The Evolution of Sustainable Personal Vehicles

By

BRYAN DALE JUNGERS
B.S. (Humboldt State University) 2004

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

in the

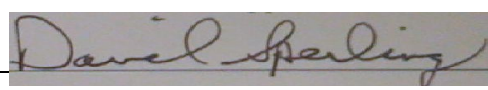
OFFICE OF GRADUATE STUDIES

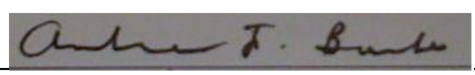
of the

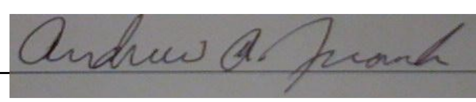
UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

 (Chair)





Committee in Charge
2009

Abstract

Through mechanisms of industrial globalization, modern societies are moving ever closer to capitalist ideals, emphasizing consumer choice and free competitive markets. Despite these ideals, relatively few choices currently exist for the typical personal vehicle consumer with respect to powertrain technology, fuel selection, and vehicle weight/size. This lack of market diversity is often blamed on the auto industry, the energy industry, the ignorant or fickle consumer, and/or the lack of long-term government support and financing of alternative technologies. Though each of these factors has certainly played a part in maintaining the status quo of a perpetually stagnant personal vehicle market, I will argue here that the existing problems associated with personal vehicles will be addressed most effectively by the fundamental reorientation of *personal & institutional values*. Such evolutionary shifts in perspective should be applied broadly by designers, engineers, business leaders, and government officials.

I have explored several *fundamental value shifts* toward the evolution of sustainable personal vehicles. The personal vehicle serves as an apt metaphor for both the freedoms and follies of modern experience. By way of modeled examples, I define and evaluate the qualities of a sustainable personal vehicle and its infrastructure. Many of these concepts should also be applicable for other segments of the industrialized World. In no particular order, the following list summarizes potential value shifts.

1. Using *rules of ecology* to govern the cost-benefit trade offs between economic and social needs.
2. Designing new systems with *eco-efficient* use of resources and in harmony with living systems.
3. Eliminating the need for end-of-tailpipe regulation through *eco-effective* design & engineering.
4. Measuring system performance as achievement of *steady-state sufficiency*, not limitless growth.
5. Measuring energy/work efficiency based on *total benefits* to humans and local environments.
6. Working as individuals within *cooperative communities* to share knowledge and skills globally.
7. Slowing industry to a pace that enables the discovery of *appropriate questions & solutions*.

“*What is necessary to keep providing good care to nature has completely fallen into ignorance during the materialism era.*”

- Rudolf Steiner

“*Humanity is acquiring all the right technology for all the wrong reasons.*”

- R. Buckminster Fuller

“People are not machines, but in all situations where they are given the opportunity, they will act like machines.”

- Karl Ludwig von Bertalanffy

“*I am life wanting to live with life that wants to live.*”

- Albert Schweitzer

“*...[Today's scientists] wander off through equation after equation, and eventually build a structure which has no relation to reality.*”

- Nikola Tesla

“*We must learn to love the children of all species, for all time.*”

- William McDonough

“*If I had an hour to solve a problem and my life depended on the solution, I would spend the first 55 minutes determining the proper question to ask, for once I know the proper question, I could solve the problem in less than five minutes.*”

- Albert Einstein

Acknowledgments and Dedications

All of my love and sincere appreciation go to my family, friends, and colleagues. My life has been sufficiently enriched by your support and dedication. I would like to also sincerely thank Andy Burke, Deb Niemeier, Dan Sperling, Joan Ogden, and Andy Frank for their guidance, mentorship, and support of my work. I owe them each a great debt of gratitude and mountains of respect.

In general, this thesis is dedicated to all of the ordinary citizens who are striving to live by an ethic that knowledge and power are more valuable to humanity as shared resources than as privately held commodities. There is only one type of people in this World, and we are it.

In particular, I dedicate this thesis to my father, a man driven to the outer edges of sanity by his perceptions of an unjust society. May he one day find peace, be it in this life or the next.

Nomenclature

AC- alternating current
AER- all-electric (driving) range
AFV- alternatively fueled vehicle
AH- ampere hour
AT- appropriate technology
BAU- business as usual
BEV- battery electric vehicle
BMS- battery management/monitoring system
C2C- cradle to cradle
CARB- California Air Resources Board
CEV- city electric vehicle
CO_2e- equivalent carbon dioxide emissions
CPE- criteria pollutant emissions
DC- direct current
DSM- demand-side management
EESD- electrochemical energy storage device (e.g. battery)
EM- electric motor/machine
ERI- externally replenishing ions
EV- electric vehicle
EV1- electric vehicle one (by GM)
FCEV- fuel cell electric vehicle
FCHEV- fuel cell hybrid electric vehicle
GHG- greenhouse gases
GUI- graphic user interface
HEV- hybrid electric vehicle
ICE- internal combustion engine
ICV- internal combustion vehicle
IP- intellectual property
IRI- internally replenishing ions
kWh- kilowatt hour
L- liter
Li-Ion- lithium-ion (batteries)
NEV- neighborhood electric vehicle
NGO- non-governmental organization (i.e. non-profit)
NiMH- nickel metal hydride (batteries)
OEM- original equipment manufacturer
OS- open source
PEM- proton exchange membrane
PHEV- plug-in hybrid electric vehicle
PSAT- powertrain systems analysis toolkit
PZEV- partial-zero emissions vehicle
RD&D- research, development, and demonstration
RFG- reformulated gasoline
SOC- (battery) state of charge
SOHO- self-organizing hierarchical open (system)
SULEV- super ultra-low emissions vehicle
ULEV- ultra-low emissions vehicle
WKTEC?- Who Killed the Electric Car? (movie)
ZEV- zero emissions vehicle

Table of Contents

Illustration Index

Index of Tables

Chapter 1. Introduction & Motivation

Personal Motivators

I consider myself to be a serious student of engineering, though I have often been criticized for being *unrealistic* and *idealistic* when speaking of my research and related interests. These two descriptors are not commonly applied to engineers, which in my experience are among the most practical people in the World. I eventually came to realize that my so-called idealism had less to do with my practice of engineering, of which I am quite fond and modestly accomplished, and more to do with my relatively unique perspective on engineering design and analysis. For example, my *rejection of economics* as the predominant tool for constraining a given engineering problem seems particularly difficult for many people to accept. As my first Systems Engineering professor put it, "*The objective is always to minimize cost. There are no exceptions.*" In a similar vein, another of my professors once quipped that, "*Anyone can build a bridge, but an engineer can build a bridge at the lowest cost.*"

Upon my discovery of the economic bottom line in engineering design, I briefly considered the pursuit of a different livelihood, as I was already sitting on the left-most fence of the engineering discipline; *environmental engineering* (EE) is considered by a great many professional engineers (outside of EE's) to be the softest, simplest, and most liberal of the engineering disciplines. Rather than abandoning all hope, in 2007 I decided to delve ever-deeper into the bowels of environmental engineering theory. It was there, among many long forgotten ideas, that I found the work of Howard T. Odum. Nearly everything Odum produced over his long and prolific academic career seems common sense to my mind, and I have since adopted Odum's own term for the discipline and livelihood which it seems he himself was branded, that of an *ecological systems engineer*. My perceptions of engineering and of systems design have been drastically altered by Odum's deep and lucid insights, and I am now happy to include myself among the growing global community of ecological systems engineers. I will forever be indebted to Odum for his dedication and perseverance in the engineering discipline. Aided by further deep insights from (r)evolutionary designer R. Buckminster Fuller, philosopher Robert Pirsig, and many other deeply concerned and contemplative individuals, I have made modest attempts at understanding Odum's engineering analyses and representing them here from a fresh perspective.

While I will concede from the start that much of my writing may seem unrealistic from the reader's perspective, I will not admit to being an impractical person. On the contrary, I was raised in a modest, hard-working, blue collar family. I have a miner for a father, a butcher for a mother, and a barber for an older sister. Upon graduating from high school, I received a full scholarship to pursue a degree in Environmental Resources Engineering (ERE) at Humboldt State University (HSU). The possibilities of a clean vehicle future later attracted me here, to the ITS graduate program at the University of California, Davis. After 21 years as a perpetual student, I am no more an expert of the World than I ever have been, though I have certainly witnessed a great number of its intricacies, complexities, and the local & global scales of the many challenges facing my generation. These challenges can be daunting and intimidating at times, yet we have little choice but to face them head on and with the utmost self-criticality. As humans we do much to create the World in which we live, and therefore we are all responsible for the injustices, deficiencies, and degradations which exist as a result of our life choices.

My attempt to remove economic constraints from their current position of dominance over engineering design and analysis is neither new nor novel. In *Small is Beautiful*, E. F. Schumacher clearly describes the many dangers associated with rampant industrial and economic growth. The book was written in 1973, at a time when the U.S. was suffering its first national energy crisis. Unfortunately for most, the global economic playing field still remains slanted in favor of larger players and *phantom wealth*[1]. John Perkins describes the persistent problem of *economic gospel* quite clearly in his brutally honest and self-critical novel, *Confessions of an Economic HitMan* (p. xii).

"   *Some would blame our current problems on an organized conspiracy. I wish it were so simple. Members of a conspiracy can be rooted out and brought to justice. This system, however, is fueled by something far more dangerous than conspiracy. It is driven not by a small band of men but by a concept that has become accepted as gospel: the idea that all economic growth benefits humankind and that the greater the growth, the more widespread the benefits. This belief also has a corollary: that those people who excel at stoking the fires of economic growth should be exalted and rewarded, while those born at the fringes are available for exploitation.*

1 For more on this, read David Korten's latest novel, *Agenda for a New Economy: From Phantom Wealth to Real Wealth*.

The concept is, of course, erroneous. We know that in many countries economic growth benefits only a small portion of the population and may in fact result in increasingly desperate circumstances for the majority. This effect is reinforced by the corollary belief that the captains of industry should enjoy a special status, a belief that is the root of many of our current problems and is perhaps also the reason why conspiracy theories abound. When men and women are rewarded for greed, greed becomes a corrupting motivator. When we equate the gluttonous consumption of the earth's resources with a status approaching sainthood, when we teach our children to emulate people who live unbalanced lives, and when we define huge sections of the population as subservient to an elite minority, we ask for trouble. And we get it."

I quote this excerpt, directly and unedited, from the introduction of Perkins' novel. I believe that it eloquently and succinctly describes the major problems with classic economic perspective that I wish to address in this thesis. While many scholars have made similar accusations against the prevailing view of free market economics, some even suggesting alternative approaches (e.g. Hawken et al., 1999), Perkins has done much to impact popular opinion by honestly reaching out to a mass audience. He should be rewarded for his bravery, as such insights provide a great service to the country in support of evaluating and repairing our many systemic economic failures. Though my reach is likely far more limited than that of Perkins, I hope to provide an honest and self-critical assessment of the state of energy and vehicle technology development, offering my thoughts on market failures and deterred technology adoption by the automobile and energy sectors. Most importantly, I hope that the work of this thesis may also help to inspire a new generation of conscientious technical designers & engineers.

As quoted from Albert Einstein at the beginning of this document, it seems critically important that the majority of our time be spent clearly defining the problems we face before we rush to make an attempt at solving them. Much academic effort has been spent in the search for solutions to the World's greatest problems, though I would agree with Einstein's assertion that the vast majority of our time should be spent first in the determination of more *powerful questions*. Too often, we approach our problems with powerless questions that are loosely defined and arrive at solutions inadequately justified, sending well-intentioned academics to act as the *blind leading the blind*. This thesis represents over 5 years of graduate-level study, yet it is dedicated almost entirely to addressing the most fundamental questions of the *sustainability trilemma* via simple definitions and my honest assessments of personal experience.

Problem Context

Energy distribution and use-patterns of the modern era illustrate an inability of human systems to efficiently use and adequately value energy resources. As one example, each day the people of the World burn nearly 85 million barrels of petroleum (EIA, 2008), much of which is consumed relatively inefficiently in the form of gasoline for powering our vehicular transportation. In single occupant vehicles (SOV), about 1% of the fuel's embedded energy is actually used to move the driver. The gasoline itself (of which 99% is effectively wasted) is a toxic, carcinogenic substance that contaminates water, air, and soil wherever it is used. And as with any geographically constrained and economically constraining resource, continued dependency on gasoline will likely necessitate further global resource conflicts (e.g. military action and competitive resource exclusion). The total dominance of petroleum in supplying the energy that builds and animates modern civilization provides an impressive growth model with staggering implications, given the extent to which societies of the so-called developed World now depend upon it.

It has long been obvious to some (e.g. Hubbert, Diesel) that trends in global petroleum consumption are *unsustainable* for long-term human development, yet there seems to still be little agreement as to what a more sustainable energy system should look like, even among so-called energy experts. Extensive and seemingly exhaustive technical reviews on the sustainability of energy and transportation have been explored (e.g. Tester et al., 2005; Hall, 2006). To the author's knowledge, a standard for developing and applying *sustainability benchmarks* by which to set and assess technology development goals and compare options has not yet been widely adopted at the time of this writing.

The identification of sustainable design benchmarks as critical elements of a larger technology assessment framework is among the pursuits of my ongoing research. To be clear, I am not suggesting that a *scientific consensus* be made before moving forward on issues of sustainable design and regulation, since most reasonable people will understand that full consensus among large or diverse groups of people is practically impossible to achieve, even within a narrow field of study. For consensus decision making, the *two pizza rule* is about as good a guideline as exists for consensus-building; you should rarely attempt to obtain full consensus on important, action-oriented decisions from more people than it takes to eat two large pizzas (i.e. ~ 6 to 8). If this sounds a lot like localized governing, there's a reason: sustainable development is both implemented and measured at local scales.

As described by Abraham Maslow some 65 years ago, the pursuit of universal human health and actualization are probably the most reasonable motivators for continued development upon the Earth (Maslow, 1943). As such, it would seem that information pertaining to the overall improvement of human health in the long-term would be most highly valued by members of society. Despite such hopeful longings for an evolutionary transition toward techno-cultural utopia, the dominant technologies of our era have a longstanding reputation of compromising the health and resilience of ecological systems (*ecosystems*), even when these ecosystems provide critical and irreplaceable support to human health. These technologies are deeply entrenched in industrial society as we know it, and thus it is difficult for many to consider a society that exists without the presence of these dominating forces. Many people resist *techno-cultural evolution,* opting rather to believe that it's "*better the devil we know than the devil we don't.*" However, the devil we know might be even worse than we think.

In response to catastrophic system failures, there is growing awareness of the many common techno-cultural human practices that are unsustainable and which may threaten the existence of life as we have come to know it on Earth. Whether by active choice or passive ignorance, humans can no longer be afforded the luxury of destroying the natural World around them, assuming of course that we intend to continue living on Earth in the future. In pursuit of more resilient and thriving living environments and human communities, concepts pertaining to *smart planning*, *intentional design*, *industrial ecology*, *ecological engineering*, and *techno-cultural evolution* are gathering widening popular support. In the view of pioneer designer Sim Van der Ryn, a more homeostatic design perspective might aptly be coined *eco-logic* (Van der Ryn et al., 1996), as it draws its criteria primarily from the practices and approaches developed in fields related to ecology. From this perspective, those systems designed upon a premise necessitating infinite or unchecked growth will inevitably commit institutional suicide. In the words of visionary technologist Amory Lovins, "*You cannot have infinite growth in a finite World.*"

With the possible exception of very new, theoretical, or highly dangerous engineering projects, detailed models of most human systems and their interfaces within the built and natural environments are rarely described *a priori*, i.e. prior to their physical existence. There is generally no mandated requirement for the development of highly detailed and dynamic systems analyses, due in part to the inherent money/time constraints of the average engineering project, and also to the general absence of the long-term data required to fully characterize a complex system and its environment (*read also*: money/time constraints). However, the few exceptions that may exist are those projects related to military offense/defense, which due to their sensitive nature require highly detailed systems analysis, integration, and control. Not coincidentally, these projects receive many orders of magnitude greater financial support than all of the other fields of engineering combined, and thus they exist within a class very much their own. You may wish to pause now and question the sense of such a value system, so heavily biased towards aggression & dominance. Though many have made similar criticisms, the numbers speak for themselves; Illustration 1 depicts the severity of inequity in funding for military vs. nearly all other development projects, including the World's *major epidemics*. Each square shown in this picture represents $1 billion in government spending. The total map represents annual World military expenditures of approximately $780 billion U.S. (WGI, 2001). If made available, these funds could theoretically be used to help address our World's major systemic epidemics **FOUR TIMES!**

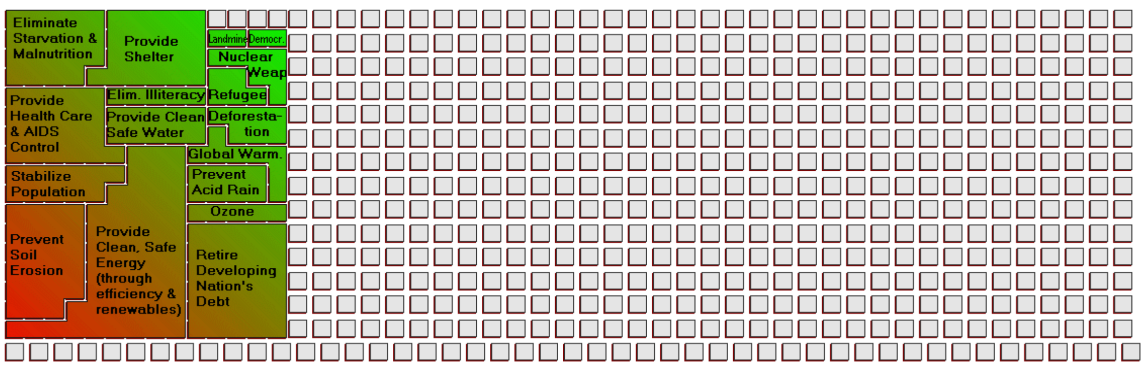


Illustration 1: Global military expenditures vs. the costs of addressing major human epidemics.

Turning now to the discussion of alternatively fueled vehicles, serious theoretical & prototypical design efforts for vehicles and their fueling infrastructure have been ongoing for over 40 years. The term *alternatively fueled vehicles* (AFV) is used here as a broad category which describes full-performance personal vehicle technologies that necessitate off-board fueling from unconventional fuels (e.g. electricity, hydrogen, and biofuels). By this definition, a hybrid (e.g. the Prius) is not considered to be an AFV unless it's engine were to be fueled by ethanol or hydrogen, for example. The relatively recent introduction of battery electric vehicles in the mid-1990's marks the beginning of a shift from theoretical & prototypical to applied & marketable engineering of mass-produced AFV, a critical point in the evolution of the common personal vehicle.

This point in time also marks the introduction of new and potentially disruptive technologies, new vehicle use-patterns and mode distinctions, and new standards for measuring vehicle performance, impacts, and consumer value. In the midst of much commotion and excitement over the future possibilities of the AFV market, it is critically important that close attention be paid to the metrics by which success and failure will be measured when considering technology specifications, market performance, and environmental interactions. The definition of fundamental problems, at both local and global scales, should be afforded the lion's share of our time and attention. If vehicle and fuel alternatives do not achieve measurable improvements over the existing system, or if they do so at costs that the average consumer and/or the environment are not able to bare, then such alternatives will be infeasible in the long-term, regardless of their perceived near-term political or industrial popularity (i.e. technologies *du jour*). California has already learned this lesson the hard way and should now be sufficiently wary not to repeat the bad habits of her youth.

Those members of industry attempting to gage their company's performance in terms of *system sustainability*, whether it be for economic, ethical, or regulatory reasons, now commonly perform what are referred to as *triple bottom line* (TBL) assessments, first developed for industry by John Elkington. Institutional performance is measured using the *Three E's* of sustainable development: *economy*, *ecology*, and *equity.* Institutions perform well on this assessment when they are able to demonstrate improvements over prior performance, typically through the reduction of undesirable externalities. This might include measurable reductions in annual expenditures, environmental pollutants (often per unit of utility or product), and/or hazards to employees, consumers, or other social groups. In theory, these three metrics of sustainability are intended to be equally weighted, though in practice the economic metrics time-and-again receive significantly greater institutional attention. As William McDonough has pointed out, these assessments may help institutions to do *less bad* in their business practices, but that should not be equated with *doing good*. An additional drawback to this approach in institutional performance evaluation is its backwards-facing nature, where sustainability metrics are applied *ex post facto*, like most other end-of-year evaluations, with relatively little recourse for low performance and only minimal feedback for improvement. Meanwhile, concerns for holistic design and sustainable business are not institutionally adopted and afforded the same level of priority as are given economic returns. Thus, the effective bottom line remains unchanged. At best, a TBL considered ex post facto can only encourage small incremental shifts away from business-as-usual (BAU) development.

A similar yet distinctly novel concept for the institutional evaluation of sustainability is that of a *triple top line* (TTL) assessment, a concept pioneered by McDonough and Braungart (McDonough et al., 2002). A TTL product assessment and valuation occurs at the beginning of any design process, prompting the consideration of impacts and decisions before any significant action is taken toward development. To loosely paraphrase McDonough on the purpose of applying a TTL, it attempts to remove the filter from the exhaust pipe and place it where it belongs: between the *designer's ears*. By applying principles of *eco-effective design*, this thesis work attempts to perform a TTL assessment through the model-based design of a sustainable personal vehicle, along the way estimating the possible future impacts of widespread AFV introduction and use. The uncertainty of the assumptions made at societal scales are large, and thus such projections should be considered only as plausible scenarios in moving forward. Nevertheless, a consideration of the AFV as an emergent consumer product provides an elucidating example for the development of a TTL valuation framework, enabling the conception and realization of regionally appropriate technical design & engineering.

Thesis Structure

This thesis is comprised of six chapters, building from the introduction (which you have presumably just read) through to the discussion of research findings & future work. Collectively, these chapters describe the conceptualization of a sustainable personal vehicle design, as well as the conditions under which such a vehicle is likely to emerge and succeed within the California vehicle market. Chapter 2 explains the need for new value structures to account for economically intangible qualities and benefits of AFV. Chapter 3 is an assessment of the sustainability concept and the metrics by which it may be measured. Chapter 4 describes energy resources & technologies with good potential to enable sustainable development. Chapter 5 describes a modeling approach for AFV. Chapter 6 describes the technical and market readiness of EV. Chapter 7 details modeling efforts for sustainable systems in general. Chapter 8 reviews the potential for a sustainable personal vehicle in the not-so-distant future. Lastly, Chapter 9 concludes with a very brief summary of observations and areas for future work.

Chapter 2. Re-Valuing Sustainable Personal Vehicles

Introduction

Engineering is an age-old tradition of solving problems, a practice that existed long before the wider considerations and formalization of modern science. Even today as a branch of applied science, the fundamental objectives of both engineering theory and practice remain rooted in the understanding & alleviation of human needs and suffering. It seems useful to now consider a few common definitions for those words which we most frequently use to define our field of engineering, followed by the descriptions of three accomplished academic departments in this field. These descriptions are intended to add clear context and minor justification for my analysis of AFV technology within such a practice and collection of knowledge as Civil & Environmental Engineering (CEE).

Civil

Applying to *ordinary citizens*, separately distinguished from the military (Miller, 2008).

Environmental

External or surrounding conditions, and as reference to how they change (Miller, 2008).

Engineering

The discipline dealing with the art or science of applying scientific knowledge to practical problems (Miller, 2008).

Civil & Environmental Engineering, Departmental Descriptions

"*The Department of Civil & Environmental Engineering integrates research, education, and professional service in areas related to civil infrastructure and the environment. We provide the profession and academia with outstanding graduates who advance both engineering practice and fundamental knowledge.*" (UCD, 2008)

"*MIT's Department of Civil & Environmental Engineering is dedicated to balancing the built environment with the natural World. In our research we seek to understand natural systems, to foster the intelligent use of resources, and to design sustainable infrastructure systems.*" (MIT, 2008)

"*Many people look at Civil Engineering and Environmental Engineering and see separate disciplines. At Stanford, we see links and interdependencies through which some of the most difficult and urgent problems facing mankind may be solved.*" (Stanford, 2008)

Proposals for a meta-discipline in *sustainable engineering* have been presented, with CEE students, professors, and practitioners now leading the charge to develop more sustainable human systems. Though more obvious among the *theoretically-oriented* programs, the intentions of sustainable systems engineering have been wholly embraced by the visions & language used by our various academic departments. Strong support from CEE professionals for groups such as Engineers Without Borders tends to suggest that this inclination toward sustainable development is not an isolated phenomenon of academia. It seems noteworthy to consider also that CEE itself is a combined discipline of study and practice which was only considered distinct within the last ~ 20 years. Thus, it may be relatively straightforward for our field to adapt to the large, multi-disciplinary challenges and engineering needs of both the natural and built environments as compared to older and more isolated engineering disciplines. Clearly, creative solutions should be encouraged in all fields related to engineering & design as we attempt to address the many daunting problems currently impacting the Earth's biosphere.

Alternatively Fueled Vehicles

The relationship between humans and their personal vehicles is perhaps the most commonly recognizable example of an economic activity that has been energetically subsidized by, and consequently made dependent upon, fossil energy resources. The personal vehicle also serves as a common metaphor for the freedoms and privileges afforded us by modern industrial civilization. Though the benefits and freedoms that the personal vehicle affords us are large and commonly thought to outweigh their relative social costs (Delucchi, 1996), the profound impacts that short-sited fossil fuel consumption and vehicle-oriented growth patterns have placed upon society and the environment seem increasingly to over-shadow the perceived benefits of private vehicle ownership. This difference in perspective presents major challenges when attempting to establish lifecycle boundaries and assign consumer value. With economics as the common tool and language, all must be equated to the dollar.

Though pervasive and often useful, the econometric approach to measuring lifecycle impact and consumer preference often ignores all factors deemed intangible (e.g. irreplaceable ecological resources & services) or destabilizing within industrial BAU (e.g. limiting/eliminating economic growth, introducing disruptive technologies). In a World where sustainable and regionally appropriate development were considered as high priority, one might wonder if the personal vehicle would persist. It seems possible that in such a World, the personal vehicle may cease to exist almost entirely, as described in Ernest Callenbach's *Ecotopia* (Callenbach, 1975). In regions like California, where politicians and regulators are taking serious steps toward constraining the externalities of personal vehicle design and use, there remains a sliver of hope that conventional vehicle technologies will eventually evolve into more sustainable alternatives (e.g. Sperling and Gordon, 2008; Sperling, 1995).

Indeed, it seems that if any region of the World is adequately positioned to produce AFV for the consumer market, California is just such a place. Already the state has witnessed relatively significant activity in early-adopter and niche AFV markets, while the political environment continues to be relatively favorable for continued growth of the green car industry (Calstart, 2004). However, several nagging questions remain largely unanswered, such as: W*hat type of AFV should consumers demand?* W*hen will AFV be ready for market? How much will an AFV cost?* and, *What benefits will an AFV provide?* On a personal level, I encounter such questions often in my attempts to describe my work to friends, colleagues, and acquaintances. Without missing a beat, they will frequently ask "*OK, but what car should I buy?*" It sometimes seems easier for me to hide in uncertainty and tell them that no good options exist, but I would certainly prefer to give them useful information about how to select sustainable personal vehicles for their various mobility needs, demanding new alternatives when their needs are not adequately met by the incumbent vehicle & energy dealers. In addition to daily conversations, I have also publicly presented my thoughts on the matter (e.g. Jungers, 2007). Herein lies a major thrust of my efforts; informing the populous by sharing practical information.

Competition, Cooperation, & Community

Identifying patterns of natural resource consumption that would best support sustainable development is an effort which itself is still misunderstood and hotly debated. The Rio Earth Summit of 1992, the same year that MIT combined their Civil & Environmental Engineering departments (MIT, 2008), seems to be widely considered the beginning of a wider global conversation on the topic of sustainable development, though localized criticisms of unsustainable industrialization date back at least to the critiques of forest management by Hans Carl von Carlowitz (1645 – 1714) and to those on population growth by Thomas Malthus (1766 – 1843). For all practical purposes, sustainability is only a useful critique of development when it can be coaxed into a well-defined description. For the purposes of this analysis, the definition of sustainability provided by C. S. Holling will be sufficient: "*Sustainability is the capacity to create, test, and maintain adaptive capability.*" (Holling,2001).

Though I most commonly refer to either systems or communities when speaking of organized groups of interacting agents, it may be useful to consider three related, subtly differentiated, yet distinctly functional terms for considering the dynamics of social groups: *communities*, *systems*, and *organizations*. Each of these categories may be considered separately as the *social locus* for technological practice and development (Constant, 1987), though arguably the most useful and holistic considerations involve all three as separate, overlapping elements. By mapping and sufficiently describing these three social groups, balancing their various social, ecological, and economical needs and values within society, it may be possible to determine what is fundamentally required in order to sustain and evolve each social sector (i.e. the *Equity* portion of sustainability concerns). Illustration 2 provides an example of such an overlapping map of social influence (Constant, 1987).

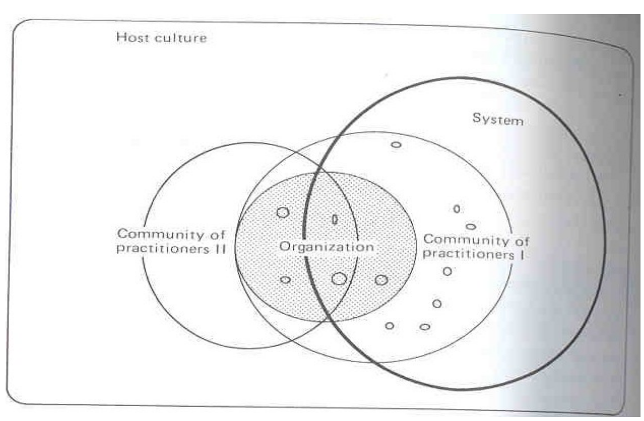


Illustration 2: A simple mapping of social group interactions (Constant, 1987).

Along similar lines, a systems-level approach to analyzing social decision making and consequent interactions can be demonstrated by a *trilemma of social choices*, represented by a simple Sierpinski gasket (Vleck and Cvetkovich, 1989). In Illustration 3, three idyllic principles of social choice are depicted (*collective rationality*, *equal participation*, and *decisiveness*) along with the three most common approaches to social decision making (*consensus*, *majority rule*, and *dictatorship*). For each of these approaches, a violation occurs for one of the three idyllic principles (i.e. at the perpendiculars).

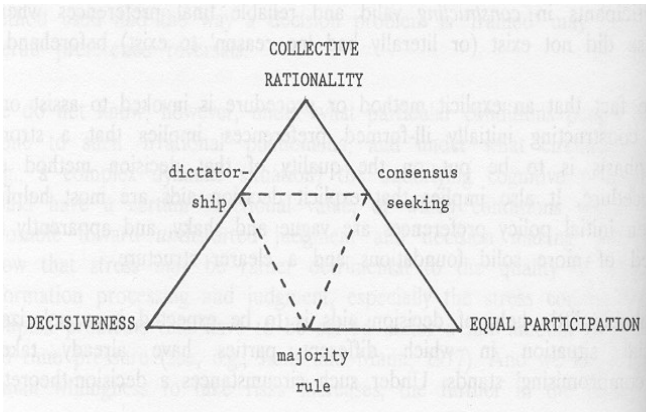


Illustration 3: A map of the social decision making *trilemma* (Vleck and Cvetkovich, 1989).

While studying ERE at HSU for my undergraduate degree, I found that energy concepts were notoriously difficult for average people, and even so-called experts, to grok. A common example is the swapping of energy and power terminology, a mix-up I once heard uttered from the mouth of our nation's Secretary of Energy, Spencer Abraham. Regardless, the basic consideration of social decision making in the distribution of energy resources can be demonstrated quite simply by a single interaction between two agents. For example, if one considers the *prisoner's dilemma* as a generic case of resource allocation, each agent may choose one of two options when interacting with another agent; they may choose to *cooperate* (C) and share their resources completely, or they may choose to *defect* (D) and attempt to collect a larger share of resources. Illustration 4 provides a depiction of the decision matrix formed by a two-agent allocation of resources in a classic case of the prisoner's dilemma[2].

2 Richard Dawkins' take on the prisoner's dilemma: http://video.google.com/videoplay?docid=-3494530275568693212.

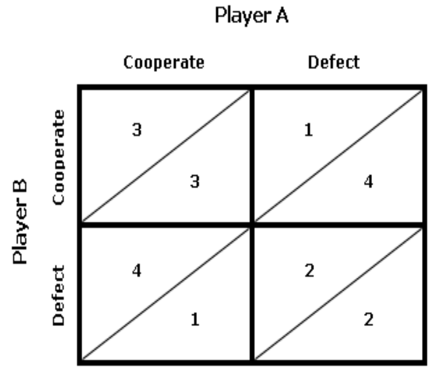


Illustration 4: The classic prisoner's dilemma, with two players A and B.

One should note that the greatest *collective good* is achieved when both agents choose to cooperate (C/C), while the greatest *individual good* is achieved when one agent defects while the other chooses to cooperate (D/C). When both agents choose to defect (D/D), the outcome is the least beneficial for both agents, and thus the most universally unfavorable outcome. The term *reciprocal altruism* has been used to denote the tendency of agents to choose cooperative relationships over defective ones, while selfish or risk-averse individuals will generally choose to defect in hopes of maximizing personal gain or minimizing loss, respectively. Through successive trials, it was found that the most successful strategy for survival in this dilemma is also among the simplest. A four-line program, referred to by its creator as *Tit-for-Tat*, was victorious in two rounds of play, simply by using the following three rules:

1. Cooperate when first interacting with another agent (i.e. default to C).
2. Remember the agent's most recent resource selection choice (either C or D).
3. Mimic this choice in resource selection; then return to Step 2.

Tit-for-Tat proved to be the best survival strategy in multiple rounds of simulation by demonstrating a disposition toward cooperation, adapting quickly, and remembering only the outcome of its most recent prior interaction. This brings to mind a quote attributed to Albert Schweitzer: "*Happiness is nothing more than good health and a bad memory.*" Could the survival and proliferation of life on Earth possibly be so simple?

Let's now consider an even more simple strategy for the prisoner's dilemma, one where both agents make completely random choices regarding resource distribution. In such a scenario, the probability of choosing to cooperate or defect should be ~ 50% (P = 0.5), and thus the probability of receiving a particular resource allocation (1, 2, 3, or 4) is ~ 25% (P = 0.25), as it is the product of the 50% probabilities of both agents' choices. In such a case, if the game is played over an extended period of time, the average resource allocation per round for either agent should be about 2.5. Obviously, when both agents choose to strictly defect or cooperate, they will each receive 2 or 3 units of resource, respectively. The *systems optimal* survival strategy occurs when both agents cooperate, as this provides the maximum combined resource allocation possible (i.e. 6 units). In a system where agents do not receive perfect information or feedback related to their choices and the outcome of resource allocation, it is not surprising to imagine that resource distribution patterns will be sub-optimal, even for the simplest of agent interactions.

It is my assertion that fossil energy subsidies and competitive capitalist market signals have provided an over-incentive for individuals to defect in their choices of energy resource allocation. Often, individual agents (i.e. energy consumers) have limited resource portfolios from which to choose, they may not have direct access to such resources, and few (if any) opportunities to directly interact with other agents. To address this system failure, one possible restructuring approach would allow for the formation of *renewable energy community cooperatives* (RECC). In forming such cooperatives, members would be expected to work together in assessing the quantity, quality, and availability of their local energy resources at the ecosystem level (e.g. watershed). Investments in renewable energy infrastructure could be made collectively, and the benefits of the cooperative would be shared among members. Similar cooperatives have been formed by necessity in developing areas, though I believe that with time we will come to see more of these groups, even within the developed World, with members electing to adopt such models of resource ownership and management. To some degree, municipal utility districts (MUD) currently serve such niche services in many regions, though there is generally not the level of active community participation and education that is envisioned here.

Real & Perceived Needs

One of the first lessons in methods of human surveying is that of distinguishing between real and perceived consumer choice and needs, if at all possible (Mokhtarian, 2005). The problem is, how do you really know what the consumer *needs*? For that matter, how does *anyone* really ever know what they need? To approach this problem, it seems useful to first distinguish between *basic needs* and *convenience needs*. In the first case, basic needs are those needs which pertain to physiology and the actualization of the individual. Some may wish to refer to these needs as *inalienable rights*, though others may wish to steer clear of such political wanderings. In either case, they are necessary to health.

One very influential consideration of human needs is that of Abraham Maslow's personal human motivators, categorized as *physical*, *safety*, *love*, *esteem*, and *self-actualization* (Maslow, 1943). Maslow developed a loose theory of hierarchy based on the relative importance and successive nature of these motivators. Though varying from person to person, Maslow believed that a person with deficiencies in their *low-level needs* (e.g. physical) would be less motivated to seek the attainment of *high-level needs* (e.g. esteem, self-actualization). A classic example is that of a hungry person who will tend to be primarily concerned about finding their next meal, while other concerns may be deemed insignificant until the person's hunger is satiated. In theory, long periods of unmet need may act to effectively eliminate the interest and concern for meeting higher-level needs (Maslow, 1943). Note that none of these needs is inherently characterized by accumulated wealth or similar signs of social status.

Every person is born with different privileges, different social expectations, and varying degrees of perceived *personal entitlement*. What one person perceives as their own basic personal needs may be considered by someone else *luxuries of convenience*. This difference in opinion can make interpretation difficult when considering the significance of consumer choice feedback. Demographic information, such as income and education level, can only provide partial insights into the individual's perspective, since much of this perspective may in fact stem from experiences that exist primarily or entirely within their subconscious mind. This is especially significant for those of lower economic standing (Maslow, 1943). For the purposes of this research, we will consider the personal ownership of any consumer product to be a necessity if and only if (*iff*) this product supports the fulfillment of one or more of Maslow's five motivators. So far, this description is not particularly useful as it does not directly address acceptable or sufficient levels of consumption. Within the context of an individual person's life, it should be more straightforward to designate those resources and consumer products which effectively and sufficiently support basic motivating human needs. This assertion is commonly reflected by introductory assignments in sustainability science and engineering courses, where students are directed to calculate and evaluate their personal consumption patterns and environmental footprints.

A History of Failure: Vehicle Concepts, Prototypes, and Start-Ups

The concept of the *alternative automobile* is an old one. In fact, alternatives to standard ICE vehicles have been under development since the beginning of automobility itself. RD&D of battery electrics, hybrids, and other vehicle/fuel alternatives have been ongoing since the early 1800's. Unfortunately for those of us seeking greater diversity in consumer choice, the ICV was first to reach mass market, encouraging large capital investments for gasoline fueling infrastructure and subsequently out-competing the electric powertrain for ~ 100 years. That's not to say there haven't been good alternatives developed over the years, but the pressures of a competitive marketplace, combined with much apparent consumer apathy and moving performance targets, have kept alternatives at a minimum.

The Scottish-Made Car (~ 1832)

The Scottish inventor Robert Anderson is credited with driving the first ever electric carriage, though several soon followed suit. To my knowledge, this is the first and last car publicly developed in Scotland, but I could easily be wrong. America quickly took the lead in electric vehicle manufacturing, though as mentioned previously, no electric vehicle manufacturer ever succeeded in achieving the widespread proliferation of vehicles that was attained by Ford and other ICV manufacturers of the era.

Porsche Makes Hybrids (~ 1900)

Ferdinand Porsche worked as an engineer for Jacob Lohrner's electric car company in Vienna around the turn of the 20^{th} century. Porsche was the first to develop a drivetrain based on hub-mounted electric motors, and he incorporated them into hybrid drives with electric front hubs and a petrol-driven rear. One of his hybrid vehicles may have also been the first all-wheel-drive automobile (Illustration 5).

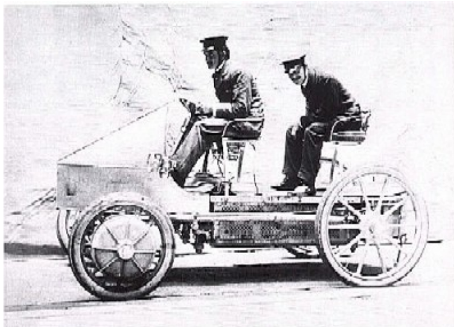
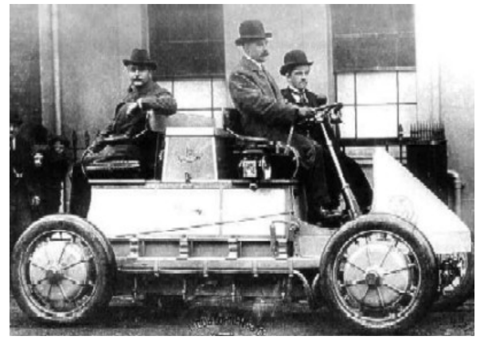
 

Illustration 5: Ferdinand Porsche and his hybrid vehicles of the early 1900's.

Veggie Diesels (1893)

Rudolf Diesel first proposed his concept for a *rational heat engine* in 1892 (Weather and Hunter, 1986). His original efforts were aimed at powering this heat engine from coal dust, but this endeavor was not successful. Eventually, Diesel developed the compression-ignition internal combustion engine and was able to power it on liquid fuels. There is some evidence to suggest that Diesel later intended on powering his engines from vegetable oils, and that he demonstrated the use of peanut oil as a renewable replacement for petroleum fuel, though this assertion is poorly documented and inadequately referenced in the popular literature. What is commonly known, however, is the ease with which the diesel engine may be powered by such biologically derived oils. Case in point: I currently own and operate a 2000 Volkswagen Golf TDI powered by biodiesel made from waste vegetable oil treated with lye and mixed with ~ 10% methanol. Though no local fueling stations exist for biodiesel in the city of Davis, I typically refuel at a semi-local station at the Solar Living Institute in Hopland.

Bucky's Blimps (1933)

One of the earliest, most fancifully conceived, and highly efficient demonstrations of holistic and sustainable vehicle design can be found in R. Buckminster Fuller's *Dymaxion Car* series (three vehicles produced in all). The *Dymaxions* were designed for near-optimal drag resistance (given the materials available and modeling capabilities of that time), as the vehicles were intended to one day be functional for transport by land, water, or air. As such, Fuller is reported to have referred to them as *Omni-Medium Transport* (Discoe, *unpublished*[3]). The *Dymaxion* was built to transport 10 passengers and a

3 Freelance computer engineer Ben Discoe, living *the life* in Hawaii: http://www.washedashore.com/.

driver (the second version incorporated a fold-out, queen-sized bed!), it reportedly achieved between 30 and 50 mpg fuel economy, weighed less than 1,000 lbs, and could travel at speeds up to 120 mph powered by a 90 hp engine (taken from an old *Ford* of the same era). A fatal crash in a rag-top version of the *Dymaxion* called into question the safety of rear steering for large 3-wheeled vehicles.

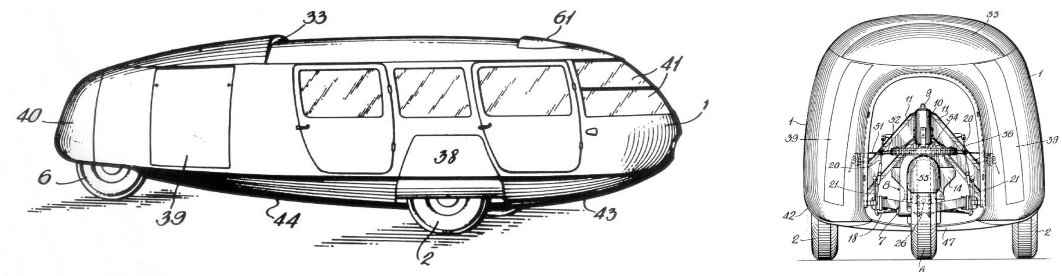


Illustration 6: Side- and rear-view schematics from the *Dymaxion* patents (Discoe, *unpublished*).

Tucker: A Man and his Nightmare (1948)

Heaven only knows why Preston Tucker was so obsessed with the rear-mounted engine, but you have to give him credit for putting up a hell of a fight against fierce opposition from the big, incumbent automakers. His car was called the Tucker 48 (after the model year in which it was made) and there were only 51 ever built. For those interested to learn more about the Tucker, I recommend reading his *Open Letter to U.S. Newspapers*, written by Preston Tucker and submitted on June 15, 1948[4]. He claimed to have raised $25 million in capital investments (which would be ~ $250 million today), yet he was still somehow unsuccessful in bringing the Tucker 48 to market. Ouch.

A Plethora of Prototypes

There have been more *vehicle concepts* produced by the major auto manufacturers than one could easily remember. Though exciting and inspiring in their many various designs, ideations, and aesthetics, the realization that such a staggering number of concepts have been produced and have not seen the light of day is a sobering fact, if not downright depressing. A collection of such vehicular eye candy, the more celebrated (yet never commercialized) concepts through the late 1990's have been documented in Chris Rees's coffee table offering, *Concept Cars* (Rees, 1999). A simple *Google Image*

4 From the Tucker historical preservation site: http://www.tuckerclub.org/html/openletter.html.

search brings up many more and newer models, but why aren't we driving any of these marvelous machines of engineering prowess? Cost is one candidate; technology deterrence from automakers is another; and, both have been well considered (e.g. Bunch and Smiley, 1992). Whatever the reasons, before I die I wish to somehow acquire a vehicle that meets all of my most fanciful desires.

Illustration 7: GM's *Urban EV* circa 1973, GM/MIT's *(G)race H-type*, and Moeller's *M200G*.

The Car that Couldn't (1996)

The *EV1* had the lowest drag coefficient (and was among the most efficient) of any production vehicle ever built. General Motors was way ahead of the competition when they released the *EV1* for lease in 1996 in Southern California and Arizona. However, they apparently had not properly considered their business case for electric vehicles before bringing them to market, as the company eventually made the decision to pull their support for the *EV1* project and recalled all vehicles for demolition at the GM Proving Grounds outside of Phoenix, AZ. This has been thoroughly documented in the soon-to-be cult classic, *Who Killed the Electric Car?*, a movie more appropriately named *Who Killed the EV1?* Though biased, accusatory, and one-sided, this film contains much historically accurate information.

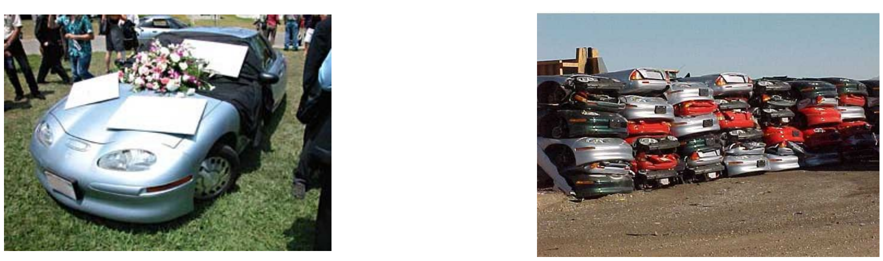


Illustration 8: We know who killed the *EV1*, but can we evolve it into a car for the masses?

Hubris Motors: The Moxie to Try Again

As I've mentioned before, we're currently in the midst of America's *second wave* of electric vehicle development fervor and yet another economic crisis. Each of the major automakers is taking a different approach, hoping to prove they can provide ample supply to meet future demands of AFV. Nissan is the only large company making a public push for BEV, though Better Place is giving everyone a run for their money with their new, high-profile business model that looks more like a cell phone service than anything Detroit has ever offered. GM is touting it's bigger, better, and flashier electric vehicle the *Volt*, and the story holds that they will eventually manufacture it, though it is not a pure EV. They're calling it an *extended-range electric vehicle* (EREV), though the configuration is more commonly known as a plug-in (or pluggable) series hybrid electric vehicle (SHEV). Honda is pushing for direct hydrogen fuel cell electric vehicles (FCEV), and they seem to have a more advanced fuel cell system than any of the major competitors. Toyota is making small changes to their already impressive *Prius* platform, and there are even rumors that they will make the *Prius* its own line using multiple platforms. Presumably, Toyota may decide to offer multiple battery choices for these models, building further plug-in capability (i.e. > electrification) into their existing parallel hybrid electric vehicle (HEV) architecture.

Illustration 9: Tesla's *Roadster*, the *Tango*, and the Wrightspeed *X1*.

On the start-up side of the fence, there are ~ 40 small car companies (and possibly more underground) who are vying for the currently unmet electric vehicle demand. Some of the leaders include the now infamous Tesla *Roadster* , the Washington-based Aptera *2e*, the Oregon-made *Tango*, AC Propulsion's *Ebox* (converted from a *Scion* platform), and the *Wrightspeed X1*, based on the British-made Ariel *Atom* platform. I can't afford any of these cars, and you likely can't either. Oh well. Keep demanding the best, and who knows? Maybe you'll get it.

Ecological Product Design and Consumer Value

The widespread and still growing patterns of gasoline ICV use and its impacts are among the most glaringly ubiquitous signs of social inequity, environmental degradation, and continued dysfunction of modern global development now known to humanity. One critical leverage point of this man-made problem seems to lie within the unmet economic need of alternatives to become competitive. As the argument goes, poor cost competitiveness follows energy research and development (RD&D) underinvestment, continued technological and market stagnation, and so on *ad infinitum* (Herzog et al., 2001). As another example of green market stagnation, solar-electric photovoltaics (PV) are a long developed and well proven technology, yet the typical PV system is not yet cost-competitive with more conventional forms of electricity production, such as coal or natural gas fired power plants. One analysis has estimated that public investment of ~ $200 billion/yr, or about 1/3 the current annual U.S. energy budget, would eventually lower the purchasing price of PV electricity to that of electricity from coal, with PV cost reductions and manufacturing improvements assumed to follow trends from the computer chip industry of the 1950's (Nordhaus and Shellenberger, 2007). It seems feasible that other so-called high technologies capable of storing and converting renewable energy resources to useful work, such as electrochemical batteries and fuel cells, could follow similar cost reduction trends relative to increases in public RD&D investments.

The proper design of more appropriate technologies requires a thorough consideration of a product's lifecycle, including the context and environment in which it will be used and the often shifting needs of those who will use it. This may take a long time, but as William McDonough is fond of saying, "*Sustainability takes forever. That's the point.*[5]" What is appropriate and sustainable now will not necessarily be so in the future, as the World and its inhabitants constantly change and shift and grow. McDonough is extremely concerned about sustainable design and development, and his opinions seem highly regarded in the upper echelons of both design theory and industrial management. McDonough's theories on design are, from my perspective, just as pertinent to engineering as they are to design, where engineering is considered the *applications arm* of much technical design. As a recent visiting scholar in Civil & Environmental Engineering at Stanford, I think McDonough would tend to agree.

5 Among other places, McDonough made this statement during a speech to the 2000 Bioneers conference.

R. Buckminster "Bucky" Fuller was a man truly beyond his time in seeking to live the life of a designer and engineer for a more sustainable World. In a league all his own, he has been referred to as a *solutioneer*. Fuller has been quoted also as saying that "*a designer is an emerging synthesis of artist, inventor, mechanic, objective economist, and evolutionary strategist*.[6]" As Bucky has described it (now too many years ago), appropriate and sustainable design requires a deep consideration of the human experience and the context in which it is taking place. Falling short of gaining such awareness, we may find ourselves living within a built environment that does not meet our collective or individual needs, using technologies that do not improve our quality of life, and degrading natural resources and environmental services in ways that cannot easily be justified nor remedied. It is both our greatest opportunity and most difficult challenge as designers of the built environment to plan and build human systems and institutions in a manner that supports and strengthens healthy living systems. As McDonough so often points out, this requires the cultivation of *love for all living things, for all time*.

Resilience is a term sometimes used to describe a system's ability to *bounce back* from the effects of stress or other disturbances within an environment (Holling, 2001). The ecological theory of bouncing back from environmental stresses has even been theoretically applied to the entire universe (Gribbin, 1976). This so-called resilience of a system to perturbations is often considered a positive measure of a system's adaptability, diversity, and connectedness. Complimentary to the concept of sustainability, resilience has been observed and characterized for natural systems, particularly with respect to the modeling of interactions within ecosystems (e.g. Odum, 1971). One prevailing framework for developing a complex and adaptive ecosystem model is to consider it as a nested, self-organizing, hierarchical open (SOHO) system (Kay, 2002). An open system, like an ecosystem or built environment, processes a continual flow of high quality energy (Odum, 1994), which for both cases enables living agents to self-organize and form increasingly complex nested structures. A large perturbation (e.g. catastrophe) may inflict stresses that exceed a system's threshold for resiliency, thereby forcing system processes into states of nonlinear, chaotic, and/or unpredictable behavior (Holling, 2001). Full-functioning natural systems will resist such a movement away from equilibrium by effectively dissipating energy inputs, sometimes through the emergence of higher levels of self-organization (Kay, 2002; Odum, 1981). The mathematical description of this thermodynamic observation, both for living and non-living systems, has been described many times, first by

6 From Bucky's *protoge*, J. Baldwin: http://www.solutioneers.net/solutioneering/index.html.

Schrodinger in 1943 and later by Odum, Jorgensen, Kay, Schneider and others. According to Odum, a healthy and stable system will flow power maximally until such time as it is faced with a large fluctuation in energy input, causing it to evolve to accommodate such changes in energy availability (Odum, 1971). If the system is resilient and energy fluctuations are relatively minor, the system should remain stable. However, if the energy fluctuations are extreme and/or prolonged, the system will experience evolutionary trends toward either greater or lesser agent-interaction diversity (Odum, 1971).

Possibly the most basic underlying premise of sustainable design is that the existence and continuing evolution of human life on this planet is something that *should* be sustained and enabled, an assumption which will remain unchallenged in this thesis, though others have made such challenges (e.g. Benatar, 2006). Thus, when viewing human development through the lens of sustainability, it is necessary to identify those agents or processes within the system which *do not support life*. Basic examples of unsustainable agents and processes are things like toxic materials and widespread homicide (e.g. war), respectively. By their very definitions, these two system characteristics do not support the organization and perpetuation of diverse, nested life and thus are maladaptive to sustaining living systems. As such, if a given techno-cultural practice cannot be implemented without inciting the use of persistent toxins or war, as two common examples of maladaptive system attributes, then such a practice should likely be considered an unnecessary aspect of the human condition and be gradually phased out of common experience. In addition to evaluating human behavior and activities for their life-supporting qualities, it is also necessary to closely examine the intricate workings of nature to better learn how these processes might be supported, and in some cases mimicked, through sustainable development. Modeling human systems to resemble analogues in nature is a practice now commonly referred to as *biomimicry.*

Biomimicry Within Industrial Ecosystems

Evaluating the regional sustainability of techno-cultural practices requires an assessment of their ability to flow both energy and materials in quantities and at frequencies that are appropriate for the size and functions of the local ecosystem(s). A techno-cultural practice that sufficiently matches its inputs and outputs to the needs and functions of its surrounding environment could be described as a *biomimicking practice*. The determination of success in biomimicking requires the development of models that represent complex system configurations and interactions. These models are computational representations of system agents, groups, interactions, and processes that can be used to simulate real system performance over time and under varying environmental conditions. Development of such models requires a synergy of new and traditional methods in systems engineering & design.

Industrial ecology was first openly proposed as a concept for further inquiry in a 1989 article of *Scientific American* (Frosch et al., 1989), addressing the question of how an industry might function were it to operate more like a natural ecosystem. In theory, such an industry would feed any remaining unused energy or materials from one process directly into another, repeating this process of *waste recovery* until nothing usable remained. When applied in succession toward its practical limits, this would form a *process chain* with the greatest collective energy/materials efficiency. The useful measure of efficiency for such a process chain also requires the distinction and full accounting of energy types by their ability to perform desirable work, thereby providing the basis for calculating energy dissipation and useful production at each stage (Odum, 1971). This distinction has been documented (e.g. Kay, 2002), though the designation of quality and value for different energy resources remains an arguably obscure and confusing area of research. Attempts at improving this situation employ the use of Odum's terms (e.g. exergy and emergy) to refer to more valuable and useful forms of energy. Returning to the concept of biomimicry, we continue in search of natural analogues which may serve as *thermodynamic benchmarks* for appropriate technology design and implementation, allowing for a consideration of technology as if it were a living organism acting appropriately to its function, scale, and environment.

Introduced only within the last 10 years, the concept of biomimicry seems to be gaining relatively wide support as a useful and holistic design perspective for observing those interactions taking place at the interfaces between human and natural systems. In theory, natural systems produce the most efficient processes for materials and energy utilization with respect to their evolved functions. As Johannes Kepler once wrote, "*Nature uses as little as possible of anything.*" Stated another way, natural process serves as the highest known standard for industrial process efficiency. If a natural process appears to be inefficient, it is probably more likely that the full form or function of the process is not yet clearly understood. In a critically resource-constrained and over-populated World, this is an important observation which cannot possibly be overstated. If global society can develop such a level of *eco-logic* and *eco-effectiveness* in its pursuit of continued human development, it may be possible to achieve global resource abundance for all, rather than simply more poverty and perceptions of scarcity at the societal fringes. Thus, our need for sustainability measurement, the topic of our next chapter.

Chapter 3. Sustainability & Related Metrics

Introduction

It may be commonly observed that the ideal of sustainability is widely appealing and frequently referenced, but like any other abstract concept, it is only useful as a conceptual framework if it can be clearly communicated, understood, applied, and measured. Those working within the energy-related fields of academia (myself included), industry, and policy are currently having a difficult time in clearly describing the qualities of sustainable systems. It seems that most of us are hesitant and suspicious of using terms like sustainability to serve as any sort of *performance indicator*, tending to prefer more concrete or well-developed metrics of system performance, such as cost and utility. This hesitation does not appear to exist for lack of interest or capability, as some of the most intelligent people I have yet had the pleasure of meeting seem perpetually compelled, often to points of energetic exhaustion, by their desire to sustain living systems and improve universal human conditions. Rather, I think the overwhelming size, complexity, and even contradictions within the macroscope (i.e. the unaided human sensory level), coupled with the often unpredictable and seemingly erratic behavior of nested processes, serve as common deterrents and excuses for our continued hesitation in adopting standard methods, measures, and metrics of sustainability. I am now throwing my hat into the ring, attempting to quantify and qualify the *sustainability trilemma*, coax it into a more useful form, and apply it to design.

Whole Systems Thinking

Holistic thought requires some degree of acknowledgment and identification of the individual's place as a participant (i.e. agent) within the living World, not just as passive or unbiased observer. Even within the most controlled and well-defined experimental environments, the very act of observing has measurable effects on the object of inquiry. Speaking to my own biases in observation, I am youthful and idealistic, having little interest in activities supported by seemingly unstable resource consumption and waste in modern societal development. Through my lens of observation, much human intelligence and enthusiasm seem too often turned to jaded apathy as the result of valueless socialization, lifeless economic interactions, and mindless resource consumption. Far too many people routinely submit their lives to a captive participation in malignantly cancerous patterns of growth. If anything is ever to be done to sustain a universally higher quality of human living condition, it will be necessary to first solidify our understanding of, and moral obligation to, the conditions of *sustainable living systems*.

From the perspective of systems theory, adaptive capability is related to the ease and reliability with which the agents within a system collectively transform available energy and materials to perform useful processes that enable and sustain self-organization (Jorgensen et al., 2007). It is also a measure of system resistance to perturbations and stress, a characteristic sometimes used to describe material properties and referred to commonly as *resilience* (Nicolis and Nicolis, 2007). A well-adapted system is one which best utilizes local energy resources to *optimally connect* diverse agents coexisting within the system (Holling, 2001). The development of this description has deep roots in ecological systems modeling (Jorgensen, 2007), and thus an old and stable ecosystem may commonly be described as a system which has developed high resilience over time. For this analysis, *sustainable development* is considered to be the application of techno-cultural solutions toward the formation and stabilization of adaptive connections between diverse members of living systems (i.e. human techno-cultural adaptation that enables the evolution of adaptive, resilient, and well-connected organisms).

Karl Ludwig von Bertalanffy was a biologist living and working at around the turn of the 20th century. He is commonly credited with contributing some of the most fundamental scientific insights to the initial development of *General Systems* theory, though his work is only scarcely documented. The significance of Systems Theory to the technological development of the modern World cannot be overstated, as it has influenced every field of applied science over the last 60+ years, contributing to the development of advanced electronic and circuit theory, general network analysis, controls & feedback theory, systems engineering, ecology, psychology, neuroscience, cybernetics, and so on. Not only has this theory played a prevalent role in expanding technological development during this time, many of its practitioners remain insistent of its potential to describe *any natural system* using the same general methodologies for agent definition, interaction, and system topology.

A strong and vocal proponent of General Systems theory was Howard T. Odum, an ecological engineer who spent most of his academic career researching and teaching at the University of Florida in Gainesville. He authored and co-authored several textbooks in the field of Systems Ecology, the most famous is likely his undergraduate text, *Environment, Power and Society*. Among his many contributions to the field, arguably the most noteworthy was his categorization of various agents based on their fundamental behavior and subsequent formalization of systems language (Odum, 1971).

Through this work, Odum was among the first people to develop *energetic analogs* and *equivalent circuits* (Illustration 10) in his attempts to predict energy/material flows in natural and human systems.

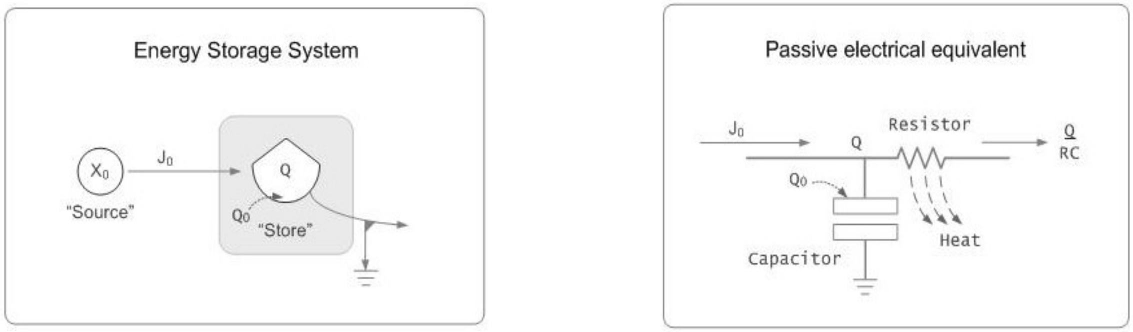


Illustration 10: H. T. Odum's *Systems Language* and *electrical analogues* (Odum, 1971).

In engineering practice, issues of cost tend to outweigh even considerations of the universally fundamental 2nd Law of Thermodynamics. For example, improvements in energy quality or efficiency are most often only considered to be as valuable as their relative cost-effectiveness (Brodyansky, 1994). One difficulty in changing such perceptions is the coexistence of corollary perceptions that are pervasive in science. I have observed that many scientists are hesitant, if not downright hostile, to accept universal standards of quality and value. If they do, it is generally coupled in some way to economics. In my not-so-humble opinion, *pure scientists* have no business biasing their work with judgments of economic value, assuming of course that scientific discovery itself is their primary motivator! However, engineering as an *applied science* necessitates the incorporation of real-world value structures, including those values imposed by the rules of economics. At the same time, there are many important features of life with high quality and low economic value (e.g. friends, family, food). As Luther & Janet say, "*The best things in life are free.*" Economics should not be the predominant metric by which quality and value are measured in life. Hesitation to adopt more holistic measures and indicators will result in continued failure at *full-cost accounting* and fall far short of *full-functioning* systems, leaving out those many (worthless?) bits of life that make human life worth living.

Admittedly, there are many straightforward rationales for placing cost-effectiveness highest among priorities in engineering development. First of all, little question (at least in the mainstream) has ever really been given to whether or not new growth and development is actually needed, much less a *good* *thing*. In this way, economic growth is almost universally assumed to be a *natural good*. Unspoken assumptions build; development is implicitly presumed to be beneficial; technological advancements are assumed always to be improvements over what existed previously; and, the services provided are somehow readily deemed necessary and sufficient to the lives of local inhabitants (Bookchin, 2005). A *no build option* is rarely considered with any serious scrutiny, despite its environmentally regulated requirements. Thus, popular perspective is that development *and* growth inextricable, natural goods. And thus development continues as it typically has, much like a highly competitive game without consistently explicit rules, boundaries, or values. "*..., we ask for trouble. And we get it.*" (p. 3)

Sustainability: A Perennial Philosophy?

As mentioned in Chapter 2 (*Competition, Cooperation, & Community*, Illustration 3), there exists (at least in theory) a trilemma of human experience that can be categorized for different social groups. In that section, I mentioned also the three *idyllic principles* of social decision making: *collective rationality*, *equal participation*, and *decisiveness*. Each principle is violated by the common approaches to group decision making (i.e. *dictatorship*, *majority rule*, and *consensus*, respectively). This problem of balancing three spheres of human experience is quite common, seeming to date back as far as human history itself. Table 1 provides a theoretical comparison of some (relatively) common trilemmas (i.e. *trinities of value*) that have been used traditionally to segment and categorize common human experience. These trinities seem to be apparent and somewhat consistent across cultures, socio-economic-political barriers, space, and time. The significance of recognizing similarities in these three categories of the age-old trilemma is not entirely self-evident, though presumably such recognition may assist in the further structuring of system models and the categorization of useful knowledge.

Dan Kammen and Michael Dove have written a seminal paper (*The Virtues of Mundane Science*) that outlines the need for scientists and academics to more fully embrace and accept the *challenge of the mundane*, addressing those problems most commonly faced by the majority of our World's population, each and every day. Part of this challenge requires a shift in priority toward the *design for the other 90%*, recognizing and accepting that modern design efforts have until now been focused primarily on development that improves life for only the richest 10% of the World's population[7]. Among other

7 Learn more about this current design movement online by visiting http://other90.cooperhewitt.org/.

hurdles, this requires that individuals working in academia begin to reject long-standing biases toward purely *high-tech* or *cutting-edge* research. Much of the World's mortality and illness is entirely preventable, caused by unsafe conditions that can be remedied with relatively small amounts of money, using existing skills and available knowledge (Kammen and Dove, 1997). Thus, if we hope to address the problem of the mundane, we must accept Perkin's challenge to deny greed as our primary motivator and seek RD&D opportunities that more adequately address mundane problems.

Table 1: Perennial philosophies concerning the trilemma of sustainability.

Frameworks of Reality	***Elements of Framework***		
Taoism (ancient China)	yin	yang	tao
Merkabah (ancient Hebrew, mysticism)	body	light	spirit
Platonic Metaphysics (~ 400 BC)	matter	mind	spirit
Holy Trinity (Christianity)	son	father	holy ghost
Personal Motivation (Alderfer, 1972)	existence	relatedness	growth
Metaphysics of Quality (Pirsig, 1974)	static	dynamic	value
Psychoenergetic Systems (Krippner, 1979)	matter	consciousness	energy
Energy Systems Modeling (Odum, 1994)	storage	work	source
Sense & Soul (Wilber, 1998)	self	other	whole
Eco-Effectiveness (McDonough et al., 2002)	economy	equity	ecology

Over the past six years, I have been involved with an engineering association whose stated mission is to address these very issues of the mundane. There are several such organizations, but the one I am most familiar with through personal involvement is called Engineers Without Borders (EWB). This group seeks to engage engineers in local, sustainable projects that are initiated by communities around the World, primarily in developing countries. Though chronically under-funded and bogged down in bureaucracies at all levels (not unlike most NGO), their work theoretically serves to train a new generation of conscientious engineers, providing them with valuable real-world experiences. I've been involved with a number of EWB projects around the World, and though I believe it is far from a perfect solution in and of itself, the vision and ethic of the association is very much in line with the concepts of mundane science and appropriate technology. However, like all NGO work, EWB projects can actually serve to spread further injustice if not approached with respect, humility, and solidarity. Without these precepts, Western engineers will perpetuate such fallacies as the *white man's burden* and *noble savage*.

One fundamental *culprit of perception* with regard to widespread societal neglect of the human condition may in fact lie with the West's very concept of space and time. An interesting critique of our distinctly Western perceptions can be found in Edward Wachtel's *To an Eye in a Fixed Position: Glass, Art and Vision*. Wachtel describes the western perspective in art as a trained perception that has largely influenced the social lens of western development, rather than being simply a stylized artistic representation of little consequence (Wachtel, 1995). He describes the Western view of physical existence as an empty cardboard box of 3 spatial dimensions (sans cardboard), flowing along a one-dimensional current of time that is commonly assumed to be linearly progressing in a single direction. Einstein made similar descriptions of Western perspective, noting that theoretically the distinction and relationship of space and time is not easily distinguished, as evidenced by the common use in physics of an inseparable continuum known as space-time. To Wachtel, the western perspective seeks to reduce time to an *instant of non-existence*, depicted in western perspective art by a 3-dimensional rendering without any sense of movement or the passing of time (Wachtel, 1995). By placing squarish frames around our worldly perceptions, we find ourselves living in squarish buildings, driving in squarish cars, and living squarish lives. How *square* is that?

Generally speaking, *quickly squared* is an apt description of the perspective of Western technological development; the simplest elimination of time as it exists between a *subject* and its *object* of need or desire, connecting discrete points with straight lines. An interesting paradox forms from this pursuit as an unattainable goal, with the ever-changing and expanding perceptions of human need and desire, along with fluctuations in the perceived usefulness of skills and knowledge. A common example of this phenomenon is evidenced by energy efficiency improvements that serve only to increase levels of human consumption and activity (Hawken et al., 1999). If Western perspective is truly intent on eliminating time from the human experience, then it may be better served to incorporate more Eastern philosophical perspectives such as meditation, mindfulness, and presence. Otherwise, we will likely witness the further proliferation of time-saving conveniences, rushing us straight into a square grave.

Another interesting and seemingly plausible culprit in this *rush-to-the-end* Western perspective dates back to the early development of arithmetic. In its very simplest forms, mathematics requires the mental abstraction of numerical tools from the natural worldly counterparts from which they were originally born. Though indeed powerful, mathematics serves just as any other human tool; its value should be measured by its ability to provide benefits to individuals and society. If only used for causing headaches and havoc, then why bother with all the math? Why indeed. A call for reform has been made to reduce the level of abstraction that exists between nature and its mathematical representations (Hamvas, *unpublished*[8]). One might readily see how an abstracted, valueless mathematical perspective might complicate its appropriate applications (e.g. economics, sociology, ecology).

The issue of technology appropriateness could easily fill many volumes, and much like other seemingly subjective considerations, it can also be widely debated from a number of different perspectives. Since the vast majority of scientific and engineering publications neglect to attempt any explicit discussion of their underlying philosophies or metaphysical assumptions, I do not feel overwhelmingly compelled to present here an exhaustive review of the different philosophical bridges linking science, technology, and engineering, though there are numerous texts which have made such attempts (e.g. Mitcham, 1994). I do, however, feel compelled to explicitly describe the particular philosophy of technology that I believe to be most fundamental to issues of sustainable engineering and development. This perspective follows a lineage of perennial philosophy, a selection and synthesis of those *good things* that exist in natural systems, and the identification and correction of risky or harmful *systemic failures*.

The English word *technology* derives from the Greek word *technologia*, which is a compound of two terms: *techne*, which is often translated as art or craft, and *logos*, which can be translated as the study, description, or logic of some thing (Miller et al., 2008). In the modern era, it can be difficult to envision technology as the *study of art or craft*. More commonly, those who choose to study art and craft explicitly will probably find themselves to be less involved with modern scientific and technological development than those who would tend to entirely ignore what we consider to be art and craft today. The Greek consideration of *technologia* may be made more clear through a comparison of its root *techne* with the term most commonly associated with the modern definition of knowledge, *episteme*. In this sense, it is useful to consider *techne* as a measure of *human skill*, while *episteme* serves as a measure of *human understanding*. The pursuit of modern technological development relies upon some degree of balancing human skill with our evolving understanding of nature. To Aristotle, this balance

8 Provides an interesting account of Hermetic thinking: http://www.tradicio.org/english/hamvastabulasmaragdina.htm.

could be found through the pursuit of a life grounded in the limits of the *common good* of the individual, their family, and their greater community (Bookchin, 2005). However, such Aristotelean limits of equitably serving human needs do not appear widely self-evident in modern societies.

Concerning *appropriate technology*, the philosophy and application of which must be designed to accommodate the ecological limits of the Earth, let us also consider the roots of ecology. The word ecology is also derived from Greek, stemming from *oikos* which means household and *logos,* or description. Ecology first developed as the study of life, its distribution, and the complex interactions occurring between agents within the Earth's biosphere. The study of Ecology has now grown beyond applications in the biosphere to encompass a more general and scalable approach for describing the apparent self-organization of natural systems to process energy, materials, and information, though its most common application remains the study of interactions between organisms at the Earth's surface. After billions of years of evolutionary development, life on Earth has become efficient in its persistence and proliferation. Seemingly operating beyond the capacities of most ecological checks and balances, the human species is embarking upon a rate of degradation of energy and material resources within the biosphere at scales that are often difficult to practically comprehend. This degradation compromises the Earth's very ability to serve as a continued home to other living organisms and systems, as evidenced by accelerating rates of species extinction worldwide.

If sustainable development can be thought of as a societal re-structuring that supports the *common good* of the individual, the organizations to which it belongs, and its associated networks, then *appropriate technology* can be considered as one half of the techno-cultural means to that end (where supportive community culture provides the second half). The intricate interdependencies between technology and culture in the modern World make the two considerations nearly impossible to cleanly separate from one another, and thus it seems generally more useful to simply describe the techno-cultural aspects of society than to consider either technology or culture in isolation, pretending perhaps that the influences of one on the other are minor. The distinction of technology from the society it is meant to serve is a seemingly impossible task, more so each day as ever-growing numbers of human interactions are predicated upon the required use of technological agents within built environments.

As Murray Bookchin described it, today's technological society seems much like a runaway car with the questionable presence of a driver (Bookchin, 2005). To Bookchin, it's a split dilemma: either there is no driver (i.e. humanity is effectively dead), and thus technological society is being propelled forward outside of human control; or, the driver alive but asleep at the wheel, suggesting that it may be possible to awaken humanity from its slumber. Bookchin assumes this latter situation to be the case. To Bookchin's mind, a *wake-up call* might be delivered through the effective separation and distinction of social value and necessity from technological development, where the former primarily evokes the latter and the *necessary and sufficient* limits of consumption in pursuit of *the good life* may again be identified and ultimately achieved (Bookchin, 2005).

To follow Bookchin's lead, attempting to separate *social* from *technological* development, a straightforward concept that has been often considered, is to tread a rough path. For instance, it is often the stated purpose of government policy and regulatory action to guide technological development that best meets the needs of human societies and the environment. However, it seems that as long as the desire for money and stature serve as our primary motivators, then a sufficient consideration of social and environmental implications is unlikely to result. A societal bias also exists in favor of *value-free* and *technology-neutral* approaches to innovation and development. These biases of the modern age can be identified by their misrepresentation of *technics* as pure science (Bookchin, 2005) or as the designation of technology as *obviously good* (similar to mathematics, economics, or development).

Though Bookchin's metaphor for the current state of humanity is fitting for the topic of this thesis, I nevertheless prefer the imagery of a man (*note*: this my seem sexist, but in this case it's a compliment to women), wandering through the desert alone. Not only does this man not understand how he came to be in this desert, he appears to have lost any sense of direction or intuition for finding his way out. Despite having a map in one hand and compass in the other, he wanders confidently for a long time, further and further in the wrong direction. The heat & hostility of the desert create stress & anxiety, as the man stumbles and clambers in delusional search for the familiarity of another place and time. Though he knows not where he is or why, he continues to wander, faster and with more frustration, until eventually he collapses and surrenders to this cruel situation and his inevitable demise. This is the desert of the mind, full of fear, scarcity, and maddening frustrations in an unfamiliar land.

My interpretations of technological development have led me to a philosophy of sustainable development that is premised upon a careful consideration and understanding of ecology in developing a solution to the sustainability trilemma. From this approach, rules of ecology serve to govern the economic and social needs of human systems. Economic knowledge is concerned with an understanding of the need for resource collection and the cultivation necessary for complex evolution (e.g. *emergence*) within diverse living systems. In addition, the equitable distribution of resources, including knowledge, enables capacity-building within the system for sufficient resource processing and growth. The energy and material resources are used as equitably and efficiently as possible, then reinvested and stored within the system for future use. A stable, evolved system will achieve maximum power flow by evenly dividing resources among maintenance needs (equity) and stored investments (economy). This has been described as the *Maximum Power Principle* (e.g. Cai et al., 2006).

Perceptions of Scarcity & Abundance

William McDonough has often made reference to Western society's fixation with *resource scarcity*, despite the Earth's abundant stocks of known renewable and recyclable resources and services, all of which nature provides free of charge. McDonough makes a plea to his audience to adopt technological development and social networking that foster abundance rather than the manipulation and control of scarce resources for greater economic profit. In today's *knowledge-based economy*, the very understanding of technology itself is often treated as a scarce and proprietary resource, with the value of knowledge commonly placed higher, or even in substitution for, that of practical skills (Bookchin, 2005). Odum referred often to the *evolutionary superiority* of knowledge resources and the need for knowledge storage (Odum, 1971). Inequitable distribution of technical skill and/or knowledge leads to technological development that fosters perceptions of scarcity, and vice versa (Bookchin, 2005). However, in today's technologically advanced global economy, it is becoming increasingly clear to most conscious individuals that perceptions of resource scarcity are more a tool for societal control and repression than real physical constraints. A prime demonstration of this reality is provided by MIT's now famous *One Laptop Per Child*[9] program. Not only can shared resources meet the global physical needs of our entire human community, but quite likely higher-order, knowledge-based needs as well.

9 Amazing MIT project in collaboration with Continuum Design: http://www.laptop.org/.

I don't believe in zero-sum gain, and neither did Paul Shepard apparently. He describes the Western developmental perspective as stemming from the desert's edges (Shepard, 1982), where the seed of our modern civilized perceptions is buried deep in the sands of the World's great deserts (e.g. Egypt, Sumer, Assyria, Palestine, Eastern Europe, and Eurasia). As a son of the desert (Mojave, CA), I can relate to many of Shepard's descriptions of the desert experience and their metaphorical relationship to our scarce Western perspective. The desert is a powerful and awesome place, where senses can be overwhelmed, ironically, by both silence and emptiness. As Shephard puts it "... - *too little life, too much heat, too little water, too much sky ... its hidden life and conspicuous shapes seem at once to dwarf and to emphasize the human figure.*" (Shephard, 1982) Since the seed of human societal development was planted in the desert, and there remained for much of early human existence on Earth, it is perhaps not surprising that presumptions of scarcity, fear of lack, the inevitability of struggle, and the negligence of ecological process remain so ingrained in current societal orientations. Obvious consequences of these perceptions include sub-optimal agent interactions that require cheating, hording, stock-piling, competitive exclusion, and other aggressive tactics for strategic survival.

Though ubiquitously present in the subconscious yet rarely addressed directly, the perception of scarcity is neither universally accepted nor entirely uncontested. Among its more vocal observers, McDonough speaks often of the need for a shift in emphasis and value toward perceptions of *abundance*. Such a World view would institutionalize concepts such as *up-cycling* and *up-grading* (i.e. continuously converting resources into ever-more-useful, valuable forms), replacing *less bad* efforts in *eco-efficient* industrial process with full re-designs that are actually *eco-effective* (i.e. *waste = food*, using current *solar energy income*, and universally respecting diversity). Adoption of these concepts will presumably help to begin this shift away from a World dominated by limits and constraints (McDonough and Braungart, 2000). Shephard describes such *ecological thinking* as that which "*reveals the self ennobled and extended rather than threatened, as part of the landscape and the ecosystem ... We must affirm that the World is a being, a part of our own body.*" (Shepard, 1982)

Measuring Sustainability

In designing and assessing a fully globalized energy system, many meaningful factors of performance, such as social equity and human health, appear to remain abysmally unaccounted for. A common scapegoat for such negligence is the historical use of single-variable economic performance metrics, such as the Gross Domestic Product (GDP), accounting for economic interactions but not explicitly considering the relative value to society, like impacts to human health and the environment. One economic metric proposed to replace the GDP is the Gini Coefficient, which measures the distribution of wealth across a given population, enabling the consideration of regional economic equality. Yet another metric for the consideration of human development is the Genuine Progress Indicator (GPI), which is intended to evaluate the sustainability of human progress from a more holistic, multi-variable perspective through the measurement of biological productivity & human health and development.

Widespread use and evaluation of such indicators will be integral to the pursuit of sustainable human development. Another interesting metric is the Gross National Happiness (GNH) index, developed by the King of Bhutan in 1972. For the peaceniks among us, there is also the Global Peace Index (also GPI), where Norway so far is ranked # 1. There are at least 14 common alternative metrics to the GDP (Ferguson, 2007), while probably many more exist but have not yet been widely considered. Illustration 11 demonstrates the difference in trends of GDP and GPI in the U.S. over time, as well as the correlation between GDP and *happiness*. Notice that there seems to be some threshold of economic activity beyond which very little if any increases in happiness are observed. These trend seems to suggest that *inherently sufficient* levels of consumption may exist and should be further explored.

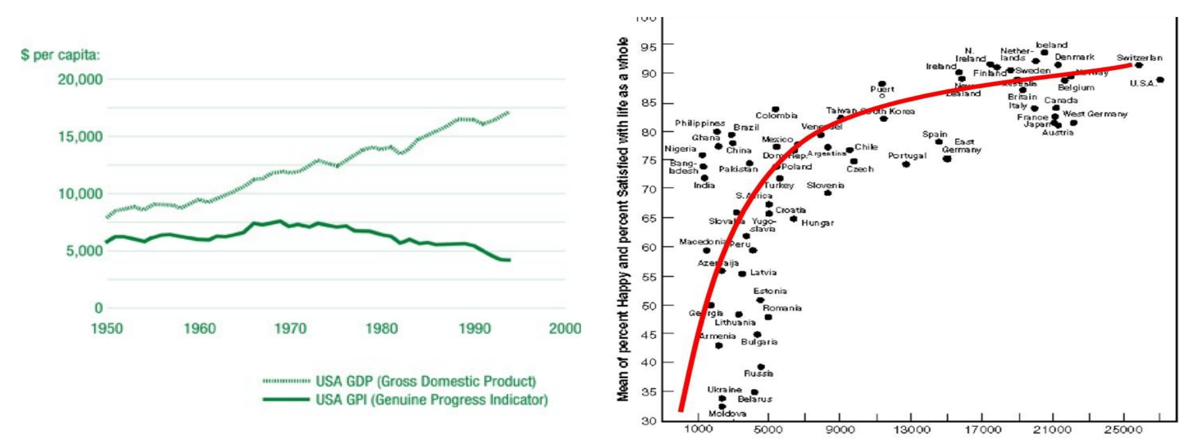


Illustration 11: U.S. GDP vs. GPI and GDP/cap vs. *happiness* Worldwide (Inglehart, 1997).

Regional indicators of sustainability are sensitive to spatial and temporal scales and dynamics, sometimes varying locally as contradicting techno-cultural characteristics (e.g. jobs vs. degradation). These conflicts have proved to be quite difficult to overcome for many institutions and political agencies in their attempts at adopting standard indicators. Rather than adding excessively to the already verbose theoretical discussions on such indicators (e.g. Hall, 2006), I will simply state that specific indicators should be selected at the community, system, or organizational level based on group needs, desired outcomes, and existing states of performance. Also, these indicators *should not* be applied like a TBL is applied in business, assessing the impacts of industrial activity at the end of the line. Rather, assessment in support of more eco-effective industrial ecologies will require sustainability indicators and guidelines that can be applied at the very beginning of industrial design.

Indicators of Eco-Effective Industrial Design

Engineers, economists, and others who work with project planning and development are undoubtedly familiar with the assessment of *cost-benefit ratios*. If the costs outweigh the benefits over the lifetime of the project, or over some acceptable period of payback, then the project is typically considered to be a *non-starter*. By and large, these cost-benefit assessments compare dollars invested to dollars returned on the investment, with lots of assumptions about interest rates and acceptable payback periods and so on. In considering the *eco-costs*, or costs of industrial activity to the environment, consideration is generally only given to the cost paid by the institution to secure resources and conform with environmental regulations. There is an incentive to make the process as clean as it needs to be in order to meet regulated limits, but generally no cleaner, as this would presumably cost more money and thus there is an economic disincentive. In some cases, compliance with environmental regulations is actually perceived to be more costly than the regulatory fines, in which case some may opt to save money through non-conformity. Actual costs to the environment and the organisms living within it (including humans) are seldom fully assessed and accounted for in a classical cost-benefit analysis.

In an attempt to better account for *eco-costs*, one approach is to determine an institution's *eco-efficiency*. In general, this approach requires that the institution estimate the environmental impacts of its industrial processes all along its supply chain, or from *cradle-to-grave*. The eco-efficiency of the institution is determined as the ratio of the total value derived from the product divided by the total economic costs *plus* the total eco-costs incurred over the entire supply/process chain. The common mainstay of eco-efficient processing the use of the 3-R's: *reduce*, *reuse*, and *recycle*. For industrial products which require many inputs from different suppliers (e.g. automobiles), it may be quite difficult to accurately estimate and limit the impacts of a long and varied supply chain. While this approach does more to help address sustainability issues and environmental degradation than simple cost-benefit analyses, it nevertheless falls short of ensuring truly sustainable industrial processes in the long-term.

The reason that eco-efficiency falls short of making significantly large and sustainable improvements in industrial performance is that it follows the same line of reasoning and holds a similar perspective to that of classic cost-benefit assessments. That is to say, it still views the environment as a collection of extractable and degradable resources, attempting to reduce environmental impacts as long as economic gains remain in tact. As Albert Einstein famously pointed out, it is difficult (if not impossible) to solve a crisis from the same perspective that created it in the first place. Thus, an entirely new perspective will be needed in order to transform the industrial processes and business practices that have long existed into sufficiently safe, healthy, and ecologically sustainable means of economic production. McDonough refers to such means of production as being *eco-effective*, a term he uses to mean that these approaches are effective at mimicking natural ecological form, function, and frequency.

Sustainability metrics might effectively be categorized by the three areas of sustainability concern that were previously mentioned: *ecology*, *economy*, and *equity*. Metrics of *ecological sustainability* are those which pertain mostly to lifecycle function, agent interactions, and placement within the built and natural environments (i.e. topologies). Such metrics include *degrees of mode separation* (% separated), *longevity of use* (years), *consumer accessibility* (% of population), and *connectivity* (% connected). Metrics of *economic sustainability* are those which pertain mostly to lifecycle product costs, materials movement, and built capacity & storage. Such metrics include *population costs* ($/person), *mass-miles* (kg-miles traveled), *reusability* (% reusable), *recyclability* (% recyclable), and *knowledge storage & accessibility* (gigabytes, kilobytes/s). Metrics of *equitable sustainability* are those which pertain mostly to lifecycle distributions, energy & work requirements, and health & safety. Such metrics include *direct solar energy fraction* (% solar), *energy efficiency & effectiveness* (% sufficiency), *product safety & mortality* (injuries/year, deaths/year), *toxicity* (mg/kg dose response), and the *support of skillful livelihood* (% skilled workers). Using metrics such as these, it may be possible to ascertain the relative sustainability of a given product or system, ideally during the design phase of either.

Some people will likely argue that *eco-effectiveness* presents an *extremist view*, that industry cannot possibly be expected to mitigate the effects of resource extraction and use, and that considerations of industrial eco-effectiveness are nothing more than pretentious academic exercises in mental masturbation. From the perspective of most Western development, where cost-benefit value structures and zero-sum assumptions of resource scarcity are the norm and not the exception, I cannot say that I would blame them for saying so. Given the state of awareness on these matters, I remain less than hopeful regarding the ability of modern industry to quickly adopt eco-effective practices. However, should such values begin to permeate to the psyche of industrial design and development, I will be very pleasantly surprised. Though considered either futuristic or primitivist by the various standards of industrial development and developmental permitting, the *fab tree hab* proposed by Mitch Joachim and his team at MIT incorporates all of the features of sustainable, eco-effective design. I was fortunate to meet with Mitch in 2007 at his office in New York, and while he is certainly a visionary designer by anyone's standards, the core characteristics of this design are far from novel, in some cases dating back thousands of years. Illustration 12 depicts the conceptual design of Joachim's *fab tree hab*.

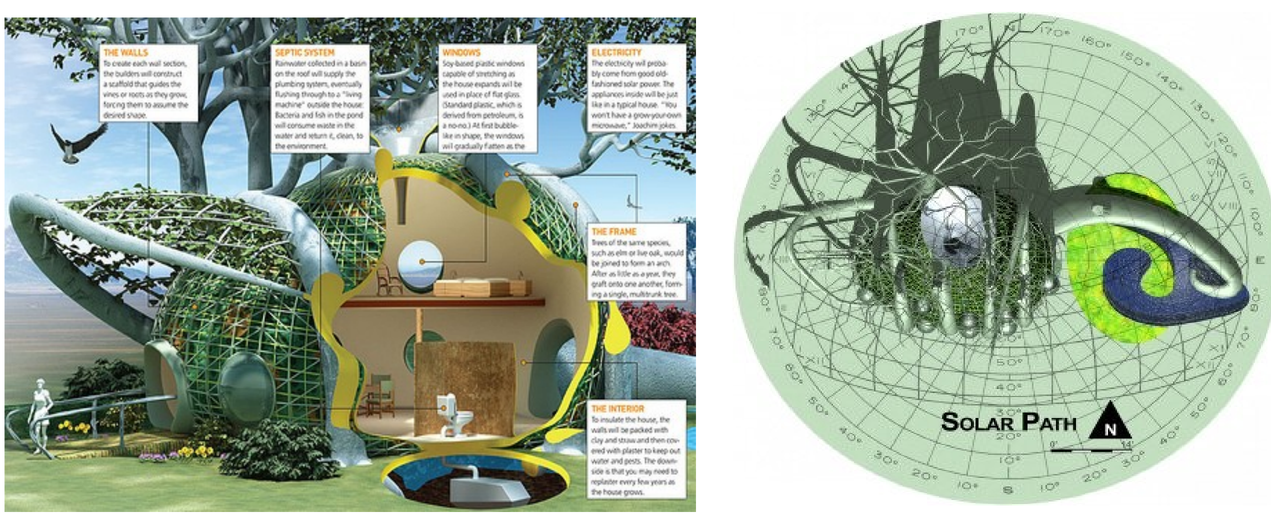


Illustration 12: Cut-away view of the *fab tree hab* and aerial view of solar path (Joaquim, 2008).

The fab tree hab design is a perfect example of eco-effectiveness, exactly as McDonough has described it; the home is made from living trees in such a way as to provide human shelter without significantly compromising the natural services provided by the trees. Human waste is composted and fed as nutrients to the tree and backyard gardens. Rainwater is collected and recycled multiple times through various household systems, eventually circulating back to the gardens. The tree itself remains fully intact and healthy, while its human inhabitants now have obvious incentives to aid in supporting the continued health of their living home. One requirement of this design is that the tree be capable of self-grafting in order that *pleaching* techniques may be used to construct the dome's lattice walls. Trees capable of self-grafting include various species of ficus (e.g. fig), live oak, and olive, among others. The art of pleaching has existed since the dawn of civilization, and yet it is no less pertinent or sustainable now than it ever has been. In addition to all of the ecological benefits of a living tree house, these houses could provide their inhabitants with both food and shelter. Thus, a design for more eco-effective homes has been proposed using a tree for its analog. Our next challenge: *eco-effective cars*.

Chapter 4. Sustainable Energy, Fuel, & Vehicle Technologies

Introduction

It is common sense that some forms of energy are more useful to human development than are others. Specifically, it is those energy resources that are most concentrated and enduring that enable prolonged work and subsequent growth of society. Such energy resources have been described by Odum as *force sources*, with a supply that is supported in such a ubiquitous and continual way as to make energy available to the end-user as a seemingly limitless force. One example of a force source is an electric utility powerplant, where initial home appliances tapping into this source experience no apparent decrease in the available supply of energy. In comparison, a *flow source* of energy resources is one which is relatively limited, with a flow that is inherently controlled at the source. A good example is the sun, which provides an intermittent, diffuse, and inherently limited radiative energy for a given area on the Earth's surface, cycling on and off daily. Illustration 13 shows useful energy (i.e. exergy) fluxes.

With seemingly limitless fuel availability at the pump and relatively low prices paid, the U.S. has secured a petroleum fueling network that mostly resembles a force source. On the *bleeding edge* of industrial development, the least economically privileged of the World tend to also be less dependent upon petroleum as a source of energy, though their use of biomass for energy serves as another drastic example of degrading resource use-patterns. In developing places around the World, lung disease from the inhalation of smoke (often from inefficient cooking stoves) is an even greater threat to life than estimates for other global pandemics, such as HIV (Kammen and Dove, 1997; WHO, 2005). In this case, preventable lung disease causes widespread suffering and death, while proper prevention necessitates only that human communities take notice and proper action in order to disseminate more appropriate technological options. Unfortunately, judging from past performance, civilization's collective capacity to respond to problems occurring at such ecological and global scales is lacking.

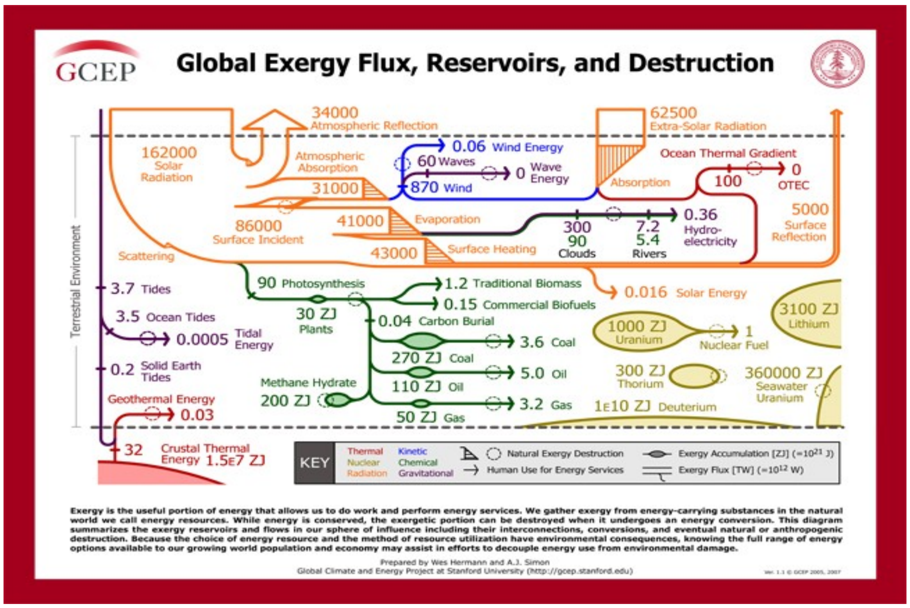


Illustration 13: Global useful energy (i.e. exergy) fluxes of the Earth (GCEP, 2007).

Sustainable Energy Resources

A key aspect to the development of long-term, sustainable energy resource use-patterns is a shift away from dependence upon *solar energy savings* and toward the use of *solar energy income*. An economist, accountant, or savvy entrepreneur can quickly tell you that the economic success of any business, household, or other money-making institution is dependent upon its ability to survive off of its income rather than depending predominantly upon its savings (e.g. storages, reserves, stock-piles). Current energy consumption patterns can be considered in much the same way, where ancient biological matter (first produced by the sun and then sequestered in the Earth for millions of years) should be viewed as our solar energy savings; used sparingly, valued highly, and drawn down only when unforeseen or uncontrollable bottlenecks in income necessitate their use.

The distinction between energy savings and income is a perfectly practical conception, though near-term implementation will require social consensus on two critical points. First, that all human energy requirements on a day-to-day basis can and should be met by currently available solar energy resources, or income (i.e. PV, solar-thermal, wind, biomass, and so on; Table 2). Secondly, that preferential incentives should be given to encourage the development of efficient solar energy conversion technologies in order for exhaustible, energy-dense stores of energy to be more highly valued and sparingly used toward their most beneficial ends. Renewable energy resources now make up only about 1 - 2% of annual energy consumed in the U.S., though this is not for lack of available resources. Rather, there has been much hesitation to adjust priorities to design systems that are more energy efficient and which accommodate flow-type energy sources (i.e. cyclical, relatively diffuse).

Table 2: Land-use requirements for solar energy resource conversion (NREL, 2004).

PV: The Land-Area Advantage

Technology	Converter Efficiency (%)	Capacity Factor (%)	Maximum Packing	Land per year for: GW	GWh
Flat-Plate PV	10%–20%	20%	25%–75%[d]	10–50 km^2/GW	5000–25,000 m^2/GWh[k]
Wind	Low to 20%[a]	20%[c]	2%–5%[e]	100 km^2/GW[g]	140,000 m^2/GWh[i]
Biomass	0.1% total[b]		High—plants compete for sunlight	1000 km^2/GW[h]	500,000 m^2/GWh[i]
Solar Thermal or PV Concentrators	15%–25%	25%	10%–20%[f]	20–50 km^2/GW[h,j] 20 km^2/GW[j]	10,000–20,000 m^2/GWh

[a] www.windpower.org
[b] 0.5% or less light-to-biomass; then 33% to electricity, 0.1% total
[c] Site dependent
[d] Tilted arrays at high latitudes versus flat ones at the Equator; room between for maintenance
[e] Pimentel 2002; Dohn Riley et al.
[f] Tracking arrays need wider separation to avoid shadowing
[g] Hansen 2003
[h] Hughes 2002
[i] Pimentel 2002
[j] Cohen 2003
[k] At 15% module efficiency, 12% module-to-system operating efficiency losses

Sustainable Vehicle Energy Storage

Due to its high energy content when compared to most commonly available substances (Table 3), petroleum-derived liquid fuels are extremely difficult to compete with in terms of both gravimetric (by mass) and volumetric (by volume) energy density. However, with greater emphasis placed on carbon-reduction, a change is value to support low-carbon storage options seems to be gaining wider acceptance. One of the inherent limitations of electric-drive vehicles is their limited range due to the relatively low energy density of electricity storage, either by batteries, ultracaps, or hydrogen. Based on real World experience with the ZEV Mandate, battery cost and limited vehicle range (i.e. energy density) were the primary deterrents of electric vehicle commercialization. Thus, a better understanding of the status of battery technology, including the most promising types, their cost, durability, and performance is a critical *first step* in assessing the near-term prospects for electric vehicles of all kinds. In addition, this requires accurate and efficient energy storage management.

Table 3: Energy densities by mass and weight for possible vehicle fuels (Bambuca et al., 2006).

Energy Carrier	Gravimetric E.D. (W-hr/kg)	Volumetric E.D. (W-hr/L)
Diesel	13,762	10,942
Gasoline	12,200	9,700
LNG	12,100	7,216
Ethanol	7,850	6,100
Li-Ion Batteries	105	284
Flywheel	120	210
NiMH Batteries	60	100
Compressed Air	34	17
Lead Acid Batteries	25	40

The key requirements for the energy storage unit of a particular vehicle design are *usable energy stored*, *peak power*, *cycle life*, *calendar life*, and *affordability*. These requirements must be met with a unit whose weight and volume meets specified values based on packaging requirements for the entire electric drivetrain. Differences in storage performance have a large influence on the performance (i.e. acceleration and driving range) of electric vehicles. In addition, the cost and cycle life of the storage media have large effects on the potential marketability of electric vehicles. Whether a particular type of storage is suitable for electric vehicles depends on the desired characteristics of the vehicles for which it is intended. High performance requirements typically mean large, powerful, and expensive storage.
Many different types of storage have been considered and developed for electric and hybrid vehicles over the last thirty years. At the present time, batteries are the most commonly considered and developed for electric vehicle applications. Typical chemistries include *lead-acid*, *nickel metal hydride*, *lithium-ion* & *lithium polymer*, and *sodium nickel metal chloride*. Each of these battery types have advantages and disadvantages, and unfortunately none are attractive in all respects for electric vehicles.

In addition, there are trade-offs between energy density, power density, cycle life, and cost such that even for a particular type of battery, it is necessary to design a new battery system for each specific application. While there is no clear choice of the best battery for all BEV, *nickel metal hydride* and *lithium-ion* batteries are the most promising near-term chemistries under development for vehicle use today. Most of the electric vehicles produced and sold/leased so far have used either lead-acid or nickel metal hydride batteries. A limited number of vehicles have used lithium-ion or sodium nickel chloride batteries. Lead-acid batteries are used primarily in low-speed, neighborhood EV, having a relatively short range (25-50 miles). Many of the electric vehicles sold/leased as part of the ZEV Mandate (1995 - 2002) used nickel metal hydride batteries and had a driving range of 80 to 120 miles between charges. The energy density (Wh/kg, Wh/L) and power density (W/kg, W/L) characteristics of the various battery chemistries vary over a wide range as shown in Table 4. These differences in battery properties have a large influence on the performance (acceleration and range) of vehicles that can be designed and produced using them. In addition, the cost and cycle life of the batteries will have a large effect on the adoption of electric vehicles. Different electric vehicle types have different characteristics and performance requirements, such as size, weight, acceleration performance, and driving range, which determine the types of batteries or other storage devices that are most appropriate (Table 5).

Table 4: Battery performance characteristics for several different chemistries (Burke et al., 2007).

System	Specific Energy (Wh/kg)	Peak Power (W/kg)	Energy Efficiency (%)	Cycle Life	Self-Discharge (% per 48 hr)	Cost ($/kWh)
lead/acid	35-50	150-400	>80	500-1,000	0.6	120-150
nickel/cadmium	50-60	80-150	75	800	1	250-350
nickel/iron	50-60	80-150	75	1,500-2,000	3	200-400
nickel/zinc	55-75	170-260	65	300	1.6	100-300
nickel/metal hydride	70-95	200-300	70	750-1,200	6	200-350
iron/air	80-120	90	60	500	?	50
zinc/air	100-220	30-80	60	600	?	90-120
zinc/bromine	70-85	90-110	65-70	500-2,000	?	200-250
vanadium redox	20-30	110	75-85	?	?	400-450
sodium/sulfur	150-240	230	80	800	0	250-450
sodium/nickel chloride	90-120	130-160	80	1,200	0	230-345
lithium/iron sulfides	100-130	150-250	80	1,000	?	110
lithium-ion	80-130	200-300	>95	1,000	0.7	200

The major requirements of any electrochemical energy storage device (EESD) are: to provide *adequate power;* to provide *adequate energy storage*; and lastly, to operate for an *acceptable calendar life*. The EESD must provide power (kW) within the appropriate voltage range for the power electronics/motor to properly meet the driver's acceleration requests. It must also store sufficient energy (kWh) such that the vehicle can be driven an acceptable range (miles) before recharging. The power supply and energy storage requirements will impact EESD weight and volume, affecting overall vehicle design. The EESD must be able to be charged/discharged a specified number of cycles before the performance degrades and the EESD must be replaced. The initial cost of the EESD is also critically important, since high costs will make it difficult to market the vehicle to a mass consumer audience.

Table 5: Battery characteristics for various chemistries and vehicle types (Burke et al., 2007).

Battery Technology	Vehicle type	Ah	V	Wh/kg At C/3	Resist mOhm	W/kg Match. Imped.	W/kg 95%eff.	Max. Useable SOC,
Lead-acid								
Panasonic	HEV	25	12	26.3	7.8	389	77	28.00%
Panasonic	EV	60	12	34.2	6.9	250	47	----
NiMH								
Panasonic EV	EV	65	12	68	8.7	240	46	----
Panasonic EV	HEV	6.5	7.2	46	11.4	1093	207	40.00%
Ovonic	EV	85	13	68	10	200	40	----
Ovonic	HEV	12	12	45	10	1000	195	30.00%
Saft	HEV	14	1.2	47	1.1	900	172	30.00%
Lithium-ion								
Saft	HEV	12	4	77	7	1550	256	20.00%
Saft	EV	41	4	140	8	476	90	----
Saft	HEV	6.5	4	63	3.2	3571	645	20.00%
Shin-Kobe	EV	90	4	105	0.93	1344	255	------
Shin-Kobe	HEV	4	4	56	3.4	3920	745	18.00%
A123	HEV	2.2	3.6	90	12			
Altairnano	EV	11	2.8	70	2.2	2620	521	60.00%
Altairnano	HEV	2.5	2.8	35	1.6	6125	830	60.00%

Similar challenges and performance requirements exist for all EESD technologies, including such devices as capacitors and fuel cell systems. However, these EESD tend to have further technical hurdles in addition to those of batteries, such as insufficient energy storage capacity (e.g. capacitors) or highly sensitive, complex, and extensive *balance-of-plant* auxiliary system requirements and controls (e.g. fuel cells). To compare any of these EESD technologies directly without fully describing such functional and topological differences in system requirements would be erroneous and misleading. While the fundamental processes of ion transport are similar, the engineering implications are not.

To be sure, a direct comparison of the fundamental ion transport taking place within the electrolytic material of batteries and fuel cells is not, in-and-of-itself, an erroneous act. There is much that can be learned through such direct comparisons of basic chemical properties, such as the behavior of novel electrolytic materials and the improved understanding of various *material defects* that may impact EESD performance. A simplistic diagram of ion transport within the electrolytes of batteries and fuel cells is provided in Illustration 14. One way of discerning these two technologies from one another is by distinguishing *internally replenished ions* (IRI, batteries) from *externally replenished ions* (ERI, fuel cells), where positively charged ions (i.e. *cations*) act as the charge carrying media for these EESD.

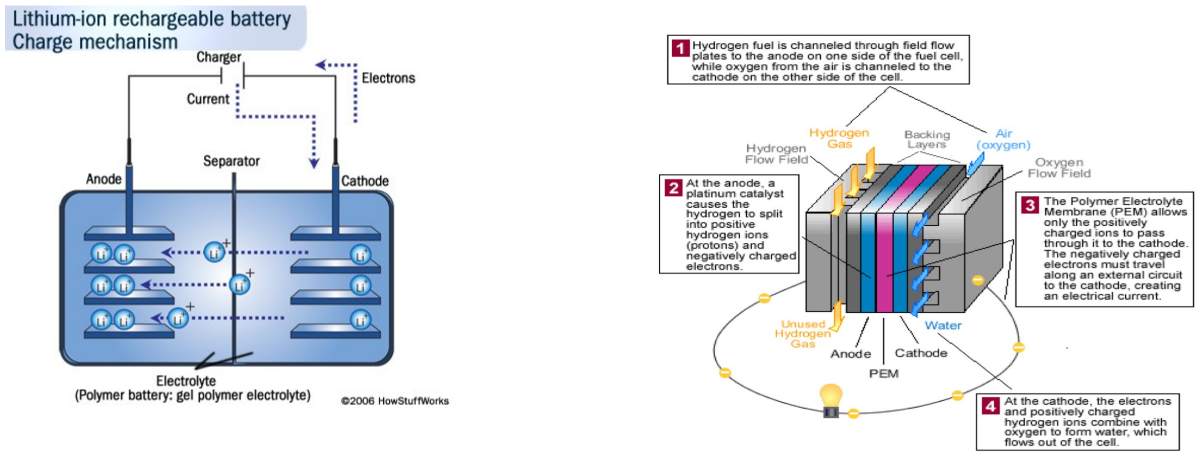


Illustration 14: Battery (left) and fuel cell (right) fundamental ion transport mechanisms.

There are a number of benefits and drawbacks to both internal and external approaches to ion replenishment, such as EESD recharge time, ion transport density (i.e. *current density*), auxiliary system requirements, and so on. The fact remains that there is no clear answer to the question of which approach is fundamentally more appropriate for electricity storage and conversion to useful work; each engineering application must be considered individually based on load requirements, cost, longevity, and environmental constraints. However, it is often the case that the full lifecycle pathway for conversion of electrical energy resources will be shorter (i.e. more effective) for IRI systems. Illustration 15 provides a comparison of a NiMH battery cell with the membrane electrode assembly (MEA) from a direct hydrogen PEM fuel cell, both of which serve the fundamental function of ion transport within these two types of EESD. You may notice at this level, the differences in system configuration seem relatively minor.

Illustration 15: Battery (left) and fuel cell (right), highlighting details of modules and MEA.

Now, as one moves on to higher levels of engineering system integration (i.e. cell aggregation), there are significantly more distinctions which must be specified for a complete description. As an IRI EESD, batteries are effectively self-contained. Depending upon system specifications (e.g. load/power profile, battery chemistry), the thermal management of and IRI system will tend to incorporate direct heat exchange using some form of gas (e.g. air, refrigerant) or liquid (e.g. water, propylene glycol). For ERI systems, thermal management takes place by way of two mechanisms; via direct heat exchange as described for the IRI system (generally liquid-cooled); and, by way of indirect heat exchange via hydrogen, water, and air transport at the anodes and cathodes of the *fuel cell stack* (i.e. series of *sandwiched fuel cell membranes*). The thermal management for ERI systems tend to be more complex than for the IRI systems due to greater sensitivity of the PEM to temperature change.

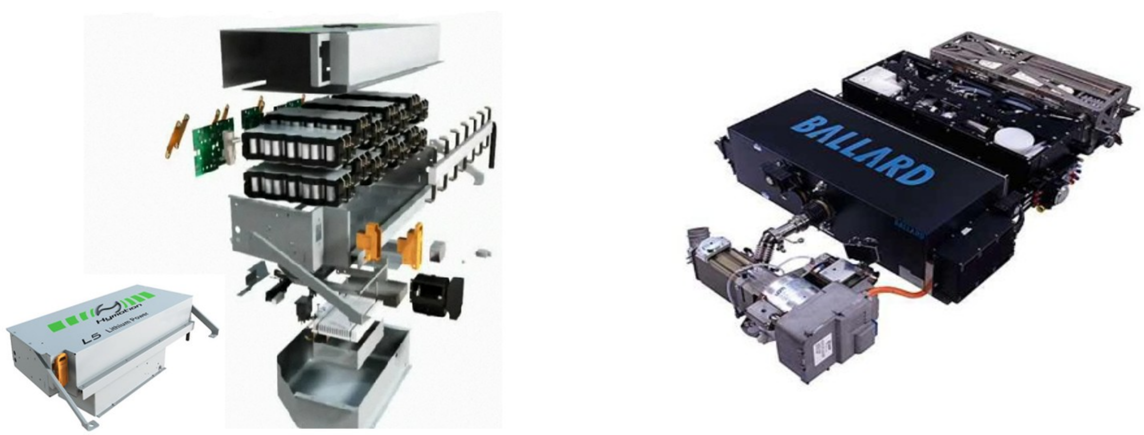


Illustration 16: Battery pack (left) and fuel cell system (right) for vehicle applications.

Though probably counter-intuitive to some (due in part to the *exploded view* of the battery system in Illustration 16), the battery (left) is a less complex system than the fuel cell (right). Without some experience in EESD design or engineering, it may be difficult to quickly identify the major differences between a modern commercial battery system and those of a fuel cell system. One thing to consider is that, if the fuel cell system were to also be shown in exploded view, the pieces of the system would not easily fit within the boundaries of this page. This is not due to the inherent complexity of the fuel cell stack *per se*, but rather a result of the size and complexity of the many auxiliary sub-systems which are required in order to maintain a balanced and properly functioning fuel cell stack. Illustration 17 provides the flow diagrams for a fuel cell stack with auxiliary support and a full FCHEV powertrain.

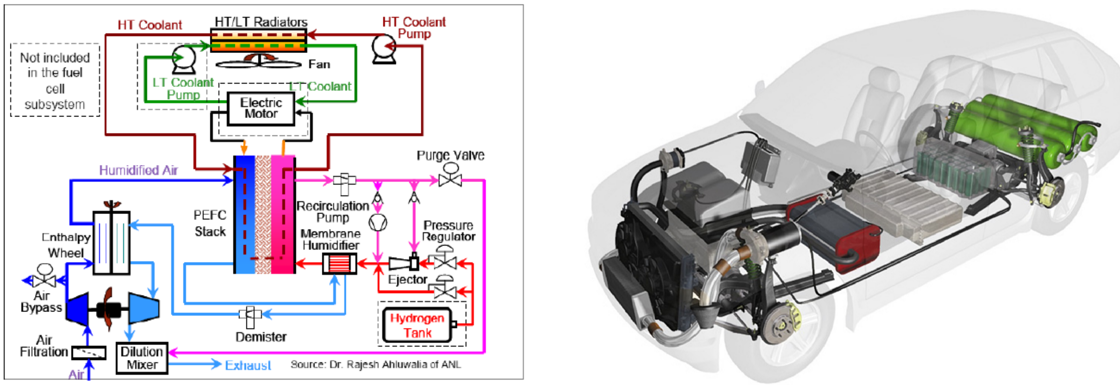


Illustration 17: Flow diagram for a hydrogen fuel cell system (left) and FCHEV packaging (right).

In addition to differences in system configuration and complexity, there are also a number of different practical operating and performance considerations for different ZEV technologies (e.g. BEV, FCEV). The most obvious operational difference, and the real selling point for FCEV over BEV technology, is related to the issue of *refueling time*. In the absence of quick-charging and/or battery-swapping stations (neither or which really exist yet), BEV are inherently limited in their driving range by a relatively long re-charge time, particularly for vehicles with significantly long driving range. Since FCEV use fueling networks and stations to provide hydrogen in much the same fashion as existing gasoline fueling infrastructure, this technology enables the customer familiarity and quick refueling that vehicle drivers are now much accustomed to. Is a visit to a fueling station an inherently good thing? Not really, as the majority of people surveyed say that they would pay a bit more for their vehicle to avoid trips to the fueling station, all else being equal. Probably more important in explaining the attractiveness of FCEV technology is the familiarly attractive *business model* it enables for the energy sector. While the BEV charging and battery-swapping infrastructure proposed by Better Place is unlike anything we've seen before, the hydrogen fueling infrastructure required for FCEV operation will be remarkably similar to that of ICV.

Until now, I have only described EESD options for energy storage, leaving out altogether a discussion of the many different liquid and gaseous fuels that exist for vehicle applications. This is not a matter of negligence on the part of the author, as I have willfully chosen to do so for the very specific reasons. Namely, that as energy carriers go, electricity has the greatest potential for efficiently converting our current solar income (Table 2) into vehicular mobility, and to do so with the greatest potential for lifecycle carbon emissions reductions. Though biofuels and other hydrocarbon fuels will undoubtedly play their part in moving the personal vehicle toward greener pastures, they are likely to play only supporting roles with respect to electricity, which is arguably the most likely energy carrier in the future of mobility. This can be seen in projections for the gradual evolution of the HEV to PHEV, where electrification is anticipated to increase while reliance on other energy carriers will decrease. Presumably, a steady-state vehicle architecture will be achieved when vehicle emissions no longer pose a measurable threat to human health and when all other system costs have been minimized.

Sustainable Vehicle Powertrains

Due to the distinct difference in refueling and recharging requirements for FCEV and BEV technologies, it is difficult to compare the two as apples-to-apples, even when technical system design is completely ignored (i.e. the *technology-neutral* consideration). The reason these two vehicle technologies are so often compared and debated is less a matter of any notable similarities in technical design or driving performance, and more a matter of their perceived *environmental performance* and the regulatory implications of mass marketing. Both technologies are considered by CARB to be zero emissions vehicles (ZEV), and thus both may be eligible to receive industry credits and/or consumer fee-bates if marketed in California. Though other potentially feasible technologies may exist (e.g. compressed-air storage), these are the only two ZEV technologies which have been seriously considered for wide commercialization within the United States. Under CARB regulation, some credits are also given for partial-zero emissions vehicles (PZEV), which include pluggable HEV and EREV (i.e. parallel and series PHEV configurations). Despite their differences in regulatory designation and on-road emissions, it actually makes more sense to consider FCEV and PHEV for performance parity.

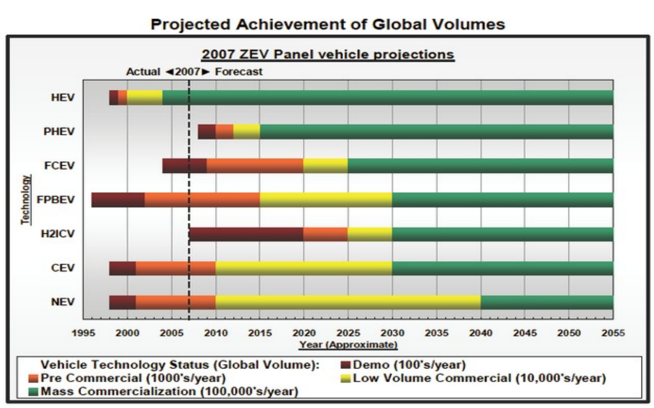


Illustration 18: Vehicle production estimates from ZEV technical panel (Kalhammer et al., 2007).

Despite greater regulatory incentives to produce ZEV technologies, it seems most likely that SULEV and PZEV technologies will remain dominant in AFV markets for the next 20 years or more (Illustration 18). To understand the implications of a staggered vehicle technology roll-out, it is probably useful to first review the differences between powertrain technologies for the various types of AFV. The only fundamental difference between AFV technologies is that of powertrain selection.

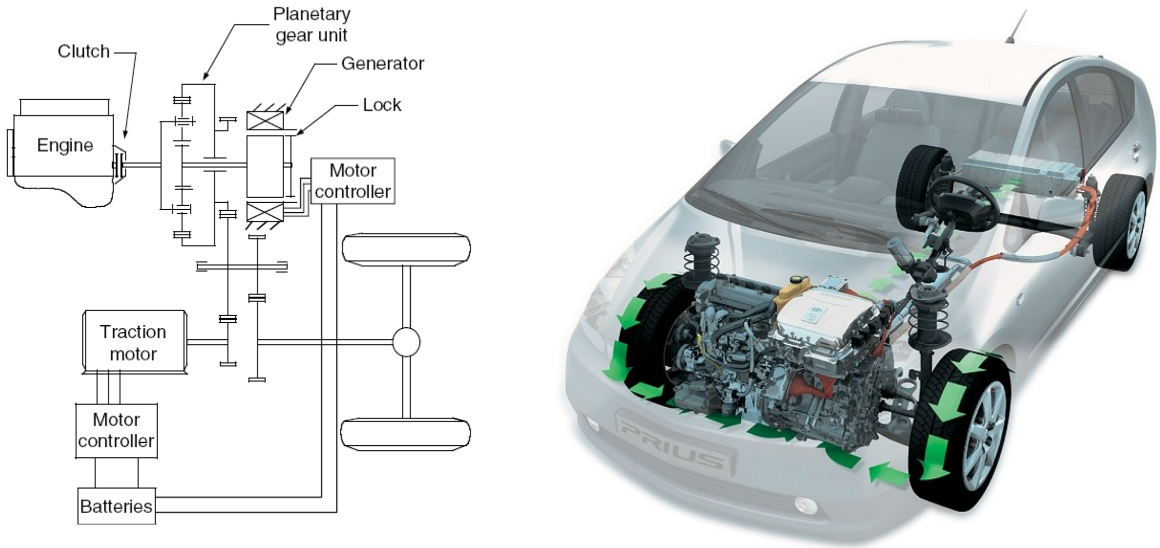


Illustration 19: Toyota's power split parallel HEV powertrain configuration (Ehsani et al., 2005).

Toyota's Prius is far and away the most popular HEV technology produced to date (Illustration 19). The Prius incorporates a parallel HEV powertrain technology known as the *power split*, providing direct tractive force to the wheels from both either engine or electric motor via torque transfer through the a set of *planetary gears*. It's planetary gear set includes a single sun gear (center), a ring gear (outer), and multiple smaller planet gears (between). Though a relatively complex transmission from a controls perspective, Toyota's execution and driveability is really quite impressive. As mentioned in a previous section (Chapter 1, *Problem Context*), the Prius and other HEV architectures are not considered AFV technology unless their engine has been modified (e.g. for ethanol or hydrogen) or extra batteries have been added to enable off-board electric charging. While other HEV architectures do exist, they can be viewed for our purposes as relatively minor mechanical variants of the Prius, with different methods of torque-coupling, gas-electric power splitting (e.g. *degree of hybridization*), and/or engine clutching.

If a vehicle's degree of hybridization (i.e. electrification) is increased beyond a given threshold, meaning that it's electric motor(s) and batteries are sufficiently large meet vehicle performance requirements, then it will generally be prudent to shift from an HEV design strategy to that of a plug-in HEV, or PHEV. Such a design modification does not necessarily have a significant impact on vehicle performance, though it does allow for greater degrees of freedom in vehicle powertrain control and energy sourcing. Among the first and best-known demonstrations of this technology are Dr. Andy Frank's PHEV prototypes developed over a 20 year period here at UC Davis. Illustration 20 shows the powertrain line and packaging diagrams for Dr. Frank's latest prototype *Trinity*.

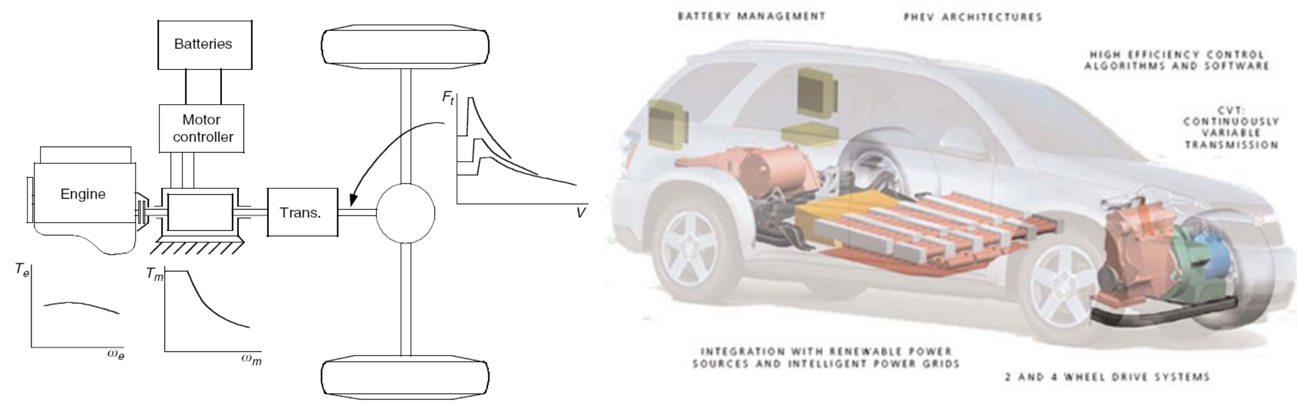


Illustration 20: The pre-transmission parallel PHEV powertrain architecture (Ehsani et al., 2005).

In the case where the electric-drive portion of the powertrain is capable of meeting full vehicle performance requirements all-electrically (i.e. maximum acceleration), powertrain designers will theoretically have greater flexibility for efficient and adaptive powertrain control. This is generally the only circumstance in which the application of a series HEV architecture makes practical sense. The latest electrified offering from General Motors, the Chevy *Volt*, is commonly touted as an electric vehicle though in reality it is actually a series PHEV, or EREV. Like Dr. Frank's *Trinity* prototype, the Volt is anticipated to have approximately 40 miles of all-electric range (AER) capability from fully charge. Unlike *Trinity*, the *Volt* is capable of full performance driving all-electrically, though obviously at a cost to all-electric range. Illustration 21 shows the series PHEV powertrain architecture for the *Volt*.

The only common (electrified) powertrain architecture variation that has not been illustrated so far in this report is that of the BEV, simply because it is a simply a less-complex variation of the EREV, with a larger battery pack and the absence of any auxiliary power unit (APU, e.g. engine-generator). One proposition in support of ending the batteries vs. fuel cells debate, is to develop EREV platforms that can (relatively) easily be modified for a fuel cell APU once FCEV technology has fully matured.

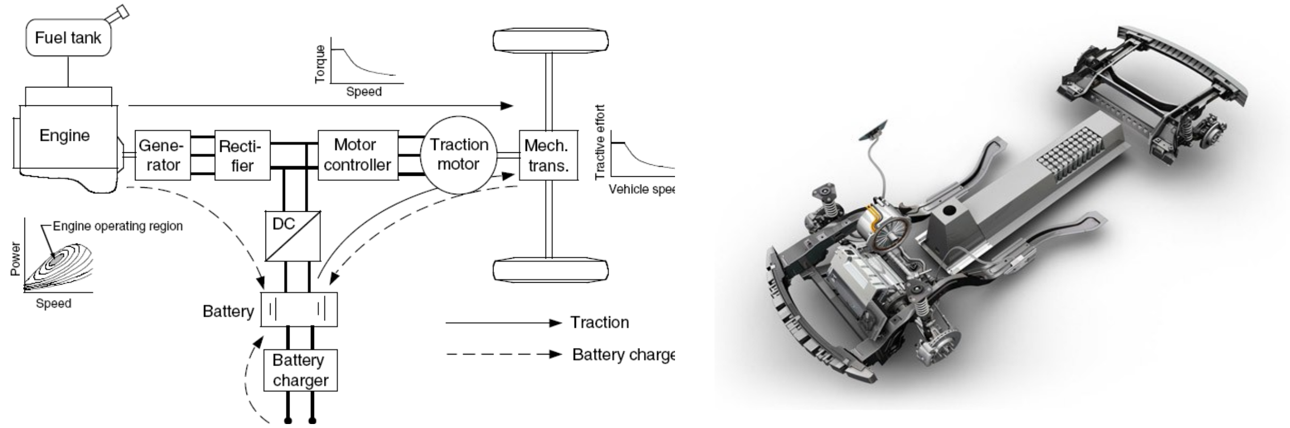


Illustration 21: The series PHEV (or EREV) powertrain architecture (Ehsani et al., 2005).

A common metric for engineering system performance is that of *system efficiency*, a term that has been used and abused on a regular basis since the 19th century. The fundamental concept of efficiency is to compare the ratio of desired work performed to energy invested. Though simple in theory, the problem of setting system boundaries and of fully considering all desirable system processes remains difficult even today. A given industry may seem efficient at first glance when they achieve greater yields over time without raising their costs of production. However, this provides only one narrow view of system efficiency (i.e. *economic efficiency*). From such a view, many variables of system performance remain unaccounted for, such as the appropriateness of energy and material use, the scope of impacts to the environment (e.g. toxic loading, topsoil run-off), the happiness and welfare of employees, and so on. In this sense, it is often misleading to consider measures of efficiency as useful metrics of performance in-and-of-themselves, efficient use of materials and energy is certainly one important aspect of eco-effective system performance. Eco-efficiency is just one piece of the overall goal of eco-effectiveness.

It is also important not to immediately discount the feasibility of a given technological option based on perceptions of low end-use efficiency. For example, it is a general rule that the greater the number of energy or material conversion steps taken in a given process, the less efficient the overall process will be. This is a common argument by many engineers for discounting the feasibility of the EREV architecture. This may seem intuitively obvious, but as it turns out, most real-world systems are not quite so simple. The efficiency of a process has much less to do with *how many* steps are taken through the process than it does with *how large* those steps are, as well as *how often* each step is taken. These issues of magnitude and frequency are fundamental to all system processes, and from the perspective of eco-effectiveness, we wish to take steps that most closely match the requirements of the work we desire, while any waste is fed directly into parallel processes. In a densely populated and relatively resource-constrained World, this seems the only option for the future of sustainable industries.

As mentioned previously in the discussion of industrial ecology and biomimicry, an industrial process chain that mimics a natural system will convert energy and materials from one form to another by the most efficient methods possible, feeding any unused energy and materials from one process in the chain directly into the next with minimal losses. McDonough calls this concept of eco-effective industrial design *waste = food*, a natural phenomenon in healthy ecosystems. The most commonly recognizable application of this concept can be seen in *powerplant co-generation*, where energy in the form of heat from a power plant such as an engine or fuel cell is used to run a secondary process (e.g. heating water). Though this is probably the most common form of industrial waste-feeding practiced in industry, as we begin developing more sustainable industrial ecologies, powerplant co-gen of waste heat is among the minimum requirements of eco-effective industrial process chains. Before recuperating lost energy, it's even more important to reduce losses in the first place. Table 6 compares some typical average values for energy consumption for different modes of transport.

Table 6: Energy use characteristics for general transport modes and personal BEV.

KW/h Passenger/speed= Energy-per-km	**Boeing 747** jumbo jet	**Queen Marry** or large ocean liner	**SUV** or large car	**Bicycle**	**Person** on foot
Weight	369 tons (fully loaded)	81,000 tons	2.5 tons	100 kg with person	80kg (176 lb)
Cruising speed	900km/h (560 mph)	52km/h (32mph)	100km/h (62mph)	20km/h (12.5mph)	5km/h (3.1mph)
Maximum power	77,000kW (100,000hp)	120,000kW (160,000hp)	200kW (275hp)	2000 W (professional)	2000 W
Energy at cruising	65,000kW (87,000hp)	90,000 kW (120,000hp)	130 kW (174hp)	80 W (0.1hp)	280 W (0.38 hp)
Passengers	450	3000	4	1	1
Power/passenger	140 kW	40kW	50kW	80 W	280 W
Energy/passenger.km	580 kilo joule*	2800 kilo joule*	1800 kilo joule*	14.4 kilo joule*	200 kilo joule*

Vehicle	Wh/mile	MPG
2008 Ford F150 truck 2008 Cadillac Escalade SUV	2,618	14
2005 Chevrolet Equinox SUV	1,500	24
Fuel Cell Vehicle	1,000+	35
2008 Toyota Prius	800	46
Trinity (Plug-In Hybrid Equinox)	330	111
2008 Tesla Roadster	310	118
2001 Toyota RAV4 EV	300	120
Aptera hybrid on gasoline	282	130
GM EV1	260	141
Wrightspeed X1	200 urban	183
Aptera on electricity	97	380
2008 Electrathon racer	19	1,940
2008 Eco-Marathon racer	12.9	2,843
2005 PAC-CAR II	2.9	12,665

It is important to closely monitor the inputs (feedstock) and outputs (waste streams) of each process within the industrial chain. Three common indicators for the comparison of process efficiency and effectiveness are fluxes of energy, carbon, and money. By mapping the flows of these three indicators throughout the industrial supply and process chains, it is possible to consider the relative lifecycle impacts for different processes and compare them to natural analogues for performance benchmarking. In general, the process chain most closely resembling its natural analogue will be most sustainable.

Chapter 5. General Considerations in Vehicle Modeling

Introduction

For modern engineering analysis, the designation of distinct and interacting systems is a useful tool for computing and managing useful information, generally allowing for reasonable approximations of system interactions. Such a practice of delineating discrete, dynamic systems for engineering analysis is now nearly universal to all types and scales of engineering application. Engineering systems analysis is a methodology for defining, isolating, and simplifying an engineering problem taken from the complex universe of infinite possibilities. A system is generally defined by its physical properties (e.g. temperature, pressure, volume, mass) and quantifiable flows (energy, information, material), isolated conceptually by a 'dotted line' to represent system boundaries, and simplified by aggregating the effect of significant processes and neglecting those effects or processes deemed insignificant, unknowable, or otherwise exceeding engineering tolerances (limits). In this way, engineers have discretized the World into small but manageable chunks, applying scientific theory as closely as possible in their efforts to meet real-world needs.

This thesis work incorporates the integration of results from several phases of model-based AFV design. The holistic assessment of product value is aided by the calculation of energy/carbon/monetary flows through the industrial process chain, as well as dynamic energy management and vehicle controls. The present and future potential value of AFV is contrasted with that of conventional vehicles using a fractal tile analysis (FTA) as described by McDonough and Braungart, 1996. The vehicle powertrain characteristics are sized and compared with the use of two models, SIMPLEV and ADVISOR. For calculating energy flows, a lumped-parameter (i.e. parametric) model was developed by Andrew Simpson for his Ph. D. work at the University of Queensland (Simpson, 2005) and has been modified for this analysis by the author. Simpson's model, known as the Parametric Analytical Model of Vehicle Energy Consumption (PAMVEC), was developed using spreadsheet software and has been made available for unrestricted public use. The management and control of on- and off-board energy systems is considered through simulations of vehicle systems using the Powertrain Systems Analysis Toolkit (PSAT) developed by Argonne National Labs (ANL) and the Micropower Optimization Model (HOMER), developed by the National Renewable Energy Labs (NREL). PSAT and ADVISOR run in the Simulink visual programming environment, developed by The MathWorks.

Illustration 22 provides a simple diagram of a general model-based design process. Note that the ovals (blue) indicate processes of model development, while the rectangles (orange) represent modeling goals and deliverables. What is not depicted in this diagram is the iterative feedback loops creative problem-solving required by model-based design, occurring at every stage of the engineering process. These feedbacks and dependencies are described in greater detail throughout the following chapters, and are conceptually illustrated by the opportunity map in Illustration 22. It is also important to notice that the classic engineering development process is instigated by c*onsumer choice*, the first blue oval in the sequence. Thus, all engineering activity is often viewed as a simple series of reactions, induced by consumer demand. From the perspective of creative design, the designer is the locus of the engineered system, inducing the demand for products through their creation of novel products and service chains.

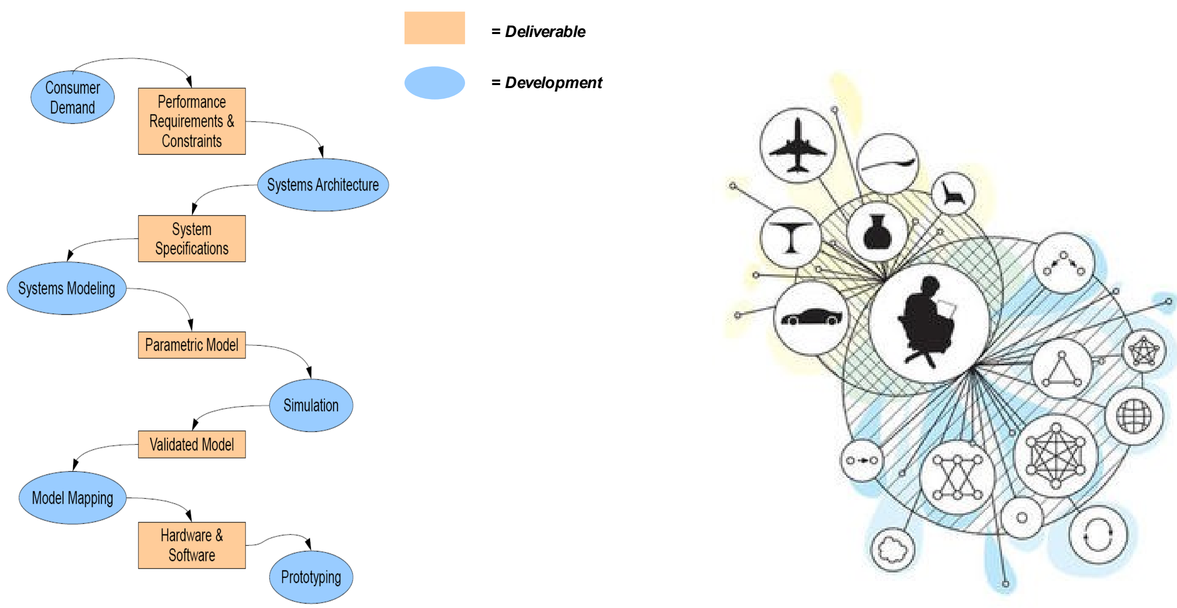


Illustration 22: An engineer's *modeling chain* (left) and designer's *opportunity map* (right).

For the purposes of assessing the appropriateness and sustainability of new technologies, it is useful to develop and analyze networks of material and energy flows. Using such a framework, a technology performing the most useful work per quantity of available energy (i.e. eco-efficient) is deemed most energetically appropriate for that application. Since this measure is highly sensitive to the agents and local environmental conditions of the system in which it operates, the results are not explicitly universal and should be analyzed separately at the regional level for each technical application. Also, the state functions produced by network thermodynamic analyses are generally not sufficient to describe the mechanisms by which they were produced, and thus a measure of the whole does not provide sufficient resolution as to the performance of its various parts. In spite of these apparent shortcomings, energetic systems analysis may be applied widely as a tool for assessing and meeting regional technological needs, even though the complexity of each new system will likely require a reformulation of the model under consideration. This is essential to practical sustainability assessment.

Vehicle Modeling & Simulation

To begin modeling, it is useful to first understand the desirable characteristics of a vehicle simulating tool. A simulation software package should (at minimum) meet the following four general requirements in order to support accurate model development and system assessment (adapted from Hauer, 1999).

1. *Theoretical Soundness*

At a given spatial and temporal scale of system operation and within specified tolerances, all models should accurately conform to both natural laws and realistic, observed system behavior.

2. *Sufficient Scope, Resolution, & Flexibility*

Simulation inputs and outputs should be specified using measurement units and orders of magnitude that adequately describe the spatial and temporal scales of all notable system interactions.

3. *Practical & Efficient Simulation*

The software should be straight-forward for use by practitioners, with short simulation run times, model input data that is practically obtainable, and model outputs that are useful and accessible.

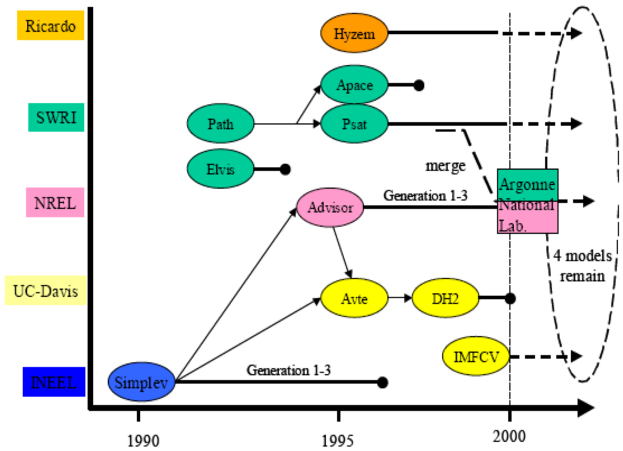
4. *Valid & Reproducible Results*

The software should produce results in a form that can be compared directly to other simulation models and test-stand data to aid in model validation.

An ideally simulated environment is one that allows for reasonable trade-offs between model computational efficiency, accuracy of results, data requirements, and user flexibility. No perfect AFV simulation software exists, though some are more useful than others in supporting model-based design efforts. For the purposes of initial powertrain component selection, specification, sizing, and simple vehicle characterization, it is often useful to apply either a parametric (static) model or a *rear-facing* dynamic simulation approach, due to their simpler structure and ease of adjustment. For more refined powertrain specifications and development of powertrain controls, a *forward-facing* approach is generally considered to be more appropriate for simulating real-world driving conditions. While a lumped-parameter (parametric) model tends to be computationally simple and provides fast results, it is unlikely to provide the resolution of detail required for a refined analysis, which is why many practitioners, especially those involved in powertrain design, opt to use dynamic simulators. The use of fundamental, first principle equations may be theoretically accurate but will require more computational time to fully describe a real-world system. On the other hand, empirical models may accurately describe the operation of a particular system but are unable to generalize for other systems, or beyond relatively narrow or isolated system operating conditions. These distinctions, developments, and the trade-offs in model selection are described in greater detail in the following sections.

Historical Modeling Developments

Efforts to develop software tailored specifically to the simulation and comparison of AFV technologies have been ongoing since the early 1980's, if not before. Some of the first development of such software was directed toward the simulation of battery electric vehicles (BEV), which had been under serious development since the early 1970's and were widely considered to be *near-market* at that time. The software platforms that resulted include CarSim, developed by Aerovironment for General Motors, and SIMPLEV, developed by Idaho National Labs (INL). Software packages were limited to the simulation of EV and series PHEV technologies. The progression and interactions of some AFV software development through 2000, as well as a more detailed listing of simulator development (by type) through 2003, are depicted in Illustration 23.



Vehicle Modelling Tool	*Type*
ADVISOR (Wipke et al, 1999)	Dynamic simulator (backward/forward)
Åhman (2001)	Lumped parameter model
Delucchi (2000)	Dynamic simulator (backward)
EVSIM (Chau et al, 2000)	Dynamic simulator (backward/forward)
HPSP (Weber, 1998)	Dynamic simulator (backward)
Louis (1999)	Lumped parameter model
MARVEL (Marr & Walsh, 1992)	Dynamic simulator (backward)
Moore (1996)	Lumped parameter model
OSU-HEVSIM (Wasacz, 1997)	Dynamic simulator (forward)
Plotkin et al (2001)	Lumped parameter model
PSAT (ANL, 2004)	Dynamic simulator (forward)
QSS Toolbox (Guzella & Amstutz, 1999)	Dynamic simulator (backward)
Ross (1997)	Lumped parameter model
SIMPLEV (Cole, 1993)	Dynamic simulator (backward)
Sovran & Blaser (2003)	Lumped parameter model
Sovran & Bohn (1981)	Lumped parameter model
Steinbugler (1998)	Dynamic simulator (backward)
Thomas et al (1998)	Dynamic simulator (backward)
V-ELPH (Butler et al, 1999)	Dynamic simulator (forward)
VSP (Van Mierlo & Maggetto, 1996)	Dynamic simulator (backward)

Illustration 23: A timeline (left) and listing (right) of AFV simulators (Hauer, 2001; Simpson, 2005).

Beginning in the mid-1990's as part of a U.S. federal RD&D initiative, the Partnership for a New Generation of Vehicles (PNGV), researchers at NREL built and validated many AFV powertrain models in collaboration with university research, most notably at Virginia Tech. These efforts collectively formed the basis for the ADVISOR software package, which seems to have incorporated a greater degree of hybrid powertrain modeling capability than any other modeling platform commonly available in the late 1990's. As indicated, one way of designating vehicle modeling tools is to categorize them by computational methodology as either *lumped parameter* calculators or *dynamic* simulators. The former uses aggregated averages to approximate vehicle performance and the latter attempts to dynamically simulate vehicle performance as a function of velocity traces (speed & time).

Over the last 5+ years, PSAT seems to have moved out ahead as the predominant AFV simulator in the United States. Though many factors may have contributed to its success, the most frequently touted feature is its greater emphasis on realistic vehicle and component controller simulation. Other, more recent contenders have been under development within the private sector (e.g. CRUISE, Modelica, and a newly privatized version of ADVISOR). An open-source version of Modelica (OpenModelica) is also currently under development. Table 7 provides an overview of some notable differences between two of the leading commercial software platforms, PSAT and CRUISE (*Note: 1 Swiss franc = 0.9128 dollars US, 2008*).

Table 7: Comparing the significant features of two leading software platforms (Wilhelm, 2008).

	CRUISE	PSAT
Cost	SFr. 3,316.00	SFr. 3,601.00
Google Scholar*	323	118
Web of Knowledge*	22	1
Engineering Village*	44	12
Scholar's Portal*	29	1
Company Technical papers	4	25
Component library	Medium - generic	Large - component specific
Method	forward facing	forward facing
Simulation	dynamic transients, 95% mechanistic	some dynamic, over 50% empirical
Familiarity	No	Yes
Support	Yes	Developer support
Industry Users	BMW, Renault, Ford + 80 others	GM, DaimlerChrysler, Ford + 60 others
Embedded Configurations	30	400
Validation	80 industry customers	within 5% hybrid Prius
Report generation	Yes	Yes
Customization of Simulink	Yes	Yes
Batch Simulation	Yes	Yes
Optimization package	Yes	No
D.O.E. built-in	Yes	No
Training	Yes	Yes
License duration	1 year	1 year

Model Comparisons

The benefits and drawbacks of using the PAMVEC model for vehicle technology assessment, comparison, and preliminary design are thoroughly discussed in Andrew Simspon's dissertation (Simspon, 2005). PAMVEC is comprised of vehicle energy use calculations (based on the classic road-load equations, described in the next section) for multiple vehicle powertrain technologies, including conventional, series hybrid-, parallel hybrid-, fuel cell-, fuel cell hybrid-, and battery-electric vehicles. Simpson's model does not explicitly account for the AFV architecture. Other parameters of interest that were not included in the original model are vehicle cost, energy cost, fuel alternatives, and energy lifecycle emissions/carbon intensity, though these calculations have been included by the author. Input, output, and intermediary variables are all accessible, clearly designated by color, and easily modifiable. This makes the model highly accessible to modeling practitioners and other interested parties. One major drawback of the PAMVEC model is its relative sensitivity to high mass-to-drag ratios, with errors as high as 15% for some drive cycles (Simpson, 2005). However, this analysis focuses mostly on the design of smaller, lighter, and more slippery vehicle designs, and thus the errors are acceptable.

ADVISOR is a dynamic, rear-facing model simulation platform, implementing a powertrain control strategy that seeks to operate the powertrain optimally, given a drive cycle that is known *a priori*, without incorporating realistic feedback or the unpredictability of the real-world driving experience.

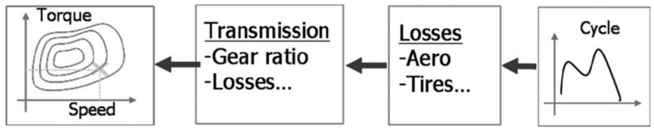


Illustration 24: The backward-facing modeling approach (e.g. ADVISOR).

In contrast, PSAT is a dynamic, forward-facing model simulation platform, implementing a powertrain control strategy that incorporates simulated sensor feedback for a (theoretically) more realistic simulation of powertrain control. Each platform is useful for different modeling applications, though it is important to understand their relative strengths and limitations as tools for model-based design.

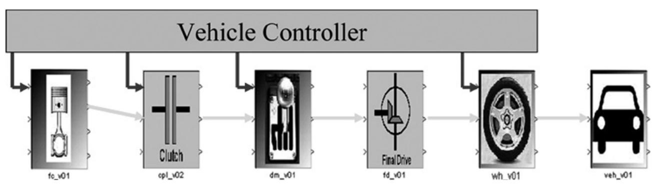


Illustration 25: The forward-facing modeling approach (e.g. PSAT).

The level of detail applied to the characterization of powertrain component operation and interaction can have profound impacts on the ability of a given software platform to meet the previously stated requirements for accurate modeling (particularly items 2 & 3). Software that avoids first principle equations and computational processing may provide too little flexibility and scalability. Those that over-describe the first principles operation of the powertrain may lead to unreasonable computational time and data error compounding. conveys this distinction conceptually.

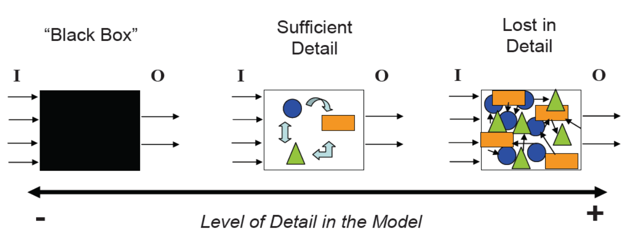


Illustration 26: Levels in modeling detail, increasing from left to right.

Uncertainties in Vehicle Modeling

Any model of a real physical system can only be, at best, a close approximation for the behavior of the real system, and at worst a poor and inaccurate abstraction of reality. As mentioned previously, a useful model should be theoretically sound, sufficiently scoped, practical, efficient, accurate, and valid within the domain of model applications. Since nearly all simulation methods require iterative mathematical approximations to calculate model interactions, one of the most significant sources of model error are generally introduced when small inaccuracies are compounded and aggregated through successively iterating programming loops. Many creative solutions have been developed in the fields related to computational analysis in an effort to control and otherwise minimize such errors. The majority of vehicle simulation methods rely upon the application of some form of the now famous road load equation (RLE, Equations 1 & 2) to approximate on-road driving performance.

$$
\begin{aligned}
P_{road} &= P_{aero} + P_{roll} + P_{accel} + P_{grade} \\
&= \tfrac{1}{2}\rho C_D A v^3 + C_{RR} m_{total} g v + k_m m_{total} a v + m_{total} g Z v
\end{aligned}
$$

Equations 1 & 2: The classic road load equation (RLE).

Where P_{road} is the road load power (W), P_{aero} is the power required to overcome aerodynamic body drag (W), P_{roll} is the power required to overcome rolling resistance at the wheels, P_{accel} is the power required for vehicle acceleration (W), and P_{grade} is the power required for changing road grade (i.e. angle of sloping road) [Eqn. 1]. These factors can be described more fundamentally in terms of physical conditions, such as air density, vehicle body drag, frontal area, speed, wheel rolling resistance, mass, gravitational force, rotational inertia, acceleration, and road grade [Eqn. 2].

For dynamic vehicle simulation, many assumptions must be made about how each variable of the RLE changes over time, whereas lumped parameter models use constant averages for these values. Typically, dynamic models incorporate the use of driving schedules based on standard cycles (i.e. time, speed, grade). These are generally the same schedules/cycles used for vehicle testing and certification, enabling model validation and cross-comparison with test results. In backward-facing models (e.g. ADVISOR), the vehicle controls are set to match the driving schedule for optimal operational efficiency. In forward-facing models (e.g. PSAT), the controller model operates more like real-world vehicle controls, and is thus expected to provide more accurate estimates of real-world powertrain performance and efficiency. For modeling existing vehicle platforms, PSAT has an obvious advantage over a model like ADVISOR. However, for the purposes of theoretical vehicle design, the error introduced by ADVISOR's controls assumptions are more than compensated for by its ease of use, modification, and debugging. For this reason, much of the modeling work for this thesis has been done using ADVISOR, which PSAT has been applied only when controller refinement has been necessary.

Model-Based Design Techniques

As mentioned previously, there are a number of useful techniques employed by vehicle engineers and other professionals in their analysis and assessment of AFV. While each technique is likely to be applied differently by a given institution (and often considered to be proprietary information), I will attempt to provide general and over-arching information about some of the more common modeling techniques, each of which is applicable to the modeling of general systems. More detailed information is available from many sources, and though by no means perfect, the most extensive repository of AFV modeling information is maintained by NREL[10].

The first technique I would like to describe is known as the Design of Experiments (DoE). Though very much standard practice in laboratory settings, the DoE is often overlooked or only lightly considered in computer-based simulation. Since computer programs can be run *ad infinitum* with relatively little cost in energy or time (more so the case every day), the benefits of painstakingly defining the experimental process are often difficult to properly value in the face of looming publication deadlines. Instead, many researchers use the *shotgun approach* to simulation, modeling anything and everything that lies within the bounds of their feasible experimental space and hoping (perhaps by chance?) to produce something of publishable quality. However, if even the experimental space itself is ill-described, such an approach will likely be slower and more painful in the long-run, not to mention only justifiable in hindsight. A properly applied DoE helps researchers to elucidate the more important experimental questions, allowing for the accurate definition of system agents, processes, and environmental conditions.

10 You can access many NREL reports on AFV technology via their website: http://www.nrel.gov/vehiclesandfuels/.

Once the objective(s) and constraint(s) of the DoE have been clearly defined, an optimization scheme may be applied to converge upon a solution. Many such schemes exist, such as the satisfaction of the Kuhn-Tucker system optimality conditions. In this case, linear approximations of non-linear differential equations are mathematically transformed and manipulated in order to locate a solution that best optimizes the experimental objective within the given solution space. When the engineering objective is assumed to be minimized cost and system constraints are set for the values of *maximum allowable* social or environmental impacts, the engineering solution will tend to converge on the minimal cost and allow levels of pollution that converge to the stated constraints. Though this experimental optimization process has been shown to be effective at modeling many engineering activities occurring within the market economy, it does little to address the problems of acceptable pollution limits, ineffective regulation, and the intangible value of natural resources and services. From such a limited analytical scope, it is impossible to describe eco-effective resource use (e.g. up-cycling).

Another technique commonly applied by modeling practitioners is that of model *composition* & *decomposition*. This approach is relatively straight-forward though immeasurably important and very often ignored. In the development of any complex system model, there are likely to be a great number of sub-systems or sub-routines. The integration of sub-systems into larger systems is not always a simple task, and all interactions between sub-systems must be carefully considered. The most useful system models are those with optimally partitioned sub-systems, grouped by function (either mathematically, practically, or ideally both). These system models add only as many sub-systems as are needed to produce solutions at the desired level of resolution and nothing more.

For the example of modeling a BEV, it is necessary to produce models of the batteries, the electric motor, the mechanical drive, and the vehicle body. In order to estimate the vehicle performance, it is also necessary to produce models for the vehicle controls, drive trace, and driver response (if assumed sub-optimal). At the vehicle level, it is difficult to closely monitor the operation of each component and understand the effects of small changes over time. For this reason, it is often useful to *decompose* the model into its sub-systems in order to add greater levels of detail and higher data resolution. Since this resolution is generally not needed at the vehicle level of simulation, there must be some method for moving between more- and less-detailed sub-system models during the model development process.

Such a technique is referred to as *decomposition*. This technique necessitates the careful construction of model libraries in which to store commonly used sub-systems, as well as *model stories*, which allow the practitioner to maintain a recorded history of a given model's evolution and topology (i.e. description of sub-systems, interactions, and environmental conditions over time and space).

Software-in-the-loop (SIL) virtual prototyping is a technique used to simulate the performance of an unknown system model using a known, validated model. For vehicle SIL development specifically, an unknown powertrain component sub-system will be tested using a well-described and validated vehicle system model, where the vehicle performance on a known test cycle can be compared to the expected vehicle performance, while the simulated performance of the component model is monitored and recorded. If for whatever reason the component model operates outside the bounds of its realistic parameters, then either the component sub-system model or its controller model are modified and the simulation is re-run. The implementation of real-time simulation software allows for fine-tuning of the component controller model using small adjustments and the relatively speedy simulation for reevaluation of results. Unfortunately, real-time development software and SIL hardware are expensive.

Even when all pertinent steps are carefully taken to prepare accurate models and establish reasonable simulating conditions, it is impossible to completely avoid error. Since AFV technology can be found in only very limited quantities, mostly in privately owned and proprietary garages and labs, it is often difficult to obtain empirical data for model validation. This should become less of a problem over the next few years, as low-production AFV begin rolling off the assembly line. Chapter 6 describes the current state of technical and market readiness for electrically dominant vehicle technologies, including BEV, PHEV, EREV, and FCHEV platforms.

Chapter 6. Technical & Market Readiness of Electric Vehicles

Introduction

Virtually every consumer wants to know the answers to the same questions, such as *"When can I buy a clean car? What makes it cleaner than the one I own now? Can I can afford to purchase a clean car?"* Though I'm really not the best person in the World to conjecture on the answers to these questions, I will attempt to answer for the simple reason that few knowledgeable people willing to even make an educated guess, and because I do feel educated enough on the matter that my guess may be just as good as practically anyone else's. This chapter summarizes findings from several RD&D projects I have worked on over the last 5 years, and I have provided several references to supporting documentation. If you would like to reference these documents but are unable to locate them, please contact me[11].

Electric Vehicle Weight & Road Load

As mentioned in Chapter 4 (Table 3), the energy density of gasoline is very large (12.2 kWh/kg, 9.7 kWh/L), about two orders of magnitude greater than even the best batteries (~ 100 - 150 Wh/L). For this reason, ICV technology is generally designed with less attention to energy efficiency than is the case for BEV. Vehicle characteristics such as weight, aerodynamic drag, and rolling resistance are often not given highest priority in conventional vehicle design. However, for EV design, the careful consideration of weight, aerodynamics, and powertrain efficiency is not simply a luxury, but rather it is absolutely necessary in order to achieve the driving range and vehicle performance drivers have come to expect from automobility. A number of BEV prototypes, as well as design and modeling studies have investigated the reduced energy usage that is possible for a BEV due to reductions in weight, aerodynamic drag, rolling resistance, and powertrain efficiency. An often surprisingly large percentage of otherwise wasted energy is recoverable in an electrically dominant vehicle through regenerative breaking (regen), up to 50% or more according to some BEV test data (Brooks, 2006). Unlike other features of a BEV, regen can actually be more effective at recapturing energy for relatively heavier vehicles, since energy lost in braking is largely a function of momentum.

11 E-mail bryan.jungers@gmail.com or visit my site at http://steps.ucdavis.edu/People/bdjungers/bdjungers_homepage.

Achilles Heels: Driving Range & Recharge Time

Full-performance electric vehicles with driving ranges of 50 to 200 miles have been designed and built using various types of batteries. The short-range vehicles typically use lead-acid batteries as they are most cost-effective, while long-range vehicles use Li-ion batteries, with vehicles using NiMH batteries having intermediate driving range. Building vehicles with larger range would be very expensive as well as reduce vehicle cargo space. The acceleration performance of an electric vehicle is primarily dependent upon the power (kW) of the motor and the weight of the vehicle. Electric motors have excellent low-speed torque characteristics and consumers generally like the feel and responsiveness of electric vehicles. Vehicles have been built with 0 - 60 mph acceleration times on the order of 3 seconds, but in general the acceleration times are between 8 and 12 seconds. The recharge time of the battery in an EV is primarily dependent upon the electrical characteristics (voltage & power) of the charger and the electricity source to which it is plugged. Most batteries can be recharged in less than 30 minutes when the proper charger and electricity source are available, though longer charge times are more typical due to maximum current constraints on charging circuits.

If it were not for these inherent constraints in BEV recharging time and driving range, it is unlikely that we would even be interested in other technologies. To the folks at Better Place, the problems of limited range and long recharge time apparently look like a good business opportunity, a stance I would like to see more companies adopt in moving forward on advanced energy and vehicle projects. Turn your problems into opportunities by asking the right questions and seeking innovative solutions! Unfortunately, I think my pragmatic side may actually be winning over my idealism for a change, since I really don't believe that Better Place will be able to implement their business model worldwide in either the near- or mid-term without suffering catastrophic economic losses, barring huge subsidies and a Manhattan Project level of innovative battery development. For these reasons, we may still be interested in other alternatives to the BEV for quite some time.

Family Tree of Sustainable Vehicles

The EREV is the most similar technology to that of a BEV, only without either of the critically limiting *Achilles heels* of BEV technology (i.e. range & recharge). The EREV incorporates a smaller battery pack than a typical BEV, usually allowing for anywhere from 20 to 60 miles of all-electric driving. If the battery is sized adequately, it should be able to provide full, electric-only performance for the entire

AER (as claimed by the Chevy *Volt* with its 40 miles of AER). The reason the EREV can use fewer batteries and provide a shorter electric driving range is that the powertrain design also incorporates the use of a small, on-board energy conversion device to provide auxiliary electric power to re-charge the batteries and/or drive the electric traction motor. This device is typically referred to as an auxiliary power unit (APU), most commonly in the form of an engine-generator set.

Though not technically a ZEV, it is theoretically possible to design an EREV that will drive mostly in electric mode (based on daily averages) but will still be capable of driving long distances with extremely low on-road emissions via the operation of an optimally tuned and controlled APU, especially when fueled by natural gas, propane, hythane, hydrogen, or compressed air. I will openly admit that this powertrain design is my favorite among the choices I am aware of, even over BEV and FCHEV options. It provides fuel flexibility and the ability to upgrade to different APU systems; it down-sizes the battery pack without sacrificing all-electric performance for average daily ranges; and, it allows for tighter constraint and quasi-steady-state operation of the combustion engine (assuming one is used as an APU). If one lived in an area with readily available hydrogen fuel, they they could opt to purchase an EREV with a fuel cell APU. Compared to a typical FCHEV, this would be a battery-dominant fuel cell vehicle, but as we observed in prototyping for the VDS 1.0[12] project, this may be a cheaper and more efficient overall vehicle design, particularly from a full lifecycle perspective.

I find it sometimes useful to consider the evolution of the sustainable personal vehicle as following two distinctly separate lineages (Illustration 27). One branch of development stems from the continual improvement of the conventional ICV, from engine efficiency improvements to electric hybridization and eventually parallel plug-in hybrid vehicles (e.g. *Trinity*, *Prius+*). The second branch of development stems from the age-old struggle to popularize and commercialize BEV technology, where an EREV serves as a design compromise to an all-electric ideal for the sake of vehicle versatility and consumer acceptability. Though I can sympathize with the *EV purist* mentality, in the words of Chauncey Starr, I prefer to make decisions and act as a *pragmatic idealist*, where in this case pragmatism is the defining distinction. Since we can't all have our cake and eat it too, there will have to be some concessions made, and I for one am willing to concede the pure electric dream (at least in the near-term) in order to drive a drastically more efficient and fuel-flexible vehicle today.

12 The Vehicle Design Summit 1.0: http://turbo.discovery.com/convergence/green/mit_vds/main.html.

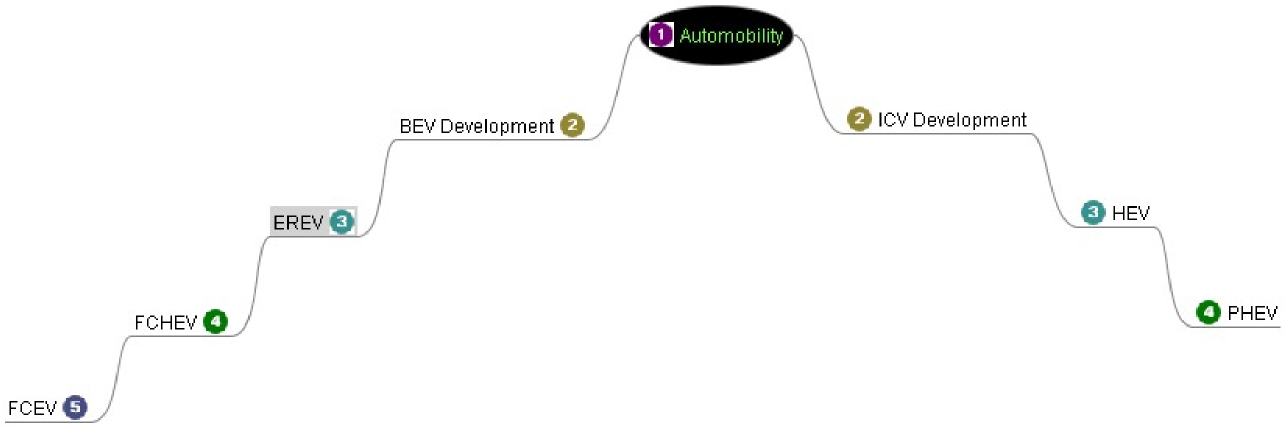


Illustration 27: The evolving family tree of personal automobility.

Powertrain Components & Configurations

The driveline configuration for the *electric branch* of vehicles can vary somewhat from one model to the next, but they are generally quite similar. The drivelines consist primarily of an electric motor, power electronics (including charge controller and DC/AC inverter), and a battery pack. The battery pack for a BEV can be large, often weighing at least 200 kg, since it is the primary energy storage unit and must provide all of the energy needs (propulsion & auxiliaries) of the vehicle. The electric motors provide all of the wheel torque to accelerate the vehicle, as well as energy recovery during regenerative braking. The motors and power electronics must be sized to meet the maximum torque required at the wheels to adequate meet acceleration and braking demand, and also to maintain the maximum speed of the vehicle on a grade or under towing conditions (if applicable). The various components in the electric driveline are discussed in the following sections.

Electric Motors

An electric motor is used to convert the electrical energy from the battery to mechanical energy to power the vehicle. Electric motors are very efficient conversion devices of electrical energy into mechanical torque, with efficiencies generally ranging from 70 to 95%, depending on operating characteristics. The torque from the electric motor is applied to the drive shaft of the vehicle and the wheels, often through a single gear reduction rather than a multi-gear transmission. Electric motors have higher power densities (power per unit weight or volume) and advantageous low-speed torque characteristics when compared to internal combustion engines. The result is a smooth, rapid acceleration of the electric vehicle from rest, assuming a skillful integration.

A number of different types of electric motors have been used for electric vehicles. These include series and separately excited DC motors, as well as induction, permanent magnet, and switched reluctance AC motors. The power electronics convert DC power output from the battery pack to whatever form is required by the selected motor option over its complete range of torque and speed (RPM). DC motors, both series and separately excited, utilize brushes for commutation and power electronics are used to control the effective voltage applied to the armature and field windings of the motors. The lowest cost electric drive units are those using series DC motors, but they are applicable only in low speed vehicles. Separately excited DC motors can be used in higher speed vehicles, though most BEV at present use some type of AC motor. The brushes in the DC motors limit their maximum RPM and to some extent the system voltage, which necessitates periodic maintenance and inefficient operation.

In general, the AC motor systems are smaller, lighter, more efficient, and lower cost than the DC systems, especially as the power requirements for the systems have increased. High performance, high speed electric vehicles have been designed and built using both induction and permanent magnet types of AC electric motors. At the present time, the permanent magnet motor seems to be the choice for small, low- to moderate-power systems (~25 - 150 kW) used in passenger cars, and the induction motor type is the choice for large vehicles like heavy duty trucks and transit buses. The permanent magnet (PM) motors tend to be smaller and easier to control than the induction motors at moderate power, but the induction motors are more durable and lower cost when the power required is high (> 200 kW).

A low resolution torque-speed-efficiency map for an induction AC motor is provided in Illustration 28 to demonstrate the general shape of the torque and efficiency curves, along with a more detailed efficiency curve map from ADVISOR. Note that the efficiency varies significantly with torque and RPM, that efficiency is higher at low speeds and high torque and lower at higher speeds, and that no single value of efficiency is applicable for a motor in a vehicle operated over a driving cycle. For most vehicle configurations and driving cycles, simulated energy usage of vehicles using PM motors has been shown to be lower than those using the induction motors (Burke et al., 2007). The differences do vary with driving cycle, but are within the range of 10 – 20%, with the largest differences being on city cycles (i.e. under stop-and-go conditions). The improved efficiency with the PM motors would translate directly into a longer driving range for the battery pack size (kWh).

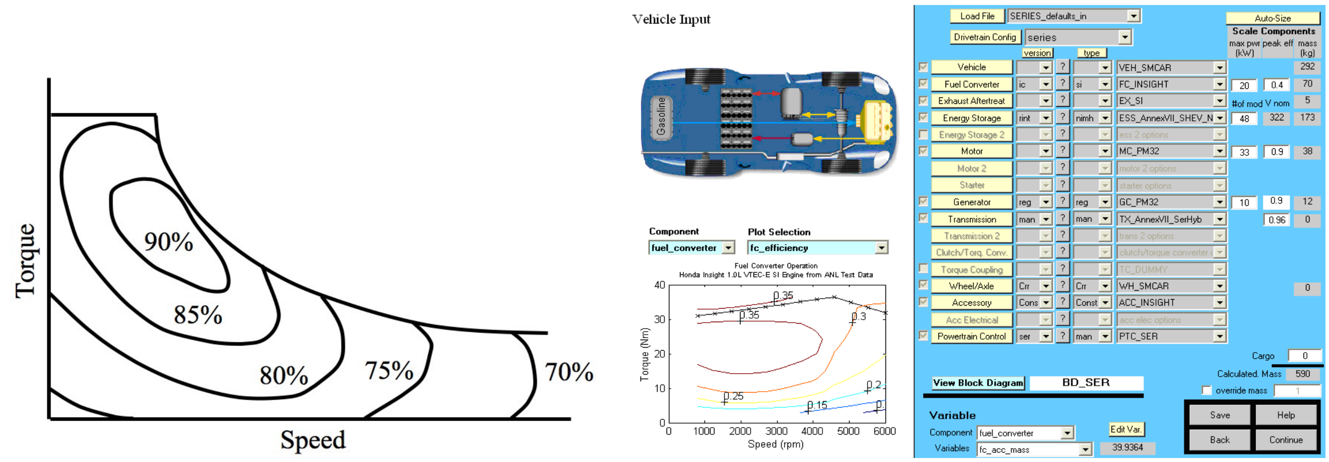


Illustration 28: Efficiency map for an AC motor and powertrain selection in ADVISOR.

Power Electronics

The peak power rating of electric drivelines used in electric vehicles has increased significantly over the last ~10 years. This is due primarily to the improved performance (current and voltage limits) of the semiconductor switching devices used in the power electronics. The DC/AC inverter in the driveline system includes at least six switching devices to control the time varying voltage fed from the battery to the electric motor. The technology improvements in the switching devices has not only improved their performance, but has also lowered their cost and increased reliability substantially. The efficiency of the power electronics is typically in the range of 95 – 98%, meaning that nearly all of the losses in an electric driveline occur in the electric motor, which is itself highly energy efficient. In addition, much progress has been made in developing and implementing new control algorithms for the various types of AC motors that permit motor operation at high efficiency over a large portion of the motors' torque-speed map. Using present motor and power electronic technologies, average electrical to mechanical work efficiencies of 85 - 90% over typical driving cycles are not uncommon.

Battery Selection

There are a number of ways to express battery performance. The simplest approach is to state the energy density (Wh/kg) and peak power density (W/kg) as shown in Chapter 4 (Table 4). This approach is useful for showing the relative performance of various types of batteries, but it does not provide information about the detailed performance of a particular battery chemistry over different operating conditions. Detailed information of battery operation, such as the Ragone curve (Wh/kg vs. W/kg for constant power discharge), open circuit voltage and resistance vs. state-of-charge (SOC), capacity (Ah) vs. discharge current and temperature, and the charging characteristics of the battery at various rates and temperatures, are all needed in order to begin an assessing the suitability of a particular battery type for a specific electric vehicle application. Even then, on-road demonstrations are needed to validate the selection and to monitor the batteries for premature material and performance degradation.

As shown in Table 4, batteries can be designed with significantly different energy and power characteristics, even within the same class of battery chemistry. For each battery type, there is a trade-off between energy density and power density, with the higher power batteries having significantly lower energy densities and subsequently higher unit cost ($/kWh). In general, the battery pack in a BEV is sized for energy storage requirements (kWh), while the vehicle's power requirements (kW) are met inherently due to the large size of the battery pack. For mid-sized battery packs (e.g. PHEV and EREV), the battery chemistry should provide some elements of both an energy battery and power battery, particularly if the vehicle is designed for low AER (e.g. < 25 miles) and/or the batteries are intended to provide power for full vehicle acceleration without assistance from an engine or other APU (e.g. full-performance EREV).

Battery Safety & Cycle Life

Most battery packs have a battery management system (BMS) to monitor cell/module voltages and temperatures. In the case of lead-acid and NiMH batteries, the purpose of the BMS is to increase the life of the pack by assuring that the cell voltages remain balanced and the temperatures do not exceed a specified upper value. In the case of Li-ion batteries, the BMS is also needed to assure that the pack is operated safely, as over-charging of the pack has previously led to thermal runaway conditions that typically cause fire and/or explosions. Much of the current research on Li-ion batteries stems from the desire to utilize electrode chemistries that do not have the inherent safety problems associated with graphite and NiCoAl electrode materials. Safety can be more of an issue with lithium batteries in BEV than in hybrid vehicles like the *Prius*, since the battery for a BEV is deeply discharged and (usually) fully recharged after each cycle. Though more deeply discharged per cycle, the total number of charge-discharge cycles for a BEV over its lifetime will almost certainly be less than for an HEV. The most aggressive duty cycle of any vehicle platform is probably that of the pluggable hybrid (i.e. EREV or PHEV). These powertrains are designed for deep battery discharging on a near-daily basis, and thus it is critical, from both a business and lifecycle impact perspective, that battery selection and management be made a top priority of powertrain design for these architectures.

The battery pack must be designed with sufficient cooling to permit sufficiently fast charging without overheating and damaging the battery. Heat generation in the battery is significantly higher during charging than during normal use in driving the vehicle. For most battery technologies, there is a relationship between cycle life, depth-of-discharge before recharge, and time to recharge. In general, battery cycle life is maximized for modest (i.e. slower) rates of recharge (greater than 1 - 2 hours) and moderate depths-of-discharge (50 - 60%). In addition, the maximum battery temperatures should be limited to 50ºC or lower. In general, batteries are *happiest* when operated at moderate temperatures and with relatively gradual charge and discharge fluxes. In this way, you can consider a battery pack to be similar to a human being; if you maintain it at somewhere near body temperature and don't stress it out too much or for too long, it can be expected to live a long and productive life!

Because they are still a new technology, with very high power characteristics and the potential to catch fire or explode, the proper design of a Li-ion battery management system (BMS, Illustration 29) is extremely important. Each individual cell within the battery pack must be monitored, along with each aggregated module, and data must be fed from the cell data collectors to the module controller on the order of 1/100 of a second, with data updates from the modules to the BMS motherboard occurring around every second or 1/10 of a second. Depending upon the size of the battery pack, there can be a fair amount of data transfer taking place over the course of a given drive cycle. If the BMS controllers detect an imbalance in the battery pack (e.g. temperature spike, current spike, over/under voltage, etc.), a module will be electronically isolated and an error message will be sent to the main vehicle controls to alert the driver. In the case where more than one module is affected, the entire battery pack may become isolated and inaccessible to the other components within the electric drivetrain. In such a critical situation, assuming that the vehicle is still drivable, it may be beneficial to have an APU on-board to provide enough power to drive the vehicle to a local repair shop.

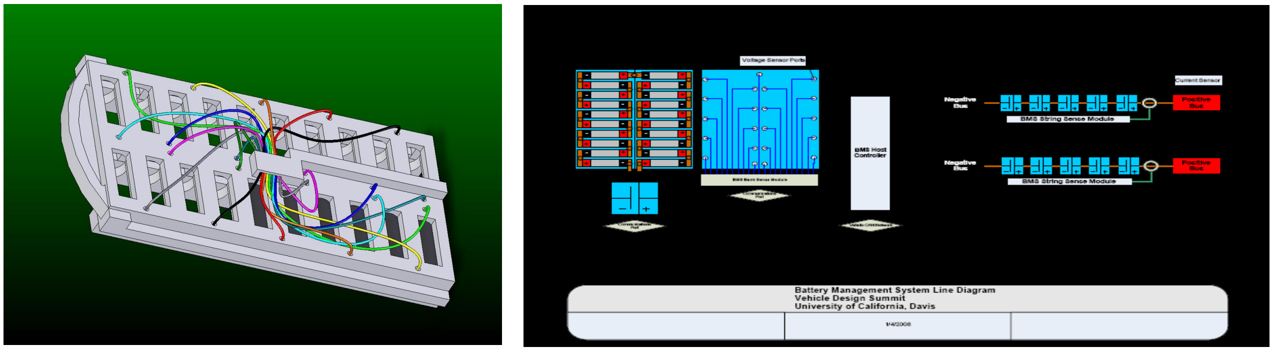


Illustration 29: A Li-ion battery module w/ BMS wiring harness and board schematic.

In evaluating battery technologies for electric vehicles, cycle life is one of the key determinants of the economic viability of a particular battery technology. The cycle and calendar life (i.e. actual useful battery lifespan) depends critically on how the battery is operated, including the rate of discharge, the depth of battery charge and discharge, and the battery's operating temperature. Of particular importance are the depth-of-discharge before recharge and the battery state of charge before each discharge. As shown in Illustration 30, the cycle life increases dramatically if the depth-of-discharge of the cycles is less than 50%. Both of these factors directly influence the usable energy and energy density of the battery and the range of a vehicle for a given weight of the battery. Hence careful attention should be given to the test procedures for both the battery capacity and cycle life tests.

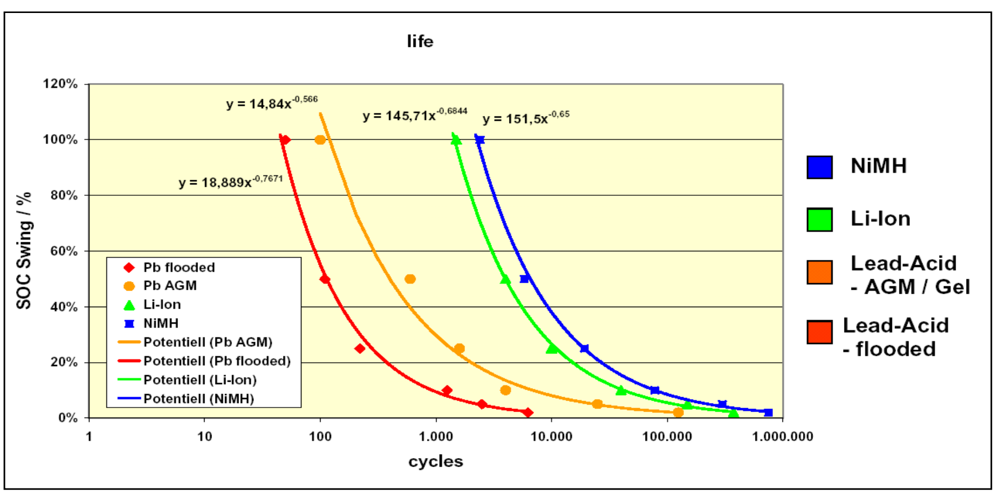


Illustration 30: Battery cycle life as a function of depth-of-discharge (Rosencranz, 2005).

real-world situations seems to indicate that cycle life for nickel metal hydride batteries is good, lasting a minimum of five years and 2,000 cycles, even under very deep discharge duty cycles. The cycle life of the lead acid batteries is much shorter, typically lasting only 2 - 3 years and a few hundred cycles. More testing is required before reliable cycle life information for lithium ion batteries can be reported. The USABC has set a calendar life goal of 10 years and a cycle life goal of at least 1,000 cycles to 80% depth-of-discharge as needed for commercialization of electrified vehicles. Recent data indicate that the USABC battery life goals are attainable with NiMH batteries, and they are likely also to be attainable with the use of Li-ion batteries.

Battery Cost

The cost of the battery is an obviously sensitive issue for battery dominant vehicles, especially in the automotive industry where marginal returns can be relatively tight. While the experience with battery life has been encouraging, so far battery costs have not. At the present time, large energy batteries for electric vehicles are very expensive, on the order of \$700 to \$800/kWh for NiMH and even more for Li-ion batteries. The cost of lead-acid batteries for BEV is about \$100/kWh, which is why many BEV use them even though their relative performance is low. It is anticipated that the cost of advanced batteries will decrease markedly when they are manufactured in high volumes. A key question is how low the cost/price of the advanced batteries, in particular the lithium-ion batteries, will fall in high volume. Most projections for the future cost of Li-ion batteries are in the range of \$300 - \$500/kWh in mass production (> 100,000 packs/year). In order to achieve comparable range as an ICV (~400 miles), BEV battery costs alone, assuming these cost projections, would be between \$30,000 and \$50,000.

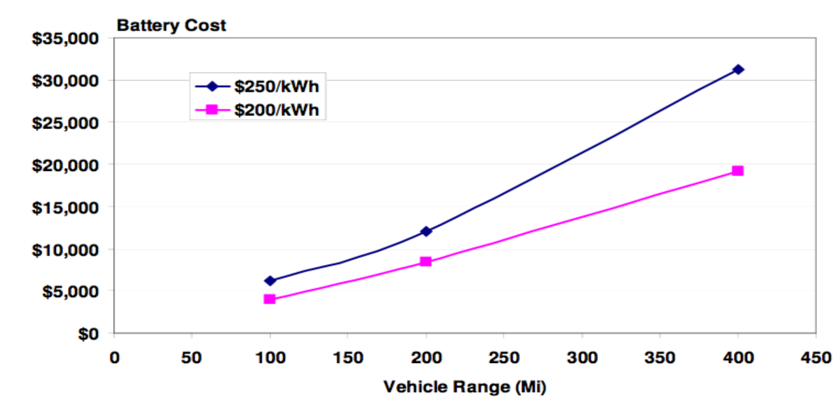


Illustration 31: Battery cost as a function of vehicle driving range (Burke et al., 2007).

Small cell (1 - 2 Ah) lithium-ion batteries are manufactured in very large volume (many million cells per year) and their cost seems to be about \$1/Ah, which corresponds to \$250/kWh (Burke et al., 2007). The USABC has set a selling price goal for advanced batteries of less than \$150/kWh for long term commercialization of electric vehicles at a volume of 25,000, 40 kWh packs per year. The long-term goal for large volume production is \$100/kWh. It is highly questionable whether these cost targets are attainable for either Li-ion or NiMH. Note that these cost targets are for the selling price and include the cost of the battery management/monitoring system, the battery box, and battery heating & cooling.

It is important to realize that if vehicle range is increased by adding additional battery storage, the fuel efficiency of the vehicle (e.g. mile/kWh) will decrease due to the additional battery weight. For a vehicle with a 200 mile range, the batteries can weigh over 300 kg. Thus, the additional range achievable with additional batteries is non-linear and declines as battery weight increases. Kromer and Heywood assign the highest long-term risk in electric vehicle commercialization to battery costs, as energy storage and the associated range issues lead to larger, more expensive battery backs. Barring unforeseen breakthroughs in battery materials and technology, meeting cost targets, such as the USABC goal will be challenging. As Better Place would agree, that sounds like a business opportunity.

Considerations of Vehicle Cost & Ownership

The cost of electric vehicles relative to conventional ICV of similar size and functionality is an important metric for understanding the viability of these vehicles and the likelihood that consumers will purchase them. Some additional initial price may be tolerable if the lifecycle cost of the EV is equal to or lower than that of the corresponding ICV. The functional utility of the EV must also meet the perceived needs of the consumer. As would be expected, the potential market increases as the driving range of the EV increases and/or the refueling (recharging) time decreases. Range and battery cost considerations have already been discussed in earlier sections of this Chapter. In this section, the lifecycle costs of electric vehicles are considered further.

The cost of the driveline in an EV is simply the sum of the cost of the electric motor and power electronics, the cost of the APU and fuel storage system, and the cost of the battery system, including the BMS and charger controller (*note*: battery pack charge controller may be integrated with other power electronics). Since the EV is likely to be heavier than the baseline ICV due mainly to heavy batteries, there may be an additional cost in strengthening the chassis and suspension to carry the additional weight, depending upon battery pack size and on-board placement. If the weight of the EV is reduced by light-weight material substitutions, that may also add to vehicle cost.

$$\text{OEM motor cost} = -111.3 + \left(127.7\ln\left(P_{peak,kW}\right)\right)$$

$$\text{Power electronics cost} = 480 + \left(2.95\ln\left(P_{peak,kW}\right)\right)$$

Equations 3 & 4: Estimations for motor & power electronics cost to the OEM.

The relationships in Eqns. 3 & 4 are valid for high production rates of 200,000+ units/yr. The electric driveline cost depends on the power rating of the electric motor, which in turn depends primarily on the design specification for maximum vehicle acceleration (e.g. time to accelerate from 0 - 60mph). For most EV, the peak motor power is on the order of 30 to 100 kW. The APU cost is also a function of peak power, though it will vary widely depending upon fuel selection and total vehicle driving range. For example, the choice of a hydrogen fuel cell APU would likely raise the vehicle price significantly.

The cost of the battery is dependent primarily upon the design specifications for electric driving range or equivalent capacity. In almost all cases, the battery is sized by the energy storage required (kWh) to meet this specified AER equivalence. The energy storage requirement (kWh_{batt}) can be calculated from the energy consumption of the vehicle (kWh/mi) from the battery and the specified range [Eqn. 5].

$$\text{Energy storage required } kWh_{\text{batt}} = (\text{Driving Range, } mi) * (\text{Efficiency, } kWh/mi)$$

Equation 5: Estimation for battery storage capacity based on desired range and average efficiency.

For a compact car using batteries in the range of $200 - $400/kWh, the OEM battery cost would be $6,000 - $12,000. Reducing the AER of the vehicle and maintaining the same motor power (same acceleration performance) would mean that the required power density would increase in proportion to this reduction in range, likely requiring a redesign of the battery system. This may result in a reduction in battery energy density and higher cost per unit energy stored. These are two important examples of *design coupling* for EV: vehicle performance & range, as well as battery performance & cost.

One factor in the marketability of EV is their cost relative to conventional ICV and whether the additional cost of the EV can be recovered by the lower cost of energy to operate the vehicle. One metric of the economic competitiveness of the battery-powered vehicle is the *break-even price of gasoline*, or the point at which the lifecycle costs of the EV equals the cost of the gasoline to operate the ICV over its expected lifetime (e.g. 100,000 miles). The break-even price of gasoline associated with vehicle price varies between $6,000 for compact vehicles and $9,500 for a large SUV. Assuming average lifetime consumer electricity prices of $0.06/kWh, the break-even gasoline price is somewhere between $2 and $3/gallon of gasoline for an EV with 100 miles of AER (Burke et al., 2007). For a vehicle with 100 miles of AER or less and at gasoline prices of $2 - $3, the cost premium for an EV should be recoverable well before the end of that vehicles useful life, though the exact payback period will depend upon interest rates, inflation, battery storage capacity, and fluctuations in energy price.

Table 8: Determining the break-even gasoline price for an EV with 100 miles of AER.

Vehicle types	**Energy Use [*Wh/mi*]**	**Battery Energy [*kWh*]**	**Retail Differential Price (*$*)**	**Cost of Electricity for 100K miles at *$0.06/kWh***	**Gasoline for Baseline ICV [*gal*]**	**Break-Even Gasoline Price (*$/gal*)**
Compact Car	202	20.2	6,280	$1424	2941	2.62
Mid-size Car	249	24.9	6,543	$1763	3448	2.41
Full –size Car	285	28.5	6,664	$2010	4000	2.17
Small SUV	319	31.9	9,164	$2256	3846	2.97
Mid-size SUV	333	33.3	8,734	$2348	5000	2.22
Large SUV	380	38.0	9,462	$2679	5555	2.19

Other cost studies have shown similar or higher incremental prices of BEV. Kromer and Heywood detail a baseline incremental cost of $10,200 for a BEV with 200 miles of AER over a 2030 spark-ignition ICV and an optimistic incremental cost of $6,900. These incremental costs are slightly lower than the cost of the battery, as the remainder of the vehicle is generally less expensive than for the ICV.

Energy Use & GHG Emissions

In general, the total energy use & GHG emissions produced by a personal vehicle are calculated as the *on-road* (tank-to-wheels) energy use and vehicle exhaust emissions plus the *supply chain* (well-to-tank) emissions from the production and distribution of the vehicle's energy carrier (i.e. fuel or electricity). These latter emissions are sometimes referred to as *upstream emissions* because they occur prior to vehicle use. In the case of battery-powered vehicles, there are no exhaust emissions during AER operation (i.e. strictly battery charge-depleting mode), and thus the only emissions that must be calculated for EV electricity use are those that occur upstream. In this section, we will concentrate on CO_2 emissions, the most significant greenhouse gas (GHG) related to vehicle use.

The emissions (gCO_2/mi) for various electric vehicle platforms is calculated for both the California and US grid electricity mixes, with the results are shown in Table 9. In general, the CO_2 emissions for electric vehicles are low, especially when charging in California. It is of interest to compare the CO_2 emissions for the battery-powered vehicles with those for the ICV. The CO_2 emissions span a wide range between the two car and SUV platforms, and the comparison will depend upon the source of electricity generation. The use of low-carbon, solar income energy resources (e.g. solar PV, wind, and biomass) can reduce the CO_2 emissions even further compared to conventional and hybrid gasoline vehicles. Using conventional generation sources, Table 9 shows clearly that electric vehicles are a very attractive approach to enabling relatively deep reductions GHG emissions in California.

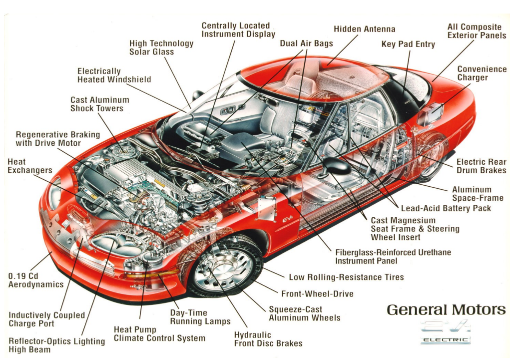
Table 9: Electric vehicle energy use and GHG emissions for different platforms (Burke et al., 2007).

Vehicle Type	**Vehicle Weight** (*kg*)	**Battery Weight** (*kg*)	**Battery Capacity** (*kWh*)	**Battery Energy** (*Wh / mi*)	**Elect. Range** (*mi*)	**GHG CA mix** (gCO_2/mi)	**GHG US mix** (gCO_2/mi)	**GHG ICV** (gCO_2/mi)
Cars								
Compact	1373	285	20.2	202	80	71	153	405
Mid-size	1695	380	24.9	249	80	88	189	472
Full	1949	475	28.5	285	80	100	216	540
SUV								
Small	2103	380	31.9	319	80	112	242	515
Mid-size	2243	475	33.3	333	80	117	253	667
Full	2701	570	38.0	380	80	176	380	756

Market Synergies for Electric Vehicles

At the risk of seeming redundant (e.g. Illustration 26), I would like to mention once more the different evolutionary branches of vehicle development. The branch stemming from BEV development consists of many different possible powertrain configurations, generally sharing common components such as batteries, electric motors, power electronics, and controllers. Examples of other electrified vehicles (stemming from the ICV branch of vehicle evolution) include HEV like the Toyota *Prius* and plug-in hybrid electric vehicles (e.g. *Trinity*, *Prius+*). Because of their shared components, development of any of the other vehicle types has benefits to the entire class of electric drive vehicles, helping to expose consumers to new technologies, flatten learning curves, reduce production costs, and spur further RD&D investments. Although full-function BEV are not likely to be mass-marketed as consumer vehicles in the near-term, development of batteries for PHEV and EREV platforms will help to bring down component costs and improve the market prospects for BEV in the long-term.

Rather than aggressively competing for limited RD&D funds and standing firm on narrow paths of technological development, the automobile industry (and anyone currently attempting to enter into it) may be well-advised to keep their windows of technical opportunity left open as widely as possible. From my observations, there is one vehicle powertrain configuration that provides the most significant long-term flexibility to account for shifting consumer preferences, tightening regulatory restrictions, evolving fueling infrastructure, and breakthroughs in energy conversion technologies. As luck would have, GM seems to have been struck by the lightening of divine ingenuity twice, currently positioned to be the first automaker to bring an EREV to market. In actuality, the inspiration for the new Chevy *Volt* came not from God himself, but from the same patron saint who brought the World its first market-ready electric vehicle: Paul MacCready. Can they learn from their recent mistakes in marketing the *EV1* and pool what resources they still have to make the *Volt* a market success? Only time will tell.



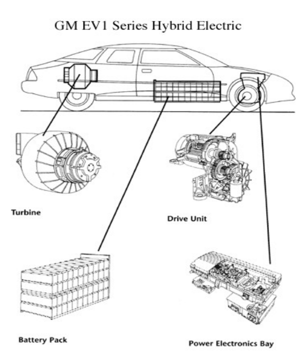


Illustration 32: Will General Motors successively market the EREV, or pull the plug yet again?

Chapter 7. The Model-Based Design of Sustainable Systems

Introduction

While multiple attempts have been made in the past to begin a shift in transportation energy use away from single-source petroleum, a large market penetration of AFV has yet to be realized. Much evidence suggests that while fuel economy improvements for petroleum-fueled vehicles can contribute to reductions in petroleum imports and GHG emissions, alternative fuels and significantly more fuel efficient vehicles are vital to obtaining the necessarily deep reductions in petroleum energy use and GHG emissions that are required for sustainable development. Given the magnitude of the challenges associated with shifting the population of vehicles and fueling infrastructure, it is important that choices about vehicle and fuel technologies be made with the long-term consequences in mind.

One class of AFV that has long been considered a prime candidate for adoption in California to meet these goals is the electric vehicle (EV). The EV benefits from zero on-road emissions, low-noise operation, and the potential to operate using renewable and/or low-carbon energy sources. The two most common types of EV are *battery electric vehicles* (BEV) and *fuel cell electric vehicles* (FCEV). For the purposes of this design, fuel cells do not have sufficient near-term technical or market potential, though I will happily update my analysis to include fuel cells in 10 years (Jungers et al., 2007). Rather, this Chapter focuses on other methods of adapting market-ready technologies to meet consumer demands for green vehicle technology without serious compromises in driving range or refueling time. Thus, I consider here the model-based design of an extended-range electric vehicle (EREV, or series PHEV). I describe two example platforms (i.e. the Chevy *Volt* and the VDS *Vision*), both of which currently exist as prototypes and are intended to reach consumer markets within the next 2 to 3 years.

Emerging Technology & Product Value

It's becoming more and more clear in the industrialized marketplace that consumers are becoming more informed on issues of sustainability and beginning to demand better, greener products. Much more variety exists for green products than did just a few short years ago, and those companies attempting to green-wash their dirty products and sell them with new packaging are already beginning to fall by the wayside. At the Detroit Auto Show this year (2009), every major manufacturer presented some form of electrified vehicle as a major showcase, a turn of events that I don't believe has ever before been seen since the beginning of the U.S. vehicle industry. Ford and GM were among that greenwashing crowd a few short years ago, playing lip service to the environmentalists but breaking their own records for SUV sales (both in vehicle size and production volume). Today, it seems that maybe our metaphorical driver has finally awoken from its slumber behind the driver's wheel, and the big OEMs are claiming more adamantly than ever before that they can build cleaner cars. Should consumers believe them?

When GM introduced the *EV1*, it doesn't seem like they really expected it to take off. It was a small vehicle (even for that era), released by their ho-hum Saturn brand. Most people probably didn't even know there was an electric vehicle available on the market, and since the production volumes were only in the low 1,000s, GM wasn't exactly enticing an onslaught of demand (e.g. did anyone see those horrific *EV1* commercials on WKTEC? That was definitely vehicle marketing at its not-so-finest hour). The mistake that was made, whether it was intentional or not, was to under-sell AND under-deliver on an otherwise breakthrough moment in the history of personal vehicle development. Having now recovered from the PR blow of WKTEC?, GM is picking themselves up, brushing themselves off, and entering the ring with an arguably even more impressive and certainly more widely publicized EV offering. So, what is needed in order to make the *Volt* a commercial success? Good engineering, wide consumer acceptance, and plenty of feedback to help improve upon the next round of development. From a sustainability perspective, we'll also need to begin evolving toward smaller, lighter EREV designs that incorporate fewer and lower-impact materials.

So far, the preliminary results of consumer acceptance research currently under way at ITS-Davis suggests that drivers do not value AER explicitly, whether full-performance or otherwise. In general, new car-buying consumers are hoping to save as much gasoline as possible at the lowest cost, a classic economic optimization scenario. If this holds true into the future, it could spell trouble not only for *Volt*, but for pretty much all electrically-dominant personal vehicles. Consumers will happily eat up whatever slight increases in fuel efficiency or minor low-speed electric range Toyota provides them. Thus, it seems that U.S. consumers are by-and-large stuck on the branch of ICV development and may not yet be willing to make that leap over to electric dominant powertrains, or at least not at any considerable increase in cost. For the *Volt* and other EREV platforms to become wide market success stories, it may be necessary to demonstrate new emergent features and also to more widely socialize the current *elitist fetishism* that exists in small EV niche markets. A sustainable car is not just for the rich.

The Elusive Fractal Tile Analysis

In McDonough and Braungart's popular and progressive novel, *Cradle to Cradle* (McDonough and Braungart, 2002a), a relatively brief mention is made of the FTA modeling approach used by their company (MBDC) to assess the sustainability of products. I've searched high and low for anything even approaching a description of MBDC's computational methods for applying such a value assessment, but to no avail. I stopped just short of contacting MBDC directly to see if they'd share their secrets with me. It's probably all for the better, since if I had asked to know their methods, I would likely be held under some *non-disclosure agreement*[13] right now, and I'd prefer to share here with you my over-simplified but (hopefully) still illustrative application of a fractal tile valuation model. Illustration 33 depicts the model resolution you can find with a quick (or lengthy) Google search.

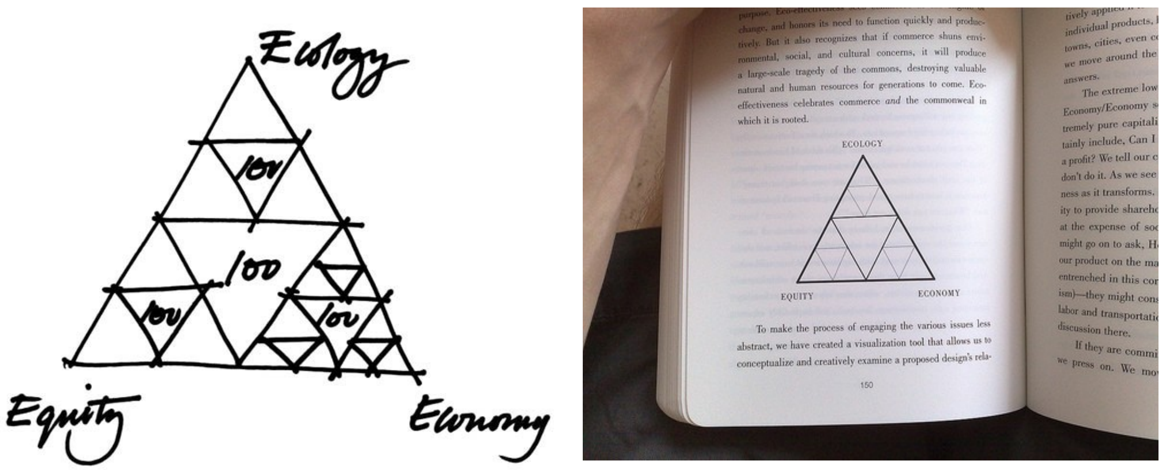


Illustration 33: All the public information you're likely to find on McDonough and Braungart's FTA.

Thinking about this model almost drove me insane. Seriously. McDonough and Co. provided just enough information about their process to make it seem enticing and effective, but that's all (s)he wrote. Literally. I sometimes wonder if other people have ever become as frustrated as I did after reading about this mysterious modeling technique, then being left relatively clueless about how to actually apply it as an educated assessment of product sustainability. I'm pretty sure that if MBDC does nothing more than scrawl little triangles on napkins like what's shown in Illustration 33, they aren't too likely to get more big contracts once they're finished cleaning up the Rouge. Needless to say, I have no way of validating my approach to FTA against that of McDonough's, but I'm hoping they will contact me when this is published so we can collaborate. Or to sue me. Either way, my efforts would be validated.

13 *Green Guru's* gone wrong? You decide: http://www.fastcompany.com/magazine/130/the-mortal-messiah.html.

The FTA description in C2C is ~ 2 pages out of 200. I admittedly am a big fan of the book for its intrinsic entertainment value, waterproofness, and inspiring allusions to *green grandeur*, but as an instructive text on green and sustainable *engineering design*, it's really neither good nor useful. So what's with the yin-yang cars on the cover? Plenty of catchy green buzzwords and 10-mile-view concepts, but little for a *car engineer* like myself to really sink their teeth into. I thought the white paper they wrote on the subject would provide more lucid details on their approach, but despite its provocative title (*Design for the Triple Top Line: New Tools for Sustainable Commerce*), it probably contains less useful information on their "*new tools*" than the 2-page description in C2C. Trying to entice people to buy the book, perhaps? Who knows, but this is the sort of proprietary approach to design that is grown from the same classically economic root that encourages greed and elitist delusions of intellectual grandeur. McDonough and Braungart are making big claims but aren't providing anyone with the means of validation. Since "*sustainability takes forever*" and MBDC's approach to design is proprietary, how can we be sure their designs are sustainable for the long-term?

All griping aside, the remainder of this section is intended to clearly describe my approach to *mimicking* the FTA model of MBDC. What I should give McDonough more credit for (*Read*: please, don't sue me), is his emphasis on taking the time to ask the good questions. Maybe he read the quote by Einstein, too. Illustration 34 depicts one of my earliest attempts at developing FTA questions for the eco-effective design of an EREV. I presented this as a poster for my research group last year. I'm pretty sure everyone who attended the conference where I presented thought I was nuts, and I can't say I can really blame them. What kind of a model is this? Lots of obscure questions and only marginally insightful answers. I was really hoping someone from GM might walk by and ask me about the poster, possibly sharing with me some insights into the company's assessment of EREV sustainability. However, judging from that whole *EV1* debacle, GM probably wouldn't claim to have much experience with sustainable EV marketing, except perhaps making suggestions of what *not to do*. Maybe that's the demonstration McDonough and Braungart are hoping to provide to green designers as well, as if there were a shortage of examples from other greed-driven, green-washed design firms.

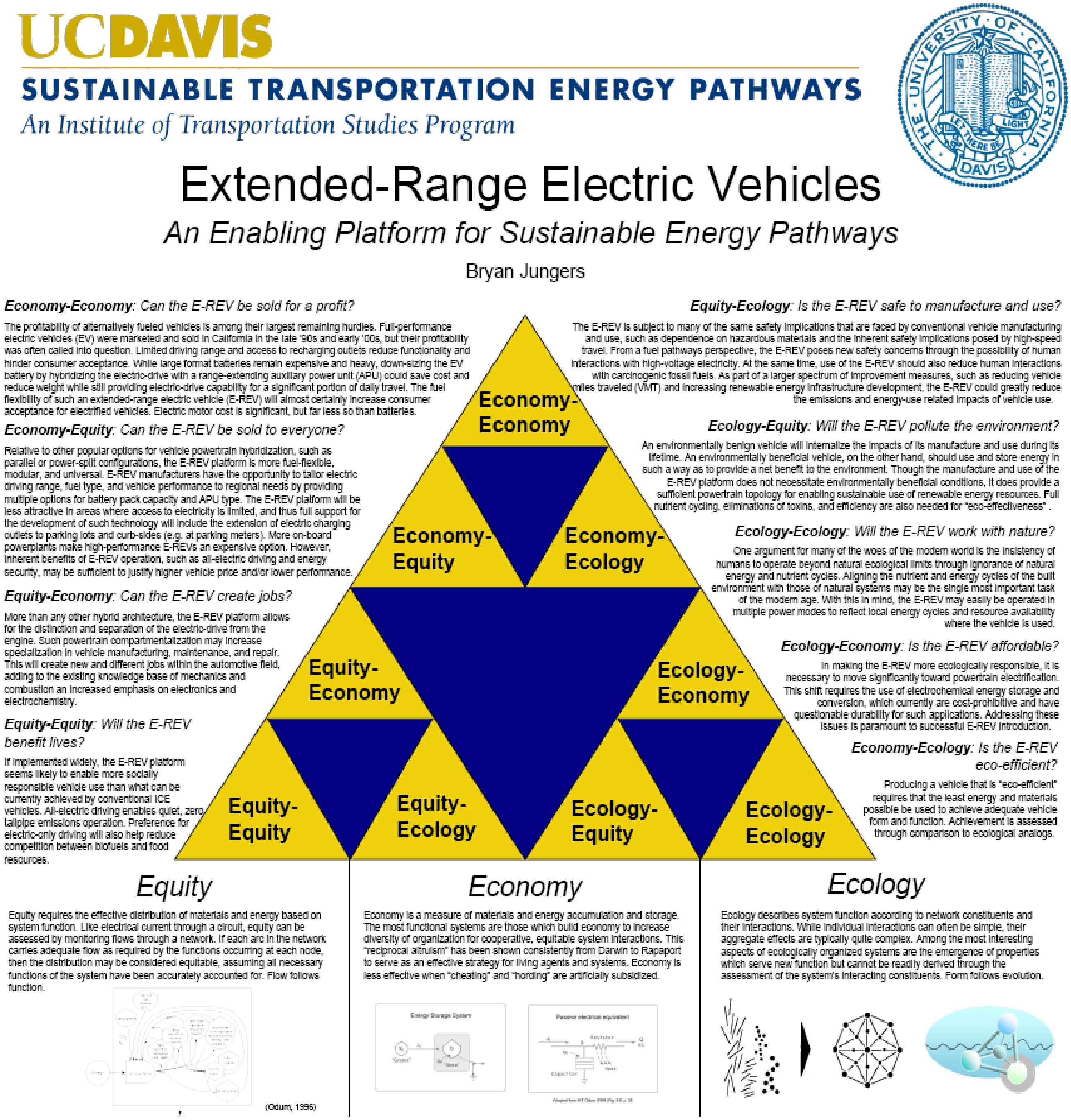


Illustration 34: A mostly qualitative FTA model of EREV eco-effectiveness (Jungers, 2008).

The exercise of compiling good questions and attempting to single out the most powerful and salient among them can be a very useful endeavor. It is actually rather amazing how quickly the right questions can float to the surface of the mind once the search has been properly scoped and provided with ample processing time. And as Einstein says, the answers come quickly when the questions are well developed. I'm not confident that all of these questions are as powerful as I would like them to be, but they're a start, and this is very much a work in progress (I still have a Ph.D. dissertation to finish, after all). If you have any ideas about how I might improve upon/include more probing and powerful questions for my design of EREV technologies, please feel free to contact me with your thoughts.

As far as quantitative modeling goes, my current application may be little more effective at validating product sustainability than McDonough's napkin scribbles (Illustration 33), though I will attempt to describe them to you anyway. I am seeking to combine methods of natural system computation (e.g. Odum, 1971), inspired by ecological awareness from several forms of perennial philosophy, including Taoist teachings (e.g. Wilhelm, 1931), holistic perception (e.g. Huxley, 1954), and theories of eco-effective design (e.g. McDonough). As one might imagine, the ideas floating around in this realm are more than a little bit ethereal and seemingly esoteric in nature and can often be difficult to practically apply. This is not an uncommon problem for people seeking the true form and function of natural systems, realizing with each new discovery the size of that *overwhelmingly large gap* which exists between what we experience in everyday life and what we know to be possible in the natural World.

Sustainable Systems Modeling

So now that the difficult part of developing powerful questions has been undertaken, the determination of a solution to this problem should take no time at all, right? I really do wish it were that simple. Believe it or not, there are actually very few models of holistic systems thinking from which I have been able to base my modeling developments. Again, if you know of any good ones I'm all-ears, but for now I'm working for the few resources I have, mostly those deep insights I've gleaned from H. T. Odum and his relatively prolific (though far from complete) body of work. Illustration 35 provides a 12-step modeling program (rehab?) and an algorithm for sustainable systems modeling (Odum, 1994).

Odum's work seems to be relatively unknown to engineers and ecologists alike. I have spoken with many students and professors on the topic of his work, most of whom haven't heard of him or believe that he's some sort of *fringe academic*, despite the many contributions he has been credited with and the universally broad fields and topics to which his modeling has been applied. I can only guess that his work has not been widely accepted because it seems far too simple to be universally applicable to so many system descriptions. For whatever reason, I find his work to be an intuitive breath of fresh air in what I have experienced as an otherwise stagnant and highly fragmented academic environment.

1. *Assemble information about the real system; assemble people knowledgeable about the system.*
2. *Together list the sources, the components that have storage, and the processes and interactions.*
3. *Make an energy language diagram by arranging sources by quality, arranging components within the system boundary also by energy-quality hierarchy, and connecting the pathways with interactions and intersections that are known mechanisms.*
4. *Draw, redraw, and make full detailed systems diagrams when inventory and scanning of all knowledge is desirable; this is usually a good first step in a new situation.*
5. *Simplify and aggregate, retaining for emphasis, the main storage of concern, the interactions that are varying, and the parts of the system that are concerned with questions and problems.*
6. *Place numerical evaluations of flows and storages on a copy of the diagram.*
7. *Make another diagram with embodied energy values, all of one type of energy (e.g. sun or coal equivalents) where energy analysis is being done for such purposes as estimated value.*
8. *Translate aggregated diagrams into differential equations for simulation.*
9. *Run simulations with families of curves to clarify relationships, sensitivities, and possible futures.*
10. *Compare performance of each mechanism and of whole models to the performances of the real world, making changes if there are contradictions.*
11. *Look for phenomena, generalized designs, and features of real world or of the models that may be new generalities. Use work of others by diagramming their equations, programs, and diagrams in other languages to find what is similar and different in their approaches and how this may be real and important.*
12. *Find ways to recognize knowledge around the relatively fewer types of systems design that are found in the universe of systems of many levels of size.*

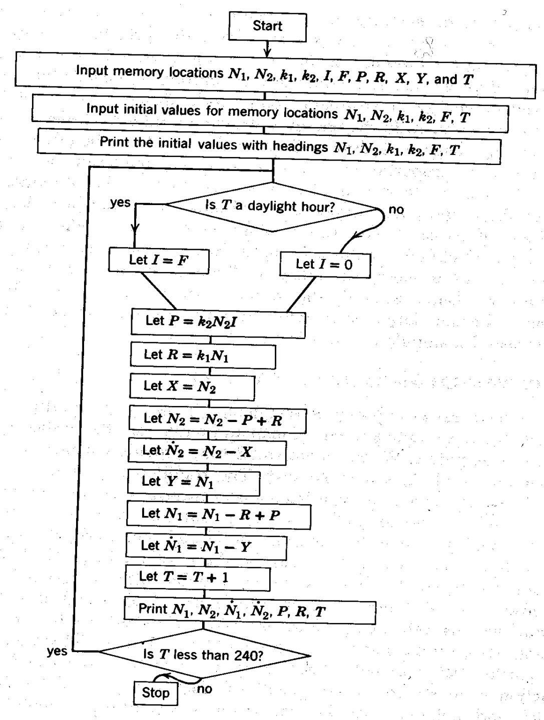


Figure 9–6 Flow chart for 10 day simulation of a balanced ecosystem of Figure 9–4(a) on digital computer. Ṅ means rate of change of N. T is taken as a daylight hour when T/12 rounded to a whole number is an even number.

Illustration 35: Odum's 12-step systems development (left) and stable ecosystem algorithm (right).

Since most of Odum's work has focused on the modeling of ecosystems to determine stable conditions, often for remediation and restoration projects, it seemed appropriate for meeting my design objectives toward biomimicry and sustainable industrial ecology. However, one difficulty I have encountered is in the translation of ecological terms to those more appropriate for clean vehicle design and development. Luckily, Odum took great pains in proposing methods for system generalization, so the interpretation process is mostly just a matter of my ability to mentally digest what Odum has written and diagrammed. So far in this thesis, I think I've done a fairly good job of describing Odum's first commandment of sustainable system development (assembling information & knowledgeable friends). If you aren't tired of thinking yet, you're in for a real cognitive treat with this next section.

The Space Between: Integrating Design & Engineering

I have been quite fortunate in my exposure to a great diversity of people and ideas on both the design and engineering sides of sustainable development, though I've found the language barrier between these two disciplines to be frustrating at times. Designers seem to enjoy the contemplation of conceptual spaces, ideal consumer groups, and infinitely evolving aesthetics. There's nothing inherently wrong with any of these things, but it took me quite some time to grow accustomed and comfortable with such orientations of perception. I spent ~ 3 months working closely with engineering students and professional designers to develop the overall systems architecture for a more sustainable personal vehicle based on an EREV powertrain configuration. I felt far out of my league and in over my head much of the time, but I came away from that experience with many new ideas about design that never would have crossed my mind otherwise, and I know that I have been better off for it.

Serving as the Systems Architecture Team (SAT) leader, I often acted as interface between SAT members (almost entirely comprised of engineering students) and the professional designers at Continuum (West Newton, MA). At first, this was a very nerve-racking space in which to exist, since before this time I really had no experience with consumer product design. The closest I had come before then was the few years I spent working with Team Fate, designing and building PHEV prototypes for Andy Frank. Eventually, I came to really enjoy the space that exists between the design and engineering disciplines, and I believe this may be a space I wish to continue occupying as for my professional career. Both fields are interesting and necessary, and I would like to help improve communications between these closely associated and interdependent disciplines.

I would like to take a step back now and explore McDonough's FTA model using a more quantitative approach. To begin with, I should probably provide a the definition of what I mean by *fractal tile*. I'm not exactly sure why McDonough chose to use this term, but the (somewhat) more common name for this triangular fractal geometry is that of a *Sierpiński Gasket* or *Sierpiński Sieve*[14]. It is named after Wacław Sierpiński, the man who is credited with first describing its form in 1915. Like many fractal geometries, the Sierpiński Gasket is formed from a self-similar set, meaning that its repeating pattern can be reproduced infinitely to any level of magnification or reduction.

14 An independent weblog that has helped me in developing my model: http://www.phidelity.com/blog/fractal/.

After first discovering this fractal, I spent quite a long time considering its 2-dimensional form, where *D* = 1.585 (the fractal dimension), meaning it exists somewhere between a line and plane. I was rather surprised to discover how many methods exist for its construction. Some of the computational approaches include *cellular automata*, *genetic growth*, *evolutionary dynamics*, *network theory*, *modified pascal*, *chaos theory*, and *sacred geometry,* among others. For me, the most straight-forward construction uses *triangle stacking* (see Footnote 14). For this approach, you begin with a single, 2-D equilateral triangle. Reduce this triangle to ½ it's original height and width; reproduce the smaller triangle twice; stack one of the triangles on top of the other two; and, allow one corner of each triangle to touch only the corner of one other, with its third corner freely directed away. A picture is probably more useful here than words (Illustration 36). Note the simple yet infinitely repeating form. Cool, huh?

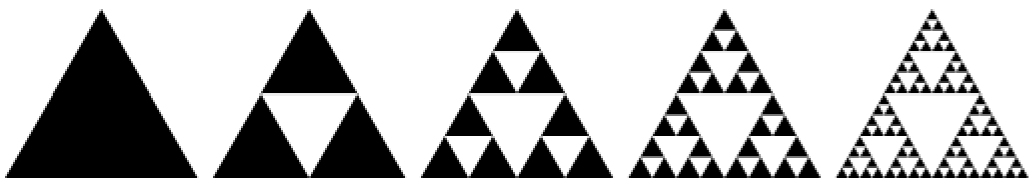


Illustration 36: Constructing a 2-D *Sierpiński Gasket*.

Unlike many fractal forms, this one is relatively easy to extend into three spatial dimensions (3-D). Rather than building and stacking triangles, simply build and stack *tetrahedron* (3-D version of the equilateral triangle, much like an Egyptian pyramid). Now, if you stack these tetrahedron in a similar way to the 2-D method, you produce a rather impressive 3-D structure (Illustration 37). A rotating 3-D gasket is provided in a video link on the weblog mentioned in Footnote 14. I highly recommend it.

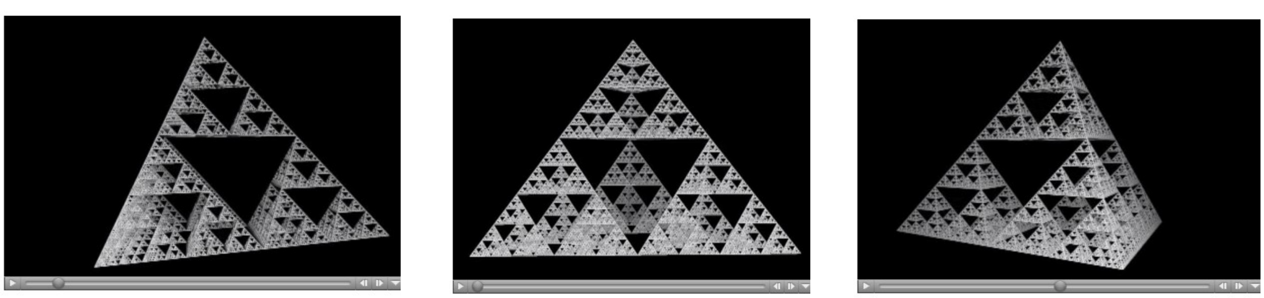


Illustration 37: Clips from the seamless video of a rotating gasket of self-similar tetrahedron.

Until now, my description of the Sierpiński Gasket should have seemed a relatively ordinary geometric consideration of form, though arguably a bit abstract. I have yet to even mention any natural systems where this form might best be applied, but we'll get there. First, let's take this geometric abstraction a bit further. You may have noticed that the four sides of the 3-D gasket are themselves each 2-D gaskets. The fractal dimension of the 3-D gasket is D = 2.322, existing somewhere between a plane and a solid. It is often difficult to imagine 3-D structures using 2-D representations, so I apologize if I've lost you during this explanation. I want to consider just one more aspect of the 3-D gasket before moving on, and that requires that we imagine the gasket as a physical object that can be moved and manipulated.

Assuming that Illustration 37 gives you some sense of what this structure looks like, I want you now to consider the movement around this gasket, viewing it from a number of different angles. Are you able to envision its various geometric forms and patterns? If not, that's okay. It has been quite difficult for me to consider this form mentally as well, and I have gone to great lengths to construct physical models that allow me to better visualize its geometry. One website I found depicts a gasket made from soda cans which, while not true to 3-D form, is a creative approach to visualization (Illustration 38). I was also fortunate to have the opportunity to climb around on a giant 3-D gasket called *Bat Country*, made entirely from softballs and bats (Illustration 38). Now, let's consider the view from above.

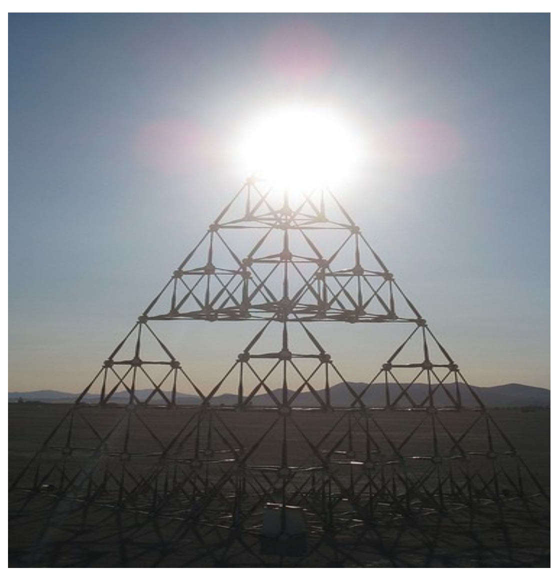


Illustration 38: Creative ways of visualizing the Sierpiński Gasket in three spatial dimensions.

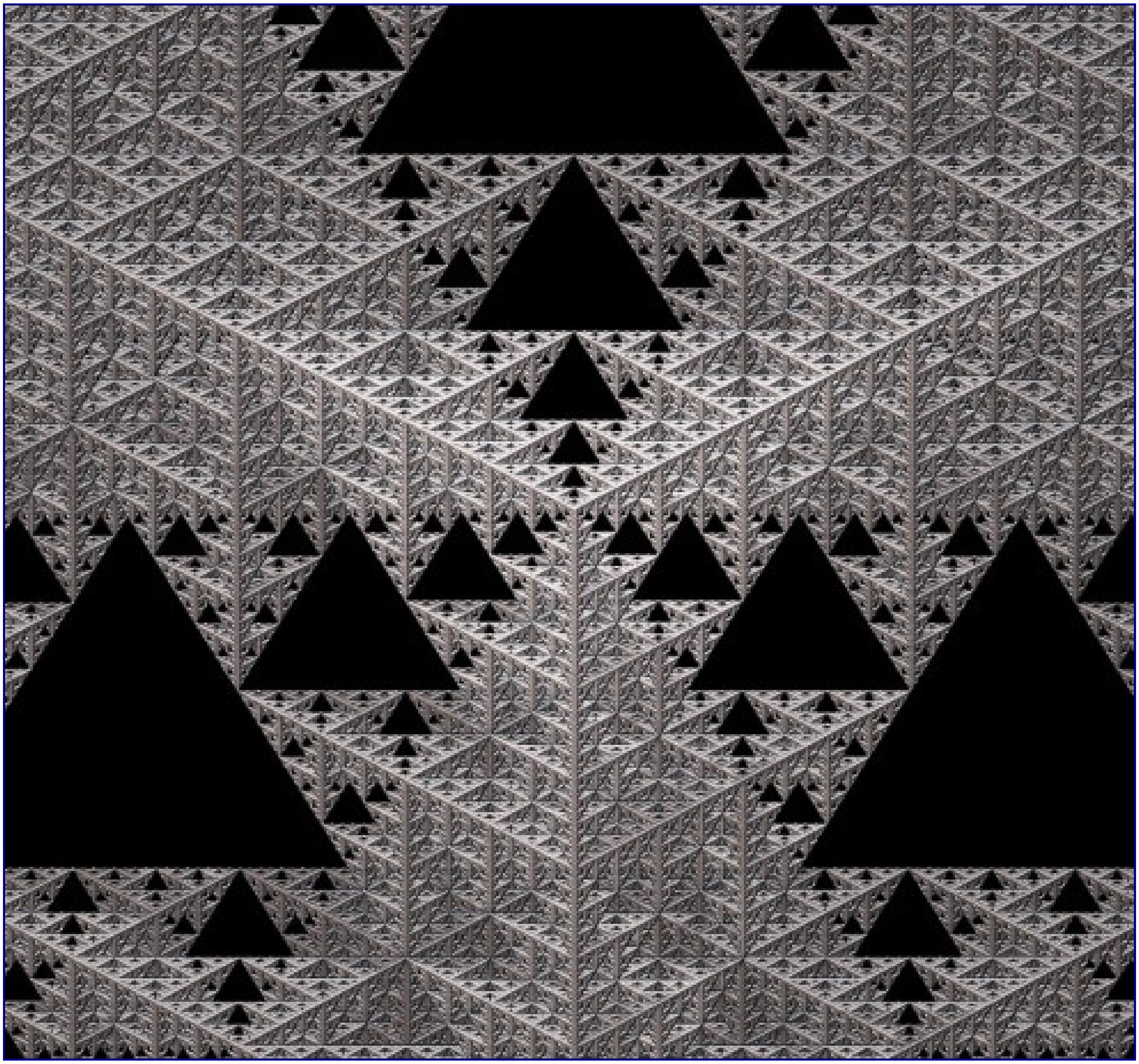


Illustration 39: The view from above a computer rendering of the 3-D gasket (see Footnote 14).

My advance apologies to anyone who finds Illustration 39 to be too intense and difficult to view, as this was not my intended purpose for including it here. I will admit that it is a striking image, though imagine if it weren't simply a 2-D digital representation, but an actual, physical 3-D object sitting right there in front of you. There is no substitute for the real thing, but hopefully it provides you with at least a small glimpse into what such a structure might look like. And now, for the million dollar question (or perhaps I should say trillion, since million isn't so impressive anymore): *what the hell is this good for?*

Take another look at Illustration 39. What sorts of shapes do you notice there? Are there any familiar repeating patterns? Believe it or not, this form produces what is commonly know as the *Flower of Life*. Among other things, all five Platonic solids can be generated from the Flower of Life's form. According to some descriptions of sacred geometry, any knowable structure in the Universe can be created through the manipulation of this single form. That's about as far into metaphysics as I'm willing to take this explanation, though I encourage the reader to explore the topic further independently. You may be amazed at what a simple internet search can uncover. Illustration 40 provides a description of octave evolution, providing a seed for the Flower of Life.

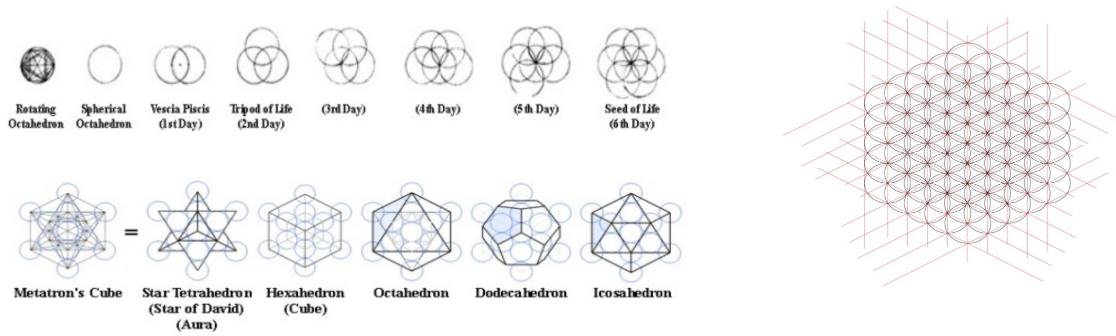


Illustration 40: The octaves and Platonic solids derived from our 3-D gasket (see Footnote 14).

In case the usefulness of this observation is not immediately apparent, please allow me to expound on the topic of form for just a moment. From my preferred perspective on appropriate design, *form follows function*. So why did I just produce a highly complex form without first describing its intended function? Am I not contradicting my own core values and doing exactly what I've been consistently berating others for doing (i.e. using abstract mathematical tools outside the scope of natural systems)? If this is what you were thinking, then you're right. That's exactly what I have done. However, if you also think back to my initial explanation of the Sierpiński Gasket (p. 88), you'll remember that it is a form that can be derived from *many different functions.* I mentioned that sacred geometry was among the these methods of derivation, along with evolutionary dynamics, cellular automata, and so on. What do all of these methods have in common? For my purposes, they are all interesting because they are all commonly used to model living systems and their various processes and transformations (e.g. growth, emergence, evolution, and so on). Thus, even though it may be quite difficult to explain exactly why the Sierpiński Gasket keeps popping up in models of natural systems, particularly since it is rarely observed within the biosphere, it is apparently a reliable form for modeling the structure of life.

Chapter 8. Prospects for Sustainable Personal Vehicles

Introduction

The development of alternatively fueled vehicles is driven by an ever-growing public awareness of the need to efficiently utilize natural resources, reduce petroleum dependencies, and minimize potentially harmful exhaust emissions, both in the form of criteria air pollutants (local problem) and greenhouse gases (global problem). Many AFV technologies exist to support the eventual replacement of conventional ICV, though as explained previously, each exists within a different state of technical feasibility and market readiness. Historically, few (if any) AFV have been able to compete as perfect substitutes for a *full-function* ICV in the market economy. However, some evidence from technology readiness assessments (TRA) of AFV alternatives (e.g. Jungers et al., 2007a; Burke et al., 2007), as well as expert government advising panels (e.g. Kalhammer, 2007), tend to suggest that AFV have good mid-term market and emissions reduction potential, addressing energy consumption issues at both the local and global scales. As discussed previously, automobile manufactures are responding to these market signals with commitments to produce and market AFV technology by as early as 2010.

Bottlenecks in Technology Adoption

Controversy over prioritizing and planning for energy resources and their various pathways is age-old, and the powering of personal vehicles is a very common topic for such debates. Still, there seems to be little disagreement that more encouragement of *all feasible alternatives* is needed. With growing popular interest and political support, the limitations of research funding may one day be eclipsed by other limitations, such as limits in *information transfer* (bandwidth) and innovative *technical education*. Some have advocated the development of more accessible, collectively supportive networks for information exchange, as well as consciously constructed, cooperative, collaborative, and (appropriately) competitive learning environments. *Cooperative learning* has long been a major challenge in engineering and mathematics education (e.g. Prince, 2004).

In addition to problems of RD&D underinvestment and technology/information transfer, there are also issues of unreasonably slow adoption of beneficial technologies (e.g. photovoltaics, solar thermal, biofuels, etc.). Though I make no assertions of conspiracy, the existence of technology deterrence within industry, especially those industries with few and large institutions (e.g. the energy and automotive industries), are known for their tendencies to avoid and deter the adoption of new technologies where possible (e.g. Smiley, 1987; Bunch & Smiley, 1992). This seems largely due to the inherent rules of economics and econometrics, where increased production allows for what is commonly referred to as *economies of scale*. Scaled economy is simply a more formal way to say that *bigger is better*, and in general it seems to be the case that as companies grow, they are able to reduce their costs, make further capital investments, widen their market base, then further expand their business, *ad infinitum*. Cost reductions are partially a result of *institutional learning*, where costs of production decline as familiarity and skills are developed. The larger the production volume, the more opportunity exists for technical skill-building, thereby (theoretically) flattening the learning curve.

Another important aspect of scaled economies involves the reduction of product price by decreasing *marginal profits* per unit sold. For example, if I wish to achieve a net return on capital investment of $100 and I'm only currently selling 10 units of product, then I need to price my product such that each unit provides me with $10 of profit. Now, let's assume that I somehow increase my production volume by one order of magnitude (i.e. volume = 100 units) as a result of process efficiency improvements and learning. Now, I only need to earn $1 of net profit from each unit sold in order to derive the same total profits. Assuming I'm a savvy businessman (i.e. profit-driven), I will probably attempt to maximize my selling price in order to increase total profits, even if $100 of profit is all I really need to cover my expenses and keep the business in operation. I decide to reduce my unit price by $5, making my product more attractive to a wider market. At this price, I should be able to sell all of my product and still earn even greater profits (i.e. $500), though I must also consider any costs incurred in the increase of my production volume (e.g. distribution, labor). Assuming the profits are sufficiently large relative to my expansion costs, I will grow the business and offer my product at prices below what was previously possible at the smaller production volumes. Obviously, this description is over-simplified, but hopefully still illustrative of the basic theory of *scaled economy* and the mechanisms that reinforce it. These processes drive industrial growth and the perceived need to continually increase production volumes in order to lower prices and reach a wider consumer market while still increasing profits.

There is nothing inherently problematic about increasing production volume and reducing prices to maintain increasing profit margins. What *is* problematic, however, is the technological entrenchment that tends to follow such increases in industrial capacity. In order to realize sufficient economic returns on capital investments for new facilities, profits must be maintained at the margins, narrow as they may be, and thus an incentive exists to avoid changes in production process that do not quickly increase profits or reduce costs. The larger the company and the greater their total capital assets, the greater their incentives for deterring adoption of newer technologies, unless of course such technologies can be easily integrated into the existing production process to provide quick incremental gains.

The Next Generation of Vehicle Design & Engineering

The author has collaborated on the model-based design of two battery-dominant hybrid vehicles; the VDS *Vision* and Team Fate's *Trinity*, both prototypes that were developed through student-led RD&D collaboratives. VDS is an international organization sometimes considered a meta team, with members living all over the world and mostly working independently, meeting now and then for conferences or intensive build sessions. Team Fate is a local design group here in Davis, housed within the Mechanical & Aeronautical Engineering Department, conceived of by Dr. Andy Frank and advised by Frank to this day. I have been extremely fortunate to help lead and advise the student members of these groups, and as a result, I have had the opportunity to work with some of the brightest young minds of my generation. In the future, I hope that even more local and meta student teams will form, and that their efforts will be increasingly encouraged and supported at all levels of university/industry/government.

Precise powertrain control is critically important to the efficient and effective operation of advanced AFV. The increasing demand for such controls development, coupled with the high cost and relative scarcity of powertrain components and their respective testing facilities, are the major drivers for model-based design efforts, particularly in the educational/academic and public domains. As a mostly *open consortium* for engineering design, VDS is concerned with using and developing tools that can be made widely available to all of its global members without IP infringement. Additionally, the success of the consortium's technology development efforts are very much dependent upon the skillful engineering application of relatively new vehicle design concept, dynamic systems, and controls. For these reasons, even though prototyping has been greatly aided by private software donations, the software ultimately used for vehicle production will most likely be based in open source development efforts, following the spirit of the consortium and the ethic of shared informational resources.

For the purposes of initial system design and component prototyping, the ADVISOR software package was selected for its simplicity, usability, and wealth of documentation. PSAT and CRUISE (developed by AVL) have also been selected for the purpose of enabling parallel, trans-Atlantic powertrain simulation and controls refinement. Here in Davis, I'm running simulations in ADVISOR and PSAT, while my colleague Erik Wilhelm is using CRUISE in his research lab at ETH Zurich. The redundancy of such parallel development provides internal validation, an extremely valuable feature when considering the relatively small temporal and large spatial boundaries of the VDS effort, little more than a collection of students from every over 30 universities around the World. Illustration 41 shows the relative locations of VDS teams around the World. The green dot there on the West Coast is me.

Illustration 41: The many university teams participating in the VDS student consortium.

The primary responsibility of designating and collecting component model data falls with the team selected to lead the design of that respective component. For example, the Belgian team at GroepT has been tasked with developing the vehicle's electric motor and chassis. They must provide the modeling teams (i.e. UC Davis, ETH Zurich, and Imperial College in London) with the equations and empirical data necessary for accurate vehicle modeling. The team at UC Davis has been responsible for initial powertrain sizing with the use of ADVISOR, as well as refined performance modeling to accommodate the vehicle's system architecture requirements via PSAT modeling. The team at ETH Zurich has used CRUISE for parallel powertrain simulation, refined controls development, and model decomposition. As advancing component development necessitates, more detailed dynamic models will be developed for all systems which require a more refined or otherwise computationally expensive process than what may be practically modeled at the vehicle scale (e.g. battery degradation modeling). This modeling effort is being led by students and researchers at Imperial College in London in partnership with model decomposition work at ETH Zurich. Our initial modeling efforts tend to favor the superiority of CRUISE over PSAT for our particular vehicle design application (e.g. Table 7), and thus a shift to the more exclusive use of CRUISE by all modeling teams appears imminent.

It has been previously demonstrated for many years throughout the recent history of engineering education that the design and development of alternatively fueled vehicles can be an inspiring and engaging learning process (e.g Future Car/Truck, Challenge X, Solar Car Challenge, Ecocar, etc.). However, the success of student *design competitions* of the past may soon be overshadowed by this new, globally collaborative, meta-style of engineering design as demonstrated by the VDS project. The coordination of design teams from all around the World, contributing to a single finished product, is much more akin to global product development and production supply chains as they exist today, but a difficult task to manage for students/volunteers. The success of the VDS demonstration is predicated upon a large team of enthusiastic students, researchers, and faculty, the project's *human capital*.

Vehicle Design Considerations

It would be uncommon for AFV to be comparable in every aspect of performance to conventional ICV. More commonly, significant trade-offs exist, with certain aspects of AFV faring poorly when compared with conventional vehicles while other features are improved. As a result, there is considerable debate concerning the functionality required of AFV if they are to be marketed in large numbers (e.g. at least 10 - 15% of total auto sales as required by the *ZEV Mandate*). It is often assumed that electric vehicles should be sold in urban areas and be used for commuting and local travel. To serve maximum utility for regional use, the vehicles would need to be freeway worthy, with top speeds of at least 65 mph. Such vehicles are often referred to as *full-function* or *full-performance* electric vehicles. Smaller markets also exist for neighborhood electric vehicles (NEV), which in the U.S. operate at top speeds of 25 mph.

Electric batteries are bulky and heavy compared to gasoline, and require a longer time to recharge. Consequently, BEV tend to under-perform compared to conventional vehicles with respect to vehicle range and refueling time. Designing a fully functional BEV requires compromises in passenger comfort and operating convenience, with typical reductions in interior/trunk space and longer refueling times, though to reach mass markets these compromises must be minimized. For a long-distance vehicle, where range is paramount, consumers may be willing to sacrifice some interior space. There are also EV attributes that may be more attractive to consumers: the possibility of home refueling/recharging, thereby reducing or eliminating the total number of trips to the gas station; quiet driving; excellent acceleration; environmental and socially responsible image (with zero emissions driving); and, greater independence from oil (Heffner and Kurani, 2006). These benefits, however, may not sway consumers who are looking for a general purpose replacement vehicle to meet all of their regular mobility needs.

One major consideration in the design of an AFV is that of typical vehicle use-patterns, such as daily driving schedules. The characteristics of the ideal personal vehicle are entirely dependent upon the manner in which the vehicle is intended to be used. The ideal vehicle for long-haul, non-stop, cross-country traveling will be much different than the ideal design for an urban commuter car. In the *most* ideal case, a consumer would be given the opportunity to design their own vehicle, choosing it's features *a la carte*, and selecting those attributes that make sense for their intended mobile applications. Illustration 42 provides a typical simplifying assumption for average vehicle use-patterns.

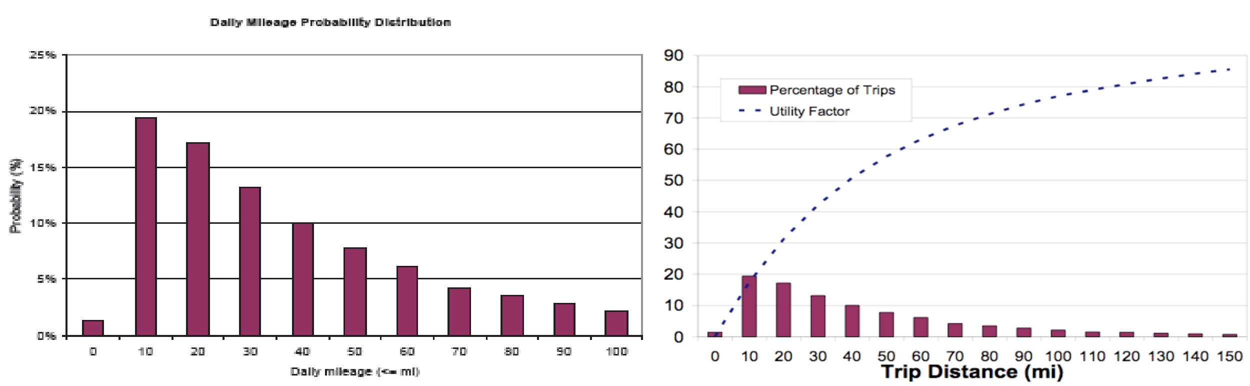


Illustration 42: Common assumptions for average daily mileage and EV utility (Markel, 2006).

Short of establishing design-it-yourself vehicle shops, much research effort has been dedicated to characterizing the *average driver*. In the United States, the most common analysis for developing this characterization incorporates the use of data from the National Household Travel Survey (NHTS) of 2001 (Illustration 42). Though obviously outdated, the NHTS data remains the most detailed information of its kind for characterizing American daily travel. According to the NHTS results, the majority of daily trips are 40 miles or less. The *utility factor*, depicted by the blue dotted line, is a measure of the expected utility of a vehicle with a limited driving driving (e.g. BEV). This measure is commonly used in determining the optimal energy storage size for EV, though it has also been used by some researchers to determine the optimal electric range and battery size for pluggable hybrids.

In addition to driving range, it's important to know the context in which the vehicle will be used. *Will the vehicle be used mostly frequently for city driving, highway, or both? What are the average speeds in these areas? Are there any specific regulations pertaining to vehicle emissions, noise pollution, or passenger/pedestrian safety standards? Are there skilled and knowledgeable mechanics who can maintain and repair the vehicle at a price the owner can afford, and/or is it feasible for the owner to perform self-repair? What does the refueling infrastructure look like? Will the vehicle be shared? If so, how, when, and by whom? Is there an intended primary user and what kinds of features do they value in a vehicle? Are they interested in exploring new options and trying new things, or do they prefer traditional and familiar? Will they modify their behavior to accommodate ownership, and if so how?*

These driving characteristics will vary person to person and day to day, but trends and cycles do exist and should be considered for any thorough vehicle design. The relatively high cost of vehicle ownership precludes the average person (particularly in the developing World) from owning multiple vehicles, assuming they can afford the first one. *Car sharing* programs seem attractive in addressing these kinds of issues, at least to some degree, allowing for the collective ownership of a vehicle fleet and the opportunity to select from among multiple types of vehicles when planning a trip. This addresses issues of *full functionality* and provides the potential for more regular use of smaller, lighter, slower, and reduced-range vehicles for the majority of trips (i.e. < 40 miles). However, in the event that more utility is needed for a particular trip, such as extended travel distance or greater cargo capacity, then the appropriate vehicle can be borrowed just as easily from the car sharing collective. Incentives can be established for selecting the most appropriate option when utility is not a significant factor, such as variable or graduated mileage/insurance/time-of-use rates and restricted rental frequencies. The VDS *Vision* has been designed specifically with car sharing programs in mind (Illustration 43), encouraging many forms of shared use though multiple aspects of its interior, exterior, and powertrain designs.

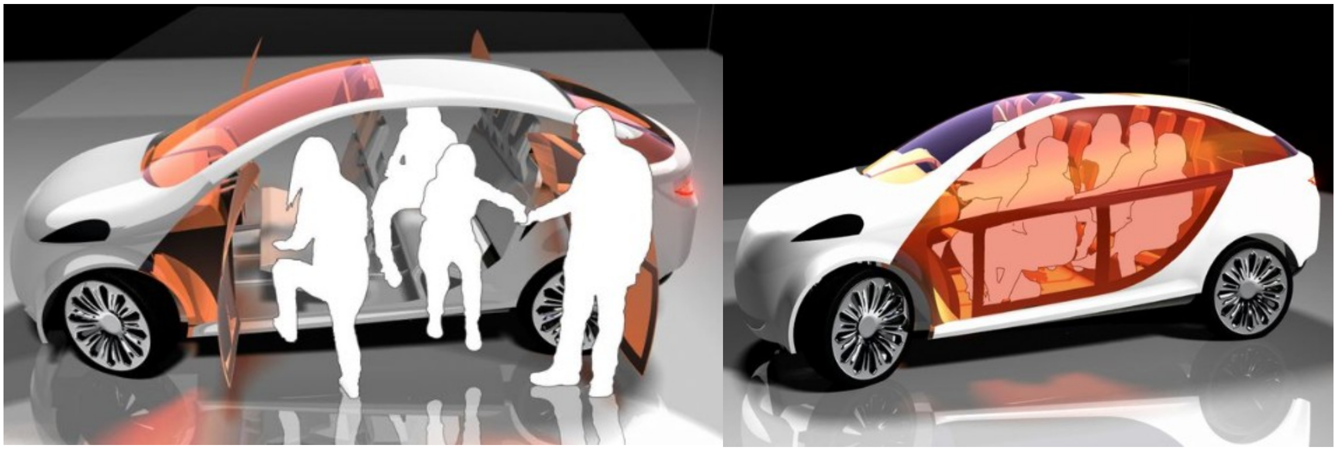


Illustration 43: Community-oriented *Vision* design concept, modeled by students at TU Delft.

In designing the Vision's powertrain, deep considerations were made of the way in which owner's may wish to use and maintain the vehicle's functionality. One major design consideration involves the selection and integration of the vehicle's APU. Since operation of the APU is dependent upon the conversion of a stored fuel to electricity, most commonly the combustion of a liquid hydrocarbon fuel, the determination of APU type, size, and operating characteristics is extremely regionally specific. So, even though the most critically sensitive powertrain component is the vehicle's battery pack (e.g. cost, weight, lifecycle), the most important aspect of regionally appropriate and sustainable vehicle operation involves the design of the APU, despite its relatively simple operating and design characteristics as compared with the engine and torque transfer systems of most modern ICV and HEV. Illustration 44 depicts the *Vision*'s conceptual powertrain flow and packaging diagrams.

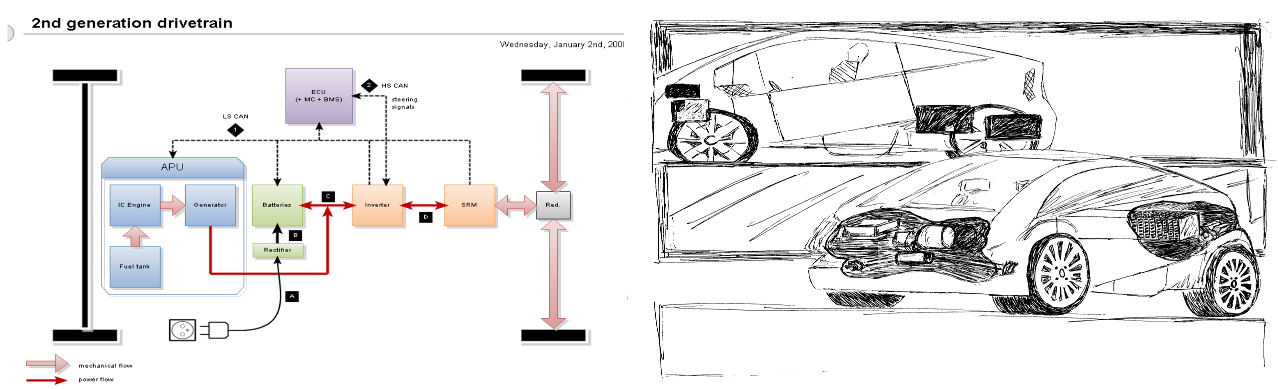


Illustration 44: Powertrain flow diagram and packaging sketch for *Vision*.

Problems in Conventional Vehicle Design

As mentioned in the previous section, there are a number of trade-offs that must be made in the vehicle design process, depending on the desired vehicle attributes. When vehicles are designed to serve very specific functions under relatively consistent operating conditions, system integration can be simple and streamlined. More often, however, designers and consumers alike make every attempt to squeeze all of their conflicting desires into a single vehicle design, with the resulting product providing sub-optimal service by most measures. Consumers claim to want high efficiency but not at the expense of performance; they want quick refueling but they don't like going to the gas station and they don't want to pay too much for fuel; they want a big, safe car but they want to drive it alone; and, they want a no-hassle driving experience and wish that everyone else would take the bus. Good luck with that design!

So it is, we are our own worst enemies. The automakers claim that AFV cannot compete with consumer demands and are therefore not competitive, and according to most people I talk with, the automakers may be right. However, fickle consumer demand may very well be just the *delirium tremens* of inebriating intoxicants such as fear, apathy, and the denial of real-world problems. Given the fact that we now know, beyond any reasonable doubt, that serious global problems not only exist but are induced and further perturbed by human (in)action, it may not be safe to trust existing consumer instincts if we really want to clean up this mess. The ZEV Mandate might be viewed as a *Hand of God* (or *Hand of CARB*), reaching down and forcing automakers to help induce greater demand for clean vehicle powertrains. Unfortunately, the mandate has been somewhat emasculated since its inception and will have questionable long-term effects unless considerable effort is made to revive and support it.

That covers two common motivators for powertrain selection: *consumer choice* and *regulatory requirement*. However, if consumers don't really know what they want and regulators aren't always capable of effectively regulating, then what should vehicle designers use as their primary motivating factor for selecting vehicle attributes? Well, we could take the status quo approach, allowing greed for profit to drive vehicle design even further into the fiery depths of Hell. Right now this would serve as a *do nothing* BAU option, since it has certainly been the road most traveled by. Another option might be the selection of vehicle attributes that best cultivate and support community, promote vehicle sharing, incorporate local and renewable energy/materials, and work *with* rather than *against* the environment in which the vehicles operate. Obviously, I'm painting two drastic and extreme cases on either end of the design spectrum, and I'm doing so for a very specific reason; we have never before seen such a large gap between the Utopian environments we know to be possible and the human-built Hell in which we all now are living. The consequences of ubiquitous car culture remain central to this ongoing problem.

Consider this dilemma: roads are unsafe for all but the most overbuilt vehicles, so if I design and build smaller, lighter, or slower vehicles, then I am endangering lives. Thus, I must build larger, heavier, and faster vehicles *ad infinitum*, as that is all the roads can safely accommodate. Such an argument makes a number of erroneous presumptions: (1) that large and/or heavy vehicles are inherently safe; (2) that vehicle designers should only (or at least primarily) consider the safety of the occupants *inside* the designed vehicle, as opposed to those *outside* of said vehicle; (3) that it is common or even likely for a driver to *accelerate out of an accident*; and, (4) that the primary responsibility of ensuring on-road safety lies with the designer rather than the operator.

As a person who not only designs vehicles for a living, but who also rides bicycles on busy roadways over typically very long distances, I have really come to detest these erroneous arguments for increasing vehicle safety standards. Accidents are never planned, otherwise they wouldn't be accidents, and it is simply impossible to safeguard the driver from all dangerous roadway encounters. A much more sane approach to transportation safety would be the proper *separation of modes* by their effective momentum, keeping bikes and pedestrians isolated from small cars, which are isolated further from larger vehicles, which are isolated from trains, and so on (e.g. *should bikes and planes share right-of-way?*) Such mode isolation might be too much to ask for, but it's important to not pass all of the burden of dealing with momentum transfer on to personal vehicle designers. Responsible driving behavior is arguably an even more important factor, yet the difficulty in attaining a U.S. driver's license is minimal.

Innovating on Vehicle Design

As mentioned in the previous sections, there are many possible motivators for vehicle design. Here, I consider the process of selecting vehicle attributes based on the projected sustainability of vehicle production, use, and end-of-life reprocessing. For materials and energy use efficiency, it is generally desirable to minimize the total quantity and mass of materials moved, from mining to manufacturing to vehicle propulsion. For widest consumer appeal, it is important to also minimize the vehicle market cost. For rapid prototyping of concepts and accelerated delivery to market, it is useful to minimize vehicle development costs. Since it is impossible to minimize all three of these costs features simultaneously, it may be convenient to perform a *triple low* design analysis, where three parallel designs are considered (i.e. lowest weight, lowest market cost, and lowest development cost). This analytical concept was presented to VDS by Alec Brooks of Aerovironment, lead project engineer for GM's *Impact* design (now working with Google). While meeting over dinner, I mentioned to Alec that lifecycle costs were also a big factor in our design process, and that we would probably modify his suggestion to perform a *quadruple low* analysis. He suggested that consumers don't really care about lifecycle costs. Unfortunately, he's probably right about that.

For the Team Fate project *Trinity*, little detailed analysis was applied to the selection of the vehicle powertrain. Rather, expert opinions and *academic wisdom* were deemed justification enough. The powertrain architecture of *Trinity* is that of a classic pre-transmission parallel hybrid using a modified continuously variable transmission (CVT), a *Prius* engine modified to run on ethanol, two electric motors (EM, front and rear), an auxiliary PEM fuel cell (removed from the vehicle after the first year of development), and a pluggable lithium-ion battery pack capable of providing ~ 40 miles of electric driving capability. This architecture has several strengths, such as the efficient and direct utilization of torque from the IC engine through the CVT, the ability to seamlessly blend power from the front EM and ICE through the CVT (at least in theory), and the ability to run all-electrically for a significant portion of typical driving without the range or performance limitations of a BEV. It also has a number of weaknesses, such as an inability to engage the ICE at very low speeds, complex and counter-intuitive CVT control requirements, potential CVT over-torquing and chain slipping, and speed-matching requirements that force trade-offs between the optimal operation of the two primary powerplants (i.e. front EM and ICE). Also, due to the highly integrated and interdependent nature of the parallel powertrain, it is difficult to substitute different fuel conversion options without a full redesign.

Though certainly an impressive demonstration of student dedication and applied engineering education, the *Trinity* prototype is by no means a *crossover to sustainable mobility*, the stated goal of DOE's Challenge X student competition, the main motivator for *Trinity*'s construction. There is nothing particularly innovative or sustainable about the materials used in modifying this vehicle, the bulk of which consisted of heavy sheet metal and welds. If powered by grid electricity and corn ethanol, especially in the Midwest, then there is also arguably nothing exceptionally sustainable about this vehicle's energy use. And of course, considering the cost of production for this vehicle's powertrain, there is probably very little that is economically sustainable about the design either. Shortcomings aside, this project has served as a useful lesson in establishing a baseline for the state of sustainable AFV development as it exists today. Driven by the same economic and performance constraints that appear to drive the industry, the boundaries of feasible vehicle design space have been closed ever tighter, even for innovative university RD&D projects. The *Trinity* concept is a far less impressive and sustainable design than *Aftershock*, the first ever successful vehicle built by Team Fate (Illustration 45).

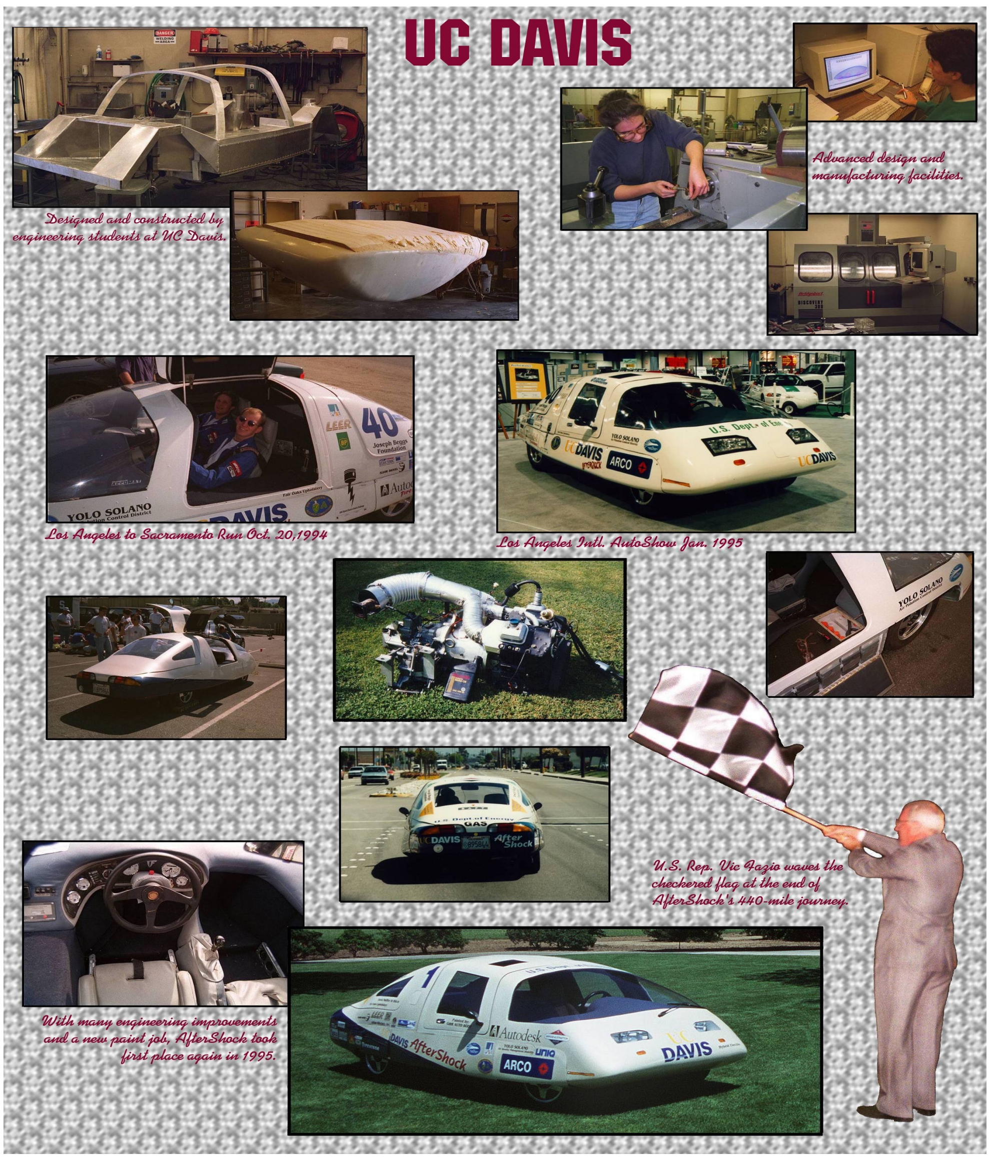


Illustration 45: Aftershock, the first plug-in hybrid prototype built by Team Fate at UC Davis.

Eco-Effective Vehicle Design

Janine Benyus, author of *Biomimicry: Innovation Inspired by Nature*, once said that "*nature does not commute to work.*" No matter how much we'd like to be green and sustainable, simply saying that we are but continuing to act in a BAU manner is not going to make it so. Loosely using green words to describe projects or products such as transport systems and personal vehicles, presumably to make them seem more attractive to funders and/or consumers, is an activity I refer to as *green-washing*. Such marketing strategies are both deceptive and regressive, and every attempt should be made to discourage these activities. It is unfortunate when an institution operates in an unscrupulous and/or unsustainable fashion, but it is egregious and entirely unacceptable behavior to add further insult to injury by claiming the sustainability of unscrupulous actions. If we truly wish to do the right thing for ourselves and the planet, then we must act as our own harshest critics and hold one another's feet to the flames.

When offered the position of SAT leader for the VDS 2.0 project (*pro bono*), I chose to accept because I wanted to help implement a more sustainable personal vehicle that also had near-term manufacturing and marketing potential. I made multiple trips to MIT in 2007, including a 3-month internship that summer, to help organize the consortium and cultivate our much needed technical support and mentorship from vehicle designers, academics, and industry leaders. Much of that summer was spent working with designers at the local Boston-based firm Continuum, who helped us to refine our concepts and define our market base. We reviewed material from all of the most significant vehicle concepts of the last century, including Bucky's *Dymaxion*, RMI's *Hypercar*, the *Impact/EV1*, the Solectria *Sunrise*, the AC Propulsion *t-Zero*, the Tesla *Roadster*, and several others. We were attempting to understand the state of the technology, the successful developments of our predecessors, and the reasons for continued failure of AFV designs to penetrate the consumer market. We set out, like so many naïve groups before us, to seek the fullest possible understanding of the problem of personal mobility, collectively delusional that we would some day design a car that would change the World.

Among the first crucial decisions was the market location: *India*. This decision was made for a number of reasons, including a quickly growing economy, large populations entering the middle class, and the drastic consequences of global climate change and energy resource limitations if every Indian were to privately own and operate a conventional ICV. With relatively high global gasoline prices and serious inspirational support from the likes of Thomas Friedman, proclaiming the increasingly *global flatness* of our modern industry, we felt well-position for a *perfect storm* in which to introduce a new, clean vehicle for India. Illustration 46 provides the design of our initial vehicle marketing concept and story.

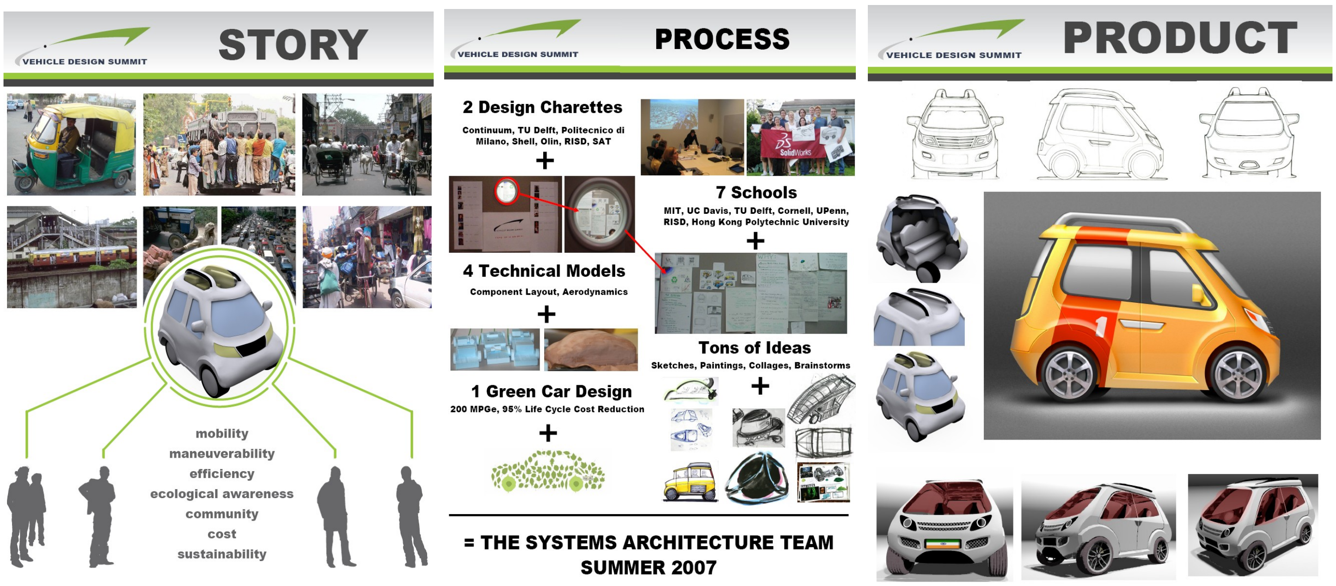


Illustration 46: Vehicle design and marketing concepts by the Systems Architecture Team.

The most critically important feature of the *Vision* design concept is its commitment to lifecycle cost reductions. The goal for reductions was set at an extremely aggressive target of 95% over the industry standard (Toyota *Prius*). That's a factor 20 improvement over already relatively impressive vehicle, supply chain, and materials use efficiencies. While much of this reduction can be achieved through gains in powertrain efficiency, fuel selection, and vehicle mass decompounding, the full reductions will only be obtained through further innovations in green material use & recycling, vehicle use reduction, and an entirely new business models for supply chain management and innovative vehicle sharing.

Now, let us again consider the tetrahedral form. Buckminster Fuller was relatively certain that the tetrahedron was the most fundamental unit of structural integrity in the universe (i.e. the strongest 3-D shape one could possibly conceive). There are a number of testaments to this assertion, including the continued stability of the ancient Egyptian pyramids and the tetrahedral-shaped molecular lattice structure of diamond, a very strong material (Illustration 47). So, if we know that there are inherently strong forms that exist and we also know how to construct them, why is that we continue designing nearly everything in our built environment from relatively flimsy, box-shaped structures? Familiarity may be the major reason, but it certainly isn't a sufficient reason to persist in such design behavior.

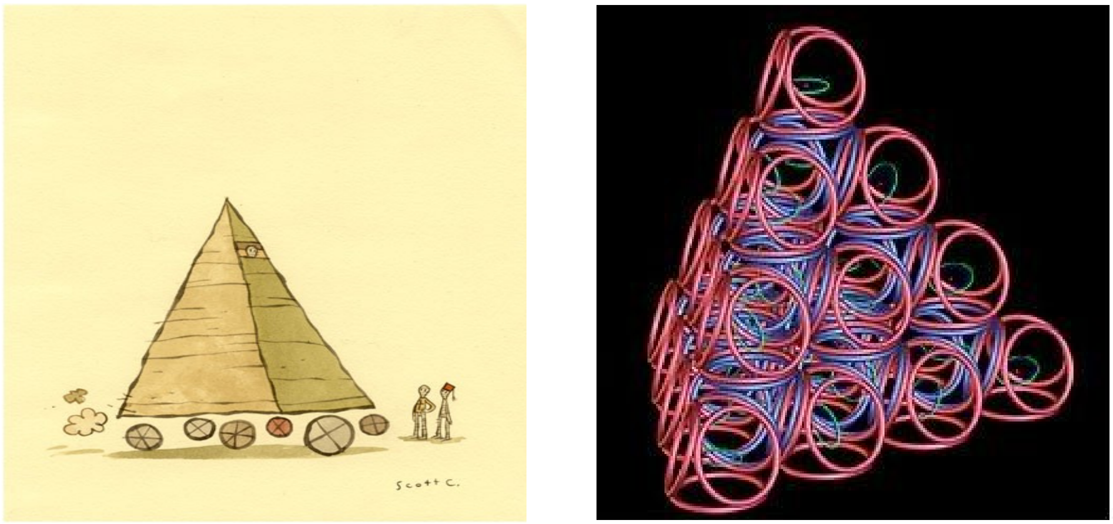


Illustration 47: Considerations of tetrahedral structure in pyramids and diamond lattice.

We can laugh at the idea of a pyramid car as pictured in Illustration 47 because of its absurdity, but is the idea of designing inherently strong products with the appropriate use of tetrahedral structures equally absurd? I think not. I spent quite some time reflecting upon the implications of a lightweight monocoque vehicle frame with a shape similar to that of the diamond lattice, and it really doesn't seem to be such a bad idea. In fact, there are a few companies that already incorporate a lightweight *safety cell* monocoque frame design that is strikingly similar to this concept, including the Brazilian company *Obvio!* Illustration 48 depicts my progression of thought on such a monocoque frame design.

Illustration 48: Original conception (left), applied to a beetle (center), and a similar concept (right).

In addition to having a strong, lightweight form, a good monocoque design is also highly dependent upon the use of strong and lightweight materials. Many materials are commonly used to replace steel, including aluminum, thermoplastics, and composites. Though relatively cheap and abundant, aluminum is typically not considered to be a sustainable alternative material due to it's highly impacting and energy intensive mining and processing requirements. Additionally, chronic exposure to aluminum in one's environment has been linked to a number of human health conditions, most notably Alzheimer's disease. Thus, a major consideration in materials selection for sustainable product design must encompass all aspects of system health, including such issues as toxicity exposure and chronic loading, materials source quantities and reliability, and recyclability or the demand from secondary-use markets.

In many cases, if a product can be made from biological materials, then that is likely the most sustainable design path, though this is far from being universally applicable. The sustainable use of biological materials in product design requires the application of *sustainable agroforestry* practices, where appropriate farming moves beyond organic certifications to real ecosystem health and vitality. This requires that the plants be considered as more than simply extractable material resources but as part and parcel to a successful and diverse ecosystem. Sustainable agroforestry incorporates practices such as crop layering and mixed land-use, selective harvesting, multi-industry materials applications, and active monitoring of local ecological performance, topsoil quality, irrigation runoff, and so on. There is nothing particularly complex about these practices, though they require a shift in priority toward reduced production volumes and smaller yields per land area, as well as longer planning cycles and more intensive measurements of system health. Two plants with good potential for applications in agroforestry, particularly in California, are *hemp* and *bamboo*. Both plants are fast-growing, require relatively low levels of external inputs and maintenance, and produce very strong materials with many wide and varying industrial applications. Calfee[15] designs bikes made from bamboo and hemp (Illustration 49), claiming they are stronger and perform better than comparably designed carbon bikes.

Illustration 49: Calfee designs high-performance bamboo and hemp composite bikes.

15 You can browse Calfee's bikes online or visit them in Santa Cruz: http://www.calfeedesign.com/.

The Vision

Through extensive modeling, design, and multiple iterations of vehicle prototyping, an increasingly refined version of the *Vision* concept is evolving toward mass-market production quality. The next major challenge will be to build ~ 20 vehicles for extensive crash-testing, fatigue analysis, and disassembly and re-processing in order to ensure that all safety and lifecycle concerns related to vehicle lightweighting and materials substitution have been exhaustively considered. The completion of this second prototype is projected for the end of the calendar year (2009). Illustration 50 is our latest *Vision*.

Illustration 50: The VDS *Vision* prototype at the Torino Dream Expo, Summer 2008.

After completing my work as the lead for the VDS Systems Architecture team, I was asked to lead the powertrain technical design group. Working primarily with engineering students from GroepT (Belgium), we have designed an EREV powertrain (dimensions in Table 10) that can provide sufficient utility and performance for emerging vehicle markets in India and other countries where unrealistic vehicle size and performance expectations have not yet been adopted. The electric drive has been designed for a high degree of power electronics integration with simple installation and removal for repairs. In contrast, the APU was designed for modularity and can be viewed as distinct from the rest of the powertrain, with easy removal and/or replacement by a different electricity generator as desired.

Table 10: Approximate dimensions for the initial *Vision* powertrain design.

Component	Length (mm)	Width (mm)	Height (mm)	Mass (kg)
Electric Traction Motor (SRM)	250	325	325	13
Gear Reduction	55	85	105	5
Power Conditioning Unit (inverter, power electronics)	300	150	100	8
Battery Pack (A123M1 cells, packaged behind rear seats)	400	900	900	120
Diesel Engine (2 cylinder, ~ 0.2 L displacement)	350	200	400	8
Fuel tank (20 L, half full w/ hemp seed oil)	250	400	200	12
Generator (SRM, directly coupled to engine)	100	110	110	5
High Voltage Wiring	2000	50	25	4
Total				***175***

The powertrain was designed primarily for energy efficiency, fuel flexibility, petroleum independence, and mass decompounding (i.e. smaller powertrain for lighter vehicle). Quick acceleration, large interior space, and ease-of-fueling from conventional networks (i.e. fossil fuels) were all low priorities of design, if considered at all. Obviously, such a design runs counter to conventional wisdom in consumer preference, and thus this design approach continues to have many adversaries. However, given the self-constraining goal of 95% lifecycle cost reductions for this vehicle, it is difficult to imagine a vehicle that could meet such rigorous expectations without the implementation of a radically different design approach. Since we decided to design and develop a car that still looks and acts like a car, but with impacts more analogous to those of a bike, it was necessary to make the vehicle small and lightweight but still able to carry a typical passenger load in India (i.e. as many as possible). The battery will store 10 kWh of energy, the APU is designed to provide 12 kW (nominally) to 20 kW (peak) of power for extended-range driving, and the electric motor provides 10 kW (nominal) to 30 kW (peak) to directly drive the wheels. A sketch of the powertrain packaging is provided in Illustration 51, along with drive traces from a Vail Grade simulation using ADVISOR, which incorporates an idealized powertrain controller for optimal energy efficiency (e.g. exact speed trace matching, max top speed of 75 kph).

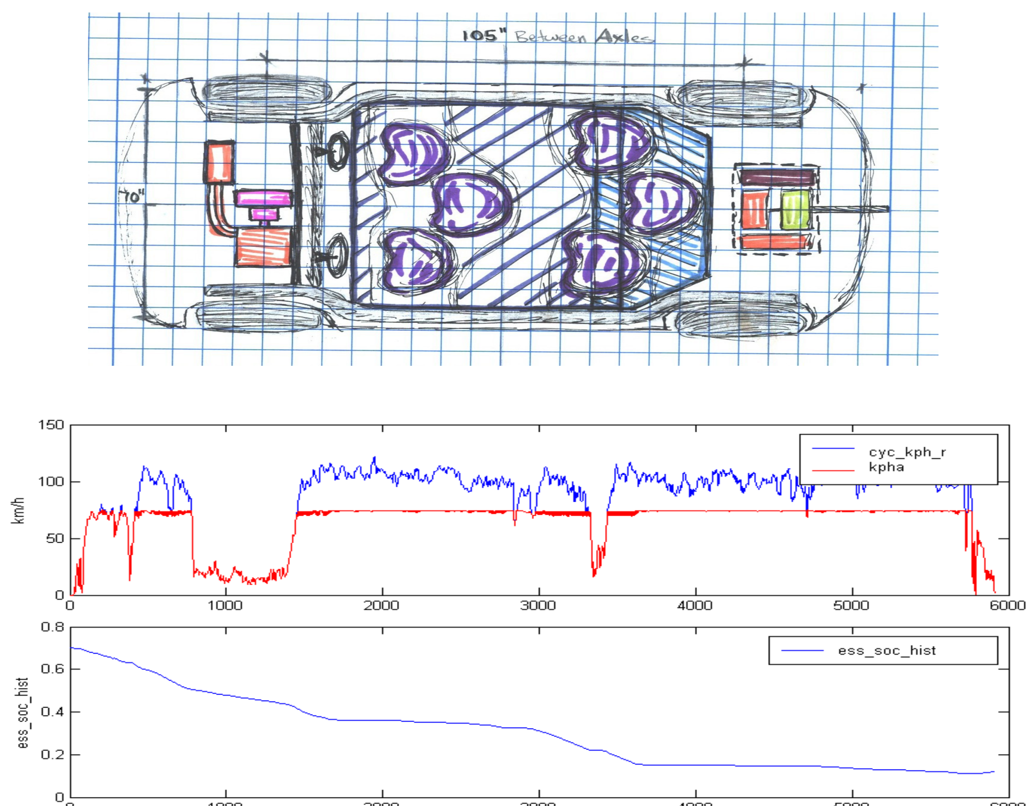


Illustration 51: A packaging sketch for the Vision powertrain and simulated performance.

As mentioned previously, the *Vision* was designed primarily to meet sustainability goals for lifecycle cost reductions of 95% over the current industry standard for personal vehicles. As one might imagine, the achievement of such rigorous design goals is far from a simple task, and is dependent upon a great many variables. Every aspect of vehicle design, deployment, and intended use must be closely considered in order to achieve this factor of twenty (x 20) reduction in lifecycle costs. Though several different methods exist for the measurement of such costs, this analysis applies the *3 E's of Sustainability* as a framework for designating and grouping such metrics. Though the exact values for each metric may vary considerably depending upon where and how the vehicle is sourced, produced, fueled, and used, Table 11 provides a few generalized examples for vehicle sustainability metrics.

Table 11: Engineering estimates for *Vision* sustainability metrics vs. OEM standard.

Metric	*Benchmark*	*Vision*	*Units*	*Factor*	*Category*
vehicle mass	1,500	500	kg	3	economy
max passengers	5	6	NA	1.2	economy
fuel economy	25	200	mpgge	8	economy
peak power	90	30	kW	3	economy
vehicle cost	25,000	10,000	$US	2.5	economy
person power	18	5	kW/person	3.6	equity
energy use	1.5	0.18	kWh/mile	8.3	equity
person energy	0.3	0.025	kWh/person-mile	12	equity
consumer access	5	25	% population	5	equity
useful life	10	20	years	2	ecology
transport sufficiency	0.1	1.3	bike fraction	12	ecology
solar fraction	0	100	% solar potential	inf.	ecology

Table 11 represents just a small handful of the many sustainability metrics that could be considered for a full lifecycle cost assessment of personal vehicle technologies. Note that most of these metrics apply only to the *use phase* of the vehicle (e.g. energy use, useful life) and consider primarily the movement of people rather than of mass/cargo. This should be consider as something of a *first order* comparison of lifecycle costs, where estimates can be expected to exist within the given order of magnitude but will vary according to fuel pathways, recharging & refueling schedules, driving characteristics, and so on. One metric of interest is transport sufficiency, where the personal vehicle is compared against the energy requirements of a bicycle (i.e. 0.03 kWh/person-mi @ 80 W). Though this does not consider the greater overall utility of a personal vehicle, it is interesting to note that this analysis shows the conventional vehicle to be 10% as sufficient (efficient & effective) as a bike, while the *Vision* is 130%.

Chapter 9. Discussion & Future Work

Discussion of Thesis

The vast majority of my thesis work has been spent in seeking out the proper frameworks within which to ask the question of "*what does a sustainable vehicle look like?*" I spent much of this time in great frustration, as I felt that it was taking me far too long to develop a useful framework and that all current models were too esoteric or poorly received by the conventional wisdom of development. However, the longer I spent thinking on this problem, the more I realized that my slow pace of progress was actually a gift in disguise, as it afforded me the time and attention I needed in order to thoroughly address the problem at hand and develop a potentially potent design framework. Using the *3 E's of Sustainability* to provide design cues and metrics by which to measure health and effectiveness, it has been possible for me to envision the evolution of a personal vehicle toward what may very well be a steady state of production and use, though it is impossible to say exactly which form of this design will be most appropriate for each location, and under what circumstances it will be used and re-used sustainably.

Future Work

Over the course of this thesis work, I explored and considered many aspects of sustainable vehicle design, including materials lifecycle costs, vehicle fuel pathways, consumer valuation of alternative vehicle technologies, vehicle performance expectations, and the equity of personal vehicle ownership. Starting from the assumption that a more holistic value structure may one day be adopted by the market economy, as described in this thesis, it is now necessary that I take a closer look at the various powertrain components of a sustainable personal vehicle in order to better describe the necessary requirements of their production. By a far margin, the most promising, controversial, and poorly understood among these components are those devices which store electrical energy for use on-board the vehicle. These are commonly referred to as electrochemical energy storage devices (EESD), as each depends upon electrochemical processes for its energy storage mechanisms despite technological differences. The potential for sustainable, localized production of EESD will be the main focus of my dissertation work. The sustainability of distributed vehicle production, fueling, and use will likely be dependent upon a de-coupling of scaled economies from industry, the effective separation of vehicles by speed and mass, and the efficient use of local solar energy & renewable material resources.

Bibliography

Ashman, A. (2006). *A Utopian Cow-Town Sees the Possible Future*. New Renaissance Magazine, Renaissance Universal. Available [online]: http://www.ru.org/ecology-and-environment/a-utopian-cow-town-sees-the-possible-future.html , January 6, 2009

Baillie, E. M., C. Hilton-Taylor, and S. N. Stuart (2004). *IUCN Red List of Threatened Species: A Global Species Assessment*. IUCN, Gland, Switzerland and Cambridge, UK

Bambuca, V., B. Jungers, P. Kaufman, T. Koelsch, Z. Lang, C. Latorraca, H. Luong, C. Reif, E. Solik, S. Vimeux, A. Frank, and Erickson, P. (2006). *Final Technical Report: Transportation Paradigm Shift*. Team Fate, University of California-Davis, Challenge X submission. Spring 2006

Benatar, D. (2006). *Better Never to Have Been: The Harm of Coming into Existence*. Oxford Press

Benyus, J. M. (1997). *Biomimicry: Innovation Inspired by Nature*. Harper Perrenial publishing

Bergveld, H. J., W. S. Kruijt, and Notten, P. H. L. (2002). *Battery Management Systems: Design by Modeling*. Kluwer Academic Publishing

Bookchin, M. (2005). *The Ecology of Freedom*. AK Press

Brodyansky, V. M., M. V. Sorin, and P. Le Goff (1994). *The Efficiency of Industrial Processes: Exergy Analysis and Optimization*. Energy Research 9, Elsevier Sciences B. V. Amsterdam, The Netherlands

Brooks, A. (2006). *Energy Usage Considerations of Electric Drive Vehicles.* Presentation by Aerovironment at the Haagen-Smit Symposium.

Brunner, T. (2007). *Liquid Hydrogen Vehicle Storage.* Presentation to CARB's ZEV Technology Symposium. BMW Group, BMW CleanEnergy – Fuel Systems. Sacramento, CA

Brylawski, M.M., and Lovins, A.B. (1996). *Ultralight-Hybrid Vehicle Design: Overcoming the Barriers to using Advanced Composites in the Automotive Industry.* The Hypercar Center, Rocky Mountain Institute, Snowmass, CO

Bunch, D. S. and Smiley, R. (1992). *Who Deters Entry?: Evidence on the Use of Strategic Entry Deterrents*. The Review of Economics and Statistics, Vol. 74, No. 3, pp. 509-521. August, 1992

Burke, A. F., B. D. Jungers, C. Yang, and Ogden, J. M. (2007). *Battery Electric Vehicles: An Assessment of the Technology and Factors Influencing Market Readiness*. Advanced Energy Pathways Project, PIER program, California Energy Commission. Davis, CA

Cai, T. T., C. L. Montague, and Davis, J. S. (2006). *The Maximum Power Principle: An Empirical Investigation*. U. S. EPA & University of Florida, Gainesville. Ecological Modelling 190, pp. 317–335. Elsevier. Available [online]: http://www.sciencedirect.com.

Callenbach, E. (1975). *Ecotopia: The Notebooks and Reports of William Weston*. Bantam

Calstart (2004). *California's Clean Vehicle Industry.* Calstart/Westart, Richmond, CA

Constant, II, E. W. (1987). *The Social Locus of Technological Practice: Community, System, or Organization?* From: The Social Construction of Technological Systems, MIT Press. Chapter 3, p. 238

Delucchi, M. A. (1996). *The Annualized Social Cost of Motor-Vehicle Use, Based on 1990-1991 Data: Summary of Theory, Data, Methods, and Results*. UCD-ITS-RR-96-3(1), Institute of Transportation Studies-Davis. Davis, CA. February 1996

Discoe, B. (unpublished). *3D Model of the Dymaxion Car.* Washed Ashore, available [online]: http://www.washedashore.com/projects/dymax/

Ehsani, M., Y. Gao, S. Gay, and Emadi, A. (2005). *Modern Electric, Hybrid Electric and Fuel Cell Vehicles*. CRC Press. ISBN: 0-8493-3154-4. Boca Raton, FL

Energy Information Agency [EIA] (2008). *World Petroleum Consumption, Most Recent Annual Estimates, 1980 – 2006*. Energy Information Administration, DOE. Available [online]: http://www.eia.doe. gov, March 11, 2008

Ferguson, H. (2007). *Wellbeing /= Consumption: The Case of Cuba During the Special Period – An Indicator Review*. Evidence Based Environmental Policy and Management, Issue 1, pp. 53-67

Friedman, T. L. (2006). *The World is Flat: A Brief History of the Twenty-first Century*. Firrar, Straus and Giroux, NY

Frosch, R. A. and Gallopoulos, N. E. (1989). *Strategies for Manufacturing*. Scientific American, Vol. 189, No. 3, pp. 144 – 152

Gladwell, M. (2002). *The Tipping Point: How Little Things Can Make a Big Difference*. Little, Brown

Global Climate and Energy Project [GCEP] (2007). *Global Exergy Flux, Reservoirs, and Destruction*. Stanford University. Palo Alto, CA

Greene, D. L., P. N. Leiby, and Bowman, D. (2007). *Integrated Analysis of Market Transformation Scenarios with HyTrans*. Oak Ridge National Laboratory Report. ORNL/TM-2007/094.

Gribbin, J. (1976). *Oscillating Universe Bounces Back*. Nature, Volume 259, Issue 5538, pp. 15-16

Hall, C. A. S. (1996). *Maximum Power: The Ideas and Applications of H. T. Odum*. University Press of Colorado

Hall, R. P. (2006). *Understanding and Applying the Concept of Sustainable Development to Transportation Planning and Decision-Making in the U.S.* Ph.D. dissertation in Technology, Management, and Policy, MIT. Cambridge, MA

Hamvas, B. (unpublished). *TABULA SMARAGDINA: Comments on the 13 sentences of Tabula Smaragdina (Hermes Trismegistos), and Introductions to Alchemy (hermetic thinking)*. Available [online]: http://www.tradicio.org/english/hamvastabulasmaragdina.htm

Hard, M. and Knie, A. (2001). *The Cultural Dimension of Technology Management: Lessons from the History of the Automobile*. Technology Analysis and Strategic Management, Vol. 13, no. 1. May 15

Hauer, K. H. (2001). *Analysis Tool for Fuel Cell Vehicle Hardware and Software (Controls) with an Application to Fuel Economy Comparisons of Alternative System Designs*. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-01-15. Davis, CA

Hawken, P., A. B. Lovins, and L. H. Lovins (1999). *Natural Capitalism: Creating the Next Industrial Revolution*. Little, Brown and Co. publishing house. Boston, MA

Heffner, R. R., T. S. Turrentine, and Kurani, K. S. (2006). *A Primer on Automobile Semiotics*. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-06-01

Herzog, A. V., T. E. Lipman, J. L. Edwards, and D. M. Kammen (2001). *Renewable Energy: A Viable Choice*. Environment, Vol. 43, No. 10

Hodkinson, R. and Fenton, J. (2001). *Lightweight Electric/Hybrid Vehicle Design*. Reel Educational and Professional Publishing Ltd.

Holling, C. S. (2001). *Understanding the Complexity of Economic, Ecological, and Social Systems*. Ecosystems, Vol. 4, pp. 390 – 405

Huxley, A. (1954). *The Doors of Perception and Heaven & Hell*. Harper & Row

Joaqim, M., L. Greden, and Arbona, J. (2008). *Fab Tree Hab: Local Biota Living Graft Structure*. Human Ecology Design, MIT. Available [online]: http://www.archinode.com/bienal.html

Jorgensen, S. E. and Fath, B. D. (2007). *A New Ecology: Systems Perspective*. Elsevier B.V.

Jungers, B. D. and Kaufman, P. (2007). *Peak Moment: "Team Fate"- Designing the Next Generation of Hybrid*. Interview with Janaia Donaldson of Peak Moment television, Episode # 113. Available [online]: http://www.youtube.com/watch?v=vmDgviOe5fU&feature=related . Nevada City, CA

Jungers, B. D., A. F. Burke, J. M. Cunningham, C. Yang, and Ogden, J. M. (2007a). *Assessment of Technical and Market Readiness of Fuel Cell Vehicles*. Advanced Energy Pathways Project, PIER program, California Energy Commission. Davis, CA

Jungers, B. (2008). *Extended-Range Electric Vehicles: An Enabling Platform for Sustainable Energy Pathways*. Presented at the STEPS Research Symposium for ITS-Davis. Davis, CA. Available [online]: http://steps.ucdavis.edu/08student-posters/Extended-Range_Electric_Vehicles.pdf

Kalhammer, F. R., B. M. Kopf, D. H. Swan, V. P. Roan, M. P. Walsh (2007). *Status and Prospects for Zero Emissions Vehicle Technology: Report of the Independent Expert Panel 2007*. California Air Resources Board. Sacramento, CA

Kammen, D. M. and Dove, M. R. (1997). *The Virtues of Mundane Science*. Environment, Vol. 39, No. 6

Kasseris, E. (2006). *Comparative Analysis of Automotive Powertrain Choices for the Near- to Mid-Term Future*. M.S. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology. Cambridge, MA

Kay, J. J. (2002). *On Complexity Theory, Exergy and Industrial Ecology: Some Implications for Construction Ecology*. Environment and Resource Studies, University of Waterloo. Ontario, CA

Kromer, M. A. and Heywood, J. B. (2007). *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet.* Laboratory for Energy and the Environment, MIT. Cambridge, MA

Markel, T. (2006). *PHEV Design Options and Expectations*. Presentation to the ZEV Technical Panel at CARB. Sacramento, CA

Maslow, A. H. (1943). *A Theory of Human Motivation*. Psychological Review #50, pp. 370 - 396

Massachusetts Institute of Technology [MIT] (2008). *Civil and Environmental Engineering* (homepage). Massachusetts Institute of Technology. Available [online]: http://cee.mit.edu/

McDonough, W. and Braungart, M. (2000). *A World of Abundance*. Interfaces, Vol. 30, No. 3., pp. 55 – 65

McDonough, W. and Braungart, M. (2002). *Design for the Triple Top Line: New Tools for Sustainable Commerce*. International Journal of Corporate Sustainability. Vol. 9, No. 3

McDonough, W. and Braungart, M. (2002a). *Cradle to Cradle: Remaking the Way We Make Things*. North Point Press

Mihelcic, J. R., J. C. Crittenden, M. J. Small, D. R. Shonnard, D. R. Hokanson, Q. Zhang, H, Chen, S. A. Sorby, V. U. James, J. W. Sutherland, and J. L. Schnoor (2003). *Sustainability Science and Engineering: The Emergence of a New Metadiscipline*. Environmental Science Technology, Vol. 37

Miller, J. M. (2004). *Propulsion Systems for Hybrid Vehicle*s. The Institution of Electrical Engineers, London, UK

Miller, G. A., C. Fellbaum, R. Tengi, P. Wakefield, R. Poddar, H. Langone, B. and Haskell (2008). *Wordnet: A lexical database for the English language*. Cognitive Science Laboratory, Princeton University. Available [online]: http://wordnet.princeton.edu/

Mitcham, C. (1994). *Thinking Through Technology: The Path Between Engineering and Philosophy*. University of Chicago Press

Mokhtarian, P. L. (2005). *TTP 200: Transportation Survey Methods*. In-class correspondence.

Moore, T.C. (1996). *Ultralight Hybrid Vehicles: Principles and Design.* The Hypercar Center, Rocky Mountain Institute, Snowmass, CO

Musso, C. S. (2004). *Beating the System: Accelerating Commercialization of New Materials*. Dissertation in Technology, Management, and Policy. Massachusetts Institute of Technology. Cambridge, MA

Nicolis, G. and Nicolis, C. (2007). *Foundations of Complex Systems*. World Scientific Publishing Co.

Nordhaus, T. and Shellenberger, M. (2007). *Second Life: A manifesto for a new environmentalism*. The New Republic, Environmental Issue pp. 30 – 33, September 24

NREL (2004). *PV FAQs*. National Renewable Energy Lab, Solar Energy Technologies Program. Golden, CO

Odum, H. T. (1971). *Environment, Power, and Society*. John Wiley & Sons, Inc.

Odum, H. T. and Odum, E. C. (1981). *The Energy Basis for Man*. McGraw-Hill Book Co.

Odum, H. T. (1994). *Ecological and General Systems: An Introduction to Systems Ecology*. University Press of Colorado

Prince, M. (2004). *Does Active Learning Work? A Review of the Research*. Journal of Engineering Education, Issue 93:3, pp. 223 – 231

Princen, T. (2005). *The Logic of Sufficiency*. The MIT Press

Rosencranz, C. (2005). [Title unknown]. Presented at EVS 20. Johnson Controls

Simpson, A. (2005). *Parametric Modeling of Energy Consumption in Road Vehicles*. Sustainable Energy Research Group, School of Information Technology and Electrical Engineering. University of Queensland. Ph.D. submitted February 2005

Schafer, A., J. B. Heywood, Weiss, M. A. (2004). *Future fuel cell and internal combustion engine automobile technologies: A 25-year life cycle and fleet impact assessment*. MIT Energy Laboratory. Cambridge, MA

Schnell, P. (2005). *Personal correspondence regarding the refueling of Quantum tanks*. Vehicle Integration Engineer, Quantum Technologies, Inc.

Shabeshevich, A., D. Sauceod, T. Williams, C. Reif, C. Lattoraca, B. Jungers, B. Weitzel, and Fank, A. (2007). *Consumer Ready Plug-in Hybrid Electric Vehicle*. D.O.E. Challenge X, Year 3 final technical report. Available [online]: http://www.team-fate.net/technical/UCDavis_Spring2007_TechReport.pdf

Shepard, P. (1982). *Nature and Madness*. University of Georgia Press

Smiley, R. (1987). *Empirical Evidence on Strategic Entry Deterrence*. Cornell University, Ithaca, NY

Sperling, D. (1995). *Future Drive: Electric Vehicles and Sustainable Transportation*. Island Press

Sperling, D. and Gordon, D. (2008). *2 Billion Cars: Driving Toward Sustainability*. Oxford Press

Stanford (2008). *Civil and Environmental Engineering* (homepage). Stanford University. Available [online]: http://cee.stanford.edu/

Tester, J. W., E. M. Drake, M. J. Driscoll, M. W. Golay, and W. A. Peters (2005). *Sustainable Energy: Choosing Among Options*. MIT Press. Cambridge, MA

University of California, Davis [UCD] (2008). *Civil and Environmental Engineerin*g (homepage). University of California at Davis. Available [online]: http://cee.engr.ucdavis.edu/

Unnasch, S. (2006). *Assessment of Full Fuel Cycle Emissions*. Presented to the CARB ZEV Technology Symposium. September 27. Sacramento, CA

Van der Ryn, S. and Cohan, S. (1996). *Ecological Design*. Island Press. ISBN 1-55963-389-1, Washington, DC

Van der Ryn, S. and Pena, R. (2002). *Construction Ecology: Nature as the Basis for Green Buildings*. Chapter 10, pp. 231 – 246. Taylor and Francis, Inc.

Vela, C. A. M. (2006). *The Duality of Innovation: Implications for the Role of the University in Economic Development*. Dissertation in Technology, Management, and Policy. Massachusetts Institute of Technology, Cambridge, MA

Wachtel, E. (1995). *To an Eye in a Fixed Position: Glass, Art and Vision*. New Directions in the Philosophy of Technology, pp. 41-61, (Joseph Pitt, ed.). Kluwer Academic Publishers, Dordrecht, Netherlands

Weathers Jr., T. and Hunter, C. (1986). *Diesel Engines for Automobiles, Small Trucks, and Small Tractors*. Prentice-Hall Inc.

Weiss, M. A., J. B. Heywood, E. M. Drake, A. Schafer, F. AuYeung. (2000). *On the Road in 2020: A Well-to-Wheels Assessment on New Passenger Car Technologies*. Report No. EL 00-003, MIT Energy Laboratory. Cambridge, MA

Weiss, M. A., J. B. Heywood, A. Schafer, and V. K. Natarajan (2003). *A Comparative Assessment of Fuel Cell Vehicles*. MIT Laboratory for Energy and the Environment Report, MIT LFEE 2003-001 RP. Cambridge, MA

Wilhelm, R. (1931). *The Secret of the Golden Flower*. Kegan Paul, Trench & Trubner

Wilhelm, E. (2008). *PSIHVM Software Tools*. Spreadsheet of model comparisons, obtained via personal correspondence

World Health Organization [WHO] (2005). *Investing in a Comprehensive Health Sector Response to HIV/Aids: Scaling up Treatment and Accelerating Prevention*. World Health Organization, HIV/Aids Plan. Available [online]: http://www.who.int/3by5/en/HIV_AIDSplan.pdf