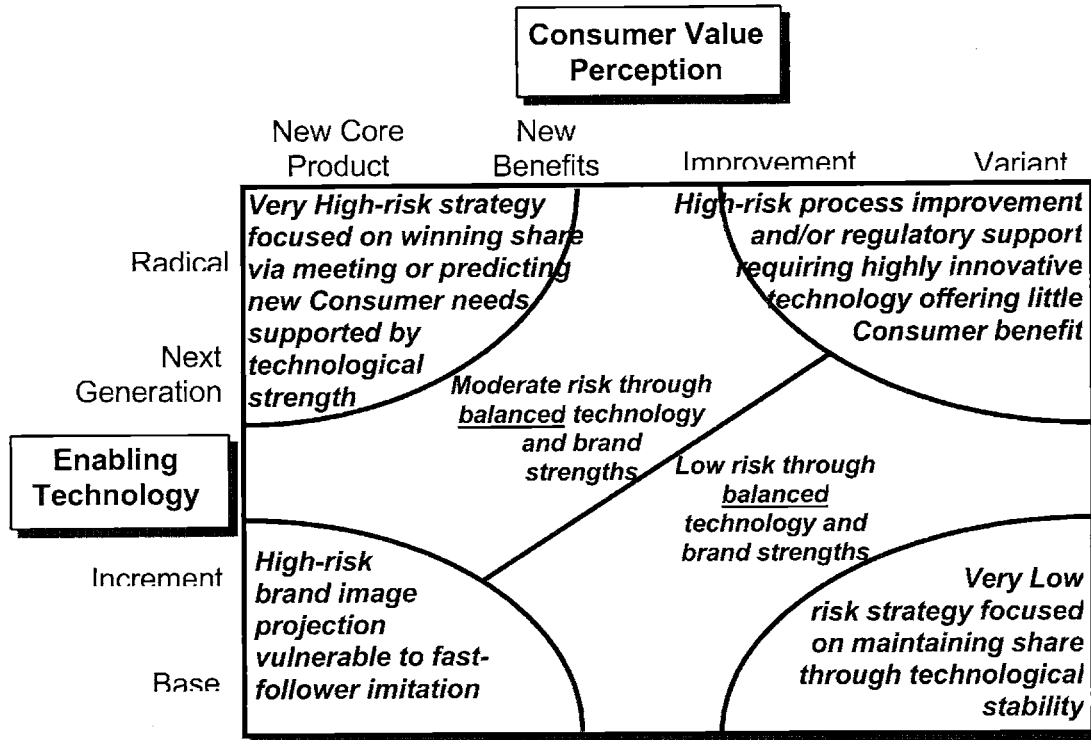


Figure 6.6 – Aggregate Project Portfolio - Consumer Technology Matrix/Risk Topography

A deep customer focus, rather than a product-centric mentality, confers a number of advantages. First, it frees the firm from a fast-follower/imitator mindset that is driving the industry toward commoditization. Second, it enables the firm to leverage a trust-based relationship to not only erect barriers around the customer, but to employ the customer as a firm asset in its effort to establish market leadership in innovative new technologies such as advanced powertrains. Finally, the strategy establishes cohesive mechanisms for the design, marketing, and sale of these products through deeply segmented consumer markets.

In sum, new technologies must be carefully and deliberately rolled out to the appropriate market segment under a “total customer solutions” value proposition. Continuing under best product paradigms will only serve to relegate domestic automakers to the follower role that has witnessed the slipping of market share to foreign market leaders.

6.4 RECOMMENDATIONS FOR POLICY

Achieving significant air quality improvements requires a multimedia approach to the emissions issue. This means intervening to create economic incentives to enable desired behaviors by affected stakeholders. A two front “war” is necessary. The first front involves stimulating innovation in the most capable of industries and redistributing costs via programs such as fee-bates to lower the entry price of cleaner technologies. The second front involves regulatory interventions that catalyze technological innovation in the longer term to affect more sustainable practices as well as the development of an infrastructure to perpetuate the continued use of those practices.

Although the United States requires the use of state-of-the-art pollution control devices, consistently low gas prices reduce the cost of vehicle ownership and thereby fail to reflect the real cost, or externality cost, to society due to their increased usage. Therefore, little incentive exists for consumers to modify behavior that is aligned with emissions and energy dependence reduction goals. A good deal of the potential for vehicle emissions reductions involves removing the fleet of “dirtier” vehicles from the road earlier. Unfortunately, the costs imposed by the requirement for more fuel efficient vehicles has, in concert with factors such as vehicle safety and crash worthiness, increased the real price of new cars, with consequences that work counter to emissions goals. Higher purchase prices translate to lower turnover, as consumers must amortize the higher cost over a longer period of ownership. Lower turnover means the worse polluting vehicles stay on the road longer. To contend with this perverse incentive, policies should work to increase the *operating* cost of the worst polluting vehicles, including trucks, SUVs, and minivans, while simultaneously redistributing vehicle purchase prices to reflect implicit externality costs. This can be achieved by levying an “emissions tax” with annual vehicle registration and renewal. Authorities can then target these moneys, in concert with point of sale fees, toward point of sale and registration-based rebates for relatively cleaner vehicles.

In addition to policies that encourage diffusion of cleaner technologies, authorities must incentivize behaviors beneficial to air quality in the longer term. Considerable air quality gains can be achieved via the encouragement of higher-occupancy modes of transport. Most importantly, however, authorities must provide transport mode choice to the public. Moneys

collected from low-occupancy transit can be redistributed to expand the metro network. Additionally, coordination at the metropolitan level must expand to comprise land use planning activities that incentivize transit-oriented development efforts by offering tax-relief and credits to builders who choose to build near strategic transit destinations. This also means increasing taxation on those developers who choose to operate irrespective of development guidelines. Such efforts can go far toward mitigating the air quality impacts of urban sprawl in the longer term.

Another key enabler for public intervention is education and awareness. Contemporary acceptance of harmful motor vehicle emissions bears striking similarities with early efforts to understand and eventually curb tobacco use. As evidence from the medical community implicated tobacco products and exposure to second-hand smoke with increased incidence of lung disease and cancer, organizations such as the American Lung Association and the American Cancer Society unleashed a sustained blitz of media campaigns to alert and educate consumers to the hazards of smoking. Grass roots lobbying efforts further succeeded in enacting laws and local statutes prohibiting smoking in public places. The recent shift in research focus to understanding the adverse health impacts of motor vehicle emissions may portend similar developments. With mounting epidemiological evidence coming to the public's attention, awareness campaigns that warn of the hazards of motor vehicle use may emerge to educate consumers and stimulate demand for cleaner propulsion technologies.

In summary, policies should use a multimedia approach to both enabling innovative capacity and to modify consumer and industry behavior over time. Authorities should target interventions that co-optimize economic growth with tangential benefits to air quality. Establishing a fee-bate policy regime that redistributes costs to reflect externality impacts away from high emission vehicle use and toward the combination of low emissions vehicles and infrastructure-building activities that support higher-occupancy modes can achieve this. For example, expansion of the metro network combined with tax incentives and development waivers that favor transit-oriented development works on two fronts. First, it can enable technological innovation that serves to "lock-in" a more desired future by laying the mass-transit infrastructure network. Second, in so doing the inherent architecture of the network encourages and shapes future behavioral patterns of the consuming public in a direction beneficial to air quality.

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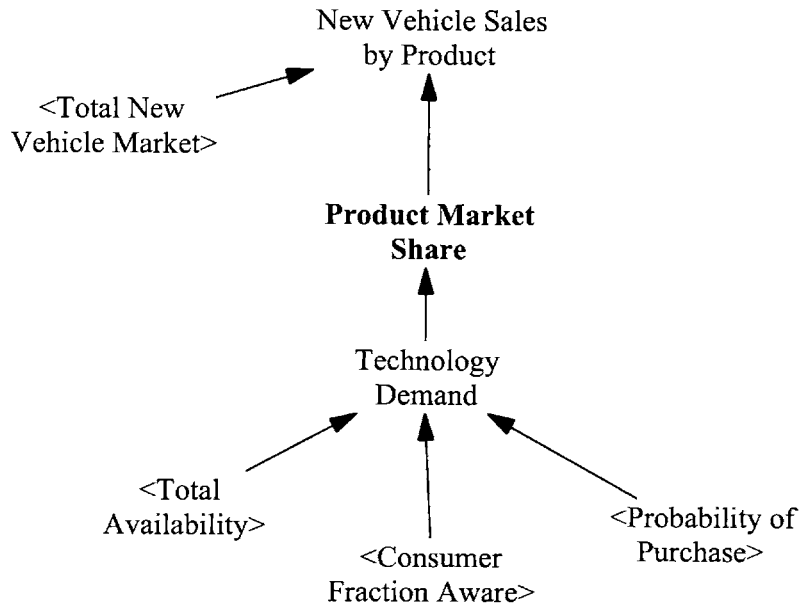
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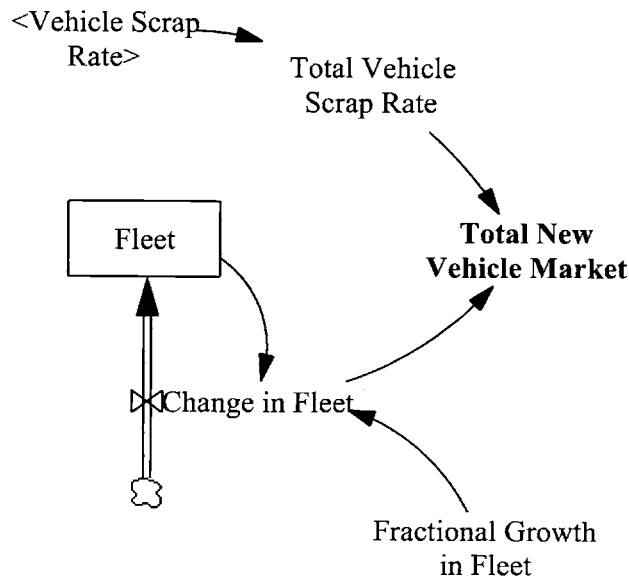
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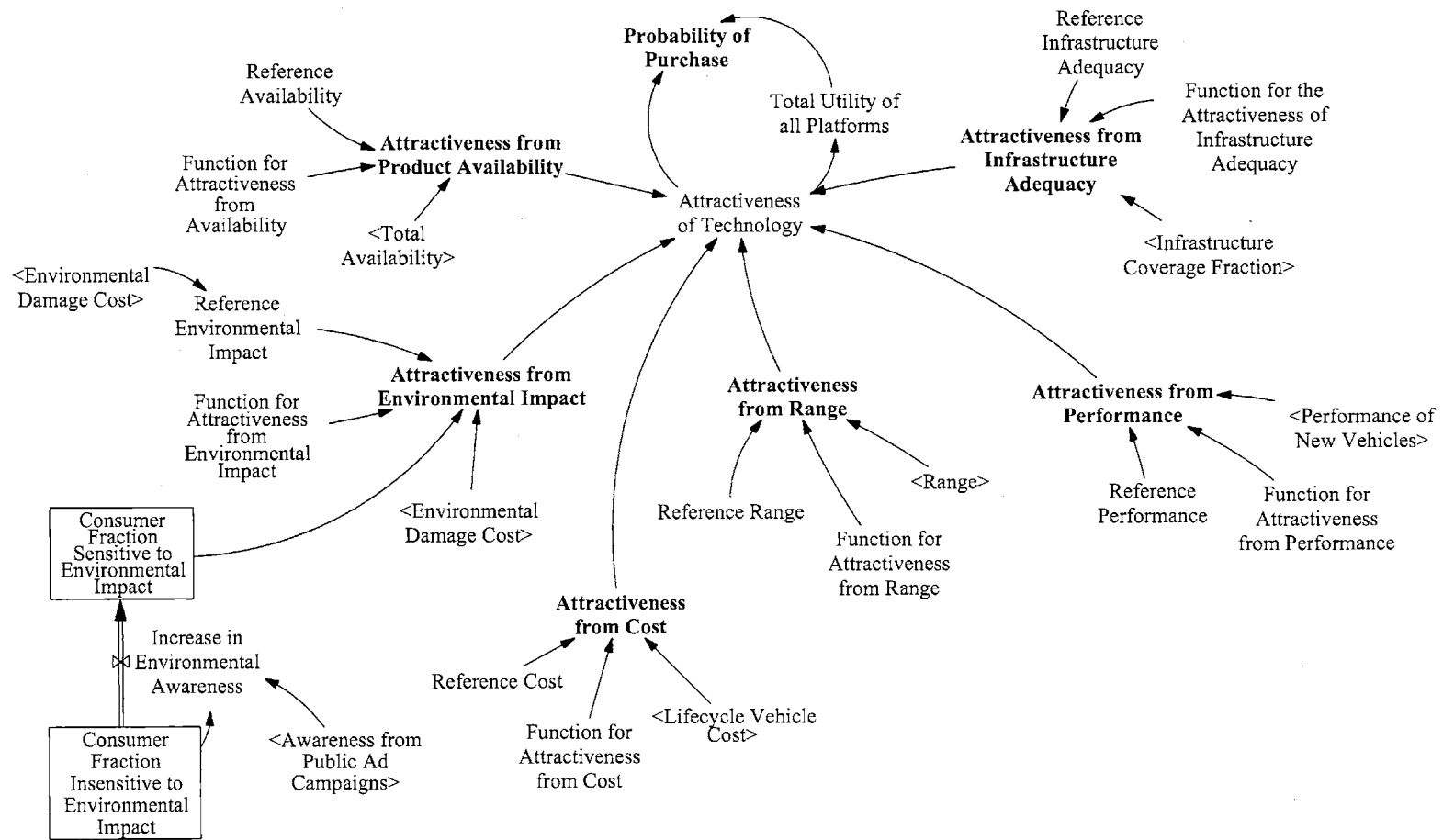
APPENDIX – MODEL DOCUMENTATION



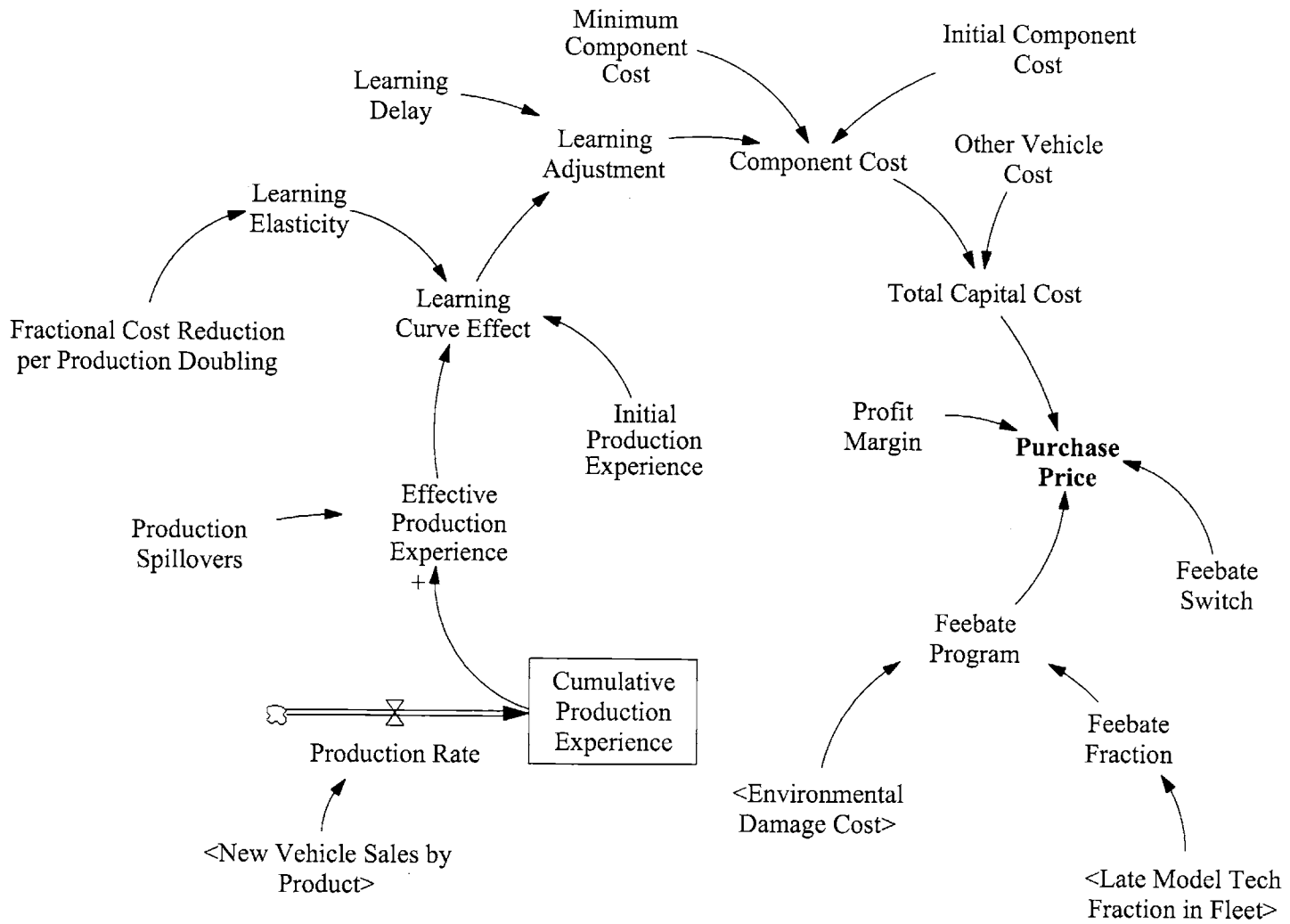
View 1 – Demand, Market Share, and New Vehicle Sales View



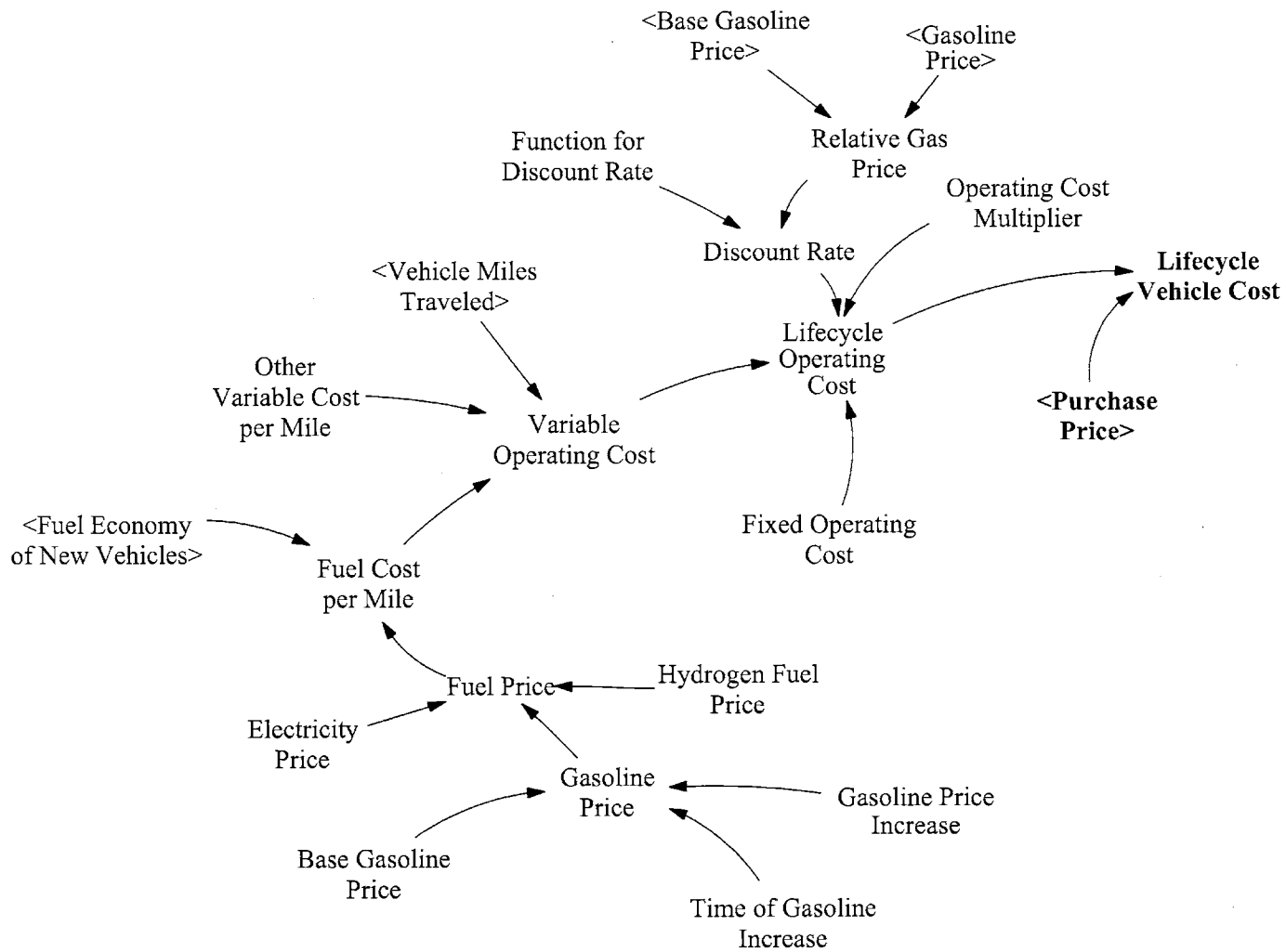
View 2 – New Vehicle Market



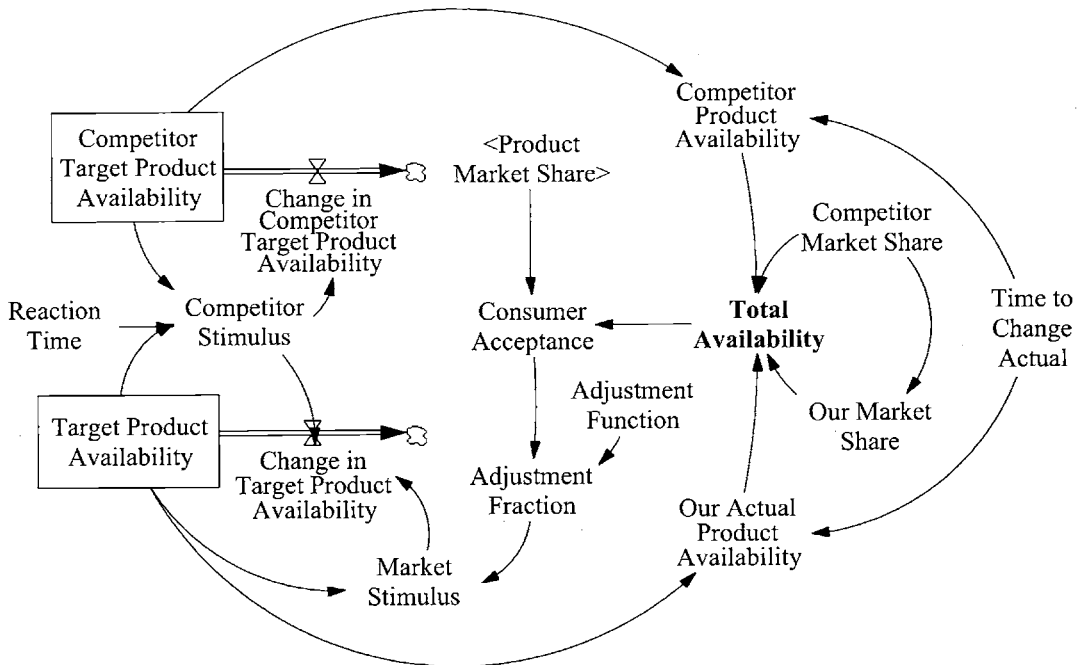
View 3 – Formulation of Probability of Purchase from Vehicle Attributes



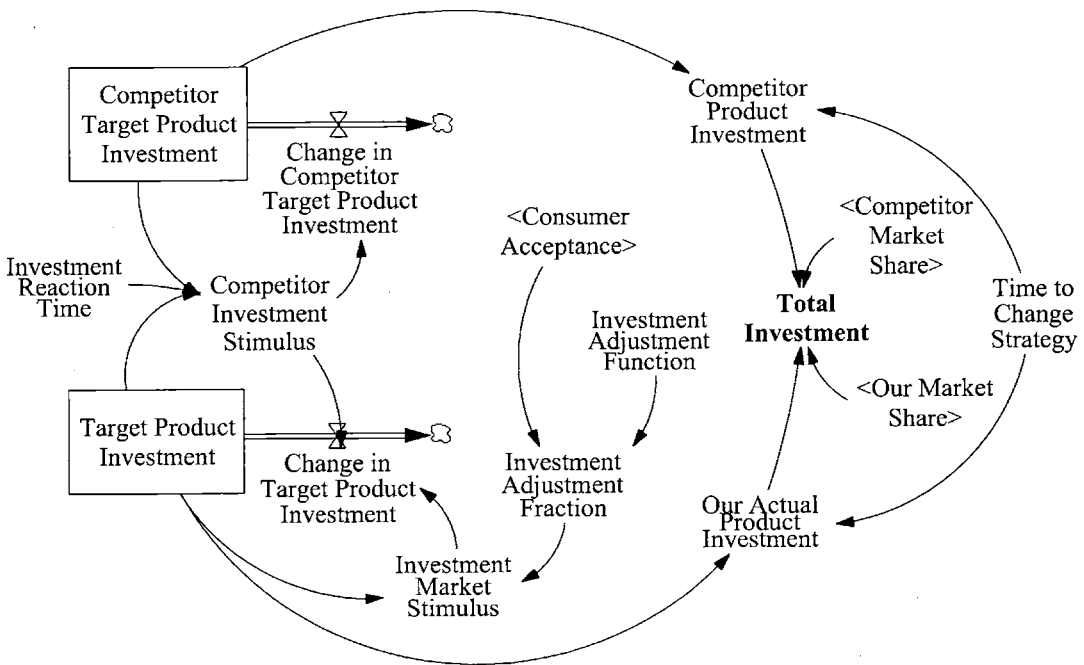
View 4 - Formulation of Vehicle Purchase Price



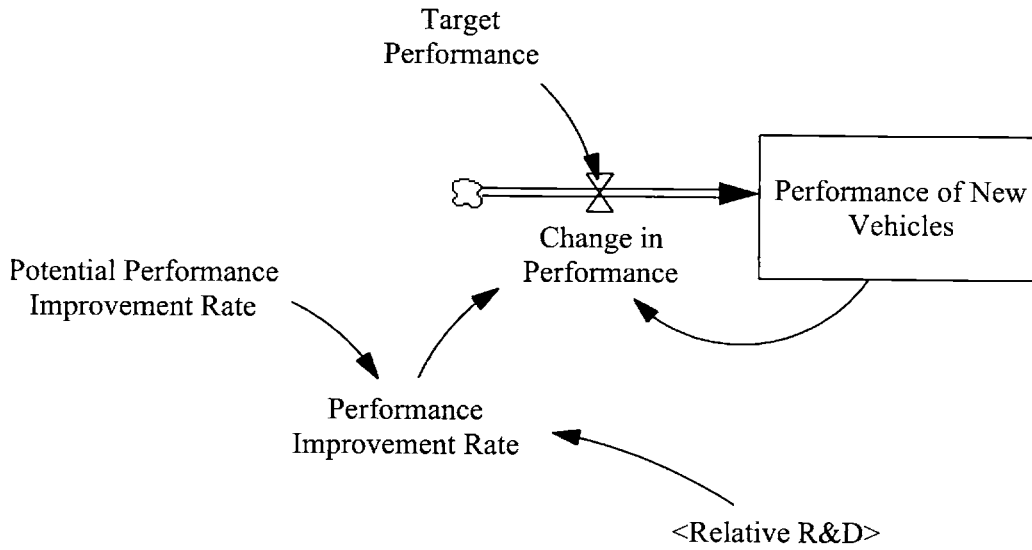
View 5 - Total Life Cycle Vehicle Cost Construct



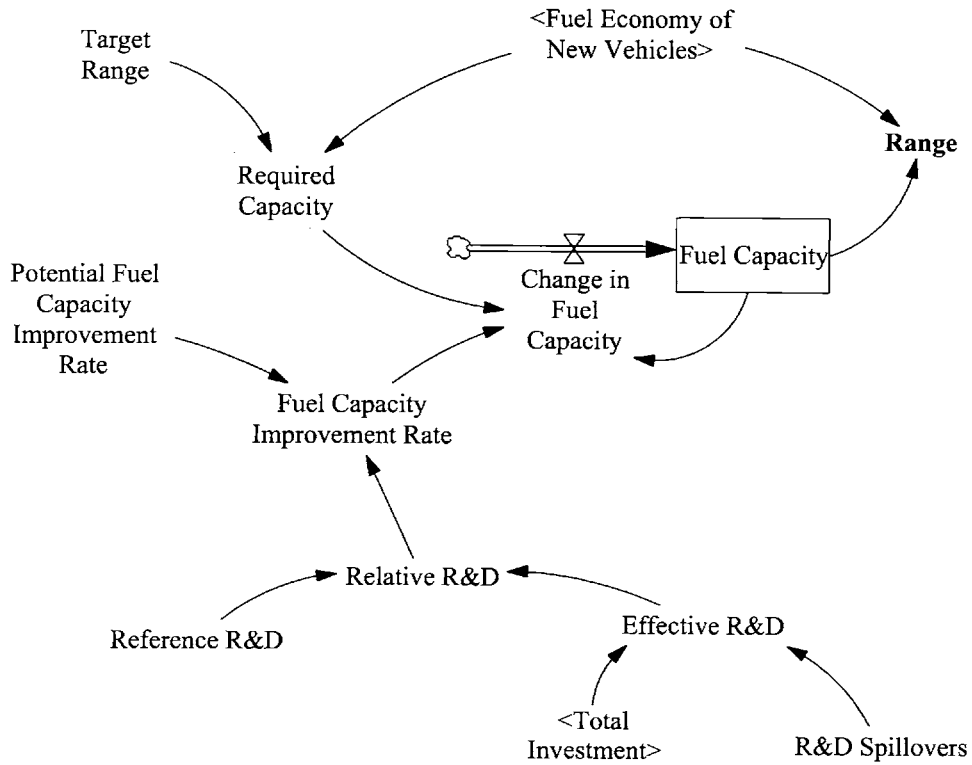
View 7 – Competitor and Market Stimulus yield Total Product Availability



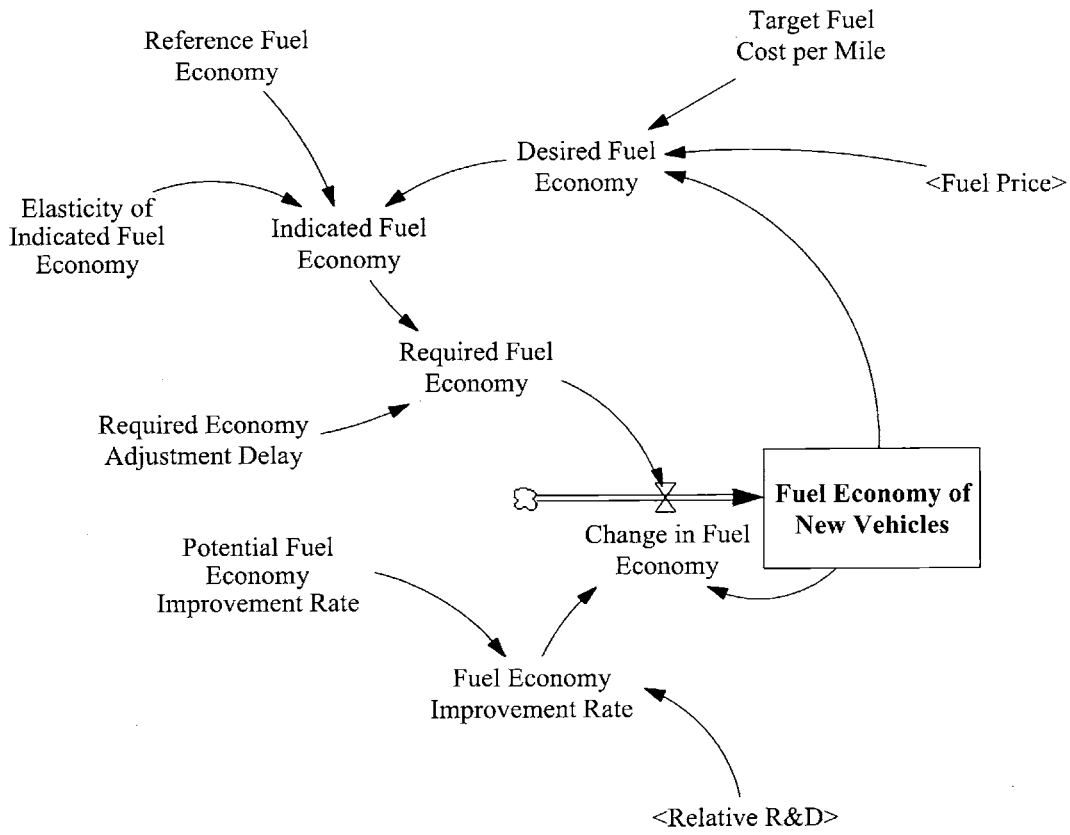
View 8 – Total Investment Input to Learning Engines



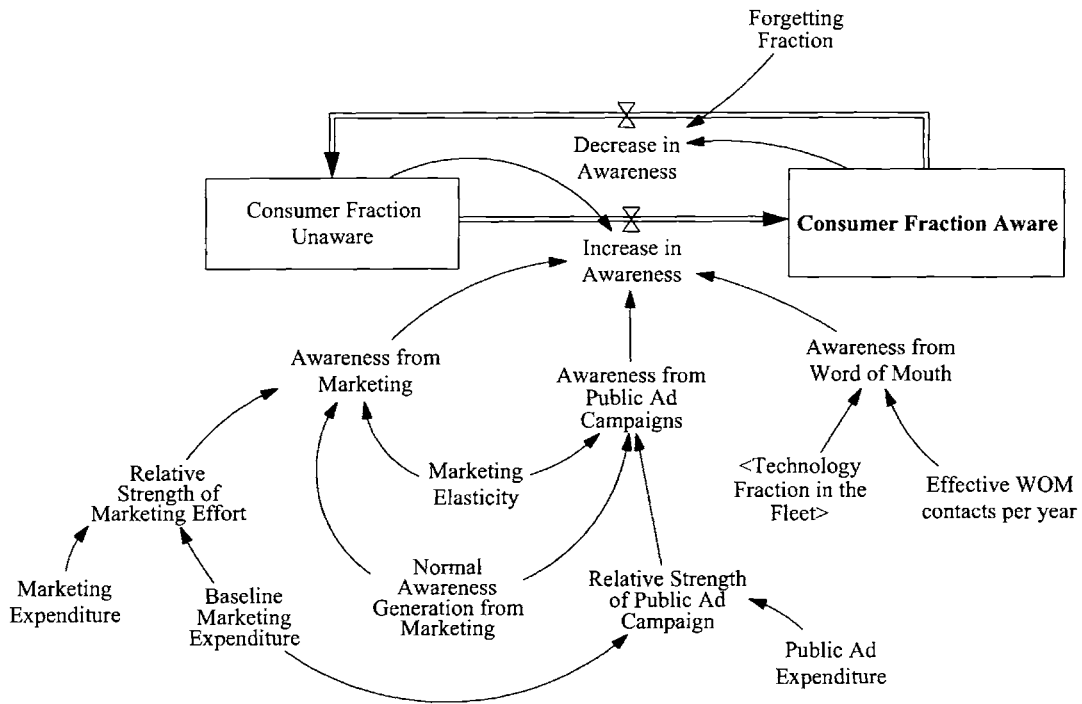
View 9 – New Vehicle Performance Learning Engine



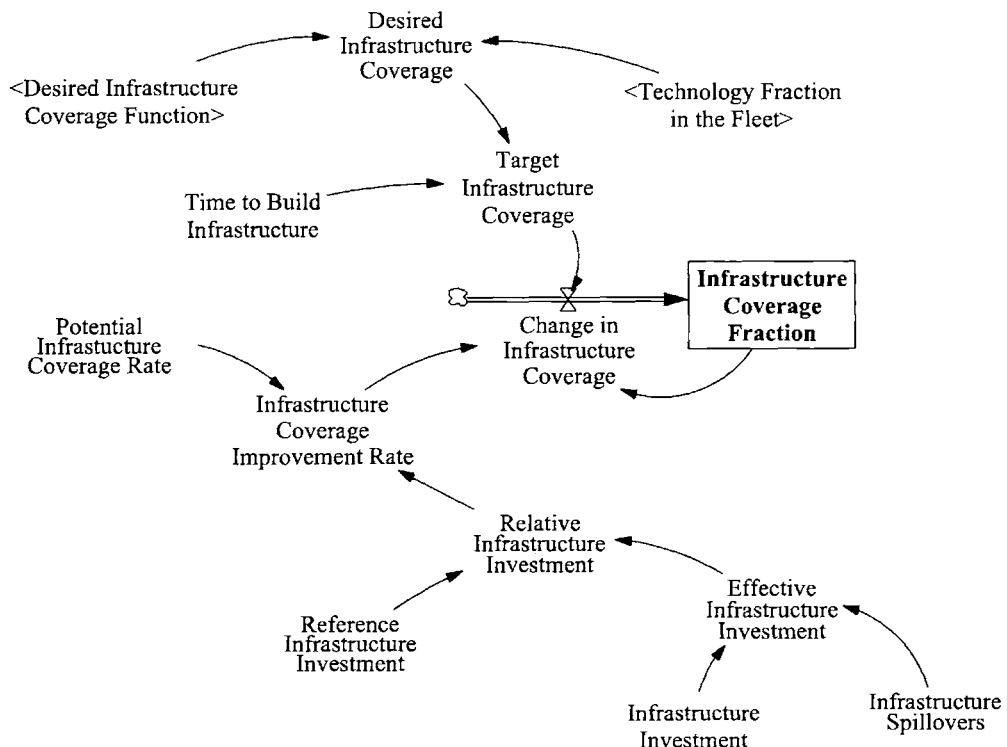
View 10 – Fuel Capacity/Energy Density Learning Engine for Vehicle Range



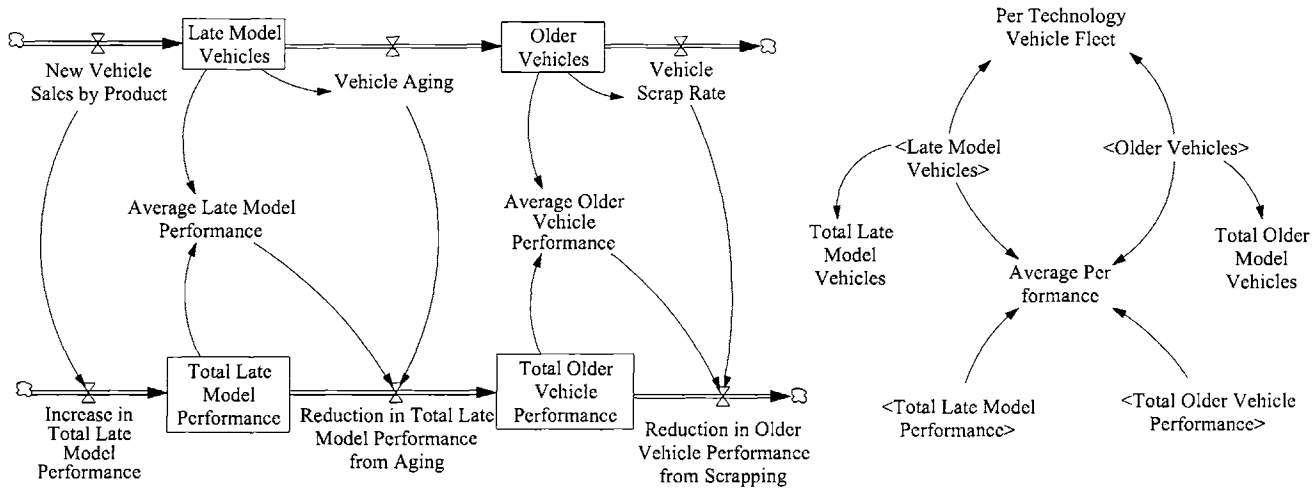
View 11 – New Vehicle Fuel Economy Learning Engine



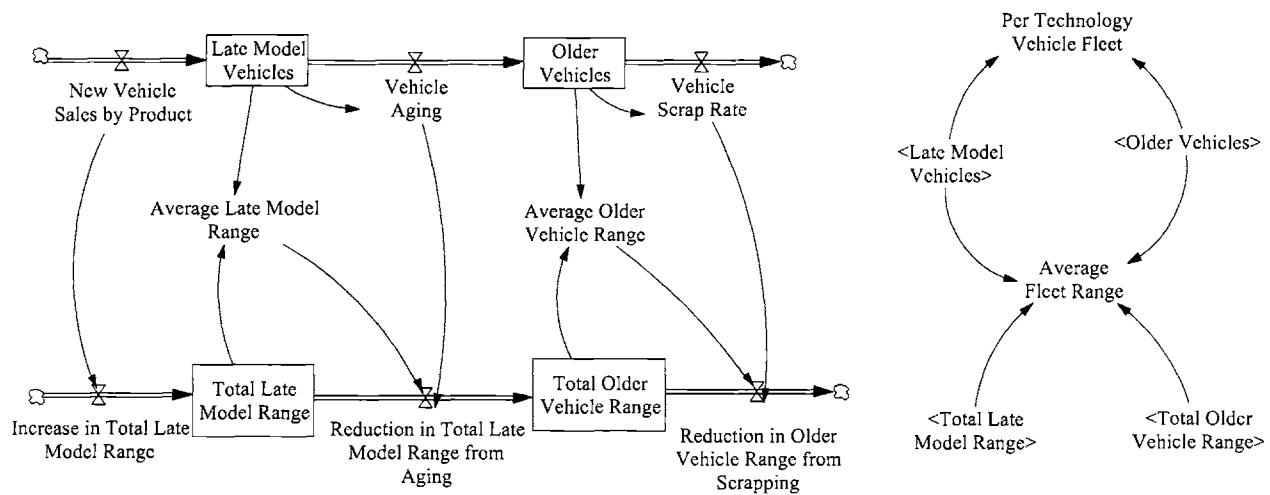
View 12 – Consumer Awareness Construct



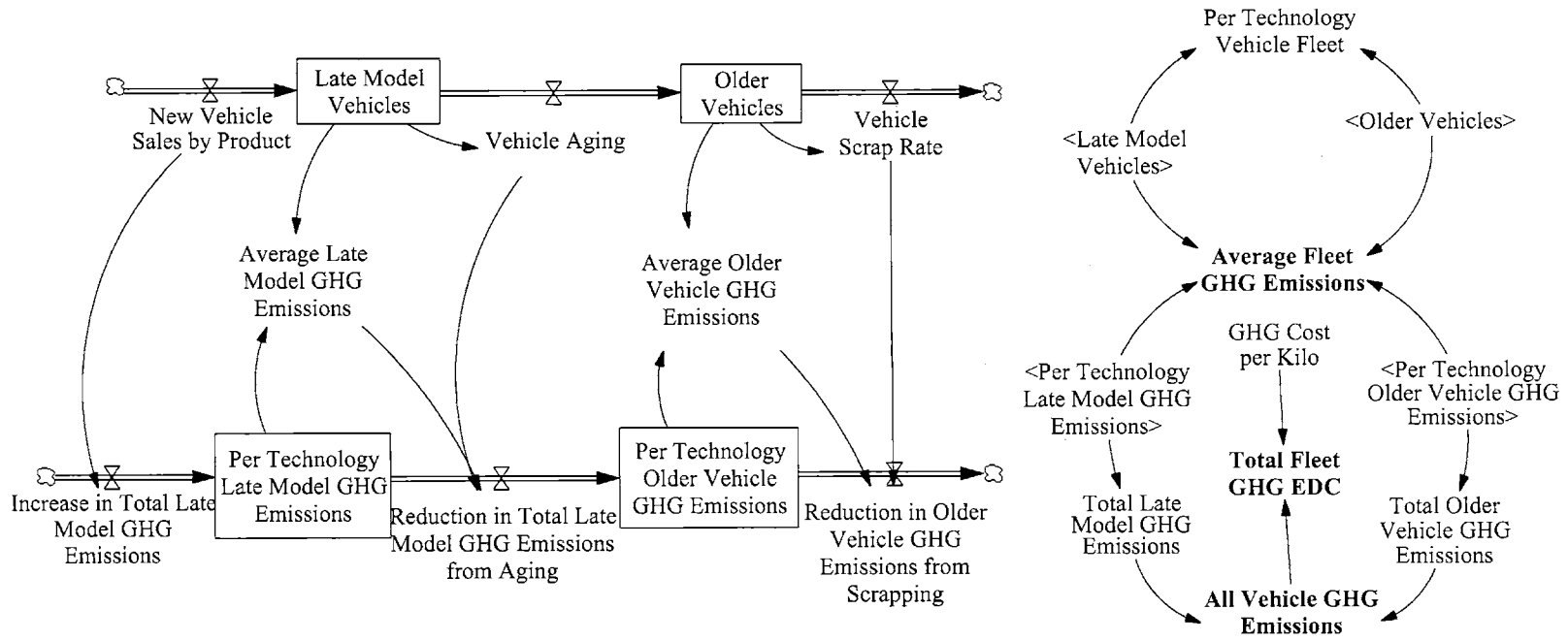
View 13 – Infrastructure Coverage Construct



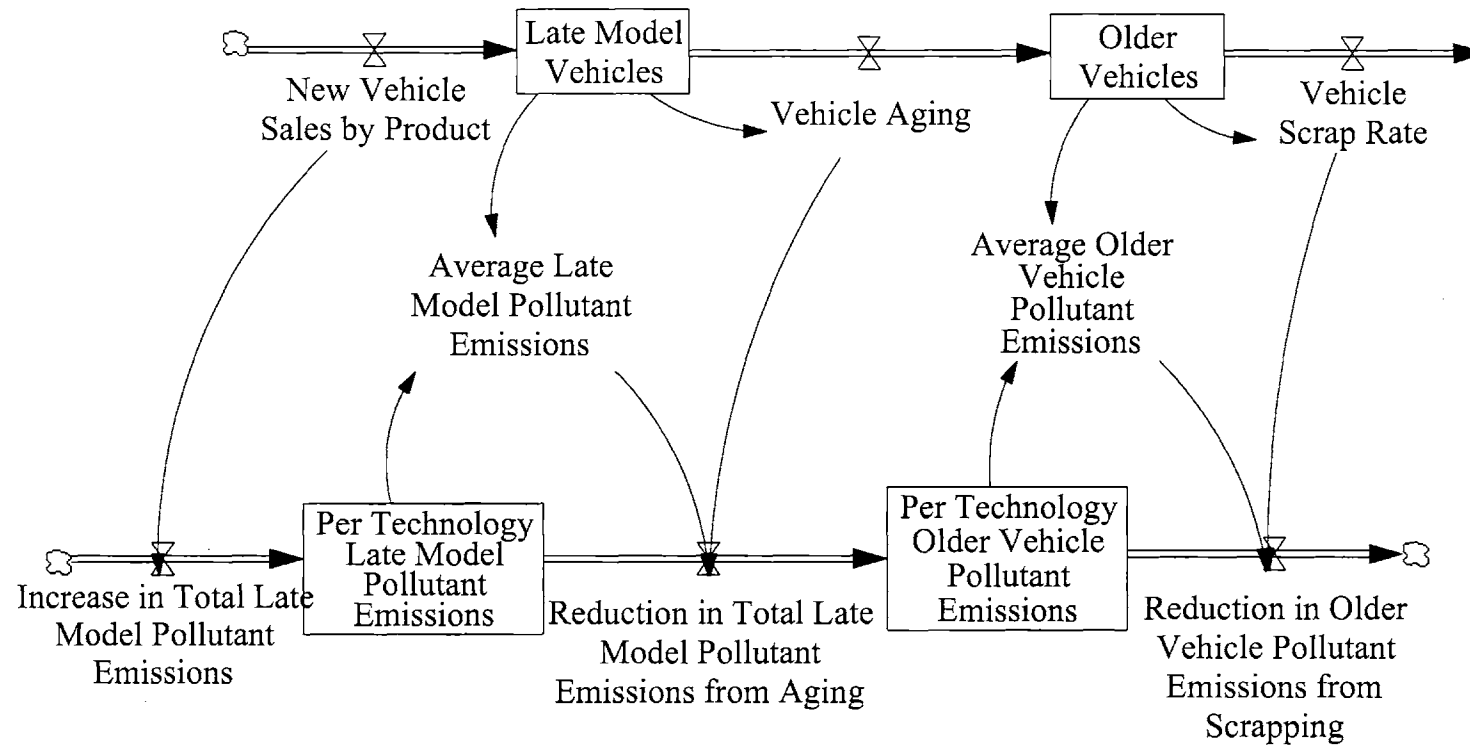
View 15 – Aging Chain & Co-flow Construct for Vehicle Performance



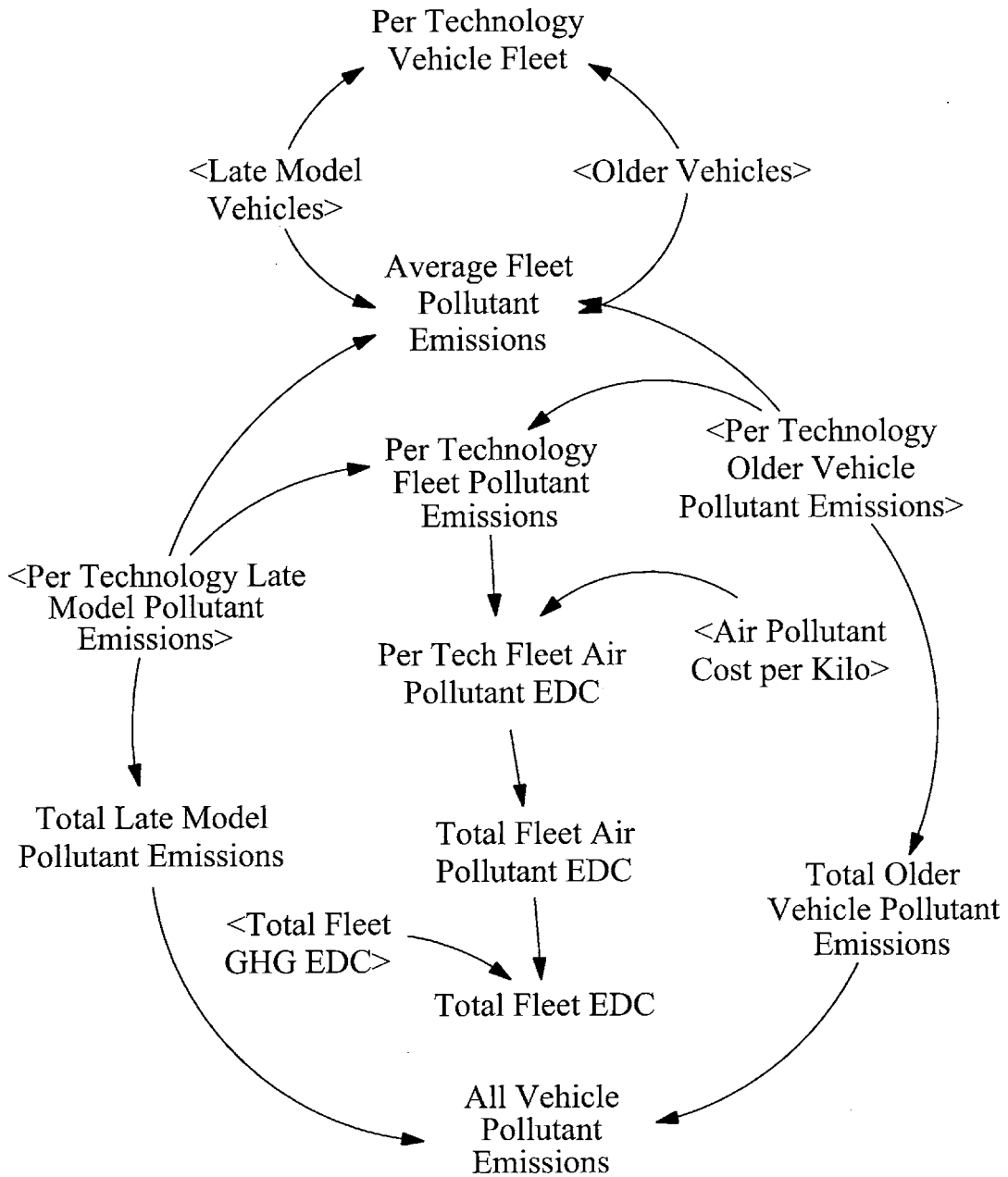
View 16 – Aging Chain & Co-flow Construct for Tracking Vehicle Range



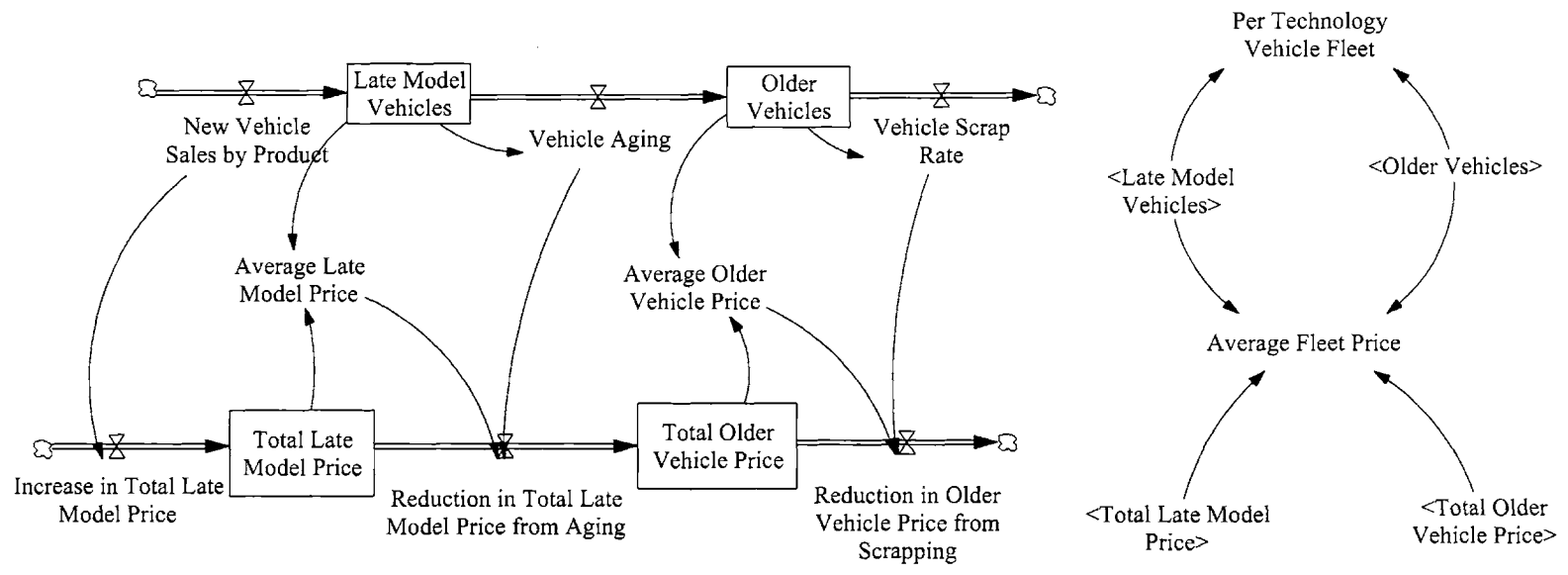
View 17 – Aging Chain & Co-flow Construct for Tracking Fleet GHG Emissions



View 18 – Aging Chain & Co-flow Construct for Tracking Fleet Pollutant Emissions



View 19 – Environmental Damage Cost



View 20 – Aging Chain & Co-flow Construct for Tracking Vehicle Price

Variable Definitions (in Alphabetical Order)

- (1) Air Pollution Cost[technology]=
Air Pollutant Cost per Kilo[technology]*Annual Pollutant emissions[technology]
Units: \$/car/Year
The cost of air pollution generated by each vehicle is the product of the cost per kilo of pollutant generated and emissions.
- (2) All Vehicle Pollutant Emissions=
Total Late Model Pollutant Emissions+Total Older Vehicle Pollutant Emissions
Units: kilograms/Year
All Vehicle Pollutant Emissions equals the total pollutant emissions of criteria pollutants by the entire vehicle fleet.
- (3) Annual CO2 emissions[technology]=
Annual Fuel Consumption[technology]*CO2 emissions per gallon[technology]
Units: kilograms/car/Year
Carbon dioxide emissions depend on fuel consumption per year and the carbon density of fuel.
- (4) Annual Fuel Consumption[technology]=
Vehicle Miles Traveled/Fuel Economy of New Vehicles[technology]
Units: gallons/car/Year
Fuel consumed per year is the vehicle miles travelled per year divided by fuel economy: more miles per year or lower fuel economy raise fuel consumption and hence emissions.
- (5) Annual Pollutant emissions[technology]=
Pollutant Emissions per Mile[technology]*Vehicle Miles Traveled
Units: kilograms/car/Year
Pollutants include NOx and particulates; the emission rate depends on fuel consumption and the pollutant load per gallon of fuel.
- (6) "Annualized All-Technology EDC"=
SUM(Annualized per Technology EDC[technology])
Units: \$/Year
Annualized All-Technology EDC represents the cumulative environmental damage cost created by all vehicles of all technology types on the road in a given year.
- (7) Annualized Environmental Damage Cost[technology]=
Air Pollution Cost[technology]+Greenhouse Gas Cost[technology]
Units: \$/(Year*car)

Annualized EDC is the Annual Cost of Environmental Damage borne by society. This includes public health, climate change, accelerated species extinction, and other externalities.

- (8) Annualized per Technology EDC[technology]=
Annualized Environmental Damage Cost[technology]*Per Technology Vehicle Fleet[technology]
Units: \$/Year
Annualized per Technology On-Road EDC represents the cumulative environmental damage cost created by all vehicles of a specific technology type on the road in a given year.
- (9) Attractiveness from Consumer Awareness[technology]=
Function for Attractiveness from Awareness(Consumer Fraction Aware[technology]/Reference Awareness)
Units: Dmnl
Other sources of value catches all other vehicle attributes not specifically broken out that the consumer factors into their purchase decision. We assume for the model that all other sources of value are equally shared by each of the vehicle propulsion/fuel system combinations.
- (10) Attractiveness from Cost[technology]=
Function for Attractiveness from Cost(Lifecycle Vehicle Cost[technology]/Reference Cost)
Units: Dmnl
Attractiveness from Cost is the utility, or value, that the consumer expects for a given cost relative to a reference cost.
- (11) Attractiveness from Environmental Impact[technology]=
(1 + Consumer Fraction Sensitive to Environmental Impact*(Function for Attractiveness from Environmental Impact(Environmental Damage Cost [technology]/Reference Environmental Impact) -1))
Units: Dmnl
Attractiveness from environmental impact is a function of environmental damage cost. The higher the sensitivity to environmental impact, the greater the affect of environmental damage on vehicle attractiveness (high or low); sensitivity of zero implies no impact on attractiveness.
- (12) Attractiveness from Infrastructure Adequacy[technology]=
Function for the Attractiveness of Infrastructure Adequacy[technology](Infrastructure Coverage Fraction [technology]/Reference Infrastructure Adequacy)
Units: Dimensionless
Attractiveness from Infrastructure Adequacy is the utility, or value, that the consumer derives from the level of infrastructure coverage associated with a particular advanced fuel/technology system.

- (13) Attractiveness from Performance[technology]=
 Function for Attractiveness from Performance(Performance of New Vehicles[technology] /Reference Performance)
 Units: Dmnl
 Attractiveness from Performance is the utility, or value, that the consumer derives from the level of performance offered by the vehicle under consideration for purchase.
- (14) Attractiveness from Product Availability[technology]=
 Function for Attractiveness from Availability(Total Availability[technology]/Reference Availability)
 Units: Dimensionless
 This parameter serves to modestly penalize those powertrain technologies that have less than the reference availability of the ICE. Although lack of availability can provide a market stimulus for the technology, it can also encourage consumers to defect to more available product technologies.
- (15) Attractiveness from Range[technology]=
 Function for Attractiveness from Range(Range[technology]/Reference Range)
 Units: Dmnl
 The Range function captures the utility derived by the customer as a function of the vehicle's range between fuelings. The consumer tends to attribute a significant preference penalty for any vehicle whose range falls under approximately 200 miles on a single fueling. Attractiveness is benchmarked against a reference range equal to 400 miles for an advanced body vehicle.
- (16) Attractiveness of Technology[technology]=
 Attractiveness from Cost[technology]* Attractiveness from Performance[technology]* Attractiveness from Range [technology]* Attractiveness from Environmental Impact[technology]* Attractiveness from Infrastructure Adequacy[technology]* Attractiveness from Product Availability[technology]
 Units: Dmnl
 The Consumer Attractiveness for a given propulsion/fuel platform is the product of the attractiveness of each attribute under consideration at the point of purchase.
- (17) Average Fleet GHG Emissions[technology]=
 ((Per Technology Late Model GHG Emissions[technology]+Per Technology Older Vehicle GHG Emissions[technology])/(Late Model Vehicles[technology]+Older Vehicles[technology]))
 Units: kilograms/(Year*car)
 Average Fleet GHG Emissions is the average per vehicle annual GHG

emissions of all vehicles, late model and older.

(18) Average Fleet Pollutant Emissions[technology]=
((Per Technology Late Model Pollutant Emissions[technology]+Per
Technology Older Vehicle Pollutant Emissions
[technology])/(Late Model Vehicles[technology]+Older
Vehicles[technology]))
Units: kilograms/(Year*car)
Average Fleet Pollutant Emissions is the average per vehicle annual
Pollutant emissions of all vehicles, late model and older.

(19) Average Fleet Price[technology]=
((Total Late Model Price[technology]+Total Older Vehicle
Price[technology])/(Late Model Vehicles
[technology]+Older Vehicles[technology]))
Units: \$/car
Average Fleet Price is the average annual per vehicle price of all
vehicles, late model and older.

(20) Average Fleet Range[technology]=
(Total Late Model Range[technology] + Total Older Vehicle Range
[technology])/(Late Model Vehicles[technology] + Older
Vehicles[technology])
Units: miles
Average Fleet Range represents the average range of the total fleet of
vehicles for a given technology.

(21) Average Fuel Economy[technology]=
(Per Technology Late Model Fuel Economy[technology] + Per
Technology Older Vehicle Fuel Economy
[technology])/(Late Model Vehicles
[technology] + Older Vehicles[technology])
Units: miles/gallon
Average fuel economy of the portion of the fleet representing a particular
propulsion technology.

(22) Average Late Model Fuel Economy[technology]=
Per Technology Late Model Fuel Economy[technology]/Late Model
Vehicles[technology]
Units: miles/gallon
Average Late Model Fuel Economy is the average fuel economy of the fleet
of all late model vehicles of a particular propulsion technology on the road.

(23) Average Late Model GHG Emissions[technology]=
Per Technology Late Model GHG Emissions[technology]/Late Model
Vehicles[technology]

Units: kilograms/(Year*car)
Average Late Model GHG Emissions is the average annual per vehicle GHG emissions resulting from the fleet of late model vehicles.

- (24) Average Late Model Performance[technology]=
Total Late Model Performance[technology]/Late Model Vehicles[technology]
Units: Dimensionless
Average Late Model Performance is the average performance of all late model vehicles of a particular propulsion technology.
- (25) Average Late Model Pollutant Emissions[technology]=
Per Technology Late Model Pollutant Emissions[technology]/Late Model Vehicles[technology]
Units: kilograms/(Year*car)
Average Late Model Pollutant Emissions is the average annual per vehicle Pollutant emissions resulting from the fleet of late model vehicles.
- (26) Average Late Model Price[technology]=
Total Late Model Price[technology]/Late Model Vehicles[technology]
Units: \$/car
Average Late Model Price is the average annual per vehicle Price derived from averaging the prices of the fleet of late model vehicles.
- (27) Average Late Model Range[technology]=
Total Late Model Range[technology]/Late Model Vehicles[technology]
Units: miles
Average Late Model Range is the average range of the fleet of late model vehicles
- (28) Average Older Vehicle Fuel Economy[technology]=
Per Technology Older Vehicle Fuel Economy[technology]/Older Vehicles[technology]
Units: miles/gallon
Average Older Vehicle Fuel Economy represents the average fuel economy for a particular technology of the fleet of older vehicles.
- (29) Average Older Vehicle GHG Emissions[technology]=
Per Technology Older Vehicle GHG Emissions[technology]/Older Vehicles[technology]
Units: kilograms/(Year*car)
Average Older Vehicle GHG Emissions is the average annual per vehicle GHG emissions resulting from the fleet of older vehicles.
- (30) Average Older Vehicle Performance[technology]=

Total Older Vehicle Performance[technology]/Older Vehicles[technology]

Units: Dimensionless

Average Older Vehicle Performance is the average performance of the fleet of older vehicles for a particular technology.

(31) Average Older Vehicle Pollutant Emissions[technology]=

Per Technology Older Vehicle Pollutant Emissions[technology]/Older Vehicles[technology]

Units: kilograms/(Year*car)

Average Older Vehicle Pollutnat Emissions is the average annual per vehicle Pollutant emissions resulting from the fleet of older vehicles.

(32) Average Older Vehicle Price[technology]=

Total Older Vehicle Price[technology]/Older Vehicles[technology]

Units: \$/car

Average Older Vehicle Price is the average annual per vehicle price derived from averaging the prices of the fleet of older vehicles.

(33) Average Older Vehicle Range[technology]=

Total Older Vehicle Range[technology]/Older Vehicles[technology]

Units: miles

Average Older Vehicle Range is the average range of the fleet of older vehicles

(34) Average Performance[technology]=

(Total Late Model Performance[technology] + Total Older Vehicle Performance[technology])/(Late Model Vehicles[technology] + Older Vehicles[technology])

Units: Dimensionless

Average Performance is the average performance of the total fleet

(35) Awareness from Marketing[technology]=

Normal Awareness Generation 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.

(36) Awareness from Public Ad Campaigns=

Normal Awareness Generation from Marketing*(Relative Strength of Public Ad Campaign)^Marketing Elasticity

Units: 1/Year

Awareness from Public Ad Campaigns is equal to the baseline awareness from marketing, multiplied by the relative strength of the public advertisement

campaign effort raised to the marketing elasticity.

- (37) Awareness from Word of Mouth[technology]=
Effective WOM contacts per year*Technology Fraction in the
Fleet[technology]
Units: 1/Year
Awareness from Word of Mouth is equal to the Technology Fraction in the
Fleet multiplied by the Effective Word of Mouth contacts per year.
- (38) Base Gasoline Price=1.43
Units: \$/gallon
The Base Gasoline Price is set at \$1.43 per gallon and are current as of
8/20/01(Source: EIA "Weekly U.S. Retail Gasoline Prices," Regular Grade
for 8/20/2001)
- (39) Baseline Marketing Expenditure=1
Units: Dmnl/Year
Baseline marketing spending (e.g., 30,000,000/year) is sufficient to generate
awareness at the normal fractional rate.
- (40) Change in Competitor Target Product Availability[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.
- (41) Change in Competitor Target Product Investment[technology]=
-Competitor Investment 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.
- (42) Change in Fleet=
Fractional Growth in Fleet*Fleet
Units: cars/Year
Change in Fleet is equal to the annual fractional rate of fleet growth
multiplied by the size of the existing fleet of vehicles.
- (43) Change in Fuel Capacity[technology]=
(Required Capacity[technology] - Fuel Capacity[technology])*Fuel
Capacity Improvement Rate[technology]
Units: gallons/Year

Change in Fuel Capacity is the rate at which automakers desire to adjust the fuel carrying capacity of a vehicle in order to achieve range targets.

- (44) Change in Fuel Economy[technology]=
 $\text{MAX}(((\text{Required Fuel Economy}[\text{technology}]-\text{Fuel Economy of New Vehicles}[\text{technology}]) * \text{Fuel Economy Improvement Rate}[\text{technology}], 0)$
Units: miles/gallon/years
Change in Fuel Economy is the rate of change of vehicle fuel economy as a function of investment spending on technologies to improve fuel economy.
- (45) Change in Infrastructure Coverage[technology]=
 $\text{MAX}(((\text{Target Infrastructure Coverage}[\text{technology}]-\text{Infrastructure Coverage Fraction}[\text{technology}])) * \text{Infrastructure Coverage Improvement Rate}[\text{technology}], 0)$
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.
- (46) Change in Performance[technology]=
 $(\text{Target Performance}[\text{technology}]-\text{Performance of New Vehicles}[\text{technology}]) * \text{Performance Improvement Rate}[\text{technology}]$
Units: 1/years
Change in Performance is the rate of change of vehicle performance relative to the gasoline ICE as a function of investment spending on technologies to improve vehicle performance.
- (47) Change in Target Product Availability[technology]=
 $\text{MAX}(\text{Market Stimulus}[\text{technology}], \text{Competitor Stimulus}[\text{technology}])$
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.
- (48) Change in Target Product Investment[technology]=
 $\text{MAX}(\text{Investment Market Stimulus}[\text{technology}], \text{Competitor Investment Stimulus}[\text{technology}])$
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.

- (49) CO2 emissions per gallon[technology]=
11.514, 11.917, 12.312, 25.805
Units: kilograms/gallon
The carbon density of each fuel is the number of kilos of CO2 generated per gallon equivalent. For electricity and hydrogen, the CO2 emissions per gallon gasoline equivalent depend on how the H2 or electricity are generated (what primary fuels are used to generate them). Data are from Weiss et al (2000)
- (50) Competitor Investment Stimulus[technology]=
(Competitor Target Product Investment[technology]-Target Product Investment[technology])/Investment Reaction Time
Units: 1/Year
The Competitor Investment Stimulus is the difference between our target investment and their target investment, divided by the time it takes to change the target investment. It impacts Change in Their Target directly, and the negative Competitor Stimulus impacts Change in Our Target.
- (51) Competitor Market Share=0.5
Units: Dmnl
Competitor Market Share is assumed to be constant at 50% of the market.
- (52) Competitor Product Availability[technology]=
IF THEN ELSE(technology=ICE, 1, DELAY3I(Competitor Target Product 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.
- (53) Competitor Product Investment[technology]=
IF THEN ELSE(technology=ICE, 1, DELAY3I(Competitor Target Product Investment[technology], Time to Change Strategy, 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.
- (54) Competitor Stimulus[technology]=

(Competitor Target Product Availability[technology]-Target Product 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.

(55) Competitor Target Product Availability[technology]=
INTEG (Change in Competitor Target Product Availability[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).

(56) Competitor Target Product Investment[technology]=
INTEG (Change in Competitor Target Product Investment[technology],
IF THEN ELSE(technology=ICE, 1, 0))

Units: Dmnl

Competitor Target Product Investment represents the allocation of the vehicle technology investment budget relative to ongoing investment in ICE

at the outset for the model period. The fraction of the total budget dedicated to a specific propulsion technology serves to accelerate development of key product attributes for consumer acceptance. This target is reflective of the competitor's technology strategy and is a stock that integrates the Change in Competitor Target Product Investment. The initial target is 0 for all technologies except ICE (which stays at a fraction of 1 throughout).

(57) Component Cost[technology]=
(Initial Component Cost[technology]-Minimum Component
Cost[technology])*Learning Adjustment
[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.

(58) Consumer Acceptance[technology]=
ZIDZ(Product 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".

(59) Consumer Fraction Aware[technology]=

INTEG (+Increase in Awareness[technology]-Decrease in Awareness[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.

(60) Consumer Fraction Insensitive to Environmental Impact=

INTEG (-Increase in Environmental Awareness, 1-Initial Sensitivity to Environmental Impact)
Units: Dmnl

Consumer Fraction Insensitive to Environmental Impact represents the pool of consumers who do not factor in environmental considerations in their purchase decision.

(61) Consumer Fraction Sensitive to Environmental Impact=

INTEG (+Increase in Environmental Awareness, Initial Sensitivity to Environmental Impact)
Units: Dmnl

Sensitivity to Environmental Impact represents the degree to which consumers consider negative air quality, health hazard, and other environmental impacts in their purchase decision. Growth to unity in 2032 can be approximated via an initial value of 0.07 with a fractional growth rate of .095. Initial Sensitivity is a scenario available and can be adjusted.

(62) Consumer Fraction Unaware[technology]=

INTEG (+Decrease in Awareness[technology]-Increase in Awareness[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).

- (63) Cumulative Air Pollution Cost[technology]=
 Air Pollution Cost[technology]*Vehicle Life
 Units: \$/car
 Cumulative Air Pollution Cost is the total monetized cost of environmental damage caused by a single vehicle over its lifetime.
- (64) Cumulative GHG Cost[technology]=
 Greenhouse Gas Cost[technology]*Vehicle Life
 Units: \$/car
 Cumulative GHG Cost is the total monetized cost of environmental damage from greenhouse gas emissions by a single vehicle over its lifetime.
- (65) 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.
- (66) Decrease in Awareness[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.
- (67) Desired Fuel Economy[technology]=
 MAX((Fuel Price[technology]/Target Fuel Cost per Mile[technology]), Fuel Economy of New Vehicles[technology])
 Units: miles/gallon
 The fuel economy consumers would like to achieve the target fuel cost per vehicle mile at current fuel prices.
- (68) Desired Infrastructure Coverage[technology]=
 IF THEN ELSE(Technology Fraction in the Fleet[technology]<0.2, Desired Infrastructure Coverage Function[technology](Technology Fraction in the Fleet [technology]), 1)
 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.
- (69) 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, coverage is 100% regardless of fleet fraction.

(70) Desired Infrastructure Coverage Function[hybrid]

$(((0,0)-(0.2,1)),(0,1),(0.2,1))$

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, coverage is 100% regardless of fleet fraction.

(71) Desired Infrastructure Coverage Function[FCEV]

$(((0,0)-(0.2,1)),(0,0),(0.02,0.04),(0.04,0.1),(0.07,0.3),(0.09,0.5),(0.11,0.7),(0.14,0.85),(0.17,0.95),(0.2,1))$

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, coverage is 100% regardless of fleet fraction.

(72) Desired Infrastructure Coverage Function[EV]

$(((0,0)-(0.2,1)),(0,0),(0.02,0.04),(0.04,0.1),(0.07,0.3),(0.09,0.5),(0.11,0.7),(0.14,0.85),(0.17,0.95),(0.2,1))$

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, coverage is 100% regardless of fleet fraction.

(73) Discount Rate=

Function for Discount Rate(Relative Gas Price)

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 36% discount rate would be considered high. The discount rate adjusts dynamically with fuel price to better represent the weight of this vehicle attribute in the consumer purchase decision at the point of sale.

(74) Effective Infrastructure Investment[technology]=

SUM(Infrastructure Investment[technology]*Infrastructure Spillovers[technology,technology])

Units: \$/Year

Effective R&D is the total R&D impact when spillovers to adjacent technologies are factored in.

(75) Effective Production Experience[technology]=

SUM(Cumulative Production Experience[technology]*Production Spillovers[technology,technology])

Units: cars

Effective Production Experience is the equivalent experience gained from the production of similar technologies. There are some learning spillovers from each propulsion technology to the others.

(76) "Effective R&D"[technology]=

SUM(Total Investment[technology]*"R&D Spillovers"[technology,technology])

Units: Dmnl

Effective R&D is the total R&D impact when spillovers to adjacent technologies are factored in.

(77) Effective WOM contacts per year=

2

Units: 1/Year

The Effective WOM contacts per year represents the fraction of awareness gained through word of mouth for each percentage market share as represented by the fraction of a given technology in the fleet. The default fraction is 2 (e.g., two consumers gain awareness for every owner of the technology per year).

(78) Elasticity of Indicated Fuel Economy=

0.5

Units: Dimensionless

The sensitivity of the response of automakers' fuel economy targets relative to the economy desired by consumers. 1 = fully responsive. <1 indicates less responsiveness.

(79) 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).

(80) Environmental Damage Cost[technology]=

(Cumulative Air Pollution Cost[technology]+ Cumulative GHG Cost[technology])

Units: \$/car

Units: Total environmental damage costs are the sum of the air pollutant (NOx and particulate) costs and greenhouse gas costs.

(81) Feebate Fraction[technology]=

IF THEN ELSE(technology=ICE, 1.2-Late Model Tech Fraction in Fleet[technology], 1-Late Model Tech Fraction in Fleet[technology])

Units: Dmnl

This feebate regime establishes a fee or rebate as a percentage of the differential in total environmental damage cost between incumbent technologies and cleaner advanced powertrain alternatives. This scheme attempts to redistribute EDC by starting at a relatively low level and then modestly increasing fees on ICE to fund rebates on new technologies. These rebates start high to help new technologies reach a market-clearing level and then phase out of existence as they penetrate the market.

(82) Feebate Program[ICE]=

(Environmental Damage Cost[ICE]-Environmental Damage Cost[hybrid])*Feebate Fraction[ICE]

Units: \$/car

The Feebate Program represents a regulatory intervention that attempts to redistribute externality costs to accurately reflect the "true" cost of the vehicle to consumers.

(83) Feebate Program[hybrid]=

(Environmental Damage Cost[ICE]-Environmental Damage Cost[hybrid])*Feebate Fraction[hybrid]

Units: \$/car

The Feebate Program represents a regulatory intervention that attempts to

redistribute externality costs to accurately reflect the "true" cost of the vehicle to consumers.

(84) Feebate Program[FCEV]=

(Environmental Damage Cost[ICE]-Environmental Damage Cost[FCEV])*Feebate Fraction[FCEV]

Units: \$/car

The Feebate Program represents a regulatory intervention that attempts to redistribute externality costs to accurately reflect the "true" cost of the vehicle to consumers.

(85) Feebate Program[EV]=

(Environmental Damage Cost[ICE]-Environmental Damage Cost[EV])*Feebate Fraction[EV]

Units: \$/car

The Feebate Program represents a regulatory intervention that attempts to redistribute externality costs to accurately reflect the "true" cost of the vehicle to consumers.

(86) Feebate Switch=

0

Units: Dmnl

The Feebate Switch is a scenario variable that allows the user to turn the feebate policy intervention on or off.

(87) Fixed Operating Cost[technology]=

1238, 1238, 1238, 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).

(88) Fleet=

INTEG (+Change in Fleet, Initial Fleet)

Units: cars

Desired Fleet is the total quantity of vehicles desired of all households in the market.

(89) Fleet Annual Oil Consumption=

Gasoline Fleet VMT/Fleet Average Fuel Economy of Gas Vehicles

Units: gallons/Year

Fleet Annual Oil Consumption is the total volume of gasoline consumed by all gasoline burning vehicles on the road.

(90) Fleet Average Fuel Economy of Gas Vehicles=

(Total Late Model Fuel Economy of Gas Vehicles+Total Older Vehicle Fuel Economy of Gas Vehicles)/Total Gasoline Vehicle Fleet

Units: miles/gallon

Fleet Average Fuel Economy of Gas Vehicles is the average fuel economy of the fleet of gasoline-burning vehicle technologies on the road.

(91) 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).

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

0.05, 0.15, 0.2, 0.15

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.

(93) Fractional Growth in Fleet=

0.016

Units: 1/Year

Based on historical estimates of Light Motor Vehicle Sales (cars and light duty trucks) from 1970-1998 provided by the U.S. Dept of Commerce, Bureau of Economic Analysis.

(94) Fuel Capacity[technology]= INTEG (

Change in Fuel Capacity[technology],

Initial Fuel Capacity[technology])

Units: gallons

Fuel Capacity is the volumetric fuel carrying capability of a single vehicle between fuelings.

(95) Fuel Capacity Improvement Rate[technology]=

Potential Fuel Capacity Improvement Rate[technology]*"Relative R&D"[technology]

Units: 1/years

Fuel Capacity Improvement Rate is the rate of technological improvement of vehicle fuel capacity as a function of automaker investment. The maximum rate of improvement is the Potential Fuel Capacity Improvement Rate.

(96) Fuel Cost per Mile[technology]=

Fuel Price[technology]/Fuel Economy of New Vehicles[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.

(97) Fuel Economy Improvement Rate[technology]=

Potential Fuel Economy Improvement Rate[technology]*"Relative R&D"[technology]

Units: 1/years

Fuel Economy Improvement Rate is the rate of technological improvement of vehicle fuel economy as a function of automaker investment in technologies to improve economy. The maximum rate of improvement is the Potential Fuel Economy Improvement Rate.

(98) Fuel Economy of New Vehicles[technology]= INTEG (

Change in Fuel Economy[technology],
Initial Fuel Economy[technology])

Units: miles/gallon

Fuel Economy of New Vehicles represents the distance a new vehicle can travel per volume of fuel.

(99) Fuel Price[ICE]=

Gasoline Price

(100) Fuel Price[hybrid]=

Gasoline Price

(101) Fuel Price[FCEV]=

Hydrogen Fuel Price

(102) 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.

(103) Function for Attractiveness from Availability

((0,0)-

(1,1)],(0,0),(0.00917431,0.324561),(0.0366972,0.557018),(0.0917431,0.74122

8),

(0.174312,0.859649),(0.33945,0.960526),(0.498471,0.995614),(0.752294,0.99

5614),(1,1))

Units: Dmnl

Function for Attractiveness from Availability translates the availability of the product to a consumer value. Attractiveness increases rapidly with increasing availability and then diminishes at the margins.

- (104) Function for Attractiveness from Cost
 ((0.6,0)-(2.5,2)],(0.6,2),(1,1),(1.25,0.6),(1.5,0.3),(1.75,0.15),(2,0.05),(2.25,0.02),(2.5,0))
 Units: Dmnl
 The level of attractiveness due to cost diminishes significantly with increasing price relative to reference price. The reference price is the price a consumer is willing to pay for a basket of attributes.
- (105) Function for Attractiveness from Environmental Impact
 (((0,0)-(2.5,2.5)],(0,2),(0.25,1.9),(0.5,1.7),(0.75,1.4),(1,1),(1.25,0.6),(1.5,0.3),(1.75,0.2),(2,0.15),(2.25,0.125),(2.5,0.12))
 Units: Dmnl
 Function for Attractiveness from Environmental Impact translates the relative "cleanliness" of alternative technologies to the ICE baseline into a consumer value parameter.
- (106) Function for Attractiveness from Performance
 (((0,0)-(2,1.1)],(0,0),(0.318043,0.0193),(0.477064,0.129),(0.58104,0.2557),(0.654434,0.4246),(0.770642,0.714),(0.911315,0.907),(1,1),(1.15596,1.066),(1.38226,1.081),(2,1.1))
 Units: Dmnl
 Units: The Performance Attractiveness 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.
- (107) Function for Attractiveness from Range(
 [(0,0)-(2.5,1.22)],(0,0),(0.15,0.028),(0.25,0.084),(0.3,0.168),(0.4,0.37),(0.5,0.6),(0.75,0.85),(1,1),(1.25,1.1),(1.5,1.15),(1.75,1.175),(2,1.2),(2.25,1.21),(2.5,1.22))
 Units: Dmnl
 This function accounts for the significant penalty attributed to vehicles with a range between fuelings less than 400 miles. The curve also reflects diminishing returns to increased range.
- (108) Function for Discount Rate
 (((1,0.12)-(32,0.4)],(1,0.36),(2,0.24),(4,0.18),(8,0.15),(16,0.14),(32,0.125))
 Units: Dmnl
 This function returns a discount rate based on increasing fuel cost as indicated by relative gas prices.

- (109) Function for the Attractiveness of Infrastructure Adequacy[technology]
 ((0,0)-(1,1)],(0,0),(0.1,0.02),(0.174312,0.135965),(0.2263,0.403509),(0.287462,0.723684),(0.394495,0.885965),(0.513761,0.969298),(0.681957,0.991228),(1,1))
 Units: Dmnl
 The Function for Attractiveness of Infrastructure Adequacy equates the attractiveness of a particular platform to the available infrastructure to support the fueling and service requirements of the platform. Unity represents the same level of service as the gasoline ICE currently.
- (110) Gasoline Fleet VMT=
 Total Gasoline Vehicle Fleet*Vehicle Miles Traveled
 Units: miles/Year
 Gasoline Fleet VMT is the total vehicle miles traveled by all vehicles that burn gasoline for motive force.
- (111) Gasoline Price=
 Base Gasoline Price + STEP(Gasoline Price Increase ,Time of Gasoline Increase)
 Units: \$/gallon
 The Gasoline Price is equal to the Base Gasoline Price plus any Gasoline Price Increase selected for scenario creation.
- (112) 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 Gas Price Increase, but this is also a scenario variable.
- (113) GHG Cost per Kilo=
 0.029
 Units: \$/kilo
 GHG cost per kilo is equivalent to the greenhouse gas cost per kilogram emitted (per Weiss et al).
- (114) Greenhouse Gas Cost[technology]=
 Annual CO2 emissions[technology]*GHG Cost per Kilo
 Units: \$/car/Year
 The cost of greenhouse gas emissions is the product of the unit cost per kilogram of CO2 and the emission rate.
- (115) 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).

- (116) Increase in Awareness[technology]=
Consumer Fraction Unaware[technology]*(Awareness from Marketing[technology]+Awareness from Word of Mouth [technology]+Awareness from Public Ad Campaigns)
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.
- (117) Increase in Environmental Awareness=
Consumer Fraction Insensitive to Environmental Impact*Awareness from Public Ad Campaigns
Units: 1/Year
Increase in Environmental Awareness is the product of the fraction of consumers who are insensitive to environmental impact and the awareness generated from public ad campaigns.
- (118) Increase in Total Late Model Fuel Economy[technology]=
New Vehicle Sales by Product[technology]*Fuel Economy of New Vehicles[technology]
Units: (miles/gallon)*(cars/Year)
Increase in Total Late Model Fuel Economy is equivalent to the fuel economy of new vehicles coming to market. It is the product between new vehicle sales and the fuel economy of those new vehicles.
- (119) Increase in Total Late Model GHG Emissions[technology]=
New Vehicle Sales by Product[technology]*Annual CO2 emissions[technology]
Units: kilograms/(Year*Year)
Increase in Total Late Model GHG Emissions is the change in GHG emissions due to movement of new vehicles into the market.
- (120) Increase in Total Late Model Performance[technology]=
New Vehicle Sales by Product[technology]*Performance of New Vehicles[technology]
Units: cars/Year
Increase in Total Late Model Performance is equal to the product of new vehicle sales and the relative performance of the vehicle technology to the baseline ICE.
- (121) Increase in Total Late Model Pollutant Emissions[technology]=

New Vehicle Sales by Product[technology]*Annual Pollutant emissions[technology]

Units: kilograms/(Year*Year)

Units: Increase in Total Late Model Pollutant Emissions is the change in Pollutant emissions due to movement of new vehicles into the market.

(122) Increase in Total Late Model Price[technology]=

New Vehicle Sales by Product[technology]*Purchase Price[technology]

Units: \$/Year

Increase in Total Late Model Price is the change in vehicle price over time due to movement of new vehicles into the market.

(123) Increase in Total Late Model Range[technology]=

New Vehicle Sales by Product[technology]*Range[technology]

Units: miles*(cars/Year)

Increase in Total Late Mileage Range is the change in the late model vehicle range attribute over time.

(124) Indicated Fuel Economy[technology]=

Reference Fuel Economy[technology]*(Desired Fuel

Economy[technology]/Reference Fuel Economy

[technology])^Elasticity of Indicated Fuel Economy

Units: miles/gallon

Indicated fuel economy is the goal for economy the automakers should strive for, given fuel prices and consumer goals for fuel cost per mile.

The sensitivity of the response depends on the elasticity. Elasticity = 1 implies linear response; elasticities < 1 imply automakers are less willing to adjust target fuel economy goals than consumers would desire.

(125) Infrastructure Coverage Fraction[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.

(126) Infrastructure Coverage Improvement Rate[technology]=

Potential Infrastructure Coverage Rate[technology]*Relative Infrastructure Investment

[technology]

Units: 1/years

Fuel Capacity Improvement Rate is the rate of technological improvement of vehicle fuel capacity as a function of automaker investment. The maximum rate of improvement is the Potential Fuel Capacity Improvement Rate.

- (127) Infrastructure Investment[ICE]=
1e+008
- (128) Infrastructure Investment[hybrid]=
1e+008
- (129) Infrastructure Investment[FCEV]=
1e+008
- (130) Infrastructure Investment[EV]=
1e+008
Units: \$/Year
This is the average current annual R&D investment level for a given platform.
- (131) Infrastructure Spillovers[technology,technology]=
1, 0.3, 0.2, 0.1; 0.3, 1, 0.4, 0.8; 0.2, 0.4, 1, 0.4; 0.1, 0.6, 0.4, 1;
Units: Dimensionless
R&D Spillovers represents correlated technologies. That is, that investment spending on one technology has applications in related technologies. For example, moneys spent to develop electric motor systems that support FCEVs will also be applicable to HEV drive systems.
- (132) Initial Awareness[ICE]=1
- (133) Initial Awareness[hybrid]=0
- (134) Initial Awareness[FCEV]=0
- (135) 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.
- (136) Initial Component Cost[technology]=
4770, 9000, 100000, 18000
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. EV costs estimated from Schnayerson, p. 205.
- (137) Initial Fleet=
2e+008

Units: cars

Initial Fleet is the initial fleet of vehicles on the road at the outset of the simulation period. It is equivalent to the approximate number of households in the U.S. market multiplied by the average number of vehicles per household (Census 2000 and Ward's Automotive Yearbook).

(138) Initial Fuel Capacity[technology]=

14, 10, 4, 2

Units: gallons

Initial Fuel Capacity is the current volumetric fuel carrying capability of a representative mid-size vehicle for each of the technology classes.

(139) Initial Fuel Economy[technology]=

22.4, 42.6, 72, 67.2

Units: miles/gallon

Initial Fuel Economy for representative powertrain technologies based on Wang 2001.

(140) Initial Infrastructure Coverage[technology]=

1, 0.9, 0, 0

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).

(141) Initial Late Model Vehicles[technology]=

$Fleet * (New\ Vehicle\ Life / (New\ Vehicle\ Life + Older\ Vehicle\ Life)) * Initial\ Vehicle\ Fractions[technology] + Minimum\ Initial\ Fleet$

Units: cars

Initial Late Model Vehicles represents the initial late model fleet vehicle composition by technology/fuel combination.

(142) Initial Older Vehicles[technology]=

$Fleet * (Older\ Vehicle\ Life / (New\ Vehicle\ Life + Older\ Vehicle\ Life)) * Initial\ Vehicle\ Fractions[technology] + Minimum\ Initial\ Fleet$

Units: cars

Initial Older Vehicles represents the initial older vehicle fleet vehicle composition by technology/fuel combination.

(143) Initial Performance[technology]=

1, 0.7, 0.6, 0.6

Units: Dmnl

Initial Performance represents the current performance of today's vehicle technologies relative to the gasoline ICE.

(144) Initial Production Experience[ICE]=3e+008

(145) Initial Production Experience[hybrid]=20000

(146) Initial Production Experience[FCEV]=100

(147) Initial Production Experience[EV]=10000

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).

(148) Initial Sensitivity to Environmental Impact=

0.05

Units: Dmnl

Units: Initial Sensitivity is a scenario available and can be adjusted.

(149) Initial Target Product 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 technologies.

(150) Initial Target Product Investment[technology]=

1, 0.2, 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, 0.2 for HEVs and 0.01 for all other technologies.

(151) Initial Vehicle Fractions[technology]=

IF THEN ELSE(technology=ICE, 1, 0)

Units: Dimensionless

Initial Vehicle Fractions represents the extent by which each of the propulsion/fuel system vehicle variants are represented in the current (initial) vehicle fleet.

(152) Investment Adjustment Fraction[technology]=

Initial Late Model Vehicles[technology])

Units: cars

Late Model Vehicles is the total fleet of vehicles considered "new."

- (158) Learning Adjustment[technology]=
 $\text{SMOOTH3}(\text{Learning Curve Effect[technology]}, \text{Learning Delay})$
Units: Dmnl
The Learning Adjustment approximates a third order learning delay for the learning curve effect to impact operations.
- (159) Learning Curve Effect[technology]=
 $(\text{Effective Production Experience[technology]}/\text{Initial Production Experience[technology]})^{\text{Learning Elasticity[technology]}}$
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).
- (160) Learning Delay=
2
Units: years
The Learning Delay approximates the time lag for learning curve effects to be recognized by personnel.
- (161) Learning Elasticity[technology]=
 $\text{LN}(1 - \text{Fractional Cost Reduction per Production Doubling[technology]})/\text{LN}(2)$
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.
- (162) Lifecycle Operating Cost[technology]=
 $(\text{Variable Operating Cost[technology]} + \text{Fixed Operating Cost[technology]}) * \text{Operating Cost Multiplier (Discount Rate)}$
Units: \$/car
The lifecycle 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, converted to present value assuming a constant discount rate and constant (real) annual operating costs.

- (163) Lifecycle Vehicle Cost[technology]=
(Purchase Price[technology]+Lifecycle Operating Cost[technology])
Units: \$/car
Lifecycle Vehicle Cost is the sum of the vehicle's purchase price and its lifecycle operating cost.
- (164) Market Stimulus[technology]=
(1-Target Product 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.
- (165) 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.
- (166) Marketing Expenditure[ICE]=1
- (167) Marketing Expenditure[hybrid]=1
- (168) Marketing Expenditure[FCEV]=1
- (169) Marketing Expenditure[EV]=1
Units: Dmnl/Year
Marketing Expenditure is the annual marketing expenditures for each platform.
- (170) Minimum Component Cost[technology]=
4000, 4000, 4000, 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.
- (171) Minimum Initial Fleet=
1e-012
Units: cars
Minimum Initial Fleet is a dummy variable that eliminates the possibility of an Initial Fleet with a quantity of zero, thereby preventing division by zero in the model.

- (172) New Vehicle Life=
4
Units: years
New Vehicle Life is the average period of ownership once a consumer takes possession of a new vehicle. After this period, the vehicle is considered an "Older" vehicle.
- (173) New Vehicle Purchase Time=
0.5
Units: Year
New Vehicle Purchase Time represents a delay reflecting the average period between when a customer identifies a need for a vehicle and the actual acquisition of that vehicle.
- (174) New Vehicle Sales by Product[technology]=
Product Market Share[technology]*Total New Vehicle Market
Units: cars/Year
New Vehicle Sales represents the number of vehicles sold per year by propulsion/fuel system variant. It is a function of demand for new automobiles, expressed as a function of Probability of Purchase.
- (175) Normal Awareness Generation 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.
- (176) Older Vehicle Life=
10
Units: years
Older Vehicle Life is the average life span of vehicles not considered new and is based on estimates used by Weiss et al (2000) indicating total average vehicle life of 14 years.
- (177) Older Vehicles[technology]= INTEG (
Vehicle Aging[technology]-Vehicle Scrap Rate[technology],
Initial Older Vehicles[technology])
Units: cars
Older Vehicles represents the fleet of vehicles no longer considered "new" or "late model."
- (178) 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: Year

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.

(179) Other Variable Cost per Mile[technology]=

0.0517, 0.0517, 0.0517, 0.0517

Units: \$/miles

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).

(180) 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).

(181) Our Actual Product Availability[technology]=

IF THEN ELSE (technology=ICE, 1, DELAY3I(Target Product 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.

(182) Our Actual Product Investment[technology]=

IF THEN ELSE (technology=ICE, 1, DELAY1I(Target Product Investment[technology], Time to Change Strategy, 0))

Units: Dmnl

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

(183) 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).

- (184) Per Tech Fleet Air Pollutant EDC[technology]=
Air Pollutant Cost per Kilo[technology]*Per Technology Fleet Pollutant Emissions[technology]
Units: \$/Year
Per Tech Fleet Air Pollutant EDC is the per technology environmental damage cost due to emissions of criteria pollutants.
- (185) Per Technology Fleet Pollutant Emissions[technology]=
Per Technology Late Model Pollutant Emissions[technology]+Per Technology Older Vehicle Pollutant Emissions[technology]
Units: kilograms/Year
Per Technology Fleet Pollutant Emission is the sum of both late model and older vehicle annual pollutant emissions.
- (186) Per Technology Late Model Fuel Economy[technology]= INTEG (Increase in Total Late Model Fuel Economy[technology]-Reduction in Total Late Model Fuel Economy from Aging[technology], Late Model Vehicles[technology]*Fuel Economy of New Vehicles[technology])
Units: (miles/gallon)*cars
Per Technology Late Model Fuel Economy is the average fuel economy of the portion of the late model fleet representing a given propulsion technology.
- (187) Per Technology Late Model GHG Emissions[technology]= INTEG (Increase in Total Late Model GHG Emissions[technology]-Reduction in Total Late Model GHG Emissions from Aging[technology], Late Model Vehicles[technology]*Annual CO2 emissions[technology])
Units: kilograms/Year
Total Late Model GHG Emissions is the difference between the increase in total late model GHG Emissions and the reduction in total late model GHG emissions resulting from aging.
- (188) Per Technology Late Model Pollutant Emissions[technology]= INTEG (Increase in Total Late Model Pollutant Emissions[technology]-Reduction in Total Late Model Pollutant Emissions from Aging[technology], Late Model Vehicles[technology]*Annual Pollutant emissions[technology])
Units: kilograms/Year
Units: Total Late Model Pollutant Emissions is the difference between the increase in total late model Pollutant Emissions and the reduction in total late model Pollutant emissions resulting from aging.
- (189) Per Technology Older Vehicle Fuel Economy[technology]=

INTEG (+Reduction in Total Late Model Fuel Economy from Aging[technology]-Reduction in Older Vehicle Fuel Economy from Scrapping[technology], Older Vehicles[technology]*Fuel Economy of New Vehicles[technology])
 Units: (miles/gallon)*cars
 Per Technology Older Fuel Economy is the average fuel economy of the portion of the older fleet representing a given propulsion technology.

(190) Per Technology Older Vehicle GHG Emissions[technology]=
 INTEG (Reduction in Total Late Model GHG Emissions from Aging[technology]-Reduction in Older Vehicle GHG Emissions from Scrapping
 [technology], Older Vehicles[technology]*Annual CO2 emissions[technology])
 Units: kilograms/Year
 Total Older Vehicle GHG Emissions is the difference between the increase in older vehicle GHG Emissions and the reduction in total older vehicle GHG emissions resulting from scrapping.

(191) Per Technology Older Vehicle Pollutant Emissions[technology]=
 INTEG (Reduction in Total Late Model Pollutant Emissions from Aging[technology]-Reduction in Older Vehicle Pollutant Emissions from Scrapping[technology], Older Vehicles[technology]*Annual Pollutant emissions[technology])
 Units: kilograms/Year
 Total Older Vehicle Pollutant Emissions is the difference between the increase in older vehicle Pollutant Emissions and the reduction in total older vehicle emissions resulting from scrapping.

(192) "Per Technology On-Road Cost of Environmental Damage"[technology]=
 Environmental Damage Cost[technology]*Per Technology Vehicle Fleet[technology]
 Units: \$
 Per Technology On-Road Cost of Environmental Damage represents the cumulative environmental damage cost created by all vehicles of a specific technology type on the road.

Per Technology Vehicle Fleet[technology]=
 Late Model Vehicles[technology]+Older Vehicles[technology]
 Units: cars
 Vehicle Fleet is the sum of all Late Model Vehicles and Older Vehicles. It is the total of all vehicles on the road.

(193) Performance Improvement Rate[technology]=
 Potential Performance Improvement Rate[technology]*"Relative R&D"[technology]

Units: 1/years

Performance Improvement Rate is the rate of technological improvement of vehicle performance as a function of automaker investment. The maximum rate of improvement is the Potential Performance Improvement Rate.

- (194) Performance of New Vehicles[technology]= INTEG (Change in Performance[technology], Initial Performance[technology])
Units: Dmml
Performance of New Vehicles is the level of performance achieved by a new vehicle of a given propulsion/fuel platform.
- (195) Pollutant Cost per Mile[technology]=
0.0215, 0.0143, 0.0016, 0.0101
Units: \$/mile
Pollutant cost per mile is the equivalent per mile cost of vehicle emissions for a given technology (Source: Wang, 2001).
- (196) Pollutant Emissions per Mile[technology]=
0.006649, 0.00431, 0.000309, 0.001929
Units: kilograms/mile
Estimates are derived from Wang (2001) and sum VOC, PM10, NOx, SOx, & CO emissions for a baseline conventional SI ICE/CG, SI HEV/FRFG2, and EV/US Grid Mix as computed by Wang for near-term technologies. For the FCEV, estimate is based on long-term projections by Wang for FCV/H2, NG Decentralized.
- (197) Potential Fuel Capacity Improvement Rate[technology]=
0, 0, 0.2, 0.1
Units: 1/years
Potential Capacity Improvement Rate is the maximum improvement rate achievable regardless of investment spending.
- (198) Potential Fuel Economy Improvement Rate[ICE]=0.05
- (199) Potential Fuel Economy Improvement Rate[hybrid]=0.15
- (200) Potential Fuel Economy Improvement Rate[FCEV]=0.15
- (201) Potential Fuel Economy Improvement Rate[EV]=0.15
Units: 1/years
Potential Fuel Economy Improvement Rate is the maximum improvement rate achievable regardless of investment spending.

- (202) Potential Infrastructure Coverage Rate[ICE]=0
- (203) Potential Infrastructure Coverage Rate[hybrid]=0.3
- (204) Potential Infrastructure Coverage Rate[FCEV]=0.2
- (205) Potential Infrastructure Coverage Rate[EV]=0.2
 Units: 1/years
 Potential Capacity Improvement Rate is the maximum improvement rate achievable regardless of investment spending.
- (206) Potential Performance Improvement Rate[technology]=
 0.1,0.25,0.25,0.25
 Units: 1/Year
 Potential Performance Improvement Rate is the maximum improvement rate achievable regardless of investment spending.
- (207) Probability of Purchase[technology]=
 $\text{Exp}(\text{Attractiveness of Technology}[\text{technology}]) / \text{Total Utility of all Platforms}$
 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.
- (208) Product Market Share[technology]=
 $\text{Technology Demand}[\text{technology}] / \text{SUM}(\text{Technology Demand}[\text{technology}])$
 Units: Dmnl
 Technology Market share normalizes New Vehicle Sales rather than Demand so that the sum of all New Vehicle Sales for each technology/fuel variant is unity. Furthermore, the revised model intends to deliver both reinforcing and balancing feedback components for all feedback mechanisms via Technology Fraction in the Fleet, since this is a more representative metric for gauging "market tip" phenomena.
- (209) Production Rate[technology]=
 New Vehicle Sales by Product[technology]
 Units: cars/Year
 Units: The Production Rate of a technology is assumed to equal the Sales Rate for each technology.

- (210) Production Spillovers[technology,technology]=
 1, 0.2, 0.1, 0.1; 0.2, 1, 0.3, 0.5; 0.1, 0.3, 1, 0.5; 0.1, 0.5, 0.5, 1;
 Units: Dimensionless
 Production Spillovers represents correlated production experience amongst technologies. That is, production experience gained in one technology translates in part to production experience in other related technologies. For example, experience producing electric motor systems that support FCEVs is shared to some degree by hybrid drive systems.
- (211) Profit Margin[technology]=
 0.05
 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.
- (212) Public Ad Expenditure=
 0
 Units: Dmnl/Year
 The annual public sector marketing expenditures for each platform as a function of the reference expenditure for marketing on established ICE technology. We assume an absence of public sector intervention as exists today. This is a scenario variable, however, and can therefore be adjusted to reflect deliberate promotion of cleaner vehicle technologies via public ad campaigns.
- (213) Purchase Price[ICE]=
 $(\text{Total Capital Cost[ICE]} * (1 + \text{Profit Margin[ICE]}) + \text{Feebate Program[ICE]} * \text{Feebate Switch})$
- (214) Purchase Price[hybrid]=
 $(\text{Total Capital Cost[hybrid]} * (1 + \text{Profit Margin[hybrid]}) - \text{Feebate Program[hybrid]} * \text{Feebate Switch})$
- (215) Purchase Price[FCEV]=
 $(\text{Total Capital Cost[FCEV]} * (1 + \text{Profit Margin[FCEV]}) - \text{Feebate Program[FCEV]} * \text{Feebate Switch})$
- (216) Purchase Price[EV]=
 $(\text{Total Capital Cost[EV]} * (1 + \text{Profit Margin[EV]}) - \text{Feebate Program[EV]} * \text{Feebate Switch})$
 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.

- (217) "R&D Spillovers"[technology, technology]=
 1, 0.3, 0.1, 0.1; 0.3, 1, 0.4, 0.8; 0.2, 0.4, 1, 0.6; 0.1, 0.6, 0.4, 1;
 Units: Dmnl
 R&D Spillovers represents correlated technologies. That is, that investment spending on one technology has applications in related technologies. For example, moneys spent to develop electric motor systems that support FCEVs will also be applicable to HEV drive systems.
- (218) Range[technology]=
 Fuel Capacity[technology]*Fuel Economy of New Vehicles[technology]
 Units: miles
 The Range represents the number of miles that can be traveled between refuelings.
- (219) 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.
- (220) Reduction in Older Vehicle Fuel Economy from Scrapping[technology]=
 Vehicle Scrap Rate[technology]*Average Older Vehicle Fuel Economy[technology]
 Units: (miles/gallon)*(cars/Year)
 Reduction in Older Vehicle Fuel Economy from Scrapping results from the gradual scrapping of older and more polluting vehicles as they retire from the fleet. It is equal to the scrap rate times the average fuel economy of the older vehicle fleet for a given technology.
- (221) Reduction in Older Vehicle GHG Emissions from Scrapping[technology]=
 Vehicle Scrap Rate[technology]*Average Older Vehicle GHG Emissions[technology]
 Units: kilograms/(Year*Year)
 Reduction in Older Vehicle GHG Emissions from Scrapping is the decrease in GHG emissions that results as the fleet of older vehicles reaches end of service life and is replaced by vehicles with improved GHG emissions characteristics.
- (222) Reduction in Older Vehicle Performance from Scrapping[technology]=

Vehicle Scrap Rate[technology]*Average Older Vehicle Performance[technology]

Units: cars/Year

Reduction in Older Vehicle Performance from Scrapping is a function of the product of the vehicle scrap rate and the average performance of the pool of older vehicles on the road.

- (223) Reduction in Older Vehicle Pollutant Emissions from Scrapping[technology]=
Vehicle Scrap Rate[technology]*Average Older Vehicle Pollutant Emissions[technology]
Units: kilograms/(Year*Year)
Reduction in Older Vehicle Pollutant Emissions from Scrapping is the decrease in Pollutant emissions that results as the fleet of older vehicles reaches end of service life and is replaced by vehicles with improved emissions characteristics.
- (224) Reduction in Older Vehicle Price from Scrapping[technology]=
Vehicle Scrap Rate[technology]*Average Older Vehicle Price[technology]
Units: \$/Year
Reduction in Older Vehicle Price from Scrapping is the change in price that results as the fleet of older vehicles reaches end of service life and is replaced by vehicles at different prices.
- (225) Reduction in Older Vehicle Range from Scrapping[technology]=
Vehicle Scrap Rate[technology]*Average Older Vehicle Range[technology]
Units: miles*(cars/Year)
Reduction in Older Vehicle Range from Scrapping is the decrease in total older vehicle range that occurs as the fleet of older vehicles reaches end of service life and is replaced by vehicles with improved range characteristics.
- (226) Reduction in Total Late Model Fuel Economy from Aging[technology]=
Vehicle Aging[technology]*Average Late Model Fuel Economy[technology]
Units: (miles/gallon)*(cars/Year)
Reduction in Total Late Model Fuel Economy from Aging represents the reduction in the stock of late model cars due to aging.
- (227) Reduction in Total Late Model GHG Emissions from Aging[technology]=
Vehicle Aging[technology]*Average Late Model GHG Emissions[technology]
Units: kilograms/(Year*Year)
Reduction in Total Late Model GHG emissions from Aging is the decrease in GHG emissions that results as the Total Late Model fleet ages and is replaced by new vehicles with improved emissions attributes.
- (228) Reduction in Total Late Model Performance from Aging[technology]=

Vehicle Aging[technology]*Average Late Model Performance[technology]

Units: cars/Year

Reduction in Total Late Model Performance from Aging refers to the decrease in the stock of total late model vehicles resulting from aging of the late model fleet.

- (229) Reduction in Total Late Model Pollutant Emissions from Aging[technology]=
Vehicle Aging[technology]*Average Late Model Pollutant Emissions[technology]
Units: kilograms/(Year*Year)
Reduction in Total Late Model Pollutant emissions from Aging is the decrease in Pollutant emissions that results as the Total Late Model fleet ages and is replaced by new vehicles with improved emissions attributes.
- (230) Reduction in Total Late Model Price from Aging[technology]=
Vehicle Aging[technology]*Average Late Model Price[technology]
Units: \$/Year
Reduction in Total Late Model Price from Aging is the decrease in vehicle price that results as the Total Late Model fleet ages and is replaced by new vehicles at different prices.
- (231) Reduction in Total Late Model Range from Aging[technology]=
Vehicle Aging[technology]*Average Late Model Range[technology]
Units: miles*(cars/Year)
Reduction in Total Late Model Range from Aging is the decrease in total late model vehicle range that occurs as the fleet ages and is replaced by new vehicles with improved range attributes.
- (232) Reference Availability=
1
Units: Dmnl
Reference Availability is equivalent to the baseline ICE availability, equal to unity.
- (233) Reference Cost=
38000
Units: \$/car
Attractiveness of a given vehicle platform is benchmarked against a reference cost. This cost represents the consumer's expected price for a given basket of vehicle attributes.
- (234) Reference Environmental Impact=
(235) Environmental Damage Cost[ICE]
Units: \$/car
The reference value for annual environmental damage costs used in the assessment of vehicle attractiveness.

- (236) Reference Fuel Economy[technology]=
 20
 Units: miles/gallon
 The reference fuel economy level for the determination of target fuel economy.
- (237) Reference Infrastructure Adequacy=
 1
 Units: Dimensionless
 Reference Infrastructure Adequacy is the baseline infrastructure coverage expected by consumers and represented by the ICE, equal to unity.
- (238) Reference Infrastructure Investment[technology]=
 1e+008
 Units: \$/Year
 Reference R&D for a given technology establishes the rate by which increased R&D spending will close the gap between the Potential Improvement Rate and the Actual Improvement Rate.
- (239) Reference Performance=
 1
 Units: Dmnl
 This is the equivalent performance of the advanced baseline gasoline ICE. It is the measure upon which the performance of all other propulsion/fuel system combinations are based.
- (240) "Reference R&D"[technology]=
 1
 Units: Dmnl
 Reference R&D for a given technology establishes the rate by which increased R&D spending will close the gap between the Potential Improvement Rate and the Actual Improvement Rate.
- (241) Reference Range=
 400
 Units: miles
 Attractiveness is benchmarked against a reference range equal to 400 miles for an advanced body vehicle.
- (242) Relative Gas Price=
 Gasoline Price/Base Gasoline Price
 Units: Dmnl
 Relative Gas Price is the current price of gasoline relative to the baseline gasoline price of \$1.43/gallon.

- (243) Relative Infrastructure Investment[technology]=

$$\frac{\text{Effective Infrastructure Investment[technology]}}{\text{Effective Infrastructure Investment[technology]} + \text{Reference Infrastructure Investment[technology]}}$$
Units: Dmnl
Relative R&D represents the degree by which Effective R&D is translated to the rate of improvement of the targeted technology attribute; in this case, fuel capacity.
- (244) "Relative R&D"[technology]=

$$\frac{\text{"Effective R\&D"[technology]}}{\text{"Effective R\&D"[technology]} + \text{"Reference R\&D"[technology]}}$$
Units: Dmnl
Relative R&D represents the degree by which Effective R&D is translated to the rate of improvement of the targeted technology attribute; in this case, fuel economy.
- (245) Relative Strength of Marketing Effort[technology]=

$$\frac{\text{Marketing Expenditure[technology]}}{\text{Baseline Marketing Expenditure}}$$
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.
- (246) Relative Strength of Public Ad Campaign=

$$\frac{\text{Public Ad Expenditure}}{\text{Baseline Marketing Expenditure}}$$
Units: Dmnl
The Relative Strength of the Public Advertisement Campaign Effort represents the amount of public sector spending to promote a given advanced vehicle technology divided by the baseline marketing spending by industry. 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.
- (247) Required Capacity[technology]=

$$\frac{\text{Target Range[technology]}}{\text{Fuel Economy of New Vehicles[technology]}}$$
Units: gallons
Required Capacity is the required maximum volumetric fuel carrying capability of a vehicle needed to achieve the target range between refuelings.
- (248) Required Economy Adjustment Delay=
4
Units: years

The time required for automakers to adjust their target for fuel economy as fuel prices and other conditions change.

- (249) Required Fuel Economy[technology]=
SMOOTH3(Indicated Fuel Economy[technology], Required Economy Adjustment Delay)
Units: miles/gallon
Required fuel economy is the operational goal of the automakers for the economy they should strive for in their R&D and development programs. It adjusts with a delay toward the indicated level based on fuel prices.
- (250) Target Fuel Cost per Mile[technology]=
0.03
Units: \$/mile
Target Fuel Cost per Mile is the consumers' target for fuel cost per mile, as a function of the consumer's expected duration between fuelings and average cost per fueling based on experience with the ICE.
- (251) Target Infrastructure Coverage[technology]=
SMOOTH3(Desired Infrastructure Coverage[technology], Time to Build Infrastructure)
Units: Dmnl
Target Infrastructure Coverage is the coverage desired of each of the fuel/vehicle system combinations relative to current coverage. The target coverage experiences a third order delay due to the time to build the infrastructure.
- (252) Target Performance[technology]=
1
Units: Dimensionless
Target Performance is the vehicle performance desired of each of the propulsion/fuel system combinations relative to today's gasoline ICE vehicle - shown as unity.
- (253) Target Product Availability[technology]=
INTEG (Change in Target Product Availability[technology], Initial Target Product 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.
- (254) Target Product Investment[technology]=
INTEG (Change in Target Product Investment[technology], Initial Target Product Investment[technology])
Units: Dmnl

Target Availability represents our availability goal. This target availability integrates the change in their target, and starts with Initial Target Availability.

(255) Target Range[technology]=

600

Units: miles

The target range is established as a rough approximation of the target that automakers might pursue for a given technology based on improvements to the benchmark gasoline ICE. This might be interpreted as the point where automakers currently believe consumers derive a maximum of utility from range. Increases beyond the target achieve only diminishing returns to the automaker. This definition is in contrast to the original model based on projections by Weiss et al to 2020. The Weiss et al (2000) report indicates potential performance normalized ranges of 397,401;407,395;387,375;and 262. These are projected ranges at the year 2020 and are weighted based on EPA methodologies (55% city/45% highway).

(256) Technology:

ICE, hybrid, FCEV, EV

Units: Four propulsion technology platforms are explored: internal combustion

(ICE), hybrid, fuel cell electric (FCEV), and electric (EV). Each platform has a variety of fuel sources to draw from.

(257) Technology Demand[technology]=

Probability of Purchase[technology]*Total

Availability[technology]*Consumer Fraction Aware[technology]

Units: Dmnl

Technology Demand is equivalent to the product of the probability of consumer purchase, total product availability, and the fraction of consumers aware the product exists for purchase.

(258) Technology Fraction in Fleet[technology]=

Per Technology Vehicle Fleet[technology]/Total Fleet

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.

(259) Technology Fraction in the Fleet[technology]=

Per Technology Vehicle Fleet[technology]/Total Vehicle Fleet

Units: Dmnl

Technology Fraction in the Fleet is the portion of the total fleet of vehicles represented by a particular propulsion technology.

(260) Time of Gasoline Increase=

2100

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.

(261) Time to Build Infrastructure=

2

Units: years

Time to Build Infrastructure is equivalent to the average period required to install new infrastructure in the form of fuel extraction, processing, storage, and distribution as well as training and certification of support personnel.

(262) Time to Change Actual=

4

Units: Year

Units: 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.

(263) Time to Change Strategy=

1

Units: years

The Time to Change Strategy is assumed to be 1 year, representing the approval process for investment funding for any given product attribute/technology.

(264) Total Availability[technology]=

Competitor Product Availability[technology]*Competitor Market Share+Our
Actual Product 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.

(265) Total Average Fuel Economy=

(Total Late Model Fuel Economy+Total Older Vehicle Fuel Economy)/Total
Vehicle Fleet

Units: miles/gallon

This is the aggregate fuel economy of all vehicle technology fleets on the

road.

- (266) 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.
- (267) Total Fleet=
SUM(Per Technology Vehicle Fleet[technology])
Units: cars
Total Fleet is the sum of all vehicle fleets by fuel/vehicle system.
- (268) Total Fleet Air Pollutant EDC=
SUM(Per Tech Fleet Air Pollutant EDC[technology])
Units: \$/Year
Total Fleet Air Pollutant EDC is the total environmental damage cost resulting from the sum of all fuel/vehicle systems in the fleet.
- (269) Total Fleet EDC=
Total Fleet Air Pollutant EDC+Total Fleet GHG EDC
Units: \$/Year
Total Fleet EDC is the total fleet environmental damage cost stemming from emissions of both criteria air pollutants and greenhouse gases.
- (270) Total Fleet GHG EDC=
GHG Cost per Kilo*All Vehicle GHG Emissions
Units: \$/Year
Total Fleet GHG EDC is the total environmental damage cost resulting from the greenhouse gas emissions of all fuel/vehicle systems on the road.
- (271) Total Gasoline Vehicle Fleet=
Per Technology Vehicle Fleet[ICE]+Per Technology Vehicle Fleet[hybrid]
Units: cars
Total Gasoline Vehicle Fleet is the sum of all gasoline-burning vehicles on the road.
- (272) Total Investment[technology]=
Competitor Product Investment[technology]*Competitor Market Share+Our Actual Product Investment[technology]*Our Market Share
Units: Dmnl
Total Investment is the sum of Our Actual Product Investment and the Competitor Product Investment, weighted by the respective Market Share of us and our competitor.
- (273) Total Late Model Fleet=

SUM(Late Model Vehicles[technology])

Units: cars

Total Late Model Fleet is the sum of all late model cars of all technologies on the road.

(274) Total Late Model Fuel Economy=

SUM(Per Technology Late Model Fuel Economy[technology])

Units: (miles/gallon)*cars

Total Late Model Fuel Economy is the average fuel economy of all late model vehicles of all technologies.

(275) Total Late Model Fuel Economy of Gas Vehicles=

Per Technology Late Model Fuel Economy[ICE]+Per Technology Late Model Fuel Economy[hybrid]

Units: (miles/gallon)*cars

Total Late Model Fuel Economy of Gas Vehicles is the average fuel economy of the pool of late model gasoline-burning vehicles on the road.

(276) Total Late Model GHG Emissions=

SUM(Per Technology Late Model GHG Emissions[technology])

Units: kilograms/Year

Total Late Model GHG Emissions is the sum of all greenhouse gas emissions of all late model vehicles on the road.

(277) Total Late Model Performance[technology]=

INTEG (Increase in Total Late Model Performance[technology]-Reduction in Total Late Model Performance from Aging[technology], Late Model Vehicles[technology]*Performance of New Vehicles[technology])

Units: cars

Total Late Model Performance is the total performance of the portion of the late model fleet that is representative of a given fuel/vehicle system.

(278) Total Late Model Pollutant Emissions=

SUM(Per Technology Late Model Pollutant Emissions[technology])

Units: kilograms/Year

Total Late Model Pollutant Emissions is the total pollutant emissions of all late model vehicles, regardless of fuel/vehicle system type.

(279) Total Late Model Price[technology]= INTEG (

Increase in Total Late Model Price[technology]-Reduction in Total Late Model Price from Aging[technology], Late Model Vehicles[technology]*Purchase Price[technology])

Units: \$

Total Late Model Price is the difference between the increase in total late model price and the change in total late model price resulting from

aging.

- (280) Total Late Model Range[technology]= INTEG (Increase in Total Late Model Range[technology]-Reduction in Total Late Model Range from Aging[technology], Late Model Vehicles[technology]*Range[technology])
Units: miles*cars
Total Late Model Range is the difference between the increase in total late model range and the reduction in total late model range resulting from aging.
- (281) Total Late Model Vehicles=
SUM(Late Model Vehicles[technology])
Units: cars
Total Late Model Vehicles is equal to the total number of late model cars on the road.
- (282) Total New Vehicle Market=
Total Vehicle Scrap Rate + Change in Fleet
Units: cars/Year
Total New Vehicle Sales is the sum of the total vehicle scrap rate and the market growth differential.
- (283) Total Older Model Vehicles=
SUM(Older Vehicles[technology])
Units: cars
Total Older Model Vehicles is equal to the sum of all older vehicles of all technology types on the road.
- (284) Total Older Vehicle Fuel Economy=
SUM(Per Technology Older Vehicle Fuel Economy[technology])
Units: (miles/gallon)*cars
Total Older Vehicle Fuel Economy is the average fuel economy of all older vehicles of all technologies.
- (285) Total Older Vehicle Fuel Economy of Gas Vehicles=
Per Technology Older Vehicle Fuel Economy[ICE]+Per Technology Older Vehicle Fuel Economy[hybrid]
Units: (miles/gallon)*cars
Total Older Vehicle Fuel Economy of Gas Vehicles is the average fuel economy of the pool of older gasoline-burning vehicles on the road.
- (286) Total Older Vehicle GHG Emissions=
SUM(Per Technology Older Vehicle GHG Emissions[technology])
Units: kilograms/Year
Total Older Vehicle GHG Emissions is the sum of all greenhouse gas emissions of all older vehicles on the road.

- (287) Total Older Vehicle Performance[technology]=
 INTEG (+Reduction in Total Late Model Performance from
 Aging[technology]-Reduction in Older Vehicle Performance from
 Scrapping
 [technology],
 Older Vehicles[technology]*Performance of New Vehicles[technology])
 Units: cars
 Total Older Vehicle Performance is the total performance of the portion of the
 older vehicle fleet that is representative of a given fuel/vehicle system.
- (288) Total Older Vehicle Pollutant Emissions=
 SUM(Per Technology Older Vehicle Pollutant Emissions[technology])
 Units: kilograms/Year
 Total Older Vehicle Pollutant Emissions is the sum of the criteria air pollutant
 emissions of all older vehicle fuel/vehicle systems on the road.
- (289) Total Older Vehicle Price[technology]= INTEG (
 Reduction in Total Late Model Price from Aging[technology]-Reduction in
 Older Vehicle Price from Scrapping[technology], Older
 Vehicles[technology]*Purchase Price[technology])
 Units: \$
 Total Older Vehicle Price is the difference between the increase in older
 vehicle Price from aging and the reduction in total older vehicle price resulting
 from scrapping.
- (290) Total Older Vehicle Range[technology]=
 INTEG (Reduction in Total Late Model Range from Aging[technology]-
 Reduction in Older Vehicle Range from Scrapping
 [technology],
 Older Vehicles[technology]*Range[technology])
 Units: miles*cars
 Total Older Vehicle Range is the difference in range resulting from reduction
 in total late model range due to aging and replacement, and the reduction in
 older vehicle range resulting from scrapping.
- (291) "Total On-Road Cost of Environmental Damage"=
 SUM("Per Technology On-Road Cost of Environmental
 Damage"[technology])
 Units: \$
 Total On-Road Cost of Environmental Damage represents the cumulative
 environmental damage cost created by all vehicles of all technology types on
 the road.
- (292) Total Utility of all Platforms=
 SUM(Exp(Attractiveness of Technology[technology]))

Units: Dmnl

The sum of exponential utilities for all the competing technologies.

(293) Total Vehicle Fleet=

$SUM(\text{Per Technology Vehicle Fleet}[\text{technology }])$

Units: cars

Total Vehicle Fleet is the sum of all cars of all technologies on the road.

(294) Total Vehicle Scrap Rate=

$SUM(\text{Vehicle Scrap Rate}[\text{technology }])$

Units: cars/Year

The Total Vehicle Scrap Rate is the sum of all vehicles by propulsion/fuel system reaching end of service life.

(295) Variable Operating Cost[technology]=

$\text{Vehicle Miles Traveled} * (\text{Fuel Cost per Mile}[\text{technology}] + \text{Other Variable Cost per Mile}[\text{technology}])$

Units: $\$/(\text{car} * \text{Year})$

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.

(296) Vehicle Aging[technology]=

$\text{Late Model Vehicles}[\text{technology}] / \text{New Vehicle Life}$

Units: cars/Year

Vehicle Aging is the rate by which new vehicles leave the fleet of vehicles considered "late model" each year and is determined by the average new vehicle life.

(297) Vehicle Life=

$\text{New Vehicle Life} + \text{Older Vehicle Life}$

Units: years

Vehicle Life is the sum of both New Vehicle Life and Older Vehicle Life and is equal to 14 years.

(298) Vehicle Miles Traveled=

12000

Units: miles/(car*Year)

The Vehicle Miles Traveled per vehicle and year is NOT assumed to be constant across propulsion regimes at 12,000 miles per vehicle-year. This is consistent with Davis (2000) only when VMT Growth Rate is set to zero and the initial VMT is set at 12,000 miles. The above relation is indicative of a 3% decrease in travel demand for every 10% increase in gasoline price (Plotkin 1997).

(299) Vehicle Scrap Rate[technology]=
Older Vehicles[technology]/Older Vehicle Life
Units: cars/Year
Vehicle Scrap Rate is the rate by which older vehicles reach their end of service life and is dependent upon the average life of older vehicles.

Simulation Control Parameters

FINAL TIME = 2032
Units: Year
Units: The final time for the simulation.

INITIAL TIME = 2002
Units: Year
Units: The initial time for the simulation.

TIME STEP
Units: Year
Units: The frequency with which output is stored.

TIME STEP = 0.125
Units: Year
Units: The time step for the simulation.