A Systems Engineering Methodology for Fuel Efficiency and its Application to a Tactical Wheeled Vehicle Demonstrator

by

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Submitted to the System Design and Management Program in Partial Fulfillment of the Requirements for the Degree of

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Abstract

The U.S. Department of Defense faces growing fuel demand, resulting in increasing costs and compromised operational capability. In response to this issue, the Fuel Efficient Ground Vehicle Demonstrator (FED) program was initiated in order to demonstrate a tactical vehicle with significantly greater fuel efficiency than a Humvee while maintaining capability. An additional focus of the program was the exposure of systems engineering practices and methodologies to government engineers.

This document provides an overview of a systems engineering methodology for maximizing fuel efficiency and its application in concept development for the FED program. The methodology is organized into a phased process, comprising definition of operational requirements, modeling of design alternatives, analysis of design space, development of product concepts, and prototype verification. Tools and methods used included requirements tradespace definition, provisional baseline product models, decomposition of energy expenditure over the product usage cycle, structured technology market surveys inclusive of lead users, surrogate model-based simulation tools, and design space exploration / Pareto optimization. Object-Process Methodology (OPM) is used within the document to illustrate process elements and their relationships.

A key element of the methodology is the intensive use of modeling and simulation to enable data driven decision making. In particular, neural network-based surrogate models of engineering code allow the evaluation of thousands of feasible design configurations. It is intended that this rigorous framework is applicable to the improvement of any attribute of any product system.

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Thanks to the Ricardo FED team, I owe the success of this project to your hard work.

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Nomenclature

AAV	Amphibious Assault Vehicle
ACTD	Advanced Concept Technology Demonstrator
ANOVA	Analysis Of Variation
ASDL	Aerospace Systems Design Laboratory
BoM	Bill of Material
BRAINN	Basic Regression Analysis for Integration Neural Networks
C4ISR	Command Control Communications Computers Intelligence Surveillance and Reconnaissance.
CAD	Computer Aided Design
CAFE	Corporate Average Fuel Economy
CCD	Central Composite Design
CdA	Coefficient of Drag * Area
CONUS	Contiguous United States
DCCDI	Define Customer Concept Design Implementation
DMADOV	Define Measure Analze Design Optimize Verify
DMADV	Define Measure Analze Design Verify
DMEDI	Define Measure Explore Develop Implement
DoD	Department of Defense
DoE	Design of Experiments
ECC	Essential Combat Configuration
EFV	Expeditionary Fighting Vehicle
EPA	Environmental Protection Agency
FCS	Future Combat System
FED	Fuel Efficient Demonstrator
FTTS	Future Tactical Truck System
GCW	Gross Combination Weight
GFE	Government Furnished Equipment
GPM	Gallons Per Mile
GVW	Gross Vehicle Weight
GWOT	Global War On Terror
HBCT	Heavy Brigade Combat Team

HMMWV	High Mobility Multipurpose Wheeled Vehicle
HVAC	Heating Ventilation Air Conditioning
IED	Improvised Explosive Device
ICOV	Identify Characterize Optimize Verify
IDOV	Identify Design Optimize Validate
INCOSE	International Council on Systems Engineering
ITAR	International Traffic in Arms Regulations
JLTV	Joint Light Tactical Vehicle
JP-8	Jet Propellant 8
LED	Light Emitting Diode
FMTV	Family of Medium Tactical Vehicles
FOB	Forward Operating Base
LAV	Light Armored Vehicle
LHS	Latin Hypercube Sampling
M-ATV	MRAP All Terrain Vehicle
MPG	Miles Per Gallon
MRAP	Mine Resistant Ambush Protected
n.d.	No Date
(O)	Objective
OEF	Operation Enduring Freedom
OEM	Original Equipment Manufacturer
OFAT	One Factor At a Time
OIF	Operation Iraqi Freedom
OPD	Object Process Diagram
OPM	Object Process Methodology
OSD	Office of the Secretary of Defense
PM	Program Manager
QFD	Quality Function Deployment
RSE	Response Surface Equation
SE	Systems Engineering
SOC	State Of Charge
(T)	Threshold

TARDEC	Tank Automotive Research, Development and Engineering Center
TOP	Test Operating Procedure
TRL	Technology Readiness Level
TST	Technology Selection Tool
TVFE	Total Vehicle Fuel Economy
TWV	Tactical Wheeled Vehicle
VCW	Vehicle Curb Weight

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1. Introduction

1.1. Fuel Economy and the U.S. Armed Forces

Within the automobile industry, for government regulators of the industry, and consumers of automobiles, the issue of fuel economy is forever a hot topic. Debate continues over increases in Corporate Average Fuel Economy (CAFE). Automakers have unveiled increasing numbers of fuel sipping hybrid-electric vehicle models. In 2008, the average price of gasoline in the United States surpassed $4/gal. So while the importance of fuel economy is clear to the driving public, one could be forgiven for assuming that fuel economy is not an issue for the U.S. Armed Forces, operators of heavy weight Humvees and Abrams tanks. However, as the largest single consumer of energy in the United States, in 2006 the Department of Defense (DoD) spent $13.6 billion to buy 110 million barrels of petroleum fuel, with just over $10 billion going toward fuel for combat and combat related systems. This was more than double the $5.9 billion spent in 2004, with most of the increase attributed to petroleum prices. As such the DoD is subject to the same concerns over volatile and increasing fuel prices as civilian sectors and transportation related industries, along with other issues facing civilian policymakers, such as dependence on foreign sources of oil (including countries hostile to U.S. interests) (DSB, 2008). As will be discussed, the U.S. Armed Forces also have a number of unique issues relating to fuel usage compared to civilian transportation, including operational effectiveness, fully burdened cost of fuel, and growing fuel usage.

1.1.1. Operational Effectiveness

"An army marches on its stomach."
-Napoleon Bonaparte

Operational effectiveness of military forces is affected by endurance (range or time between refueling) as vehicles are forced to spend time transiting to fuel sources and refueling. Regarding the 1991 advance of the 24th Infantry Division in its sweeping left hook around Kuwait, General Paul Kern commented that "As we considered the route and began planning, our biggest concern was not our ability to fight the Iraqis; it was keeping ourselves from running out of fuel." (qtd. in CNA, 2009) More famously, in 1944, General George

Patton told a subordinate, "In the last war I drained three quarters of my tanks to keep the other quarter going." (qtd. in Hirshson, 2002)

Perhaps even more significant than endurance issues though, are the resources and vulnerabilities inherent in moving and protecting fuel through a battlespace. All manner of military assets, including armored vehicles, helicopters, and fixed wing aircraft are committed to protect the movement of supplies, all of which contribute to additional fuel usage (CNA, 2009). Military planners reference operational effectiveness as a ratio of "Tooth" (resources devoted to combat operations) to "Tail" (resources devoted to support of combat resources). All operations require some manner of supply, upkeep, and logistics, but as military systems increase their specific energy usage, the proportion of Tail versus Tooth must necessarily increase, as demonstrated by the feedback loop in Figure 1-1. (DSB, 2008)

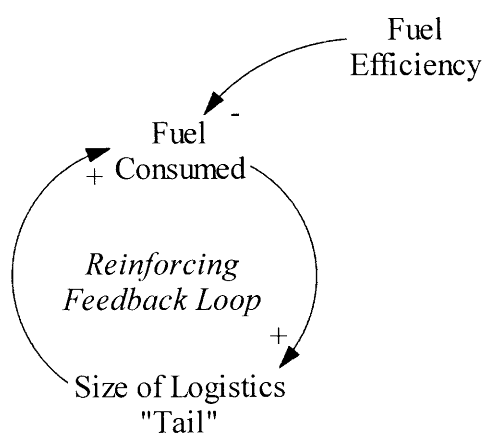

Figure 1-1: Feedback loop demonstrating influence of fuel efficiency on operational effectiveness

Beyond Tooth to Tail is the issue of vulnerability. Supply convoys are particularly at risk for Improvised Explosive Device (IED) attacks. According to a database compiled by *USA Today*, in Operation Iraqi Freedom (OIF), 42% of all fatal U.S. government casualties are credited to IED's. ("American casualties in Iraq", 2009) As shown in Figure 1-2, in Afghanistan, 3-mile fuel convoys are exposed as they crawl along dangerous mountainous routes (CNA, 2009). As the United States has shifted from the threats of the Cold War to the current asymmetric conflicts, the importance of supply line vulnerability has increased. The nature of this unconventional warfare is that adversaries will attempt to negate friendly technological superiority and strike softer targets such as logistics support (Spenard, 2005).

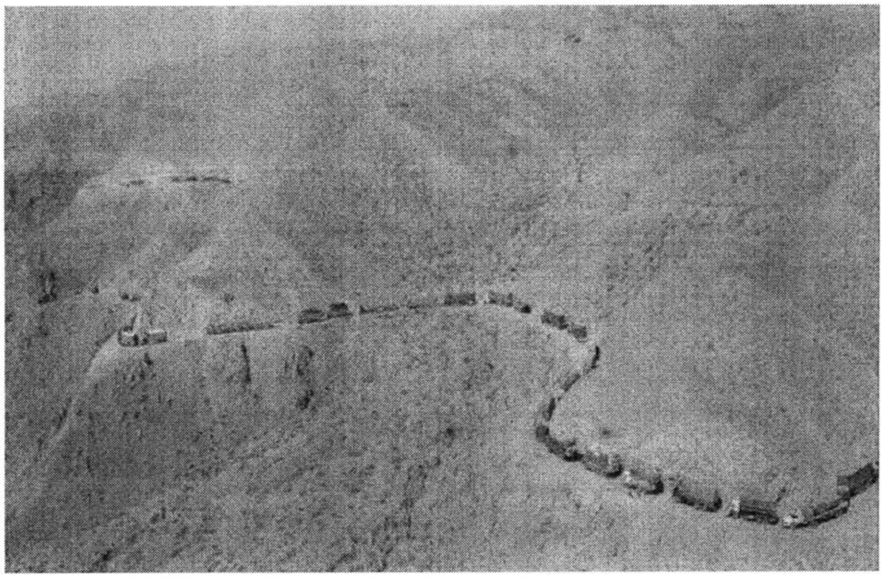

Figure 1-2: "A supply convoy snakes its way through the mountains of Afghanistan. The danger faced by the Soldiers and civilians driving and guarding these convoys stresses the need for fuel saving technologies…" (Hylander, 2009)

1.1.2. Fully Burdened Cost of Fuel

"He who wishes to fight must first count the cost."
–Ts'ao Kung (qtd. in Tzu, 2009/722-221 BC)

Having noted the issues associated with a large logistics tail within an asymmetric battlespace, it becomes easier to understand the concept of "fully burdened price of fuel." On April 1, 2007 the DoD was purchasing JP-8 (standard military diesel fuel) for $2.14. Unfortunately, this price does not capture the force structure required for the delivery and protection of fuel from commercial supply to point of use. The true cost includes delivery costs of the Military Sealift Command, Air Mobility Command, and refueling vehicles owned by the Army and Marine Corps. Fully burdened costs also include the assets used to protect fuel during its transit, including the aforementioned armored vehicles, helicopters, and fixed wing aircraft (DSB, 2008). One might even include the costs in protecting sea lanes, and operating certain military bases (CNA, 2009). Efforts have been made to quantify the costs of this infrastructure, delivery, and protection, and while these estimates vary widely, the fully burdened cost consistently far exceeds its commodity price. The cost of fuel for combat forces and Forward Operating Bases (FOBs) deep within a battlespace may be up to several hundred dollars per gallon (DSB, 2008).

1.1.3. Growing Energy Usage

Logistics operations and their vulnerabilities are an enduring principle of military operations, so why are the U.S. Armed Forces facing a unique challenge? One answer lies in the increasing consumption of fuel. As shown in Figure 1-3, the U.S. Military per capita fuel consumption is showing significant growth. The reasons for this growth are varied. One culprit appears to be vehicle weight. Many ground systems have seen increases in weight far in excess of their initial plans. In 2000 the FMTV cargo truck weighed 25,500 lbs. By 2009, largely through the addition of armor protection, the updated FMTV weighed in at 39,341 lbs. In 1984, when the HMMWV (Humvee), shown in Figure 1-4, was first fielded, it weighed 7700 lbs. Again, mostly through the addition of armor, variants of the HMMVW have more than doubled in weight, and are operating in the field at 17,900 lbs (Anderson, 2009). To provide some perspective, this vehicle added the equivalent of three mid-size family sedans to its payload.

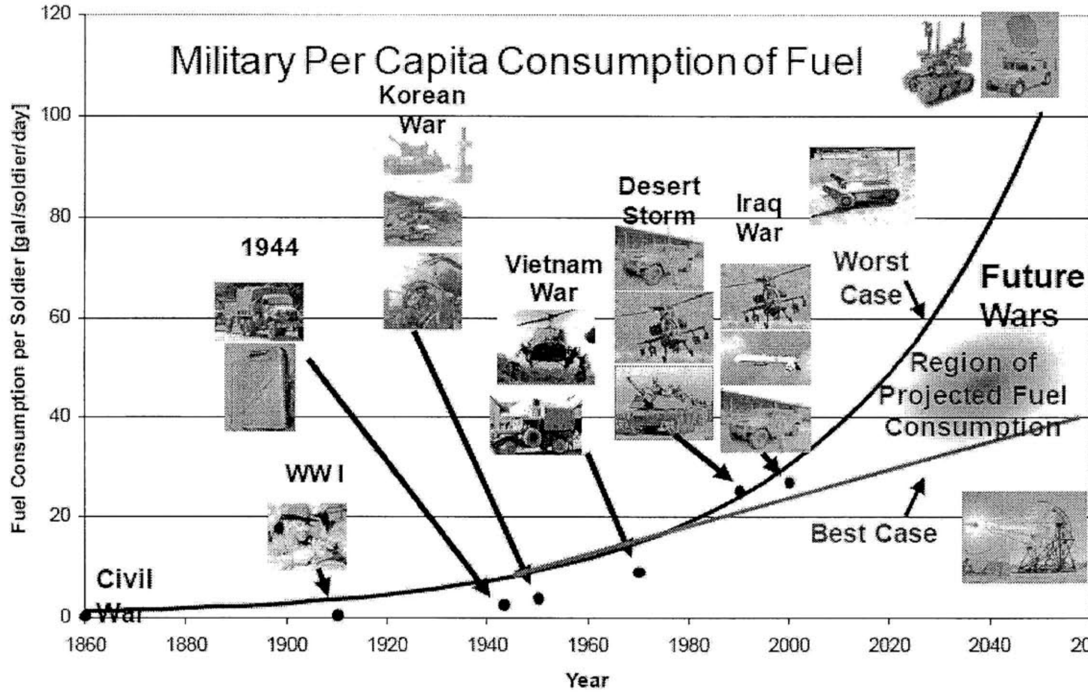

Figure 1-3: Growth of per capita fuel consumption of U.S. Armed Forces (Coutteau, 2008)

Figure 1-4: Evolution of HMMWV, from 7500 lb GVW prototype (Dunne, 1982) to 17,900 lb armored vehicle (Anderson, 2009)

Another primary contributor to energy consumption on the battlefield is the use of electrical power. Vehicles now carry a variety of new C4ISR technologies (Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance). Survivability systems such as IED defeat solutions drive additional power demands (Rogers, 2008). As the requirements for electrical power continue to grow, as shown in Figure 1-5, the fuel needed to supply this power will also grow.

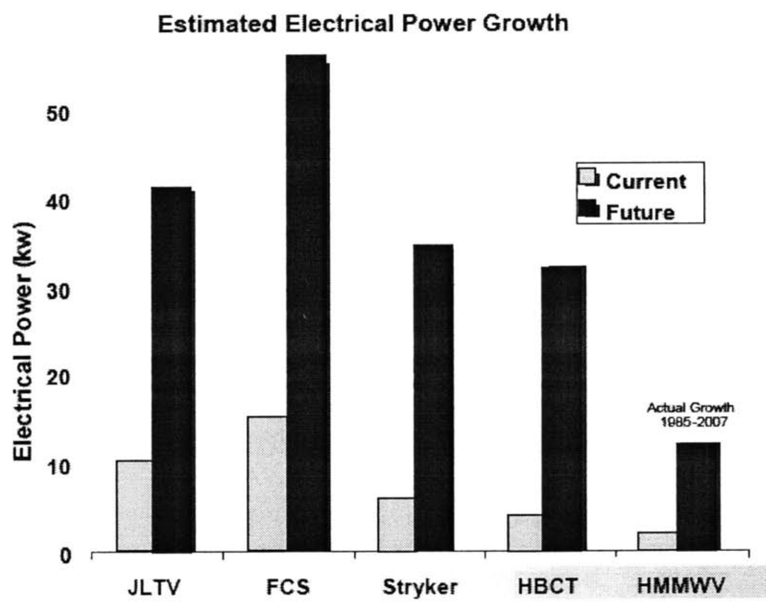

Figure 1-5: Growth of onboard electrical power generation requirements on U.S. military ground vehicle programs (Rogers, 2008)

1.1.4. Tactical Wheeled Vehicles

The Office of the Secretary of Defense (OSD) has recognized that the growing battlespace fuel demand compromises operational capability and mission success (DSB, 2008). In questioning where to begin, one might assume the heaviest, most gas guzzling combat vehicles would be a focus of effort. According to GlobalSecurity.org, an M1A1 Abrams Main Battle Tank achieves as little as 0.6 mpg. However, a study of the 2003 Marine Expeditionary Force (MEF) revealed that almost 90% of the fuel used by ground vehicles was accrued to tactical wheeled vehicles (TWVs). TWVs include HMMWVs, 7-ton trucks, and other logistical vehicles. The study was conclusive that combat vehicles such as M1A1 tanks, Light Armored Vehicles (LAVs), and Assault Amphibious Vehicles (AAVs), as a fleet consume a relatively minor fraction of fuel (NRAC, 2006). TWV's have therefore become an area of focus for reducing fuel consumption.

1.2. Fuel Efficient ground vehicle Demonstrator (FED) Program

> *"Unleash us from the tether of fuel."*
> *-Lieutenant General James Mattis, Commanding General, Marine Corps Combat Development Command (qtd. in NRAC 2006)*

According to the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC):

> "The Fuel Efficient Demonstrator (FED) Program was initiated by OSD to address energy conservation needs highlighted by the Defense Science Board: Energy Security Task Force. The overarching goal of the program is to improve military vehicle technology to reduce fuel consumption on the battlefield, and reduce our dependence on oil."

In support of the OSD, TARDEC outlined the technical objectives of the program. These included:

- "Demonstrate a tactical vehicle with significantly greater fuel economy than an M1114 HMMWV while maintaining tactical vehicle capability."
- "Integrate emerging fuel efficient technologies to demonstrate potential capabilities for the next generation of military trucks."

- "Consider higher risk/higher payoff technologies to attain the most fuel efficient vehicle possible." (Johnson, 2008)

An added focus of the program is that it "will help to document the process of how to build in fuel economy." Also, "government engineers will work side by side with the innovators and industry experts exposing them to novel and innovative design, advanced automotive engineering, and systems engineering practices and methodologies – the expected by product of this experience is that they will approach a problem differently." (Mathes, 2008)

Ricardo Inc. was contracted to utilize its "Total Vehicle Fuel Economy™" (TVFE) systems engineering expertise to support the FED program. Ricardo identifies itself as "a leading provider of technology, product innovation, engineering solutions and strategic consulting to the world's automotive, transport and energy industries." (Ricardo, 2009) Ricardo deliverables for the initial phase of the program included:

- Technology Research & Analysis
- Vehicle / Technology Requirements Definition
- Preliminary Design Concept Development

A graphical model of the Fuel Efficient Demonstrator program is shown in Figure 1-6, and is intended to demonstrate the flow of value and highlight key program elements. The diagram translates the need of the beneficiary (decreased fuel consumption by the DoD), to the solution neutral transformation of the generic operand (increased fuel economy of the tactical vehicle fleet through the FED program), to the specialized solution concept (Ricardo application of systems engineering methods to increase fuel economy while meeting HMMWV performance requirements), and finally to the specific form resulting from the process (Ricardo demonstrator vehicle). (Crawley 2008c)

This document stems from the author's leadership of the Ricardo effort to successfully meet the deliverables of FED through the use of a systems engineering-based methodology.

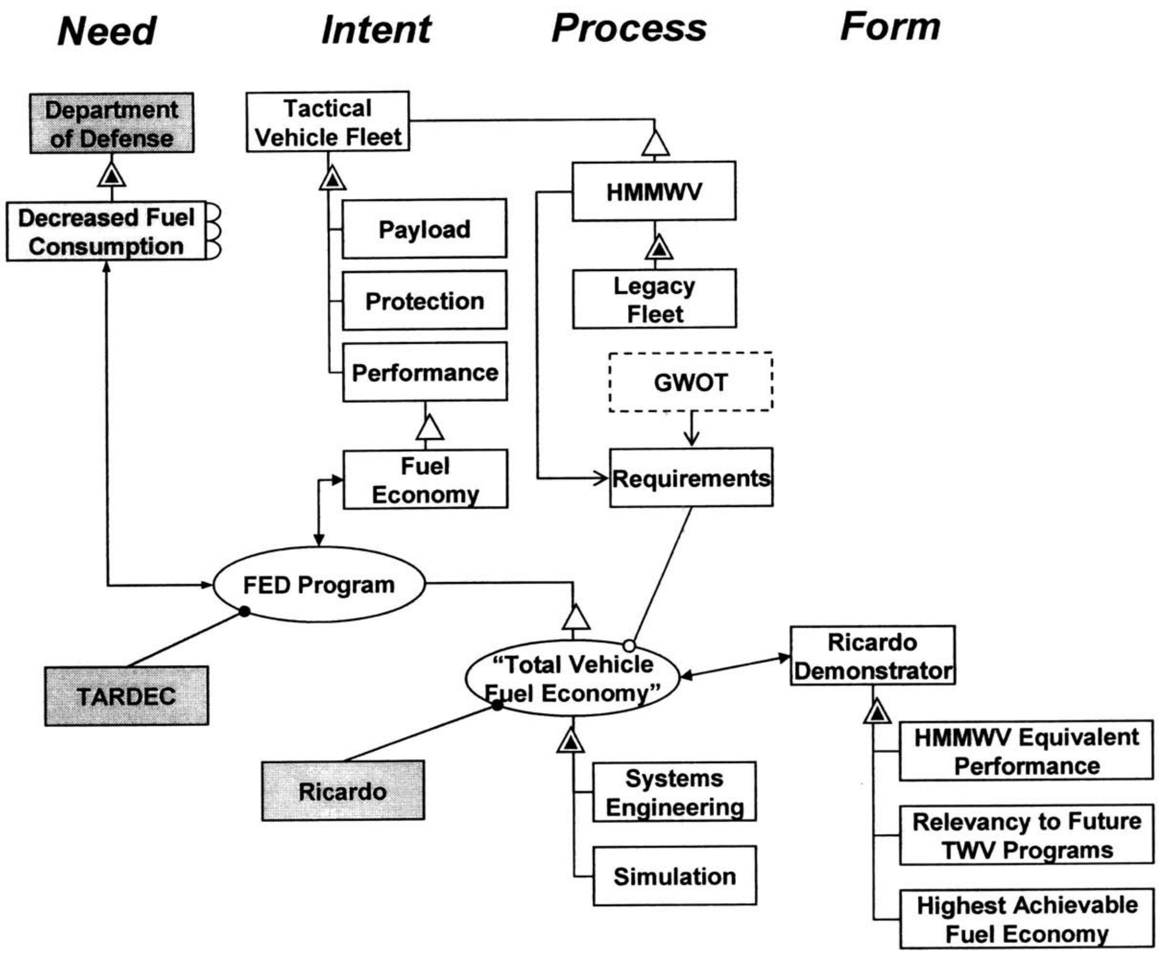

Figure 1-6: Graphical value flow for Fuel Efficient Demonstrator program (see Section 2.4 for OPM key)

1.3. Objectives

Given the aforementioned set of challenges, the Ricardo FED program has the resulting system problem statement:

> To develop fuel efficient tactical wheeled vehicle concepts, *by* integrating technological solutions with optimal vehicle architecture, *using* systems engineering methods, *while* preserving HMMWV functionality, *according to* government usage cycles, *with* tolerance for high risk in return for high efficiency gains.

The objective of this thesis is to demonstrate a systems engineering methodology and its application in maximizing the fuel efficiency of a tactical wheeled vehicle demonstrator. The application of the methodology to FED is illustrative of one specific usage, but the approach, as outlined in Figure 1-7, should be considered broadly applicable to the issue of developing concepts to improve the energy efficiency of any vehicle system, or indeed improve any product system attribute.

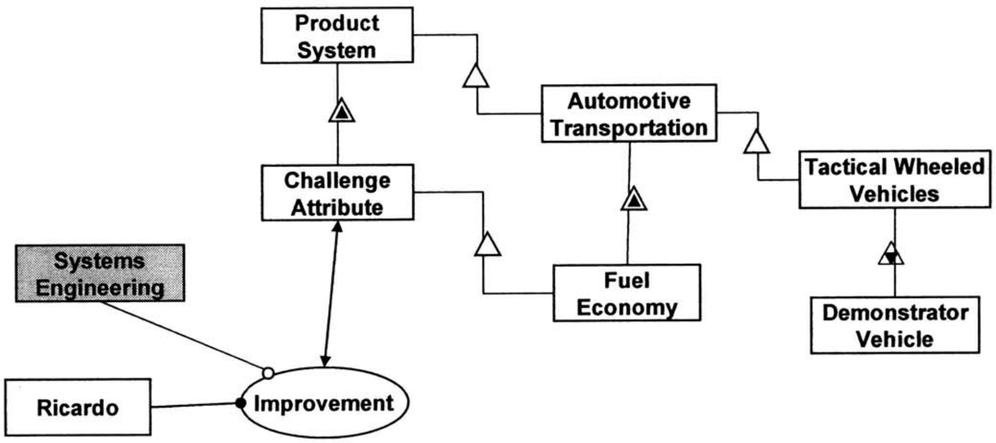

Figure 1-7: Applicability of methodology outside of tactical wheeled vehicle fuel economy (see Section 2.4 for OPM key)

1.4. Non-Disclosure / International Traffic in Arms Regulations (ITAR)

While the work carried out under the Fuel Efficient Demonstrator program is unclassified, it is subject to the International Traffic in Arms Regulations (ITAR) of the United States. These regulations dictate that certain technical information pertaining to defense and military related technologies may only be shared with US Persons. Due to the publishing of this document in the public domain, no information will be disclosed that would be contrary to ITAR. In addition, some of the work carried out was dependent upon proprietary information, subject to non-disclosure agreements signed by Ricardo and participants in the project.

As such, this document will seek to focus upon the methodology used. Military data not available in the public domain along with actual simulation results will be discussed only in general terms. In some cases, "sanitized" results will be shown for their value in illustrating the methodology while avoiding the issues associated with non-disclosure agreements and ITAR. While the inability to present all evidence in support of the methodology is a compromise, the premise of the thesis is to demonstrate the overall use and effectiveness of the methodology, rather than make the case that a particular technology will provide a certain improvement in this application.

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2. Approach

2.1. Systems Engineering

Having put forth the premise that a systems engineering approach is the appropriate way to address the issues presented, it is worthwhile to establish what this entails. One representative definition states that:

> "Systems engineering is an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for the system (Haskins, 2006)."

Another way to view systems engineering is to examine some of its main components as in Table 2-1:

Table 2-1: Elements of Systems Engineering (de Weck & Haberfellner, 2006)

Principles	overarching, long-enduring truths
Systems Thinking	world view of interrelated objects and processes
Process Model	formal building blocks of SE
Problem	tension between the current and target state
Problem Solving Process	systematic way of solving problems
System Architecture	defining the overall concept of a solution
System Design	making a system solution implementable
System Project Management	organizational questions of execution
Solution	transition from the current to the target state
Methods	procedures for solving recurring sub-problems
Tools	actual instruments to carry out the methods

One component of particular interest is the systems engineering process model. It consists of four basic ideas that combine to create a formal systems engineering process.

- "Proceeding from the *general to the detailed* and not the opposite way ('top down approach')"
- "Observing the principle of *creation and selection of alternatives*, i.e. one should not be satisfied with a single ('the first') solution but always look for alternatives"
- "Dividing the process of system development and system implementation and operation into distinct *project phases*, whereby the phases can be sequential or overlapping"

- "Using the *problem solving cycle* as a kind of thinking and working logic, no matter what kind of problem it is and in which phase it appears." (de Weck & Haberfellner, 2006)

These ideas will be a recurring theme within this document.

2.2. Design For Six Sigma

As the proposed systems engineering methodology is complex with many elements and interactions, it is useful to utilize a framework in order to present it in a less complicated manner. The framework used here is Design For Six Sigma (DFSS). DFSS is an outgrowth of systems engineering, and is intended to be a systematic methodology for improving the quality of new products. It capitalizes upon the popularity of the Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) methodology for improving existing products. While Six Sigma and DMAIC are well established and defined, there exists a plethora of competing implementations of DFSS, making it more of a general approach than a rigorously defined methodology. Examples of DFSS processes include:

- DMADV (Define, Measure, Analyze, Design, Verify)
- DMADOV (Define, Measure, Analyze, Design, Optimize, Verify)
- IDOV (Identify, Design, Optimize, Validate)
- DCCDI (Define, Customer, Concept, Design, Implementation)
- DMEDI (Define, Measure, Explore, Develop, Implement) (Simon, n.d.)
- ICOV (Identify, Characterize, Optimize, Verify) (Yang & El-Haik, 2009)

Taken in aggregate, these process definitions can be used to establish a useful modularization to work toward:

- *Define* project goals / *Identify* requirements / *Measure* customer needs
- *Characterize* / *Model* design and alternatives
- *Analyze* system alternatives / *Optimize* system solutions
- *Design* / *Develop* system concepts
- *Implement* prototypes / *Verify* performance / *Validate* customer needs are met

The systems engineering methodology presented (hereafter referred to as the FED methodology) will follow this framework and divide the process into five project phases – Define, Characterize, Analyze, Design, and Verify.

2.3. FED Methodology

The process outlined for the FED methodology can be viewed in terms of the five aforementioned process phases:

- **Definition Phase** – use of program objectives to define both system operational requirements and criterion for evaluating alternatives
- **Characterization Phase** – focus upon defining product architecture, developing system models, and identifying technology options
- **Analysis Phase** – use of simulation to evaluate design alternatives
- **Design Phase** – development of product concepts based upon predicted performance
- **Verification Phase** –implementation and testing of product prototypes

Overall, the FED methodology is intended to be an implementation of a range of existing systems engineering process, methods, and tools. There are a number of these elements which should be considered highlights of the methodology.

- **Requirements Tradespace** – the concept of defining a range for each system operational requirement to allow a wider potential solution space and enable informed balance of competing requirements (Section 3.3.1)
- **Baseline Modeling** – the construction of rough product models (CAD, BoM, Performance Simulation, etc) as provisional attempts to meet requirements and act as the center of subsequent design space exploration (Section 4.1)
- **Energy Balance** – the use of modeling and simulation to decompose all energy expenditure in order to prioritize investigation of design alternatives (Section 4.2.2)
- **Technology Market Survey** – structured outreach efforts to identify technology alternatives, inclusive of lead users, focused on obtaining quantitative data for key subsystem attributes to support modeling and simulation (4.3)
- **Surrogate Model-based Toolset** – development of neural net-based surrogate models and inclusion into an integrated modeling & simulation environment for real-time decision support on multi-attribute trade-offs (Sections 5.2 & 5.3)

- **Design Space Exploration** – generation of thousands of feasible design configurations to support Pareto optimization of requirements and technology selection (Section 5.4)

2.3.1. Methodology Summary

Phases and elements of the systems engineering methodology will be explained in detail in later sections. It is however useful to take a high level examination of the process to understand how key elements are organized and related. Figure 2-1 provides a graphical view of process highlights (many elements have been excluded for clarity).

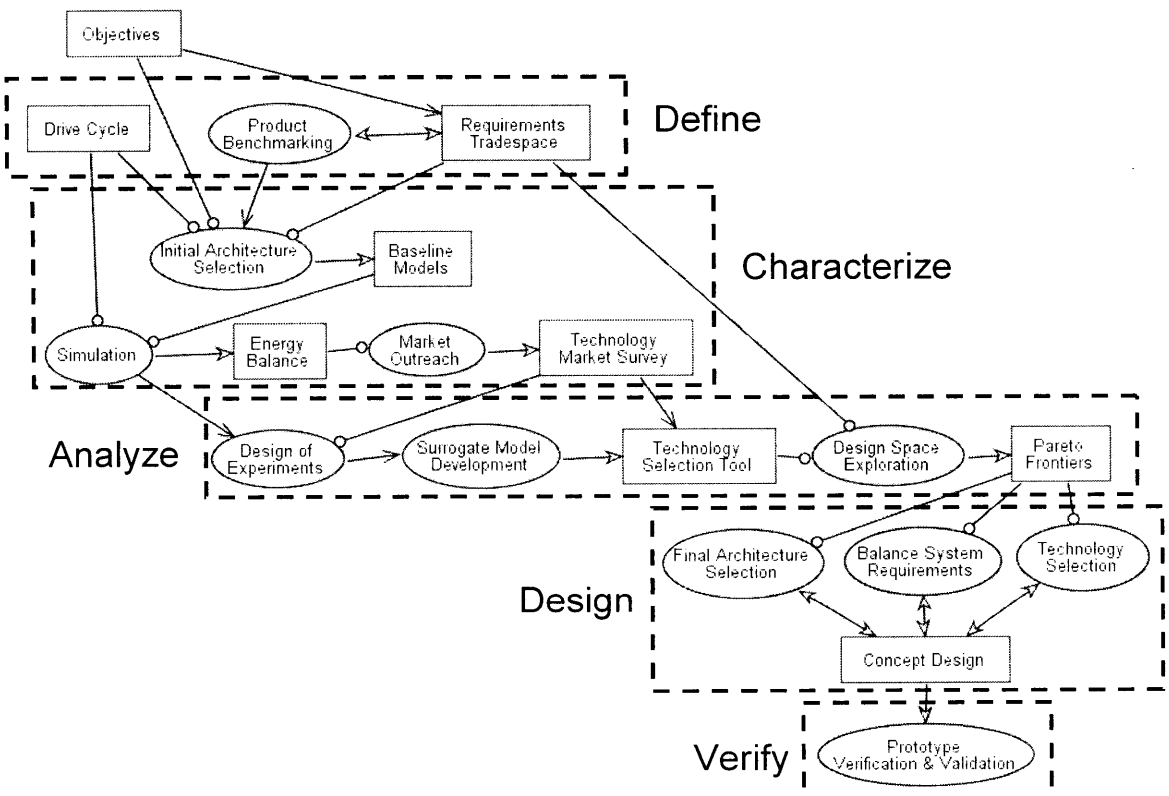

Figure 2-1: Overview of FED Methodology (see Section 2.4 for OPM key)

The FED process begins with customer inputs, primarily program objectives, along with background information on operational usage. The definition phase translates operational usage into a drive cycle, and objectives into key metrics. A combination of program objectives and product benchmarking is used to generate the requirements tradespace, defining a solution neutral range of threshold and objective requirements. The intent of the phase is to provide the engineering framework for evaluation of alternatives.

The characterization phase begins with the creation of a number of baseline models including CAD, bill of material, and performance prediction. The models require an initial downselection of product architecture to a few basic configurations appropriate to the program objectives and drive cycle. Simulation of baseline architectures over the drive cycle allows the decomposition of energy expenditure, identifying priorities for efficiency improvement. These priorities inform outreach efforts for the supply base and lead users from other industries, which obtain data to support a technology market survey. The intent of the phase is to identify design alternatives and provide the means (modeling and simulation) to evaluate them.

The analysis phase generates a design of experiments (DoE) using the performance models from the previous phase. The DoE is designed to support the development of lightweight surrogate models using neural net based response surface equations. These surrogate models are integrated into a modeling and simulation toolset, along with technology survey data, to enable real-time multi-attribute decision making. The toolset is then used for a second full factorial DoE, generating thousands of vehicle configurations for design space exploration of Pareto frontiers. The intent of the phase is to simulate design alternatives to enable informed decision making.

The design phase focuses on finalizing vehicle concepts. This includes narrowing the broad requirements tradespace into a balanced set of achievable requirements that support the objectives. Product architecture is also selected from amongst the baseline options (or some combination) along with technology options from the survey. The intent of the phase is to produce data driven Pareto optimal vehicle concepts.

The FED process ends with verification and validation. Concept designs are developed into detailed designs and prototypes are manufactured. Prototypes are then tested to verify performance. The intent of the phase is not only to verify performance, but also to correlate modeling and simulation.

2.4. Object-Process Methodology (OPM)

Definition of the FED process will assisted through the use of Object-Process Methodology (OPM), a graphical framework for modeling, communicating, documenting, and engineering complex multi-disciplinary systems. The chief advantage of OPM is the ability to represent any system in terms of both form and function within the same conceptual models. The basic construction of an Object-Process Diagram (OPD) is the division of all things into objects and processes, as well as definition of the state of, and relationships between these elements. An object is defined as "a thing that exists or can exist physically or conceptually." A process is defined as "a thing that transforms an object by creating it or consuming it or changing its state." (Dori, 2008) Included in Figure 2-2 and Figure 2-3 are descriptions of various linkages between processes and objects included within OPM. The reader should use these figures as a key to the various OPM figures that are used to illustrate the elements of the FED methodology and how they are connected.

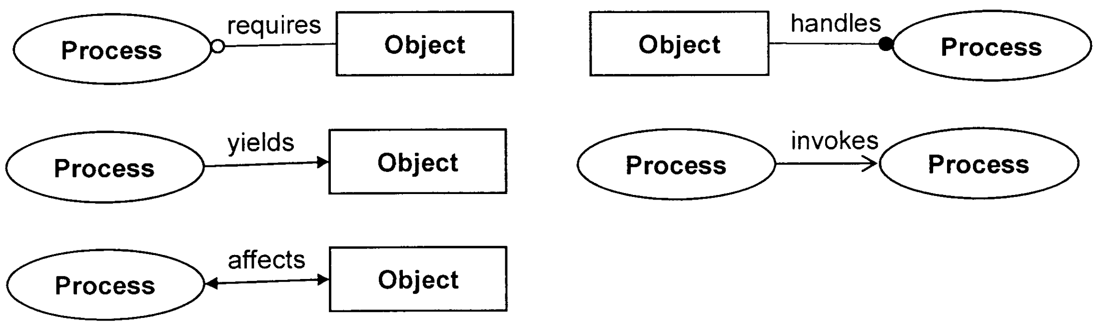

Figure 2-2: OPM process links with natural language description (e.g. Process yields Object) (Crawley, 2008b)

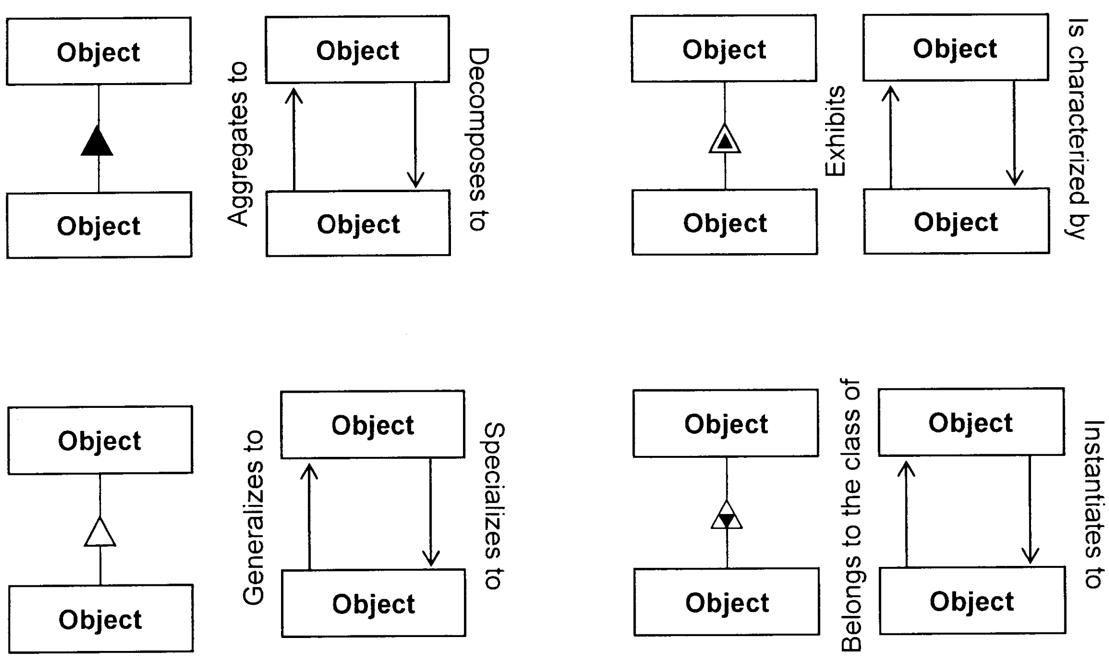

Figure 2-3: OPM structural links with natural language description (e.g. Object is characterized by Object) (Crawley, 2008b)

3. Definition Phase

The definition phase seeks to use program objectives to define both system operational requirements and criterion for evaluating alternatives. The intent is that this phase remains solution neutral, focusing on system capabilities rather than subsystem performance. Some inputs into this phase were first seen in Figure 1-6, in which the DoD need for decreased fuel consumption translates into program intent, including HMMWV-based threshold requirements and an overall objective of increasing the fuel economy of current and future tactical vehicle fleets. Significant processes for this phase, their relationships, inputs, and deliverables, are summarized within Figure 3-1.

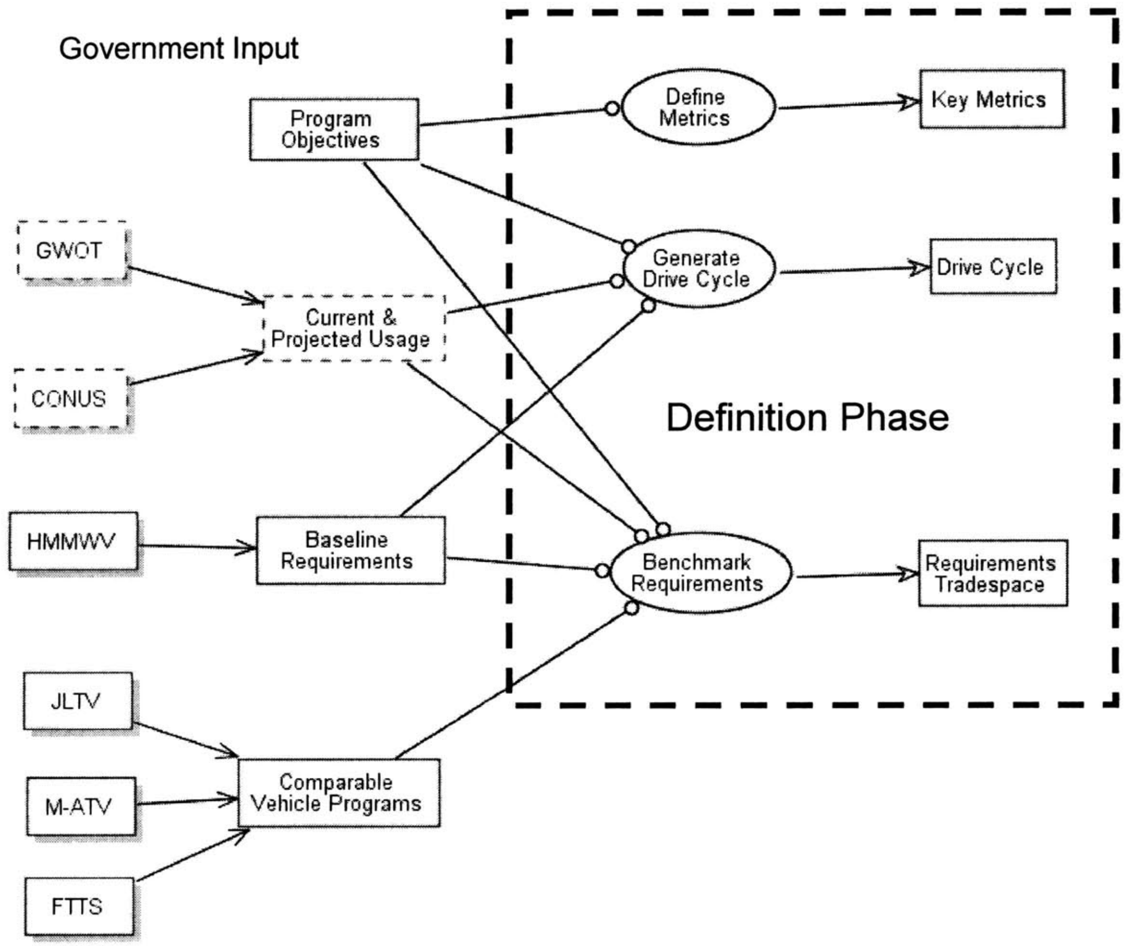

Figure 3-1: Definition Phase elements and their relationships, including key processes, inputs and deliverables (see Section 2.4 for OPM key)

The end result of this phase includes three primary deliverables:

- Key Metrics – Translation of objectives into measurable assessments of utility
- Drive Cycle – Engineering definition of vehicle usage as a basis of simulating key metrics
- Requirements Tradespace – Definition of range of values for each system operational requirement

These deliverables will be described in detail within the following sections.

3.1. Key Metric Definition

"In order to determine the goodness of a path, some goodness criterion must be present."
(Reklaitis, Sunol, Rippin, & Hortacsu, 1996)

The systems engineering process can be viewed as a search within the available design space for an optimal "solution path" resulting in the "goal state". As alternative solutions are created, some rational for evaluating and selecting a partial solution path is required. (Reklaitis, Sunol, Rippin, & Hortacsu, 1996) Therefore, a set of appropriate metrics must be determined which are aligned with the program objectives.

3.1.1. Fuel Efficiency

Obviously for the Fuel Efficient Demonstrator program, the measurement of fuel efficiency is going to be the foremost criterion for evaluating alternatives. Fuel efficiency can be measured in a number of ways, including:

- Fuel Economy – distance traveled per unit of fuel used – e.g. miles per gallon (mpg)
- Fuel Consumption – amount of fuel used per unit of distance - e.g. litres per 100 kilometers (L/100 km) or gallons per mile (gpm)
- Output specific fuel economy – distance traveled times cargo carried per unit of fuel used - e.g. ton-miles per gallon or passenger-miles per gallon.

Each of these metrics has advantages and disadvantages. A fuel economy measurement such as mpg has the chief advantage of familiarity, at least in the United States. In communicating results in mpg, the audience is likely to have some intuitive understanding of how favorable a fuel economy result is or is not, while results measured in L/100km or gpm will require some comparison or translation into mpg. Unfortunately, as shown in Table 3-1, the mpg fuel economy metric has a serious flaw in that equal increases in mpg are not equal in actual fuel savings.

Table 3-1: Comparison of mpg improvements versus actual benefits

Fuel consumed while traveling 1000 miles:			
1	Base FE	10 mpg	100 gallons used
	Improved FE	11.11 mpg	90 gallons used
	Benefit	**1.11 mpg**	**10 gallons saved**
2	Base FE	33 mpg	30.3 gallons used
	Improved FE	49.25 mpg	20.3 gallons used
	Benefit	**16.25 mpg**	**10 gallons saved**

These examples show that characterizing any improvement in terms of mpg or % improvement to fuel economy may say very little about actual fuel savings without additional context. (Larrick & Soll, 2008)

Fuel consumption metrics, such as L/100km or gpm, which are the inverse of fuel economy metrics such as mpg, solve the issue of distorted perception of results. Taking the same examples as above, but putting them in terms of gpm yields the results in

Table 3-2.

Table 3-2: Comparison of gpm improvements versus actual benefits

Fuel consumed while traveling 1000 miles:			
1	Base FE	0.1 gpm	100 gallons used
	Improved FE	0.09 gpm	90 gallons used
	Benefit	**0.01 gpm**	**10 gallons saved**
2	Base FE	0.03 gpm	30 gallons used
	Improved FE	0.02 gpm	20 gallons used
	Benefit	**0.01 gpm**	**10 gallons saved**

We can see with these results that using a fuel consumption metric, fuel savings are proportional to the metric.

Output specific fuel economy, such as ton-miles/gal, is notable because it accounts the capability of the vehicle, and can be very useful for comparing disparate forms of transportation. Using mpg as a metric, the energy efficiency of a freight train would be very poor compared to an automobile. When considering the useful output however, the metric shows that trains will typically carry a ton of payload well over 400 miles on a gallon of fuel. (Jackson, n.d.) Consideration of this metric for FED is important, as the solicitation for the

Joint Light Tactical Vehicle (JLTV) program, which is intended to replace the HMMWV, uses ton-miles/gal (based on maximum GVW) to measure fuel economy. ("JLTV Purchase Description", 2008) From the perspective of JLTV, which must compare vehicle submissions of varying capability, there are some advantages to using ton-miles/gal. The government may not want to penalize a vehicle whose inferior fuel economy results from greater levels of payload and protection. The flaw in the JLTV's implementation of the metric is that there is no accounting for weight related to payload or protection, the ton-miles is based only upon GVW. Therefore a vehicle that is overweight due to poor engineering holds an advantage with this measurement. In fact, vehicles with substandard fuel economy can actually add mass to meet the requirement, even though actual fuel consumption would worsen. Therefore, if ton-miles/gal is to be used as a metric for tactical vehicles, it should be based on some measure of useful output from the vehicle, such as payload weight-miles/gal. Even then, from the standpoint of requirements engineering, there would remain issues with convoluting separate requirements.

Each fuel efficiency metric has advantages and disadvantages to consider, but it appears that there are some best practices. In general fuel consumption (gpm) is superior to fuel economy (mpg) due to the proportionality issue. Output specific fuel economy has the potential to be an improvement, but it must be based on useful output (payload mass). The suggestion is that gallons per payload ton-mile could be used.

3.1.2. Mass

For tactical wheeled vehicles, the importance of vehicle mass goes above and beyond its contribution to fuel efficiency. TWVs have transportability requirements, which are constraints on size, weight, and weight distribution according to various forms of transportation that might be necessary to carry the vehicle, including helicopter, fixed wing air transport, sealift, train, etc. Transportability will tend to provide a fixed ceiling for the vehicle mass. If a key objective requires transport of the vehicle by a particular helicopter, then the lift capacity of that helicopter provides an absolute limit to the vehicle mass. Implementing technology that increases the curb weight of the vehicle might require that the weight is offset elsewhere to maintain the transportability.

Closely related to this issue is the DoD's increasing emphasis on vehicle survivability. Historically, the HMMWV has seen its useful payload capacity eliminated as requirements for armor protection has increased. Other more recent TWV programs have seen further increases in armor protection requirements. Much of this is driven by the nature of the current asymmetric warfare, as mentioned in Section 1.1. We can extrapolate that given the constraints on mass due to transportability requirements, specifications and technologies which increase curb weight will in general decrease the payload capacity available for armor protection. Therefore, the goodness criterion of any alternative that increases the vehicle curb weight is diminished, even if it results in an increase in overall fuel efficiency.

3.1.3. Technology Readiness Level

Technological maturity is an important consideration for any complex systems project, but particularly for one in which technology adoption and high risk/high reward is part of its *raison d'etre*. In addition, risk management is an integral part of systems engineering, and a significant proportion of risk can be associated with technology maturity. In order to support the assessment of risk, the process of evaluating and down-selecting design alternatives includes technology maturity as a subsystem attribute.

It is hardly "apples to apples" to compare the performance of an engine currently in mass production to that of a radical new engine architecture with promising new features and potential for improvement, without including some factor that characterizes the maturity issues. These issues could include late timing, performance which does not live up to predictions, or issues with secondary attributes such as cost, durability, manufacturability, etc. This is why technology readiness level (TRL) is tracked and filtered as a key metric. The TRL scale utilized by the DoD runs from 1 ("Basic principles observed and reported") to 9 ("Actual system proven through successful mission operations"). (DUSD(S&T), 2005). See Table 3-3 for a description of each TRL. Common usage of TRL is as a filter, whereas the system requirements for a program might state that a minimum TRL is required across all subsystems. A more nuanced assessment of TRL requirements can be taken, particularly for a program such as FED. Risk associated with technology maturity is one of many attributes to balance across the needs of the program. In fact, as a demonstrator program, a particularly promising technology might be included not only in spite of a relatively low TRL, but because of a low TRL. An Advanced Concept Technology Demonstrator (ACTD) has the potential to increase a subsystem TRL through successful demonstration, allowing its subsequent usage on a production intent program, providing much of its value.

Table 3-3: Technology Readiness Level definitions (DUSD(S&T), 2005)

Technology Readiness Level	Description
1. Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3. Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5. Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6. System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
7. System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.
8. Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

3.2. Drive Cycle Definition

The vehicle drive cycle or usage cycle can be defined as a characterization of the manner in which the vehicle is expected to be operated or driven, used in order to assess performance. While any specification, technology, or architecture decision relies upon a range of metrics, for a fuel efficiency program like FED the primary metric will be fuel economy. Fuel economy can only be derived according to the usage of the vehicle. A figure of say, 20 mpg, is meaningless without the context of drive cycle. Is the 20 mpg performance primarily while coasting downhill at high speeds? Or perhaps pulling a fully loaded trailer through sand? The relative effectiveness of any particular solution will be cycle dependent, and is the reason why one might see a hydraulic hybrid architecture implemented on a delivery truck and a kinetic/flywheel hybrid architecture in motorsports.

3.2.1. Drive Cycle Characteristics

Several elements are required to characterize the drive cycle. These are operational or environmental parameters, and how they vary over time or distance. Those considered here include:

- Vehicle Speed
- Elevation/Grade
- Road Surface
- Accessory Usage
- Payload

Vehicle speed is the most basic parameter used in automotive drive cycles. This includes accelerating from a stop or lower speeds to higher speeds, maintenance of targeted speeds, braking or coasting from higher speeds to lower speeds or stops, and time spent at idle (vehicle operating at zero speed). Within a simulation or dynamometer test environment, a speed trace acts as a target speed for the vehicle at any given time. When under the target speed, throttle will be applied to accelerate to the target. When over the target speed, the vehicle will coast or brake as necessary to decelerate. Regulatory bodies such as the U.S. EPA use vehicle speed versus time as the primary definition of drive cycles that measure fuel economy performance for regulatory standards (as shown in Figure 3-2), and characterize the specific differences between city and highway driving. For the U.S. Military, the Test Operating Procedure (TOP) for the Munson Standard Fuel Consumption Course actually specifies a single sustained speed be used for any particular test, presumably for test repeatability. (U.S. Army Test and Evaluation Command, 1980) This does eliminate acceleration loads from the test cycle, skewing results away from actual usage, as well as minimize braking, a significant source of energy expenditure.

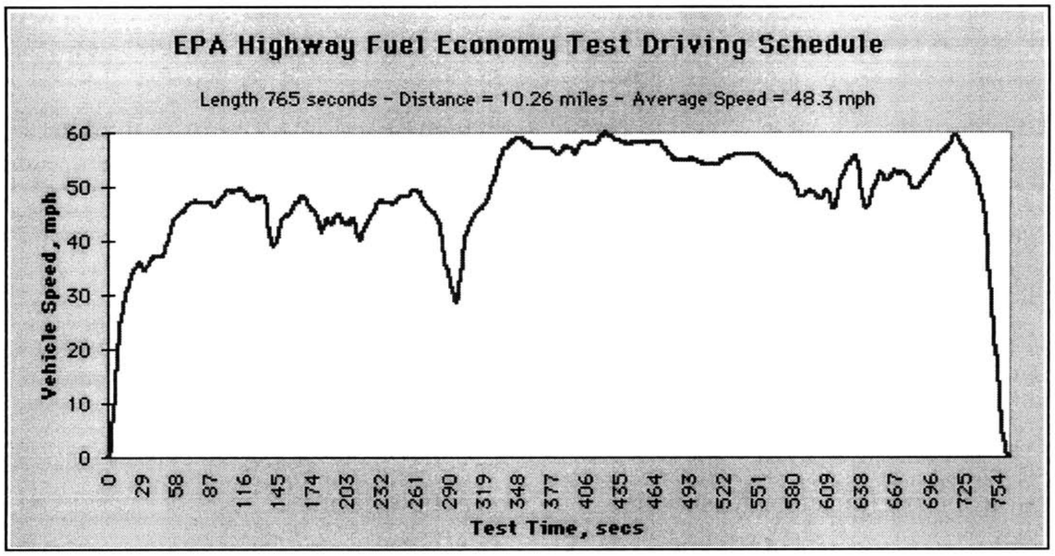

Figure 3-2: Vehicle speed versus time trace for EPA Highway drive cycle (U.S. Environmental Protection Agency, 2008)

Elevation changes are used in order to characterize flat, hilly, or mountainous terrain and its effect on performance. This includes length and grade of inclines. Not all drive cycles will utilize this information, and instead assume completely flat terrain, or at least close enough to flat that there is minimal effect on performance. The EPA for example, does not include elevation within its drive cycles. (U.S. Environmental Protection Agency, 2008) Within a simulation or dynamometer test environment, an elevation trace will require the vehicle to apply additional throttle on inclines to reach target speeds, and additional braking on declines in order to maintain target speeds.

Defining the road surface for a drive cycle is required to determine the rolling resistance of the vehicle. This rolling resistance occurs due to both the deformation of the vehicle tires and deformation of the road surface. For most automotive applications, surfaces typical of asphalt roadways are used, and rolling resistance is more dependent upon tire selection than road surface. However, rolling resistance significantly increases while driving in soft soil conditions due in part to soil deformation, so that vehicles driven off-road require additional detail in defining surface conditions within the drive cycle. In some cases it might be assumed that the road surface effects on rolling resistance outweigh tire selection and/or there is little variability in tire selection, so for the purposes of simulation the rolling resistance itself can be dictated, rather than the surface conditions. This is the case for the Joint Light Tactical Vehicle (JLTV) solicitation which specifies that performance prediction should use 44 lb/ton rolling resistance for the entire Munson Standard Fuel Economy Course, regardless of surface. ("JLTV Questions and Answers", 2008) Given the difficulties in accurately predicting soft soil rolling resistance, there are advantages to this approach, particularly when considering the need for government procurement to eliminate the "noise" of varying rolling resistance assumptions from competing contractors. However, rolling resistance is one of the greatest contributors to vehicle fuel economy, and dictating rolling resistance effectively results in ignoring engineering and technology that can be used to improve (or worsen) this attribute, at least within the simulation environment.

An aspect of road surface that is not normally considered, but is becoming important due to emerging technology, is roughness. Whether the terrain being traversed is hard or soft, there will be bumps and imperfections, with roughness increasing substantially in many off-road conditions. Even on paved roads there are oscillations dampened out by the tires and suspension, and the larger features encountered while driving off-road require additional power to push the vehicle up and over. Typically these effects, which are sometimes referred to as "terrain efficiency", would be lumped in with the more dominant components of rolling resistance. With traditional suspension technology, there would be relatively little leverage to improve the terrain efficiency. With the advent of advanced damping systems, such as active or semi-active damping, the vehicle ride and terrain efficiency may be improved enough to allow a measurable improvement of fuel economy, particularly in very rough conditions. In addition, regenerative damping technologies are under development that would convert the damping energy, normally dissipated as heat, into electrical power.

The vehicle accessory usage within a drive cycle defines the operation of vehicle systems outside that required to operate the vehicle itself. A representative example of this is vehicle air conditioning. Until recently, EPA drive cycles did not include accessories such as air conditioning, despite widespread usage by the driving public. Starting in 2008, EPA fuel economy testing added an air conditioning cycle in order to better account for actual driving conditions. (U.S. Environmental Protection Agency, 2009) Examples of other accessories typical for automotive operations include lighting, radio, and windshield wipers. For the U.S. Military, Munson continues the practice of not including accessories. (U.S. Army Test and Evaluation Command, 1980) In actual operating conditions, military accessory loads, such as for command and control electronics, far exceed automotive accessory loads, and continue to increase, per Figure 1-5.

Vehicle payload is the final component of drive cycle definition. At a minimum, vehicle operation is possible at the Vehicle Curb Weight (VCW) plus driver, defined as the total weight of the vehicle with all standard equipment and consumables, and a full tank of fuel. At its maximum the vehicle can be driven at its Gross Vehicle Weight (GVW), defined as the maximum allowable weight of the vehicle when fully loaded with payload, including passengers and cargo. Another possibility is the Gross Combination Weight (GCW), which includes the GVW plus the maximum weight of a trailer and its cargo. In addition, the U.S. Military will sometimes define a Combat Weight or Essential Combat Configuration (ECC), which rather than the maximum payload a vehicle is capable of carrying, reflects an expected minimum payload while in the field. All these options are viable alternatives for drive cycle payload, but whichever is selected should reflect the reality of operation while in the battlespace.

3.2.2. Effects of Drive Cycle Selection

As already noted, definition of drive cycle will determine the effectiveness of available solutions. The energy required to overcome air resistance per unit distance is roughly proportional to the square of speed, therefore high speed drive cycles will favor implementation of aerodynamic aids. High accessory loads will favor implementation of efficient electrical power generation. Prevalent acceleration and deceleration will favor implementation of hybrid power assist and regenerative braking. Implementing any of these requires weight, cost, and complexity, along with trade-offs in priority. For example, aerodynamic ground effects might require material and development costs, weight of additional components, and perhaps reduced ground clearance. Traveling at high speeds, the ground effects may be an effective improvement to the vehicle fuel economy. At low speeds, the additional weight may actually decrease fuel economy, let alone justify compromising ground clearance and increasing cost. An additional consideration in drive cycle definition is the risk of completely disregarding effectiveness of certain solutions. The aforementioned regenerative damping requires at least some assumption of road surface roughness. Without accessory loads, more efficient headlamps, such as LEDs, would not be accounted for. Therefore in defining a drive cycle, as complete as possible accounting of factors effecting energy usage should be adopted as a principle.

3.2.3. Drive Cycle as Exogenous Input

A flaw in the process of defining a drive cycle as an input into the development of a vehicle concept is the assumption that any vehicle concept will be used in the same manner. The vehicle speed trace dictates the speed in which the operator will attempt to drive, regardless of the vehicle specification. Typically this trace is based upon data taken from vehicle testing or operation in the field. In reality, a driver might be inclined to drive a vehicle faster or slower depending upon the available power and vehicle ride and handling. A more powerful engine might both consume more fuel during a given operation, and encourage the operator to accelerate more aggressively, resulting in additional fuel consumption. For the most part there appears little to be done as it is difficult to predict changes to driver behavior versus changes to vehicle performance parameters.

Unfortunately, driver behavior cannot or at least should not be ignored, as the fuel economy of the most efficient drivers has been demonstrated to be as much as 47% better than the least efficient. (Knee, Lascurain, Franzese, LaClair, & Otaduy, 2009) As shown in Figure 3-3, driver feedback technologies are emerging that attempt to modify behavior and close this gap. Therefore, for the study of these technologies, unique drive cycles might be generated that mimic expectations of different driver behaviors. The speed trace of the "bad" driver for example, could include more aggressive acceleration, and overshoot of target speed.

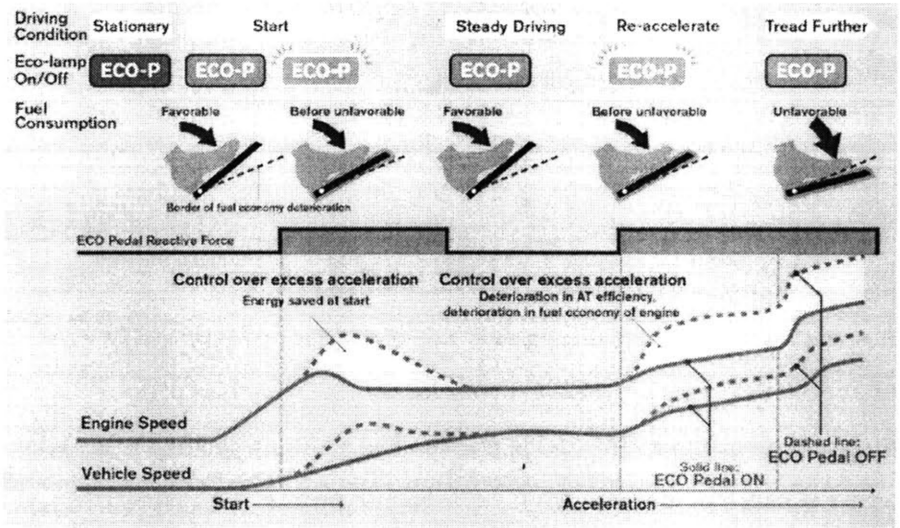

Figure 3-3: Haptic feedback accelerator pedal technology (Nissan Motor Co., 2008)

3.2.4. FED Drive Cycle Selection

In developing a drive cycle for the FED program, the first consideration was peacetime versus combat operation of tactical vehicles. While operating within the contiguous U.S. (CONUS), on base, or on maneuvers, the usage profile of tactical vehicles is likely to be very different from missions within the battlespace. Should the FED drive cycle incorporate both cycles and reflect a weighted average based upon expected split between peacetime and combat use? The decision taken, based upon the program objectives and background, was to focus on optimizing fuel economy during combat usage. As previously noted, the fully burdened cost of fuel in remote areas may more than one hundred times the commodity cost. In addition, the issues of tooth to tail, supply line vulnerability and casualties are unique to combat usage, and probably of greater priority.

Another consideration for the FED drive cycle was the breakdown of a composite cycle. For example, the EPA Combined Fuel Economy is a weighted average of 55% city cycle and 45% highway cycle. What is the military equivalent? Within the Munson TOP, vehicle operation is characterized by the following operating conditions: engine idling, paved road, secondary road, and cross-country. Figure 3-4 shows an example of a drive cycle decomposition for a "Tactical Support Schedule…role normally filled by wheeled vehicles with a high degree of off-road capability." (U.S. Army Test and Evaluation Command, 1980). For FED, a desired split was provided as part of the government's baseline requirements. Still, the government does have issues with cycle definition due to variability between combat theatres. One can presume that within the Afghanistan theatre (OEF), there is a predominance of cross-country and secondary roads, compared to the paved roads in the Iraqi theatre (OIF). Also, OEF/OIF aside, how to predict future operational modes and theaters? In order to mitigate this issue one should consider how best to develop a "robust" drive cycle.

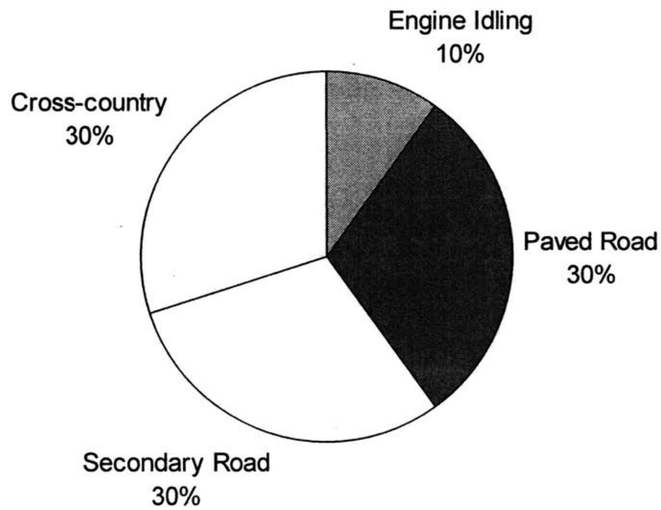

Figure 3-4: Tactical Support Schedule – Munson Standard Fuel TOP (U.S. Army Test and Evaluation Command, 1980)

Within each segment, definition of the precise drive cycle is required. This definition should include speed, elevation, and road surface, based upon data from combat missions and/or testing. For a robust drive cycle, representation of a wide range of conditions is required. For example, terrain can be hilly or flat. Speed and acceleration can reflect city (urban assault) with low speeds and stop and go driving, or highway (convoy escort) with long periods of steady high speeds. Roads can be smooth pavement, mud, gravel, rocks, etc. The drive cycle should have a reasonable blend of all these conditions. Covering a wide range of driving conditions means that a technology that is highly dependent upon a single condition, even if highly effective, should be shown at a disadvantage versus a technology that provides benefits across many or all conditions.

3.3. Requirements Engineering

"What's the good of it? For whose advantage?"
- Cicero, Oratio Pro Sextio Roscio Amerino (qtd. in Walsh, 1921)

The initial stage of a systems engineering process typically involves understanding the needs and priorities of the customer (and other stakeholders) and translating them into engineering requirements, as shown by the V-model of systems engineering in Figure 3-5.

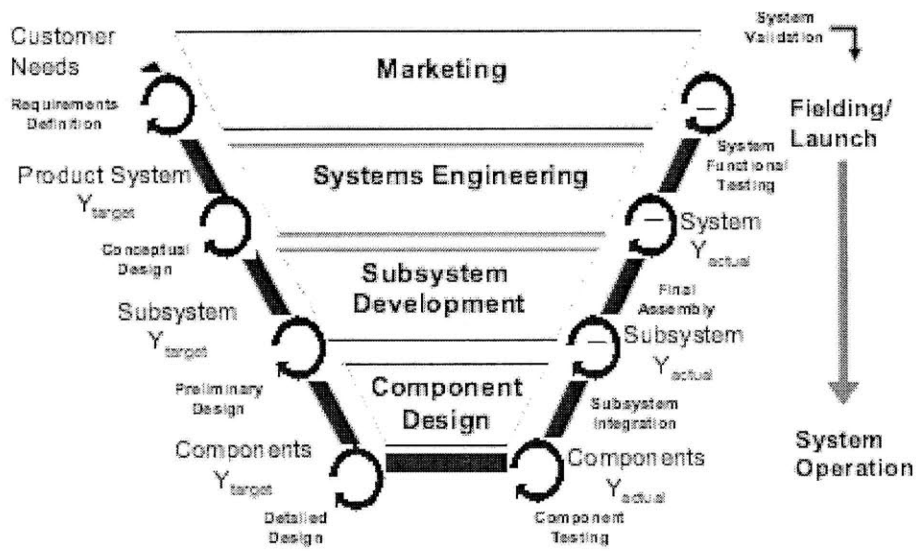

Figure 3-5: Systems Engineering V-Model (de Weck & Haberfellner, 2006)

Typical product development requires an enterprise to research the needs of a diverse population of potential customers with many disparate viewpoints and little knowledge of engineering requirements and trade-offs. Systems engineering uses Quality Function Deployment (QFD) to translate those needs into engineering metrics. In the case of an enterprise developing vehicles for the government, the situation can be different. The government, having carried out the task of analyzing their own needs, will normally provide a set of system requirements. Government requirements often include both threshold and objective values. Threshold requirements set a minimum performance level, anything below being considered unacceptable. Objective requirements are the desired level of performance, which the developer should strive for. (Wasson, 2006) This leaves the government contractor the task of developing a vehicle that best meets all of the threshold requirements, and objective requirements wherever possible.

3.3.1. Requirements Tradespace

"There ain't no such thing as a free lunch."
- Robert A. Heinlein (Heinlein, 1966)

Whether within the government's requirement setting process, or the contractor's development process to meet the government requirements, there exists a tradespace where conflicting vehicle attributes must be prioritized. "The realities of system development are that *EVERY requirement has a cost to implement and deliver.* Given limited resources and stakeholder values, bounding the *solution space* requires reconciling the cost of the desired requirements with the available resources." (Wasson, 2006) Commonly referenced is the "iron triangle" of payload, performance, and protection (see Figure 3-6). Payload might include occupants (including human factors accommodation), supplies, government furnished equipment (GFE), cargo, etc. Protection could consist of armor, ground clearance, armaments, countermeasures, etc. Performance incorporates a wide range of "automotive" attributes, such as fuel economy, acceleration, soft soil mobility, maximum gradeability, ride, handling, etc. Achieving a target in any of these areas must necessarily mean that some other attributes (including cost) suffer. An example might be a requirement to accommodate 95th percentile males within every seating position. An occupant package that is larger than it might otherwise be, (compared to 50th percentile accommodation), means that the surface area of any armor surrounding the occupants must be greater. This might then increase the weight of the armor, leading to lower fuel economy, slower acceleration, and poorer handling. Or perhaps to maintain vehicle weight, the armor thickness is decreased, resulting in greater vulnerability of the occupants. Or if protection levels must be maintained, then more exotic armor recipes might be used, increasing vehicle costs. The point here is that every system requirement is interrelated to other attributes, and must be questioned as to what level of performance is really needed, and understood as to what is being compromised. In order to enable understanding of these compromises, strict requirements are not set at this stage of the process. Instead, the requirement tradespace is specified, in which every requirement is given a range of potential values, including a low end of what might be barely acceptable, and a high end of what would be ideal.

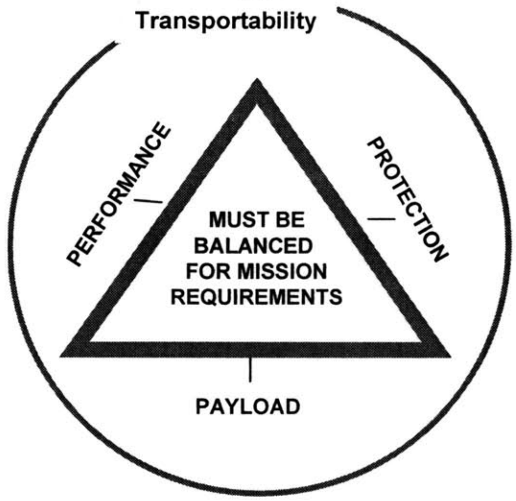

Figure 3-6: "Iron Triangle" of vehicle mission requirements (Petermann & Garza, 2008)

3.3.2. Requirements Process

As already noted, the starting point for requirements must always be the user (and stakeholder) needs, and translating them into system specifications. This will yield a vehicle wish list which is almost certain to be unbalanced and/or infeasible. The result of trying to meet this requirements wish list is a product that may be exorbitantly expensive, unreliable, or subject to lengthy development delays.

A case study in military vehicle development according to aggressive and conflicting requirements is the Expeditionary Fighting Vehicle (EFV). A core requirement of this 38 ton Infantry Fighting Vehicle was high speed (25 knot) over the horizon (75 mile) amphibious landing capability, which entails planing on the water. The demands of high performance as both a land crafting and combat vehicle have resulted in features such as a 2700 hp powerplant (more powerful than an M1 Abrams), and a flat bottom (vulnerable to mines and IEDs). Prototypes have been subject to criticism over frequent breakdowns, leaks, and corrosion, along with inability to operate in required three-foot seas. Competitive amphibious infantry fighting vehicles, such as the South Korean K-21, have made do with low swimming speeds, helping to maintain per-unit prices at a fraction of EFV costs ($3.5M versus $22.7M). (Hooper, 2008)

Included in the process should be requirements benchmarking. The benchmarking process helps to establish baseline requirements by establishing the range of existing operational performance. The low end of any attribute range might show the minimum of what would be acceptable (new programs will seldom want to aim to be worst-in-class for any attribute). The high end of any attribute range might define where increasing performance will be an engineering challenge, a compromise to other attributes, excessively expensive, or require new technology. A requirement shared across many programs might indicate a dominant expectation that will be difficult to challenge. For example, if a mobility requirement is shared across the entire vehicle fleet, not meeting the requirement may mean a new vehicle will have difficulty keeping up or crossing the same terrain. A comprehensive look across other vehicle requirements may turn up requirements which are not demanded by the users/stakeholders, but if overlooked could result in some shortcoming.

Having gone through these processes, it is possible to develop a complete baseline requirement tradespace. While not yet balanced, at least the user wish-list has been tempered by the current state-of-the-art. These requirements can be used to move forward with modeling and simulation, so that the requirements balance c an be evaluated. In particular for FED, requirements were identified according to likelihood of leverage upon fuel economy. For example, maximum speed on 5% grade capability may define the minimum power/engine size required, which impacts potential fuel economy. While the baseline requirements may set an expectation of what kind of speed on 5% grade performance is likely to be acceptable, modeling and simulation should be relied upon to establish quantitatively the tradeoffs, allowing a better informed requirements decision, and more opportunity to improve priority attributes such as fuel economy versus attributes which may be of lower value.

Ideally, vehicle requirements are written so as to be solution neutral. This means that the requirements should dictate capability, and not how that performance is accomplished. This is why requirements might require a maximum speed on 5% grade, and not a particular engine size or type. Unfortunately sometimes this is difficult or impossible, or requirements which appear to be solution neutral contain subtleties that discourage or penalize beneficial solutions. An interesting example of this is the case of infinite distance speed requirements, such as the aforementioned speed on 5% grade. Typical is JLTV, which states that "The JLTV-A-GP shall be capable of continuously ascending a 5-percent grade at 45 MPH at GVW (T), 60 MPH at GVW (O)." ("JLTV Purchase Description", 2008) The issue here is that hybrid-electric vehicle architecture derives some of its fuel efficiency benefits from the use of electric energy storage to contribute power during peak usage, so that the engine can be downsized for more efficient operation. The maximum speed of a hybrid vehicle is dependent upon its battery state-of-charge (SOC), therefore the vehicle must meet the speed requirement as written according to its performance without electric motor assist, and no engine downsizing is possible. In fact, due to the extra mass of the hybrid system, the engine might be larger than it otherwise would be. One solution is to create dash speed requirements, which allow a lower continuous performance, and recognize a shorter timeframe or distance for maximum performance. On the other hand, the user community might make the case that combat operations require robust availability of performance at any time, rather than risking mission failure due to inconvenient timing of battery exhaustion. There being no right answer, the best path is to include these issues within the requirements tradespace to be quantitatively explored though modeling and simulation. This way any preference for continuous performance requirements is informed by the inherent penalty in fuel economy, and decreased benefit of hybrid-electric architecture.

3.3.3. FED Requirements

For the FED program, the government provided initial baseline requirements based upon the performance of the M1114 HMMWV as its benchmark. HMMWV is useful as a benchmark, as it is the primary tactical wheeled vehicle for the current vehicle fleet of the U.S. Armed Forces. As an aging vehicle design, first fielded in the 1980's, it does present some advantages and disadvantages. Its primary advantage is that it provides a firm minimum for almost any vehicle attribute. It would be difficult to make the case for any aspect of the FED to be worse than a vehicle that has been in service for decades. By the same token, developing a new vehicle according to 1970's requirements could result in a lack of relevancy to today's mission requirements. Therefore, the process of requirements benchmarking identified areas that would need to be addressed in order to be comparable to current and future vehicle programs. As was previously noted, factors driving increased fuel usage on the battlefield include armor protection and electrical power generation, and so objective requirements were developed for FED in these areas, amongst others.

Also notable for the development of FED requirements was the program's objective as a demonstration rather than a production program. This allows a focus on requirements that are relevant to its mission of demonstrating fuel economy improvements, and removal of requirements that distract from that mission. An example is fire suppression. For a modern tactical vehicle expected to perform in combat operations, such as JLTV, there might be a requirement for an automatic fire suppression system that would address the effects of various threats. For a demonstrator vehicle, as long as its payload capability is great enough to incorporate systems like automatic fire suppression, there is no reason to spend finite resources on the integration of such a system. Overall focus on objectives and stakeholder needs for the demonstrator program should maximize the investment into fuel saving technologies, although it could undercut the ease in bringing the FED vehicle into production should there ever be a change in plans.

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4. Characterization Phase

The characterization phase seeks to define product architecture, develop system models, and identify technology options. The intent is to transform functional requirements and objectives from the definition phase into concepts that provide design alternatives. This phase can be considered to be primarily made up of three processes:

- Model Development – Development of a variety of models to represent the architectural design space and provide a means of predicting performance and utility. Deliverables for up to several baseline (and benchmark) architectures include:
  - CAD model
  - Bill of Material
  - Performance prediction model
- Prioritization – Use of systems engineering methods to provide focus areas for maximum improvement. Deliverables include:
  - Key subsystem attributes
  - Energy balance
  - Technology map
- Market outreach – Structured outreach efforts to identify technology alternatives, focused on obtaining quantitative data for key subsystem attributes to support modeling and simulation. End deliverable is:
  - Technology market survey

These deliverables will be described in detail within the following sections. The key processes, their relationships, inputs, and deliverables, are summarized within Figure 4-1.

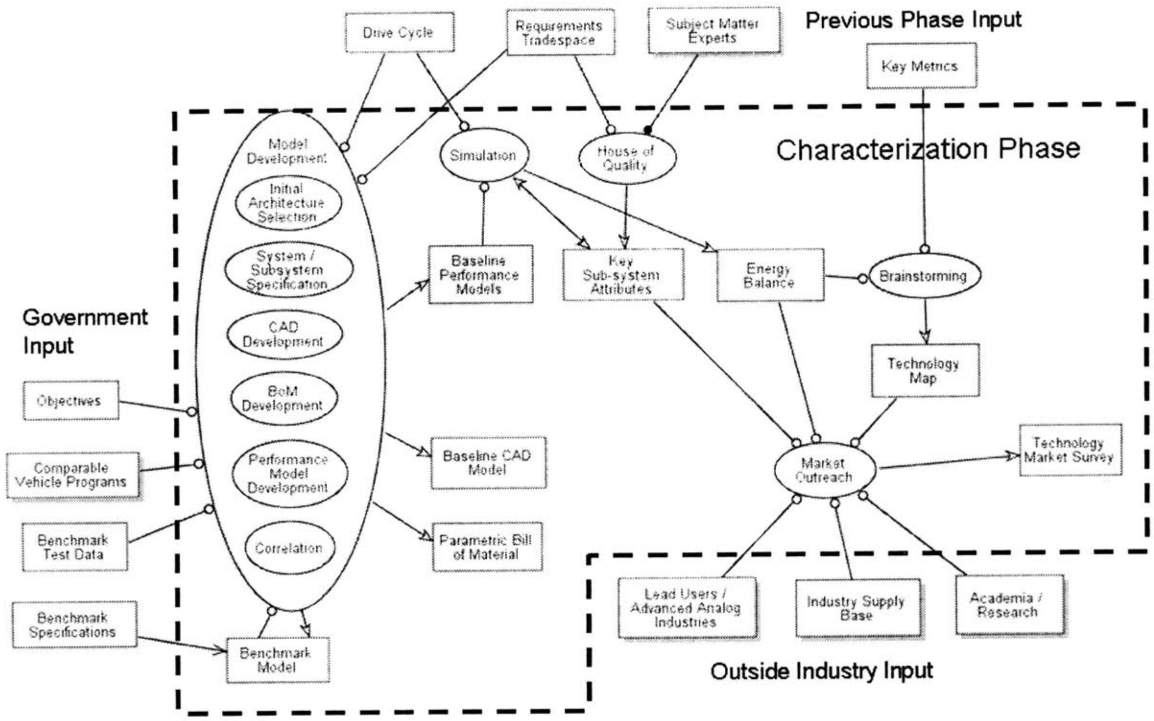

Figure 4-1: Characterization Phase process elements and inputs (see Section 2.4 for OPM key)

4.1. Model Development

"A model is a mapping of the system-of-interest onto a simpler representation which approximates the behavior of the system-of-interest in selected areas." (Haskins, 2006)

4.1.1. Baseline Architecture

It is important to the systems engineering process to understand and account for the role of system architecture. Architecture can be defined as "the embodiment of concept, and the allocation of physical/informational function to elements of form, and definition of interfaces among the elements and with the surrounding context." (Crawley, 2008a) In terms of vehicle engineering, this can be explained as the basic physical components of the vehicle and how they interface with each other for the functionality of the vehicle system. The FED for example, is intended to be a 4x4 wheeled vehicle, as opposed to a front wheel drive, a 6x6, a tracked vehicle, or even a half-track, defining some of its basic chassis and driveline architecture. The driveline architecture can be further defined according to whether the transfer case is mounted directly to the transmission, remote mounted and connected by a prop-shaft, or dispensed with altogether through the use of hub mounted electric motors. Examples of powertrain and driveline architecture are shown in Figure 4-2. These are architectural decisions, which as shown in Figure 4-3, must be made in order to develop system models.

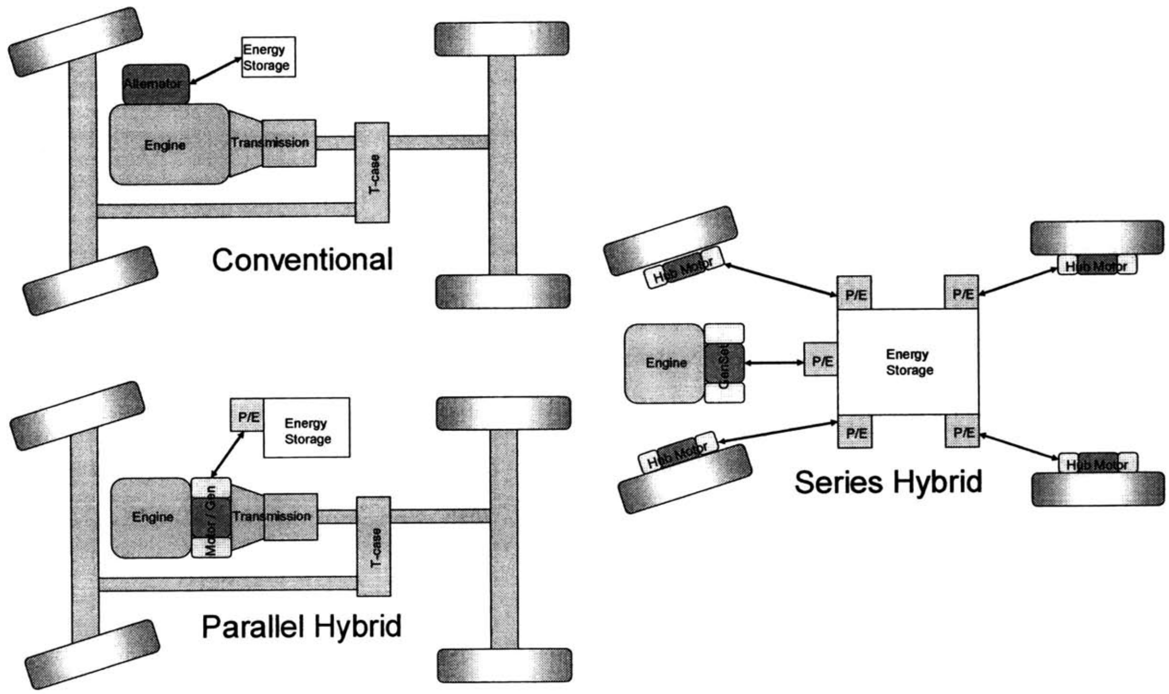

Figure 4-2: Examples of powertrain & driveline architecture

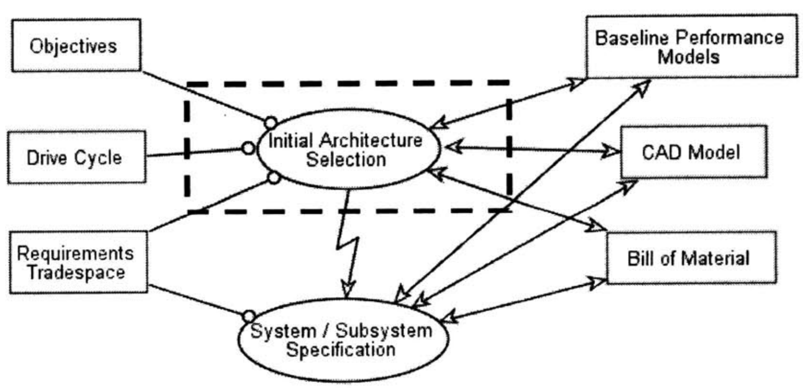

Figure 4-3: Architecture selection process, including supporting instruments and affected deliverables (see Section 2.4 for OPM key)

It is necessary to make decisions around which basic vehicle architecture will be explored relatively early within the development process. These decisions will form the basis of the design alternatives evaluated through modeling and simulation. This step does pose a dilemma in which decisions must be made without the benefit of complete quantitative data, which may result in an imbalance in operational capabilities, or even some requirements being impossible to meet. Unfortunately, it is virtually impossible to complete the requirements for a complex system without some idea of what the resulting system is likely to be. (Rechtin, 1991) However, the requirements tradespace developed within the definition phase is intended to allow some architectural freedom so that there is an iterative process of fit, balance, and compromise. Therefore each baseline architecture should be considered not as a specific vehicle design to be completed, but rather a design space to be evaluated against a range of specifications, requirements, and technologies within the modeling and simulation environment. While in some cases a single baseline architecture may be sufficient, more often it is recommended that several baselines be explored to allow a greater breadth of design alternatives, particularly if subject matter experts are unable to definitively conclude which architecture is most suitable without additional data.

Benchmark Architecture

An initial architecture that should be considered and developed within the modeling and simulation environment is that of the benchmark vehicle or class of vehicles. This is the current dominant design which any proposed improvements should be compared against. For the FED, the benchmark is the M1114 HMMWV. Even though the benchmark has an existing fleet of vehicles and test data, it is still necessary to create a simulation model of the vehicle, as it will serve multiple purposes for the FED methodology. The first purpose is that while test data exists, the project has defined a unique drive cycle, so without a model it is not known how the benchmark performs against that cycle. If the program objective is to increase fuel economy by XX%, then simulating the benchmark over the drive cycle provides the comparator for that improvement. Secondly, the benchmark fuel economy helps to establish the credibility of the proposed drive cycle. If great differences exist between fuel consumption predicted by the benchmark model and that of the existing vehicle fleet in the field, there may be a flaw in the drive cycle definition (although some difference may be driven by the specifics of the theatre of operation being more heavily weighted toward certain usages.) Finally, it is beneficial to correlate a model to existing test data, so as to ensure the accuracy of the software and modeling approach. There will of course still be potential for issues with accuracy as the technology, architecture, and specification deviate from the benchmark design, but starting with an accurate model will help to keep these issues to a minimum.

<u>Baseline Selection</u>

This methodology differs in some common nomenclature. While some studies would treat the benchmark as the project "baseline", in this case there is a clear separation between the benchmark and the baseline. The benchmark is an existing design that the project is being compared against. The baseline(s) are architectural configurations being designed to compete with the benchmark. They may or may not share common architecture with the benchmark, and each exists as the center of a design space rather than a mature design.

Defining and selecting architecture for formal evaluation within the systems engineering methodology is inherently difficult. Even within the constraint of four-wheeled vehicle systems, there exist trillions of architectural combinations. A complete, quantitative evaluation of every combination would likely require unobtainable computing power, time, and resources. Even a methodology designed to cast a wide net requires a narrowing of possibilities. However, having already defined the baseline requirements and drive cycle, it is possible to dismiss many options which are not well suited for the application, do not have a reasonable chance of meeting requirements, or are inherently less efficient than other options. For the FED, electric-only vehicles were eliminated from consideration. Potential for meeting range requirements through battery technology appeared to be many years outside the scope of the project, and electric power for recharge is not reliably available within the battlespace and might be generated by diesel generators anyway. Conversely, hybrid-electric powertrain architecture was prioritized for FED over other forms of hybridization, including hydraulic, kinetic, and pneumatic. This was partly driven by the drive cycle, and partly driven by the synergies between the architecture and the increasing demand for onboard electrical power. The driving factor behind architectural decisions such as these was the use of subject matter expertise, coupled with clearly defined objectives and usage profiles. Maier and Rechtin ask the question, "How can the architect possibly know before there is a detailed system design, much less before a system test, what details of what subsystem are critical?" Their answer is that "only through experience, through encouraging open dialog with subsystem specialists, and by being a quick, selective, tactful, and effective student of the system and its needs." (Maier & Rechtin, 2002)

Some architecture selection requires an assessment of impact on modeling and simulation. In the case of FED, modeling and simulation was focused upon performance prediction, including fuel consumption, speed, and acceleration. Architectural decisions which could be characterized in terms of attributes within the performance model could be easily accommodated. An example is the issue of whether or not to use geared wheel hubs (reduction gearing within the wheel ends). There are both advantages and risks involved with eliminating geared hubs, making it a difficult decision. At this stage of the process, there is relatively little information available to quantitatively define the advantage, or demonstrate the feasibility and any compromises; therefore if possible it is better to retain this as an option within the architectural design space. Fortunately in this case, effects of geared hubs on vehicle performance can be characterized very simply by mass and driveline efficiency. As will be seen in Section 5.1, sweeping these attributes within a design of experiments will allow vehicle level effects to be demonstrated in combination with scores of other options. Therefore, geared/non-geared hubs can be modeled as an option within the design space, rather than defining the baseline architecture itself. In contrast, a parallel hybrid powertrain compared to a conventional powertrain, carries with it a wide range of unique interactions and controls issues, and so requires a unique model for simulating its performance. Due to the computing resources required to comprehensively explore the design space around each baseline, there is a requirement at this point to narrow the field of options requiring a unique model. This field of baseline architectural options may undergo iterations as technology options are developed within the technology market survey in Section 4.3.

An additional technique for architecture development is the use of a morphological matrix. "The morphological matrix represents a methodology for organizing alternative solutions for each function of a system and combining them to generate a great number of solution variants each of which can potentially satisfy the system level design need." The format of the matrix, as shown in Figure 4-4, is a grid listing relevant functions versus possible solutions that will achieve the function. Individual solution selections are then combined into conceptual designs. This is a structured method of creating design alternatives that may not have otherwise been considered. (Weber & Condoor, 1998) Figure

4-4 shows selections that make up some typical powertrain configurations, including conventional, parallel hybrid, and series hybrid. However, even this relatively small matrix shows the potential for 216 unique powertrain configurations, many of which may not be feasible, while others may prove to be both useful and innovative.

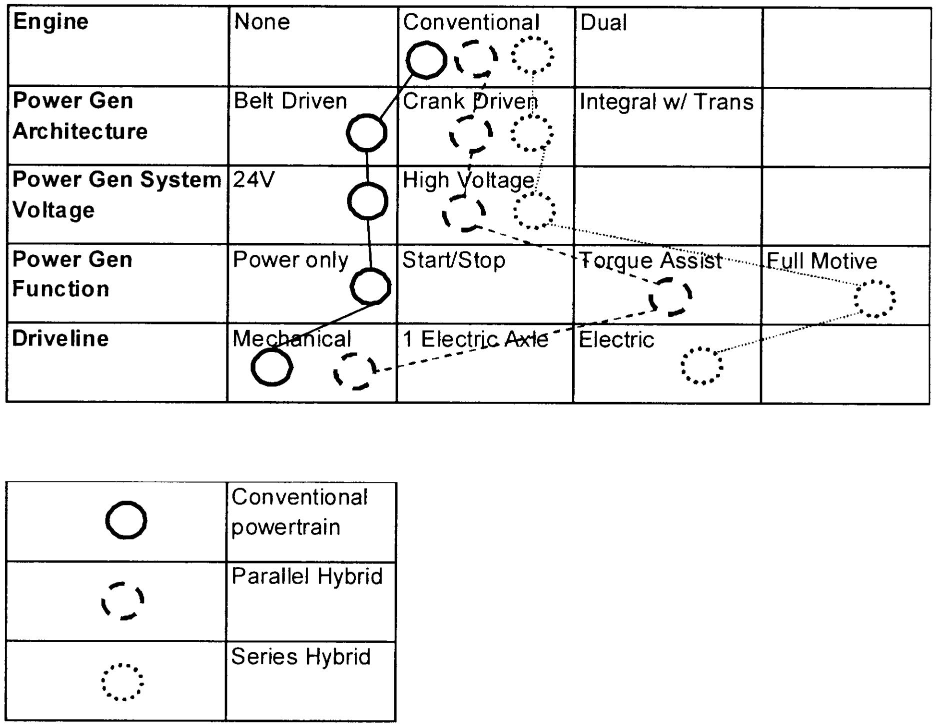

Figure 4-4: Example morphological matrix for powertrain hybridization

Baseline architectural options for FED focused upon alternative powertrain solutions, particularly the extent and type of hybridization. This does ignore a wide range of architectural options that exist in vehicle design. The vehicle structure for instance offers many architectural opportunities, including body-on-frame, space frame, monocoque, and combinations thereof. From the standpoint of the FED program however, the utility of the structure is judged primarily according to its mass, which in performance modeling and simulation is included within a simple sweep of the vehicle mass. Selection of baseline architectures should be concerned with modeling different behaviors. A series hybrid will perform very differently than a conventional powertrain and will require a unique model, while the behavior of either option is indifferent to whether the structure is monocoque, so long as the mass effects are captured.

4.1.2. Bill of Material

Most of this systems engineering methodology requires a top down approach to the vehicle system, starting from the user/stakeholder needs, translating to system requirements, and decomposing to subsystem and component specifications. The Bill of Material (BoM) is an exception in defining the vehicle system from the bottom up. The BoM should consist of a complete hierarchical list of vehicle components, along with significant information for each component. The vehicle requirements may require a curb weight of 10,000 lbs. While it is possible to simulate vehicle performance at 10,000 lbs or any other weight, the BoM provides a process of evaluating feasibility, as the mass of every subsystem or component must be accounted for. This drives discipline into the concept development process, as component and subsystem assumptions must be made explicit. As shown in Figure 4-5, the BoM also provides a useful decomposition of key vehicle metrics such as cost or weight. The process of developing a BoM is highly iterative and inter-related with development of other vehicle models, as demonstrated in Figure 4-6.

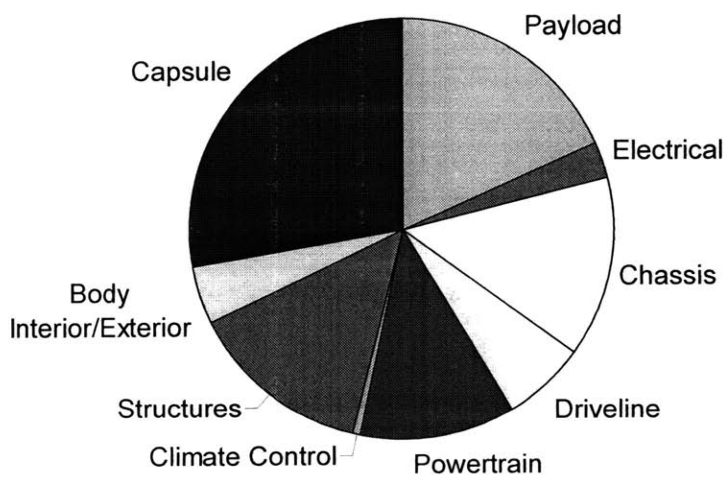

Figure 4-5: Example vehicle mass decomposition according to a Bill of Material

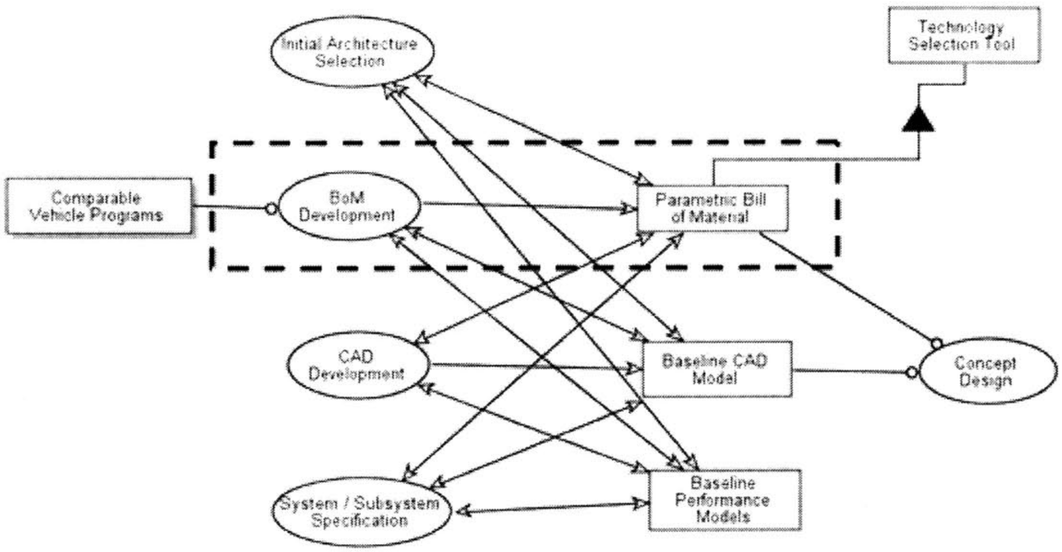

Figure 4-6: Bill of Material development process, including supporting instruments, inter-related processes, and affected deliverables. (see Section 2.4 for OPM key)

There are numerous pitfalls in the BoM development process, in particular with the accuracy that is possible during early concept development. Components are often missing, skewing total vehicle sums for cost or weight toward the low end of what is possible. Many components will lack accurate data until later in the vehicle development process, making the summation of many estimates relatively inaccurate. One method of offsetting these issues is the use of benchmark data. In particular, if the enterprise has developed other vehicles from a similar class, their BoM can be utilized as the basis of the new vehicle concept BoM, with modifications appropriate to the unique requirements. With or without such data, BoM accuracy will increase over time, subject to the subsystem specification process and supplier outreach.

An interesting aspect of this methodology is the development of a parametric BoM for inclusion to the performance generation tools discussed later in Section 5.3. This is essentially the merger of the requirements tradespace and the BoM, so that the BoM adjusts according to varying requirements scenarios. If for example the payload requirement tradespace were to vary from 2000 lbs to 5000 lbs, the vehicle system will require an upgrade to certain sub-systems in order to accommodate the 3000 lbs increase. These upgrades could take the form of higher capacity differentials, larger tires, thicker gauged structures, larger engine, etc. In order to make driveline components such as the differentials adjustable, a curve can be developed as shown in Figure 4-7 for the component weight versus capacity, based upon benchmark examples. Within the BoM, calculations are made wherein a baseline mass is adjusted according to this mass compounding effect. This is a valuable step in defining the feasible design space for the vehicle. Various requirements can drive mass compounding ("weight begets weight"). Increased occupant accommodation can result in a larger, heavier cab. More aggressive climate control requirements can result in a larger, heavier HVAC system. The level of detail and the extent of component adjustability needed are largely dependent on the tradespace identified in Section 3.3.1 and the magnitude of impact. It should be noted that the method of using a specification curve can be optimistic in its mass compounding because it assumes systems are sized precisely for the vehicle requirements, while commercial availability or commonality requirements will often dictate a step function for component specifications. Therefore in some cases a selection of single point component options rather than a mass curve should be included in the BoM.

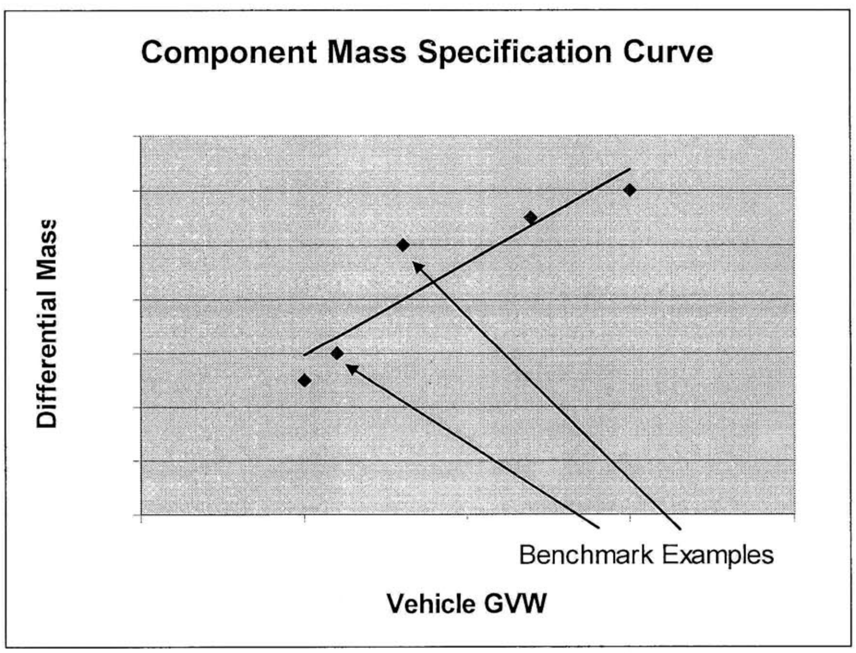

Figure 4-7: Example mass specification curve; differential mass might increase approximately linearly versus vehicle GVW according to existing benchmark components

4.1.3. Baseline CAD Model

The baseline CAD model is the development of a design representative of the vehicle concept architecture. This fulfils an important step in the development of complex systems, taking existing requirements and constructing a provisional model of the system in order to satisfy most of them. It is a similar role to the bill of material, providing feasibility to the design space assumptions. The provisional model produces questions that call for value judgments and architectural analyses, which are likely to result in modifications to both the model and requirements. (Rechtin, 1991) The baseline CAD model is also the center of the design space, used to support the development of performance simulations. Like the BoM, the development of the vehicle CAD model is highly iterative and inter-related with other processes, as demonstrated in Figure 4-8.

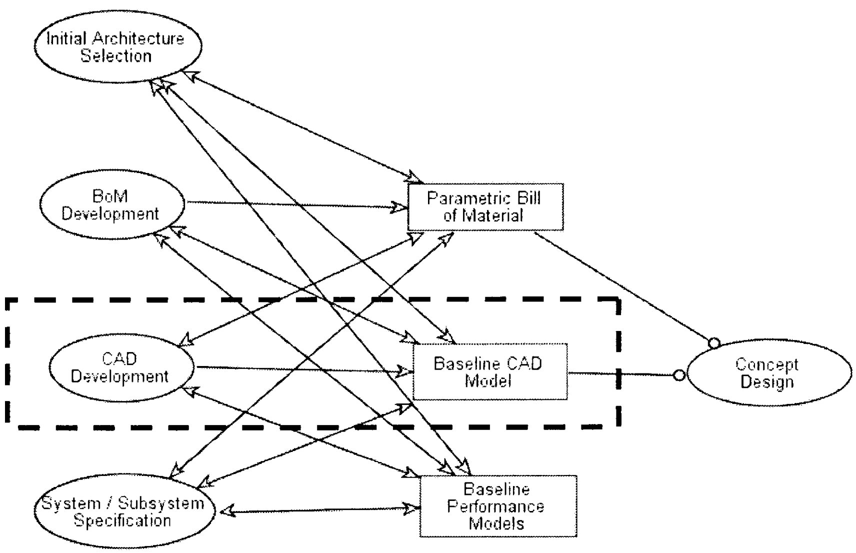

Figure 4-8: Baseline CAD model development, instruments for and outputs (see Section 2.4 for OPM key)

An example to consider is vehicle wheelbase. Based on initial engineering estimates and benchmarking, the vehicle wheelbase might be assumed to be 100 in. Until a CAD model is developed, it may be unclear as to the feasibility of the estimate. Conflicting requirements might drive a 80 in. wheelbase in order to meet an aggressive turning circle, and 120 in. wheelbase to accommodate a long capsule designed for multi-row passenger accommodation. Attempting to design a vehicle according to the baseline requirements, even at the level of concept layouts, will rapidly identify issues within the requirements tradespace. It may even identify missing requirements as the development of the design highlights parameters which are unconstrained.

4.1.4. Performance Prediction Modeling

As was previously noted, an initial step in the development of complex systems is to develop a provisional model of the system in order to attempt to satisfy the system requirements. Thus far this modeling has taken several forms including baseline architectural selections, bill of material development, and baseline CAD model development. There is any number of additional models which could be developed, constrained only by the number of meaningful vehicle attributes and available techniques including "sketches, physical-scale models, program descriptions, network maps, computer simulations, sets of equations, spreadsheets, block diagrams, charts, and graphs". (Richtin, 1991) If vehicle ride and handling dynamics are deemed to be a high priority, or aggressive requirements leave it in doubt as to whether the architecture is capable of meeting them, or requirements are likely to cause significant compromises (as demonstrated within the QFD process), then a vehicle dynamics model using software such as MSC Adams might be used. The process of developing models is outlined in Figure 4-9, including supporting instruments and processes and affected deliverables.

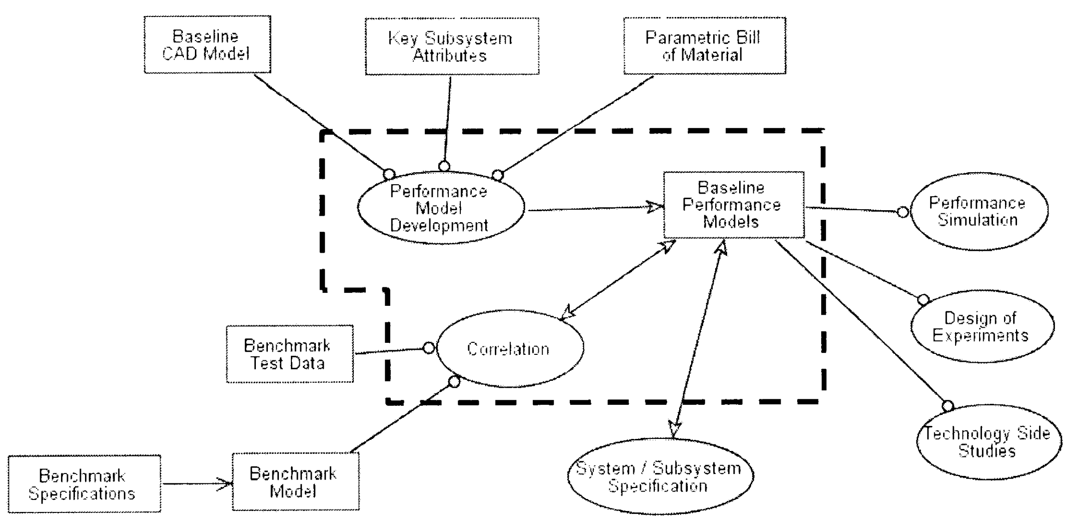

Figure 4-9: Performance prediction model development, including supporting instruments and processes, and affected deliverables (see Section 2.4 for OPM key)

In the case of FED, fuel efficiency was the overriding concern, so priority through this process was on vehicle performance prediction modeling and simulation. FED utilized MSC EASY5, a schematic-based simulation tool, "used to model and simulate dynamic systems containing multi-domain subsystems characterized by differential and algebraic equations." These systems included hydraulic, mechanical, pneumatic, thermal, electrical, and digital systems, using component libraries including the Ricardo powertrain library. Component libraries were developed in order to model automotive systems such as the engine, cycle driver, transmission, driveline, tires, etc.

Vehicle system simulation is capable of producing a range of useful information relating to performance, including maximum speed under various conditions (including grade), acceleration times, operational range, and most importantly, fuel efficiency over a drive cycle. Many inputs and assumptions are required to support this modeling and simulation. The driver model includes the drive cycle discussed in Section 3.2 , but also driver control assumptions such as tip in / tip out schedule and brake control (subject to the issue with exogenous input discussed in Section 3.2.3). The engine model requires torque curves, fuel maps, and other engine parameters. Vehicle level inputs include CdA, weight, rolling resistance, etc. In many cases the model can be kept relatively simple, lumping sub-system attributes where appropriate for a lower level of sub-system fidelity, minimizing the resources and assumptions required for useful high level results. Multiple simulations can be quickly run using selectable modifiers, set up to allow changes representative of varying vehicle architectures. (Stewart, 2008) This flexibility is crucial to the methodology, allowing eventual design space definition through design of experiments (DoE).

4.1.5. System / Subsystem Specification

The V-model of Systems Engineering, as shown in Figure 3-5, requires vehicle requirements to be cascaded and decomposed into subsystems and components. As an example, this means that system requirements such as X mph maximum speed on 5% grade, requires subsystem level specifications such as X hp powertrain, X% drivetrain efficiency, X tire rolling resistance coefficient, and X CdA. Subsystem specification development is an iterative process affecting the vehicle requirements, baseline architecture, baseline CAD models, and baseline performance models. Subsystem specifications may exist as a range of values in order to support the requirements tradespace. If potential maximum speed on 5%

grade exists as a range from 55 mph to 70 mph, then there is likely to be a range of available engine horsepower, requiring a range of engine masses within the BoM, and some consideration of maximum and minimum engine packages within the baseline CAD design. As can be seen in Figure 4-10, sub-system specification is an integral input (as well as an iterative output) of nearly all vehicle models.

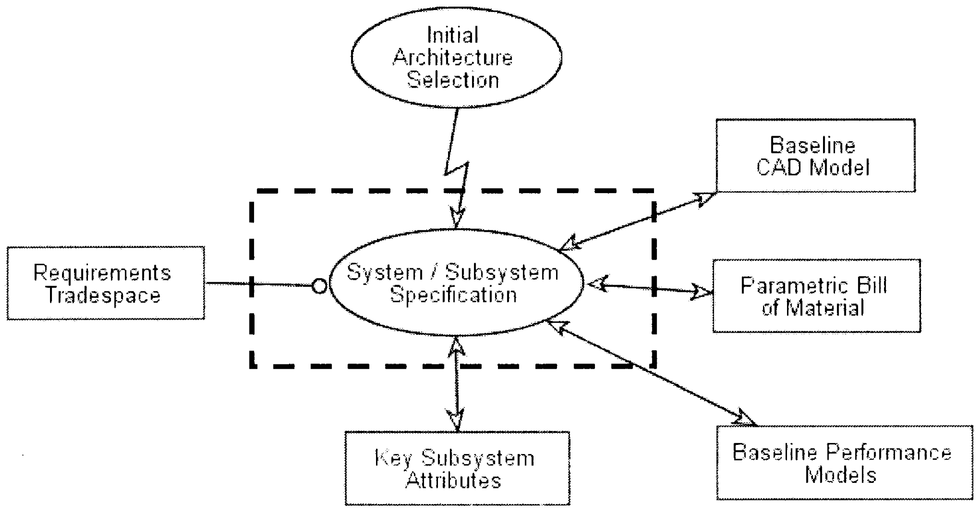

Figure 4-10: System / subsystem specification development, including supporting instruments, inter-related processes, and affected deliverables (see Section 2.4 for OPM key)

While executing the V-model through the entire development process will eventually lead to specifications for every component (traceable to system requirements), at this stage of the methodology, the level of detail should be focused on that required to support performance prediction modeling. Eventually, an engine may require specifications for its piston connecting rods in order to support requirements for power, torque, speed, durability, etc., but that level of detail does not add value to the process at this stage. The emphasis should be on understanding engine selection and its effect on vehicle fuel economy and performance, rather than the intricate details of engine design.

4.2. Prioritization

4.2.1. Key Subsystem Attributes

Another step toward characterizing the vehicle system is the definition of key subsystem attributes, their effects, and inter-relationships. As previously discussed, in the systems engineering V-model vehicle level requirements are decomposed in a top-down approach, supported by the "House of Quality", the basic tool of Quality Function Deployment (QFD). This is a qualitative approach, utilizing a conceptual map, as shown in Figure 4-11, that provides a means of interfunctional planning (Hauser & Clausing, 1988). At this stage of QFD, rather than using the House of Quality to demonstrate the relationship between customer needs and system engineering requirements, the tool is used to characterize system level requirements to subsystem specifications. If a system level requirement is the maximum speed on 5% grade, the House of Quality should then highlight subsystem attributes including engine power, driveline efficiency, tire rolling resistance, and coefficient of aerodynamic drag as correlating to some degree. The matrix would also show relationships between subsystem attributes, such as a correlation between engine power and engine mass.

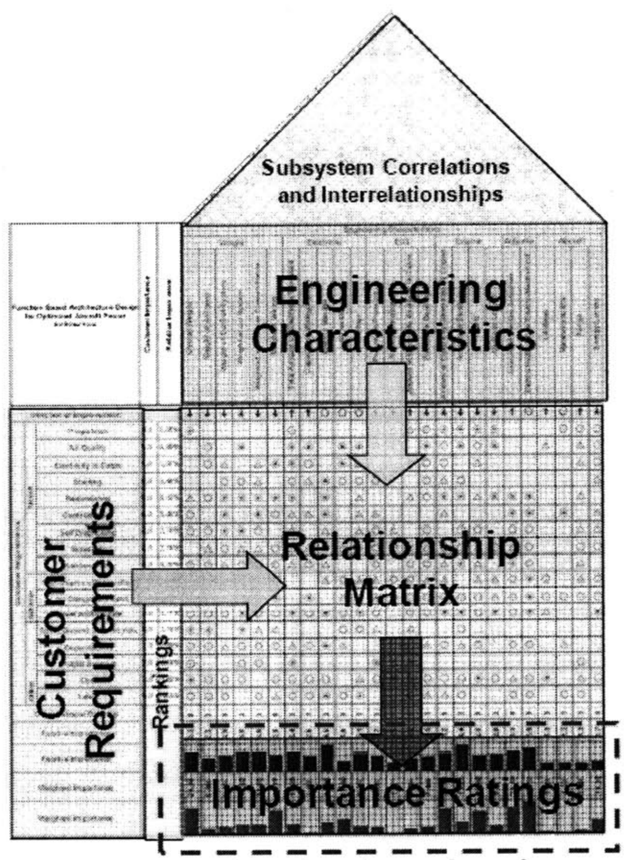

Figure 4-11: House of Quality overview (Ender, McDermott, & Mavris, 2009)

One way in which the definition of subsystem attributes is valuable is providing feedback and prioritization into other processes within the methodology, as shown in Figure 4-12. First it provides feedback into the requirements engineering process outlined in Section 3.3. As subject matter experts identify what are expected to be key subsystem attributes and their relationship to vehicle-level requirements, it becomes apparent if there are cases where no relationship exists. This indicates that there may be missing vehicle-level requirements. Likewise, if a vehicle-level requirement exists without any subsystem relationship, then the subsystem attribute process is likely to be incomplete. Identification of key subsystem attributes also highlight any issue that may exist within the model development in Section 4.1, ensuring the process accounts for all relevant inputs and effects for increased accuracy.

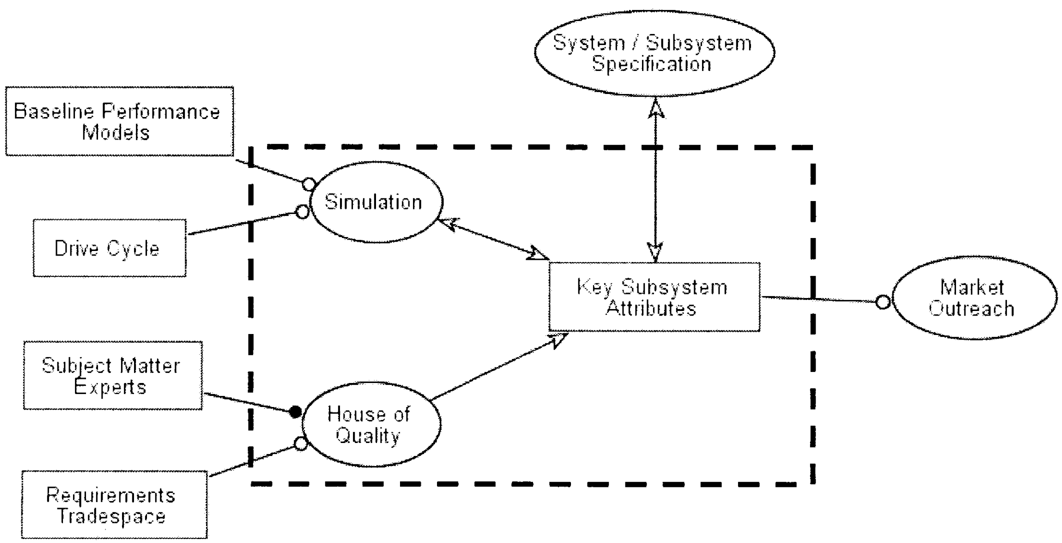

Figure 4-12: Processes supporting the identification of key subsystem attributes, and subsequent usage (see Section 2.4 for OPM key)

The key output for the sub-system attribute process is providing support for the technology market survey process, further discussed in Section 4.3. In evaluating products and technologies from the supply base and other sources, it is useful to have a complete set of attributes in which the technology will impact the system capabilities. Nearly every technology will have both beneficial and negative attributes to trade off, often with very complex inter-relationships with other subsystems. The usefulness of the technology survey is maximized by obtaining all of the data required to support multi-attribute decision making.

4.2.2. Energy Balance

In order to determine how energy efficiency of a system can be improved, it is necessary to first understand where energy is being expended. This will allow prioritization of efficiency improvements where there is the greatest potential gain, focusing later investigations of technology and design options (see Figure 4-13). The method of analysis used is the compilation of vehicle energy balance. This is a simple breakdown of the proportion of total energy expended within each area or sub-system, determined by using the baseline performance models to simulate operation over the drive cycle. Areas of expenditure might include aerodynamic drag, driveline friction losses, tire rolling resistance, accessory loads, etc. Sometimes the energy balance is separated out into two categories, the engine energy balance and vehicle energy balance, as shown in Figure 4-14. The engine energy balance diagram represents all of the chemical energy contained in every gallon of diesel consumed and losses in its conversion into mechanical energy (brake power) by the engine. The vehicle energy balance diagram represents the consumption of all of the brake power produced by the engine. Used together, the energy balance diagrams represent "tank to wheels" fuel consumption.

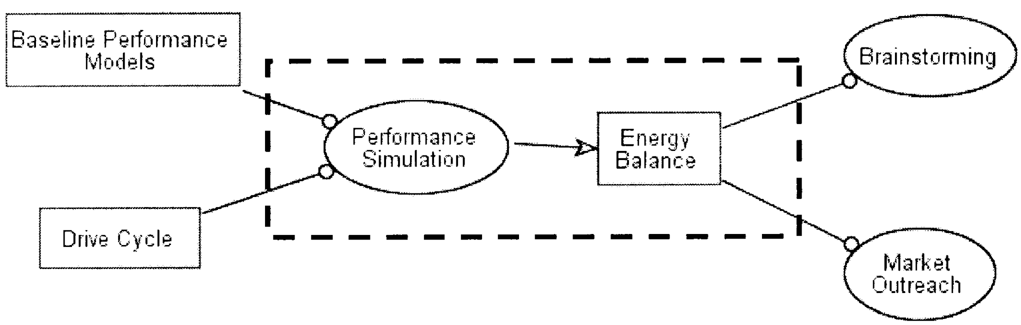

Figure 4-13: Vehicle energy balance development and affected processes (see Section 2.4 for OPM key)

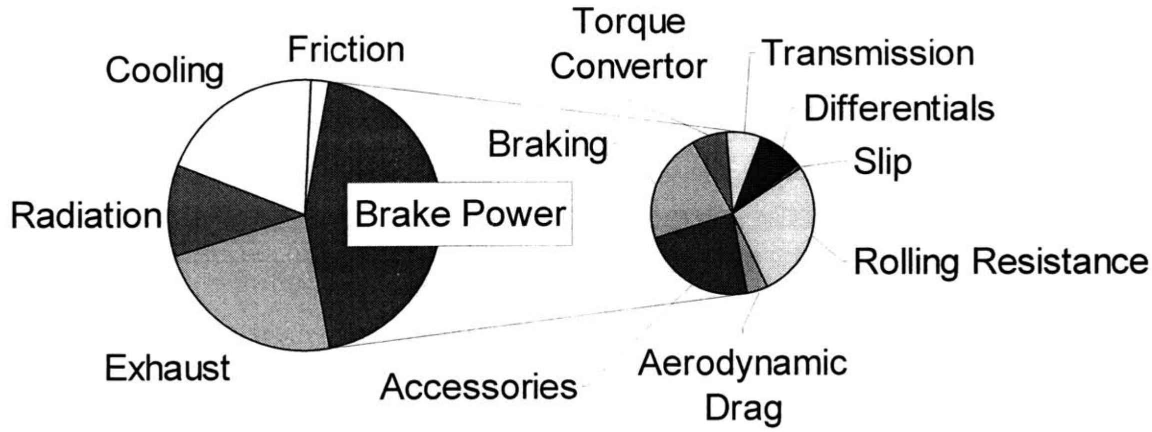

Figure 4-14: Example energy balance diagrams, including engine energy balance (left) and vehicle energy balance (right).

Each energy balance is specific to the vehicle architecture and specifications as well as the drive cycle. As noted previously, each drive cycle will demonstrate different characteristics. A high speed drive cycle will tend to accentuate aerodynamic drag, while an urban stop-start cycle might show braking as the dominant expenditure. Technology and architecture will also drive differences in the energy balance. Automatic transmissions would show torque converter losses that are eliminated using a manual transmission.

Energy balances essentially translate drive cycle data (traces of vehicle speed, climbing, etc) into discrete system / sub-system level engineering metrics. It could be seen as analogous to a QFD translation of the Voice of the Customer into the Voice of the Engineer. The specific vehicle application and drive cycle can be viewed on the basis of the energy balance, and actions taken accordingly. According to the examples shown in Figure 4-14, an engineering team might consider heat recovery technologies (reuse of the energy normally rejected through the engine exhaust and coolant) and regenerative braking (reuse of the energy normally lost as heat in the brake system). The team might also spend relatively little resources toward improving aerodynamic drag. While the examples show the energy balance in terms of a high level breakdown, more detailed study of each category is sometimes necessary in order to further guide prioritization. Accessory loads could be shown in terms of power steering, climate control, cooling pumps, etc. More detailed breakdowns can also highlight issues with the model not including all relevant factors and systems.

While energy balance can be a powerful method for guiding improvement, there are issues with its use and misuse. One is that comparing vehicles on the basis of percentile breakdowns and pie charts can be misleading. Take for example two vehicles, identical except for one which has lower accessory loads. As the accessory loads are lower, proportionally all other energy usages will be a higher percentage. Without the proper context, one could conclude that the rolling resistance of vehicle A is higher than vehicle B in absolute terms. This is one argument for presenting the data in terms of units of energy or power, rather than percentages. Another related issue is the lack of focus on total energy usage and attributes that drive energy usage across many categories. Weight for example is not included within the energy balance. Increased weight will require a more powerful engine to meet requirements, resulting in more energy lost in the power conversion. Weight will increase driveline torque, increasing friction losses, and increase the energy expended in braking the vehicle. These and other energy expenditures highlight the issue of vehicle weight, but the energy balance will not effectively demonstrate this sensitivity.

It should also be noted that energy balance only highlights the potential for increasing energy efficiency. It does not demonstrate where there is leverage to actually do so. Even if twice the energy is expended in rolling resistance as braking, that does not guarantee the technological means exists to reduce rolling resistance. The subsequent stages in this phase will focus on identifying the means to reduce the energy expediture.

4.2.3. Ideation

"Necessity, who is the mother of invention"
- Plato (Plato, 1976/360BC)

At this point in the process (as shown in Figure 4-15), the engineering team has a number of sources of information at their disposal:

- Objectives and key performance metrics
- Drive Cycle
- Energy balance

Teams of subject matter experts in various vehicle systems can now effectively generate leads for methods of increasing fuel efficiency. Obviously brainstorming can be carried out at any point in the process, but having this data allows the exercise to be guided by the objectives and key metrics, while focusing on the fertile ground identified by the energy balance. Initial vehicle concept design and usage cycle definition also provides some focus on what is likely to be appropriate for the application. Earlier brainstorming exercises might be more freewheeling and creative, with no limitations on what might be suggested. These types of sessions are valid and important and can identify breakthrough ideas. However, it is important to also proceed with the narrower exercise, where subject matter experts can focus on identifying the most viable approaches to proceed with based on the available data.

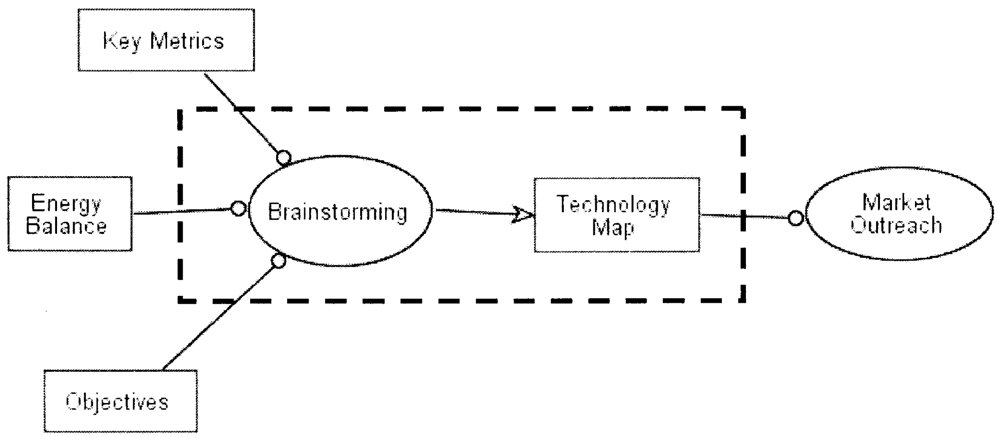

Figure 4-15: Idea development, including supporting instruments and affected deliverables (see Section 2.4 for OPM key)

During the ideation process, all areas of potential leverage on fuel efficiency should be sought. While the tendency might be to focus on new technologies, there are other areas of product definition that can make just as great an impact:

- Requirements – conditions required by the vehicle to meet objectives (e.g. 70 mph max speed on 5% grade)
- Architecture – form, function, and interface of vehicle systems (e.g. body-on-frame structure)
- Subsystem Specifications – characteristics of systems & sub-systems required to meet objectives (e.g. 300 hp engine)

Proposed fuel efficiency improvements can be organized within a "mind map" format, as shown in Figure 4-16. This is a diagram that presents ideas in a radial, graphical, non-linear manner, classified into hierarchical branches and groupings. This is in contrast to a "road map" that organizes actions into a linear series, usually versus time, as in Figure 4-17. The mind map approach allows an initial focus upon the fundamentals of energy usage, with all proposals shown according to their relationship with the fundamentals and each other.

This approach also avoids excessive focus around sub-systems. Many approaches to fuel efficiency apply to or combine multiple sub-systems. An obvious example is the hybrid-electric powertrain, which requires functions across the engine, driveline, braking, controls and electronics systems.

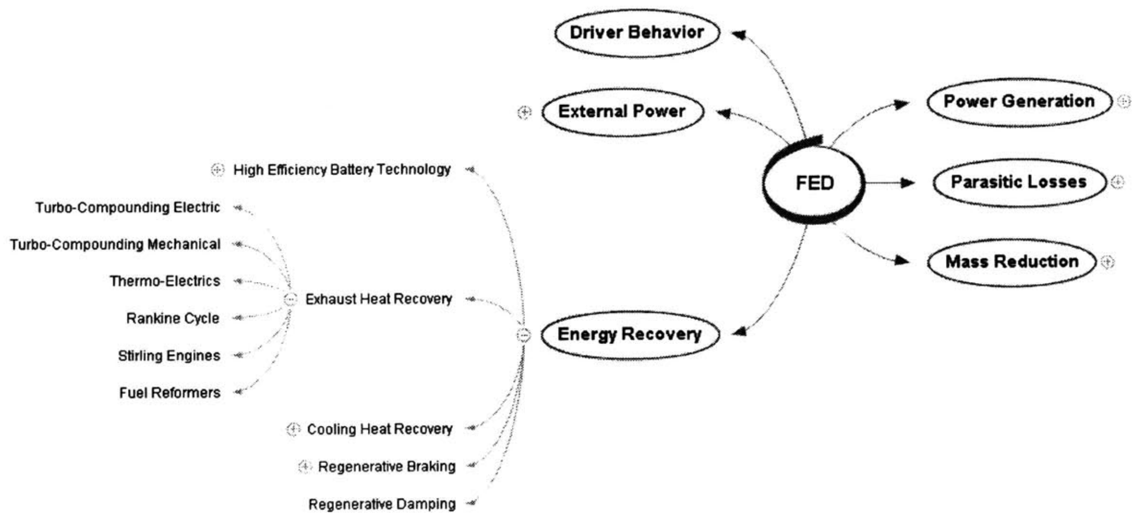

Figure 4-16: Technology mind map for fuel efficiency measures

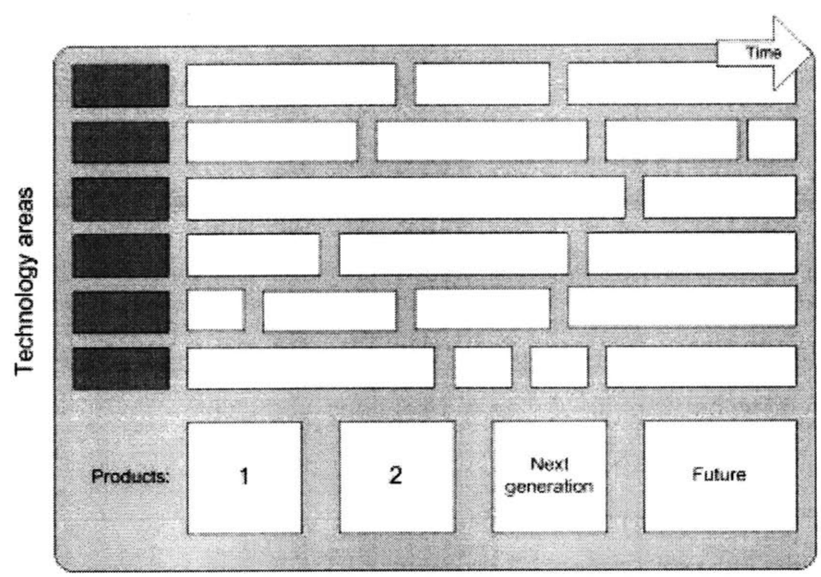

Figure 4-17: Example of linear technology roadmap (Eckroese, 2006)

Several fundamentals of energy usage should be considered as the core of the fuel efficiency mind map. These are:

- External Power (obtaining energy from sources other than fuel tank, e.g. plug-in hybrid capability)

- Parasitic Loads (consumption of all energy generated by engine, e.g. aerodynamic drag)
- Power Generation (efficiency of converting fuel into useful mechanical or electrical power or reducing overall power required, e.g. reducing engine idle operation)
- Energy Recovery (obtaining energy that would normally be discarded, e.g. regenerative braking)
- Mass Reduction (minimizing gross vehicle weight, e.g. applying lightweight material such as magnesium alloys)
- Driver Behavior (providing feedback for behavior modification for a more favorable drive cycle, e.g. haptic accelerator pedal)

The efficiency mapping process must be considered iterative. The technology survey which follows should contribute additional ideas which should be put in context within the mind map. The mapping of relationships can help to generate additional ideas and methods for consideration.

4.3. Technology Market Survey

"For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled."
- Richard P. Feynman (Feynman, 1986)

In order to both capture all avenues of fuel efficiency improvement and the necessary data for evaluation and selection, a comprehensive technology market survey is necessary. This is an outreach effort and systematic collection of data from parties that may have relevant products, technology, or research. Previous steps within the process (as shown in Figure 4-18) will have produced elements crucial to a successful technology survey:

- Significant sub-system attributes
- Energy balance
- Mind map of efficiency measures

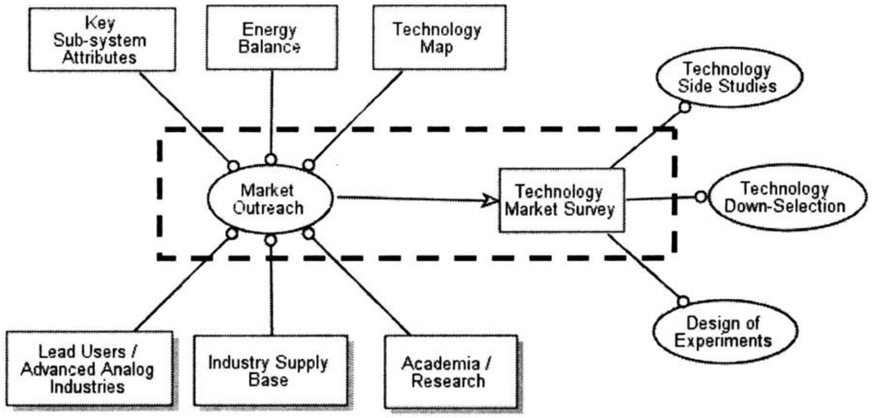

Figure 4-18: Technology market survey development, including supporting instruments and affected deliverables (see Section 2.4 for OPM key)

Objectives and key metrics are important for guiding the survey. Many technologies may arise that could significantly improve some aspect of the vehicle, but may not be relevant to, or may only marginally contribute to the project's mission. There may also be TRL limitations that will constrain the scope of the survey. Subsystem attributes must be identified so that relevant data can be collected to support evaluation efforts. Technology must be evaluated across all attributes, not only efficiency, so that the overall effect on the vehicle system can be understood. The energy balance process allows prioritization and rapid filtering of false or misleading claims. If for example an energy balance were to show only 1% of power is lost to engine friction, and an engine friction technology claims 30% improvement in fuel economy, then claims can be appropriately investigated or discarded. The efficiency mind map provides specific direction for the survey. If subject matter experts have identified driveline friction reduction through oils, finishes, and coatings as an area of interest, then companies dealing in these products can be contacted, and university research or technical literature covering those areas can be obtained.

It is important that the technology market survey is not limited to the industry of the product under improvement. Instead, "advanced analog" applications and markets are likely to produce breakthrough solutions. These are defined as applications that are at the leading edge, with the industry or users facing higher needs than anyone in the target market. (von Hippel, 2005) Figure 4-19 includes an example of advanced analog applications for automotive fasteners. In that case, the automotive fastener company, if looking to improve reliability, would look to the aerospace industry, where reliability requirements have traditionally been much higher. That same company, if looking to improve cost, might instead look toward the toy industry with its greater pressure on pricing. Applying advanced analog approach to FED means that while the defense industry is facing a newfound focus on fuel efficiency, the supply base for the defense industry is unlikely to contain breakthrough products in this area. The automotive industry is an obvious source of ideas for efficiency improvement for a project like FED, and has the benefit of producing similar products. The advanced analog approach however suggests that a perhaps a more radical outreach should be considered. Motorsport may not be thought of as an area for developing efficiency improvements, but those users require an extreme focus on weight reduction and power-stealing parasitic loads. So too do aerospace applications including helicopters and fixed wing aircraft. Additionally, industries such as racing and aerospace contain an outlook on performance versus cost which complements a military product like FED with its very high fully burdened cost of fuel.

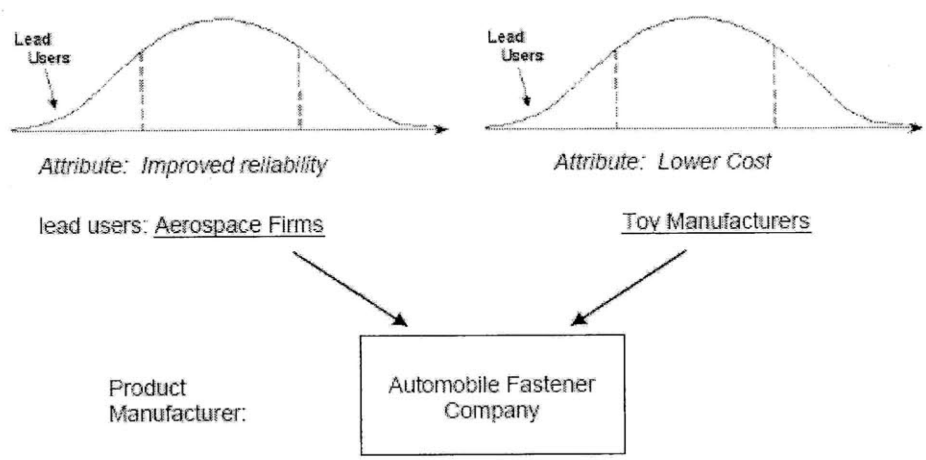

Figure 4-19: Example of lead users with respect to attributes of needs in a targeted market (Churchill, von Hippel, & Sonnack, 2009)

A subtle but important issue in conducting technology surveys, along with the entire vehicle demonstration is that of incentives. Figure 4-20 demonstrates the value network for FED, which includes the value flow between stakeholders and the relative importance of each flow to both the supplier and recipient. (Crawley, 2008d) As can be seen, the FED project has a great need to demonstrate technology to provide relevant information and guidance to TARDEC, while the supply base as the purveyor of this technology has a relatively weak demand for the program, being instead focused on selling subsystems in volume to vehicle manufacturers (OEMs). Moreover, the FED project lacks a direct linkage to two of the key stakeholders, the OEMs and the DoD Program Managers (PM's) in charge of government procurement. Therefore a concept study or demonstration effort like FED requires the project to be "sold" to the participants according to the strategic benefit of the indirect value flow. In this case, that would be the guidance provided by TARDEC to the PM's, influencing vehicle program requirements and procurement, and the increased sales opportunities between the supply base and OEM's based upon successful technology demonstration. An additional aspect not included in the value network is the issue of trust. The supply base is likely to wish to jealously guard its technological secrets. There must be safeguards in place that ensure information will not be shared between competing parties. An organization such as Ricardo conducting the survey must be seen as a neutral party with integrity. It is also beneficial if the information gathered is primarily regarding product and technology performance attributes, a "black box" without all design details.

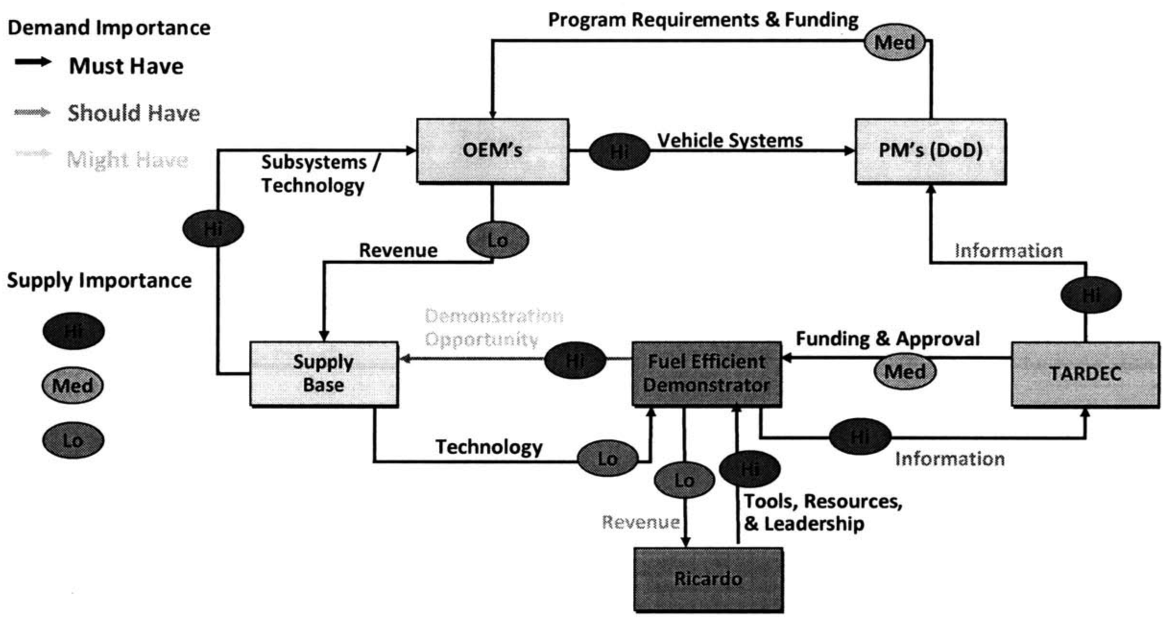

Figure 4-20: Value Network for FED – value flow between stakeholders and relative importance of flow for both suppliers and recipients

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5. Analysis Phase

Up to this point in the methodology, all modeling and simulation has been based upon single point analysis. The energy balance exercise for example is based upon running a single version of each benchmark or baseline model, with an assumed set of technology and specifications intended to meet some or most of the proposed requirements, against one or more drive cycles. Single point analysis unfortunately is limited in its ability to provide an understanding of the interactions between the requirements tradespace, vehicle specifications, and technology selections. The QFD exercise does provide some insight into these interactions, but the qualitative nature primarily supports identification of (rather than assessment of) key attributes and requirements. In order to complete the vehicle requirements and technology downselection, quantitative data from physics-based modeling and simulation is required. The engineering and computational resources required to map this design space creates a challenge.

A step taken in response to some of these issues is the use of sensitivity sweeps. This is the selection of a key sub-system attribute as an input and the use of modeling and simulation to run a range of input values in order to characterize the resulting output curve. This is certainly a valuable exercise, and essentially takes the energy balance a step further. Energy balance tells us that X% of vehicle energy is expended in rolling resistance, while the sensitivity sweep tells us that (for a specific baseline model) improving rolling resistance by Y will improve vehicle fuel efficiency by Z. There are some things that the sensitivity sweep does not demonstrate. It does not indicate what improvement is actually possible (based on the technology available), and most damning, it does not account for the multi-attribute nature of technology selection. What if low rolling resistance technology or architecture correlates with an increase in wheel and tire weight? One attribute may be working against the overall goal while the other improves it.

The multi-attribute issue leads to the use of Design of Experiments (DoE). A vehicle DoE will paint a picture of multi-attribute sensitivity, but this methodology seeks to take the analysis process a step further, utilizing the DoE results to support a surrogate modeling process, construction of an integrated modeling and simulation toolset, and finally a design space exploration, as outlined in Figure 5-1.

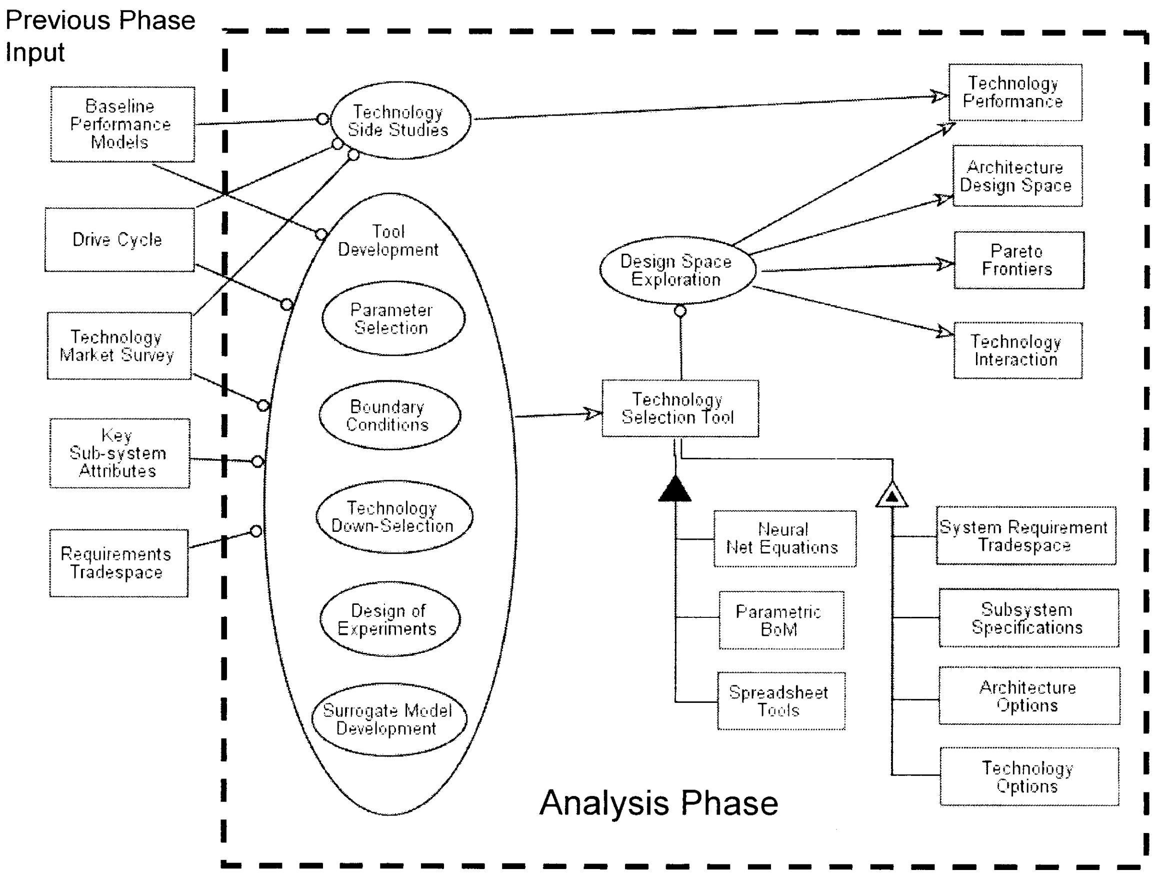

Figure 5-1: Analysis Phase process elements and inputs (see Section 2.4 for OPM key)

The end result of this phase includes several primary deliverables:

- Technology Selection Tool – An integrated modeling and simulation toolset with surrogate model-based performance prediction for technology, architecture, requirement, and specification selections.
- Pareto Frontiers – Maximum performance amongst thousands of design alternatives across multiple conflicting attributes
- Architecture Design Space – Range of potential performance capability of any given baseline architecture across multiple key attributes
- Technology Performance – Improvement (or degradation) across multiple key attributes due to implementation of technology into a variety of baseline architectures under a range of requirement scenarios.

- o Technology Interaction – Effects of various technology combinations resulting in either diminishing returns or multiplicative effects (whole is greater than sum of parts).

These deliverables will be described in detail within the following sections.

5.1. Design of Experiments

Design of Experiments is a "strategy for setting up a set of experiments in which all variables are varied in a systematic manner, for the purpose of determining the correlation between variables and to predict results." ("Dictionary", n.d.) The process begins with the identification of factors or input variables to be included. As shown in Figure 5-2, at this point in the process, key attributes have been identified in a number of ways, including identification of vehicle requirements tradespace, quality function deployment, technology survey, and energy balance simulation. In this manner, a wish list of parameters can be identified. Project timing and resources will unfortunately limit those parameters that can be included. For that reason, a target DoE size should be developed that accounts for time required for each simulation or experiment (including efficiency of setup for each), computational resources available, overall project timing, number of simulations required for each parameter (based upon DoE methods used) and risk management for issues or errors that may result in re-running simulations. It is then likely that input parameters will need to be downselected from the wish list. Sensitivity analyses including Analysis of Variation (ANOVA) can be used both to identify high impact variables and eliminate variables with little or no impact (Ender, 2009). The technology survey is also important, with subsystem attributes identified as being impacted the most by available technology (identified points of leverage). Priority should also be given to attributes that are demonstrated to be in conflict through the QFD or sensitivity analysis. This is so that resources expended through the analysis process can be spent on developing the non-obvious or counter-intuitive answers, rather than simply reinforcing decisions which can be made without this intensive process.

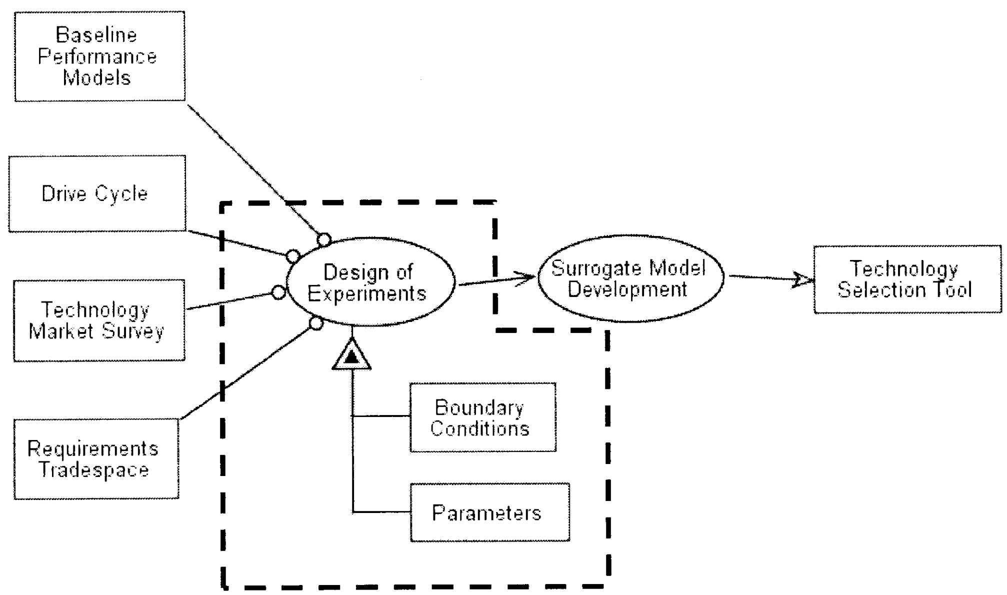

Figure 5-2: Design of experiments development, including supporting instruments and affected deliverables (see Section 2.4 for OPM key)

Having identified the parameters, the next stage in the process is defining the boundary conditions. There is a balance between a broad definition of design space and maintaining the quality of results at the boundaries. Consider for example the parameters of vehicle mass and engine horsepower. An overly broad design space might include a vehicle mass ranging from 10,000 to 50,000 lbs and engine horsepower from 100 to 500 hp. While within that design space there is likely an optimal engine horsepower for every vehicle mass, there will be extreme cases where a 50,000 lb vehicle is matched with the 100 hp engines. This is not a problem if it is simply a case of generating design combinations which are unlikely to meet any desirable set of requirements, as these combinations will be filtered out later in the process. In this example though, the vehicle is likely to be unable to complete the drive cycle simulation (being unable to climb the requisite grades) giving invalid results or even crashing the simulation. If existing benchmark examples of the class of vehicle being studied vary between 20,000 to 25,000 lbs, then it is both unnecessary and damaging to the process to bring the extremes of the boundary conditions as high as 50,000 lbs. Conversely, it is possible to be too narrow in boundaries, eliminate some of the value in the process, and potentially end up with feasible design combinations which cannot be reflected within the design space that has been defined. The guiding factor should be the use of the requirements tradespace, and the identification of parameter ranges which are likely to support requirements within those ranges (and just outside of).

For FED, a hybrid of different DoE techniques were used, chosen for efficiency in capturing information using a minimum of simulations. This included a Central Composite Design (CCD) for definition of design space extremes, as well as points generated randomly and through Latin Hypercube Sample (LHS) for sampling of design space interior points. Using MATLAB scripts, simulations were executed automatically, minimizing the human resources required for running the experiments. (Ender, 2009) The size of the DoE required to support the FED process was approximately 60,000 simulations, not including cases re-run due to invalid results or other issues.

5.2. Surrogate Modeling

The DoE executed in Section 5.1 is designed and utilized to support the construction of parametric surrogate models. These are, as outlined in Figure 5-3, fast-running approximations of physics-based simulations that can be analyzed almost instantaneously using most standard desktop computers. (Biltgen, Ender, & Mavris, 2006) Properly constructed, surrogate models exhibit negligible (but measurable) loss of fidelity compared to the actual engineering codes. (Ender, 2009) The surrogate models in this case will be integrated within a vehicle performance generation and technology selection tool, a modeling and simulation environment designed to allow a user to configure vehicles and assess performance in real time, and support a "Filtered Monte Carlo" approach for probabilistic design.

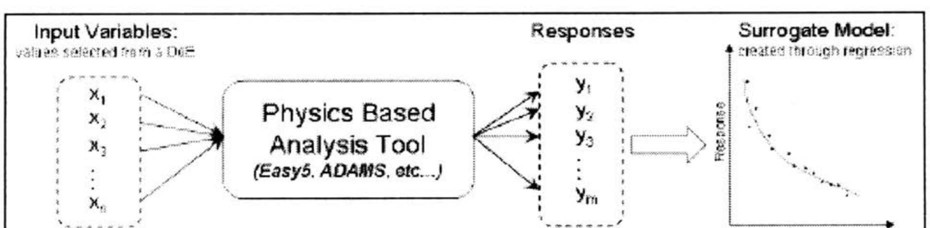

Figure 5-3: Surrogate model development of physics based analysis tools (Ender, 2009)

FED surrogate models were built using response surface methodology; equation regression representations of the more complex EASY5-based DoE results. This includes a combination of polynomial-based surrogate models and neural network-based surrogate models. The polynomial form of a second order Response Surface Equation (RSE) is shown in Equation 5-1. The coefficients are determined by regressing sample data points from the DoE against the input parameter.

Equation 5-1: Polynomial form of second order Response Surface Equation (RSE), (Ender, 2009)

$$R = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_{ii}^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} b_{ij} x_i x_j$$

Where

n = number of factors
b_0 = intercept regression coefficient
b_i = regression coefficients for linear terms
b_{ii} = regression coefficients for pure quadratic terms
b_{ij} = regression coefficients for cross product terms
x_i, x_j = design variables or factors

Neural networks are used when polynomial RSE representation lacks the complexity to accurately characterize the system behavior. Analogous to the design of interconnections of neurons, neural networks are a method of creating highly nonlinear regression models. When used to generate RSE's, "a neural network is a set of nonlinear equations that predict output variables from a set of given input variables using layers of linear regressions and S-shaped logistic functions." (Ender, 2009) The accuracy of the surrogate models versus the original engineering code can be verified through various quality checks, as seen in Figure 5-4.

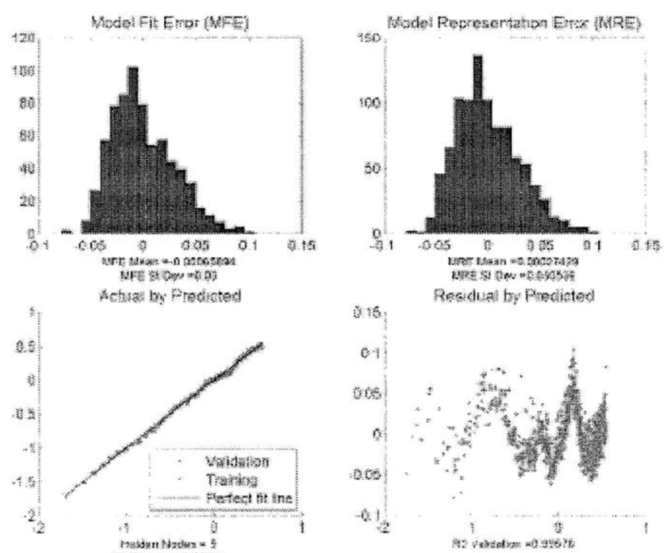

Figure 5-4: Neural network equation validation using Basic Regression Analysis for Integration Neural Networks (BRAINN), (Ender, 2009)

Both an important part of the neural network validation and useful output of the process is the visualization of trends and sensitivities. Previously a sensitivity sweep would have covered a single parameter for a single baseline model configuration. Utilizing surrogate equations as input into JMP statistical modeling and visualization software, the FED project created prediction profilers for each baseline model. As shown in Figure 5-5, one can observe the sensitivity of input attributes (e.g. vehicle mass, driveline efficiency, etc) versus various output metrics or drive cycles (e.g. idle fuel consumption, convoy escort fuel economy, etc.). The software allows a user to instantaneously vary any input selection, and simultaneously observe the change in sensitivity between every input and output. This means that as the user increases the vehicle mass, the changing trend of driveline efficiency versus fuel economy against every drive cycle can be observed. By itself, this is a powerful tool for understanding complex interactions within the design space. As a validation tool, it allows subject matter experts to review trends versus expectations and identify any incongruous results. (Ender, 2009) If, for example, the vehicle mass as an input were to demonstrate some effect on idle fuel consumption, that then might indicate an issue with the models.

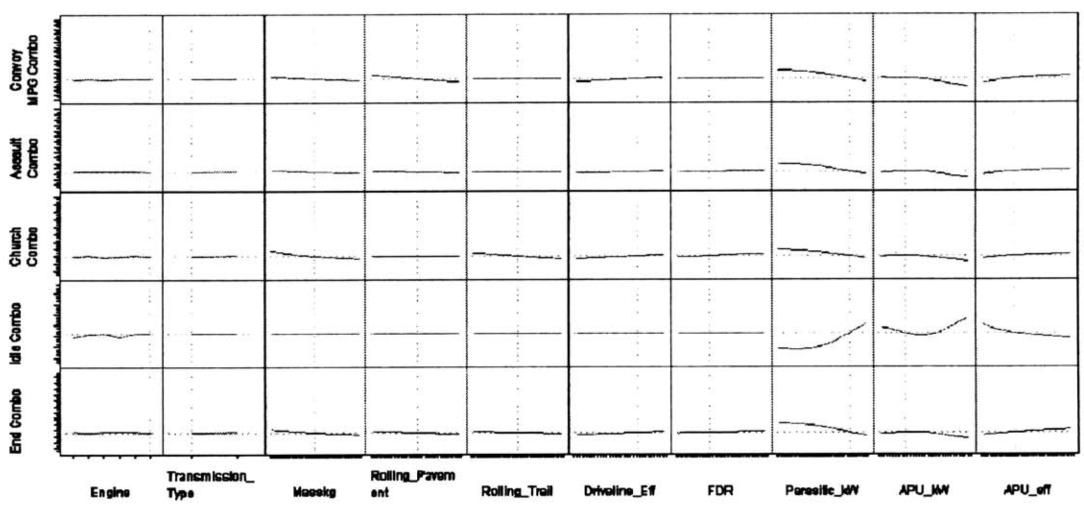

Figure 5-5: Multi-attribute trend visualization using JMP software– allows observation of sensitivity changes in real time according to changes in input

5.3. Vehicle Performance / Technology Selection Tool

The principle issue with the analyses presented thus far is the emphasis on system and subsystem attributes as generic inputs. Vehicle mass will have been clearly demonstrated to have some effect on performance outputs such as fuel economy, as well as an interactive effect on the sensitivity of performance to other inputs (such as rolling resistance). What is missing is a linkage with specific design configurations and technology selections. The DoE's carried out were based upon basic vehicle architectures downselected early within the process, but with substantial flexibility built into the models to represent as broad a design space as possible. The vehicle is modeled on architecture with four wheels and tires, but size, weight, and rolling resistance properties are left open to various possibilities. The surrogate models are now capable of predicting vehicle performance according to any combination of vehicle mass and rolling resistance. The next step is to be able to make selections such as specific wheel and tire specifications and technology and determine the overall effect of vehicle performance. This step is the development, as shown in Figure 5-6, of the integrated modeling and simulation environment that will be referred to as the "Technology Selection Tool" (TST).

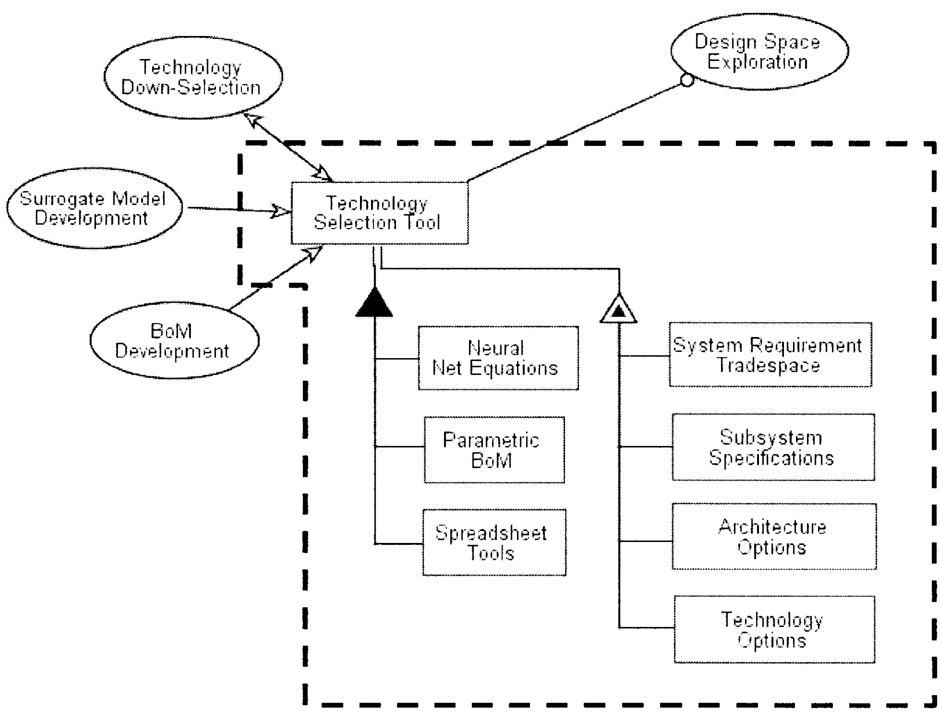

Figure 5-6: Technology Selection Tool, including supporting processes, components, attributes, and usage (see Section 2.4 for OPM key)

The TST is built upon the parametric BoM described in Section 4.1.2, combined with surrogate models of physics based modeling and simulation, along with secondary models developed in consideration of other vehicle requirements and attributes. The FED TST includes secondary models for armor mass, maximum vehicle speed, transportability, climate control performance, vehicle cone index (soft soil mobility), etc. These secondary models are typically parametric spreadsheet-based models.

In order to support the TST development, the vehicle BoM is updated to include all of the sub-system and technology options both identified by the technology survey process and enabled by the parameters and baseline architectures included within the DoE's. This means that for FED a selection of tires appropriate for the boundaries of the design space were selected and offered as options within the BoM, and characteristics such as weight and rolling resistance documented. Due to the parametric nature of the BoM, selection of options like wheels and tires can affect other subsystems, as a heavier vehicle could require a heavier upgraded driveline, resulting in a mass compounding effect. The rigorous nature of the technology survey becomes important at this time, as the data gathered against key subsystem attributes provides input in the TST.

Development of user inputs within the TST can be divided into four categories, requirements, specifications, technology, and architecture. Requirements are inputs driven by the user needs identified within the requirements tradespace. Most requirements will in fact be outputs within the TST, but this varies based on the nature of the requirement. The FED TST incorporated inputs including air conditioning requirements and armor protection levels. Specification inputs are examples of component sizing that is expected to vary based on vehicle parameters and requirements. The FED TST specifications included items such engine size/power and tire size. The technology category is intended for either additional subsystems added to the baseline vehicle BoM and or options that change the properties of specified sub-systems. For FED this ranged from optional systems such as auxiliary power units (APUs), use of lightweight materials like magnesium alloys, or application of manufacturing processes like isotropic superfinishing for friction reduction. Finally, architecture selection is in most cases the basis for selecting a completely separate set of surrogate models for an alternate baseline vehicle. The FED TST offered baseline architectures including conventional powertrain, mild hybrid, parallel hybrid, and series hybrid. The interface to the FED TST can be seen in Figure 5-7.

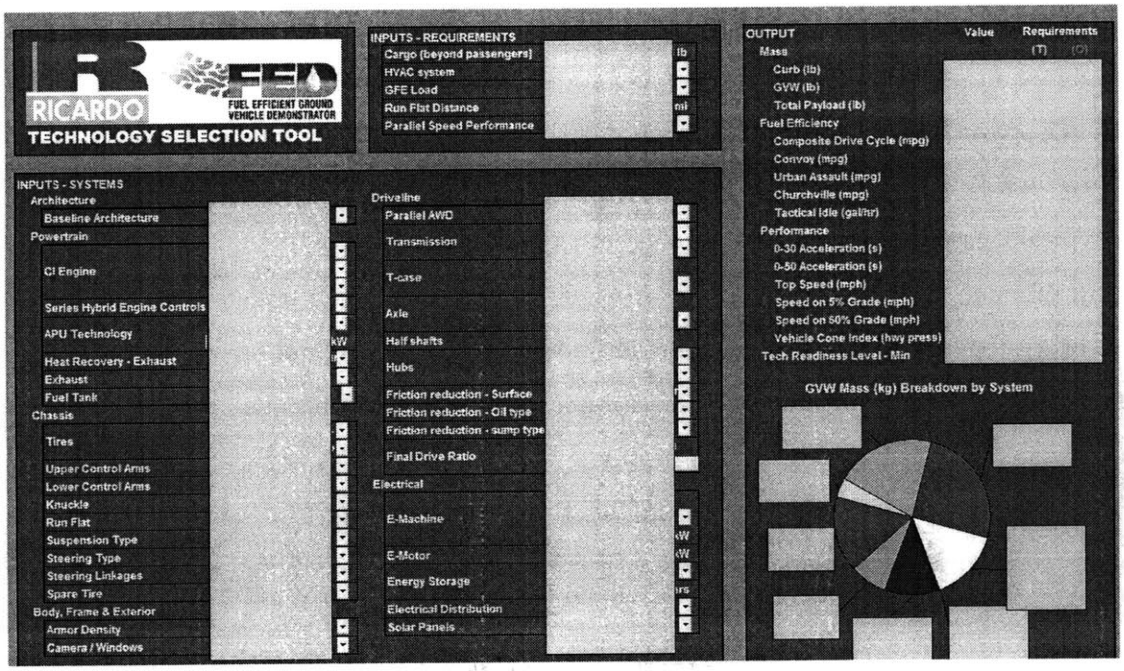

Figure 5-7: FED Technology Selection Tool interface

Development of outputs for the TST should be heavily weighted toward the key metrics for the system objectives. Due to the importance of fuel efficiency to FED, outputs included not only the fuel economy of the composite drive cycle, but also the component segments of the composite drive cycle. As the mass was identified as a key attribute on fuel economy and other requirements, the FED TST included a breakdown of vehicle mass by sub-system. All BoM selections for FED were categorized by TRL, so TST output was able to include minimum TRL for both the vehicle and subsystem. Also included as TST outputs were system performance requirements expected to have a significant impact on fuel economy, such as acceleration and gradeability.

The completed TST modeling and simulation environment provides the opportunity view the unification of various modeling and simulation techniques, taking a wide range of design configurations and viewing the results key to meeting objectives, all in real time. Essentially, this means the user can configure a vehicle to their unique specifications (or "build a truck") and instantly view nearly all results required to support decision making. Some of the inputs will be designed to provide obvious benefits to fuel efficiency (less powerful engines), but the impact will be seen across multiple attributes (slower acceleration;

lower weight leading to improved soft soil mobility). The intent of the tool is support "systems thinking". According to INCOSE, "systems thinking recognizes circular causation, where a variable is both the cause and the effect of another and recognizes the primacy of interrelationships and non-linear and organic thinking — a way of thinking where the primacy of the whole is acknowledged." (Haskins, 2006)

5.4. Design Space Exploration

The principle limitation of the Technology Selection Tool is that whilst it allows design configurations as inputs (rather than attributes) and real time assessments, it brings the process back to a one-factor-at-a-time (OFAT) method, which presents difficulties in optimization and demonstrating interactions. This is overcome through the execution of an additional system DoE, supporting a "design space exploration" (Figure 5-8). In this stage the attribute based DoE parameters (vehicle mass, rolling resistance, etc), are replaced with a full factorial DoE using discrete inputs of the TST, and the physics-based simulation outputs are replaced with surrogate model outputs. The fast run-time of the neural net equations allows very large DoEs to be executed using comparatively small computing resources. For FED, hundreds of thousands of design configurations were created, resulting in "clouds" of solution points at the system level (as shown in Figure 5-9, and a comprehensive view of the design space.

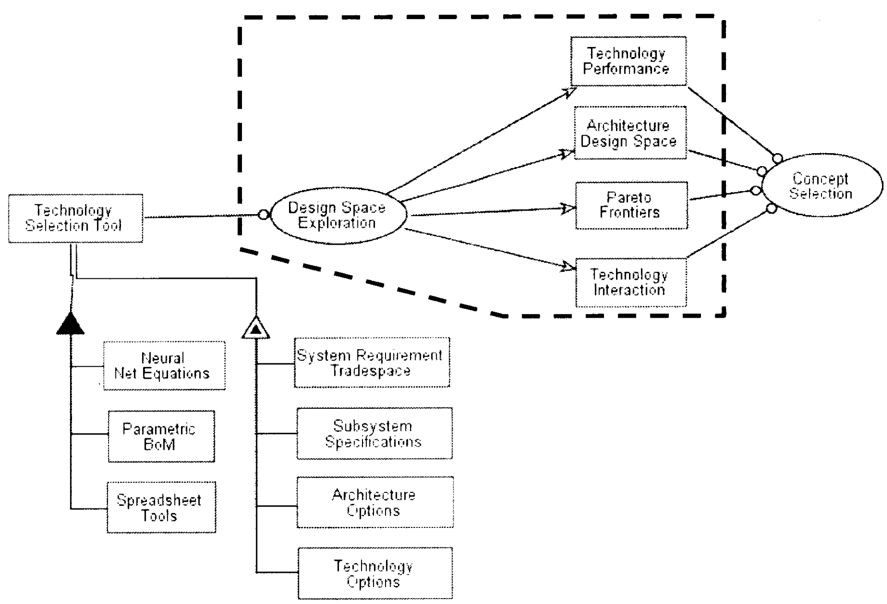

Figure 5-8: Design space exploration, including supporting instruments and usage (see Section 2.4 for OPM key)

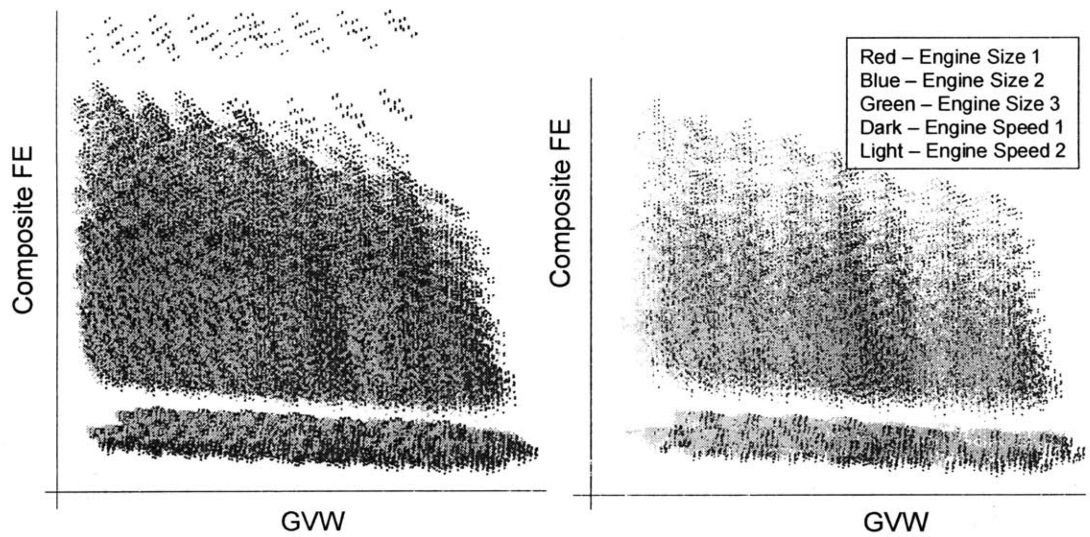

Figure 5-9: Example design space exploration, design configurations color coded according to engine parameters and results on right filtered to meet certain performance requirements

The surrogate models and TST enable "inverse design". Using this technique, any variable can be treated as an independent variable. Using JMP, thresholds can be used to filter any input or output parameter included within the DoE for a top-down decision making process. The intent is to demonstrate that there are many solutions available that meet threshold requirements, but each solution differs in fuel economy, cost, TRL, weight, performance, and any number of important attributes (or demonstrate that threshold requirements do not allow any feasible design configuration). This does created a dilemma in managing the large number of degrees of freedom available for the system. An approach used is to examine certain trades while locking other degrees of freedom, and then alternate locking different degrees of freedom to support other trade decisions. (Biltgen, Ender, & Mavris, 2006)

Beyond inverse design, an important part of the design space exploration is the generation of Pareto frontiers and Pareto optimality. "No complex system can be optimum to all parties concerned nor all functions optimized." (Rechtin, 1991) The Pareto frontier allows an evaluation of potential performance against competing objectives. As shown in Figure 5-10, design configurations along the frontier dominate those lying below, while any point on the frontier requires a tradeoff between competing attributes. So for example, while increasing payload mass will inevitably result in decrease in fuel economy, increased payload mass has a value of its own. Movement along the payload / fuel economy frontier requires making one metric worse off to improve the other. (Ross, Hastings, & Warmkessel, 2004) The design space exploration can demonstrate the frontier of maximum fuel economy that is achievable against any given amount of payload capacity. There will of course not be a deterministic solution of what is optimal. For the purposes of fuel efficiency, having no payload capacity is optimal, but this would not fulfill the needs of all system stakeholders. What the design space exploration offers is decision making informed by both quantitative data and systems thinking. An example of an important Pareto frontier for FED is fuel efficiency versus TRL. The expectation is that more advanced technology will offer advantages for this key attribute, but requires tradeoffs in risk, cost, and timing represented by TRL.

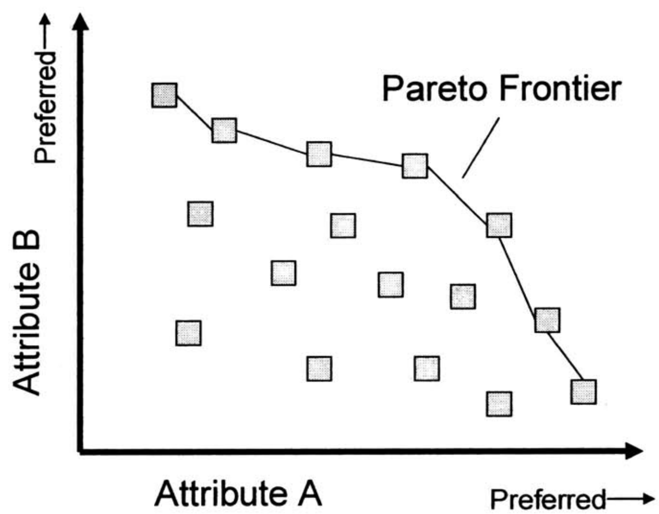

Figure 5-10: Example Pareto frontier – multiple design configurations are compared on the basis of Attribute A versus Attribute B.

The inverse design method and exploration of Pareto optimality allows three fundamental types of explorations to be made; requirements, architecture, and technology. It has been noted that for FED that a critical requirement for powertrain specification was maximum speed on 5% grade. Having mapped the entire design space, it is possible to demonstrate the maximum fuel efficiency that is possible, given all combinations of inputs, at various speed-on-grade targets. This is similar to the aforementioned payload mass Pareto frontier. The method will not demonstrate what the requirement should be, but it will identify what the cost of the requirement is to other key attributes.

Equally important is the use of the design space exploration to compare architectures that are completely normalized to meet the same minimum requirements. Filtered out are series hybrids that are not capable of meeting the same speed-on-grade requirement as conventional powertrains, for an "apples to apples" comparison. Perhaps even more interestingly, it is possible to demonstrate architecture sensitivity to requirements. Series hybrids might hold an efficiency advantage at lower speed-on-grade (or payload, or mass) targets, but see that advantage dwindle as those requirements become more stringent. Or vice versa. It is an important consideration as to whether there is a benefit to softening certain targets as an enabler to architectural solutions that will provide advantages across other attributes.

The final purpose of the design space exploration within this methodology is technology assessment. Some of this exercise is very similar to the architectural exploration, whereas the Pareto frontier for efficiency (or other attributes) is evaluated for the optimum technology options. At first glance, this employment could turn in to a simple case of more technology is better. However, most technology will have some negative qualities associated with it, or it would already be implemented into production. TRL filtering will demonstrate the technology bundles associated with maximum efficiency for any given minimum TRL. Many add-on systems result in mass penalties even as they improve efficiency. Cost is perhaps an ideal application for technology assessment, although effective implementation into the TST can be difficult, particularly for low TRLs (cost was not implemented within the FED TST). For a project focused upon off-the-shelf solutions, a cost versus efficiency Pareto frontier for technology selection would likely be a necessity. Another important aspect of the design space exploration for technology assessment is demonstrating the interrelationships between technologies and architecture. Essentially this is the determination of which technologies result in diminishing returns versus those that act as enablers. For example, multiple methods of friction reduction (isotropic superfinishing, low viscosity oil, etc) may result in maximum effectiveness when used together, but show the majority of the benefit with either one or the other. In comparison, powertrain hybridization may show its greatest benefit as a way of utilizing electrical power obtained from other systems (plug-in, waste heat recovery, etc), making the hybridization only a starting point for additional improvements.

5.5. Technology Side Studies

Clearly the design space exploration is at the heart of the methodology and a powerful method of assessing a many aspects of vehicle design. Unfortunately it is subject to some limitations. As has been noted, the DoE parameters that can be supported within project timing and computational resources is finite, especially considering the exponential growth of the DoE as parameters are added. This means that the parameters required to properly assess certain technologies may not make the cut for inclusion. Vehicle sensitivity to CdA may be relatively low due to the drive cycle, so the DoE could be carried out treating this parameter as a constant. This would preclude inclusion of any technologies relating to aerodynamic improvement. In other cases, the DoE and surrogate modeling techniques may simply be inadequate to capture aspects of the technology. Driver feedback technology, as noted in Section 3.2.3, results in unique drive cycles, which do not fit in well with the process of evaluating technology against an exogenous drive cycle. Finally, some technology requires evaluation at a greater level of detail, either instead of inclusion within the design space exploration, to supplement the process, or to actually act as an input into the DoE modeling and simulation. Vehicle simulation may treat regenerative suspension technology as simply a source of an average level of electrical power generation over a given drive cycle (along with mass). Depending upon supplier data available, vehicle suspension simulations may be required to assess the power regeneration that is possible. In this case, the detailed modeling and simulation can be used as a vehicle simulation DoE input, or simply treated as an independent study. Another example is the use of multi-mode hybrid transmissions. Even the relatively simple hybrid powertrains are very sensitive to control strategies for their effectiveness, and capturing these complex behaviors within surrogate models is a challenge. Multi-mode hybrids present additional complexity, putting them, in the case of FED, outside the scope of the design space exploration. These decisions are a compromise between avoiding watering down the design space exploration with a lack of relevant content, and producing less timely and reliable results through an excess of content. It is recognized that as powerful as the design space exploration process is, there is a need to focus the process on design aspects that result in the most value, therefore some technology assessments should be carried out to the side of that process, supported by many of the same elements of the methodology (see Figure 5-11).

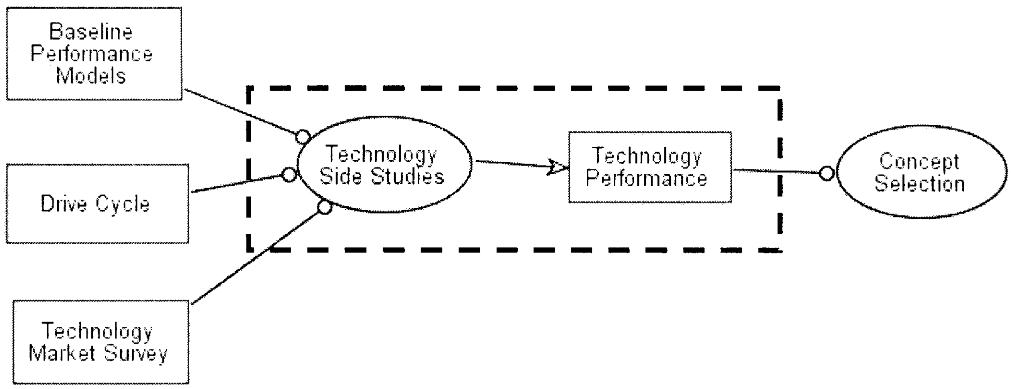

Figure 5-11: Technology side studies, including supporting instruments and affected deliverables (see Section 2.4 for OPM key)

6. Design Phase

Hitherto now this methodology has been centered upon baseline concepts developed to act as a flexible center of the design space. This has allowed an assessment of the requirements tradespace applied to a range of architectures and technology, along with the optimization of subsystem specifications for any given requirements/architecture scenario. The next stage, as shown in Figure 6-1, is to use modeling and simulation results to develop more focused vehicle concepts.

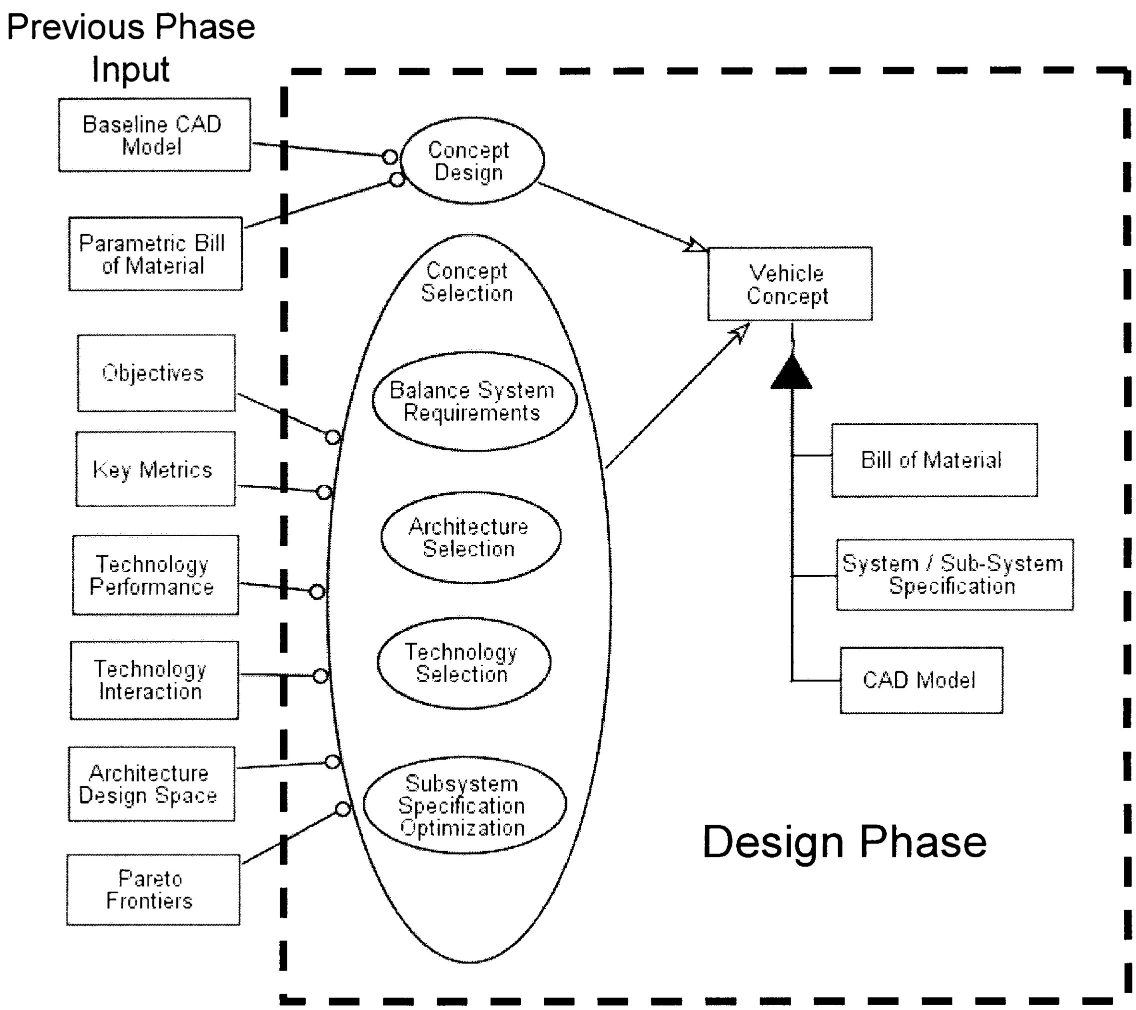

Figure 6-1: Design Phase process elements and inputs (see Section 2.4 for OPM key)

The design space exploration allows the possibility of sorting the available design configurations in a deterministic manner through the assignment of weighted utility functions to all the available performance attributes (fuel economy, speed-on-grade, payload weight, etc). According to Hazelrigg, "Given a pair of alternatives, each with a range of possible outcomes and associated probabilities of occurrence, that is, two lotteries, the preferred choice is the alternative (or lottery) that has the highest expected utility." This axiomatic approach holds the advantage of making preferences explicit, and presents a single mathematically optimal answer. However there are weaknesses with this approach. Hazelrigg also tells us that "it is common for engineers to think that a person prefers one alternative over another because it has a higher utility. The reality is that the preferred alternative has a high utility because it is preferred. That is, preferences determine utilities, utilities do not determine preferences." (Hazelrigg, 1999) This implies that the process has the most value in determining preferences, rather than identifying the result that best meets preferences.

The end result of this phase includes a single primary deliverable, the vehicle concept(s). While not intended to be a detailed design, ready for manufacture, the concept is more mature than the preliminary baselines developed initially. Included within this deliverable are:

- Vehicle Requirements – Rather than a broad tradespace, requirements are balanced according to feasibility and alignment with objectives
- CAD Model / Bill of Material– A design which reflects the selected baseline architecture, integrates technology selections, and appears feasible to meet requirements
- System / Subsystem Specification – Subsystem performance requirements (e.g. engine hp) optimized to meet vehicle requirements

These elements of the deliverable will be described in detail within the following sections.

6.1. Requirements Setting

To set requirements, the methodology must revisit the assessment of user needs. Except now, as shown in Figure 6-2, there is the ability to make informed decisions based upon the cost of a given requirement to other vehicle attributes. Rather than considering only how fast soldiers and marines need (or want) to go, the question becomes what the potential fuel economy is at any given speed capability. For FED, most of these decisions were relatively simple. In nearly all cases, the answer was to match the performance attribute of the primary benchmark vehicle, the M1114 HMMWV, as the objective of the program is to maximize fuel efficiency while meeting those attributes as a threshold. In a few cases, requirements were matched to more forward looking vehicle programs such as JLTV so as to be credible as a newly designed tactical vehicle. Given the focus on matching HMMWV, why carry the requirements tradespace through the entire process? For FED, this was because assisting the government in understanding the impact of requirements on fuel economy was as important (or more so) than the identification of technology, so as to influence requirements setting on other programs. For other programs, the requirements setting process is likely to be a more difficult balance across the "iron triangle" of performance, payload, and protection, assessing the importance of speed versus fuel economy, or armor protection versus fuel economy.

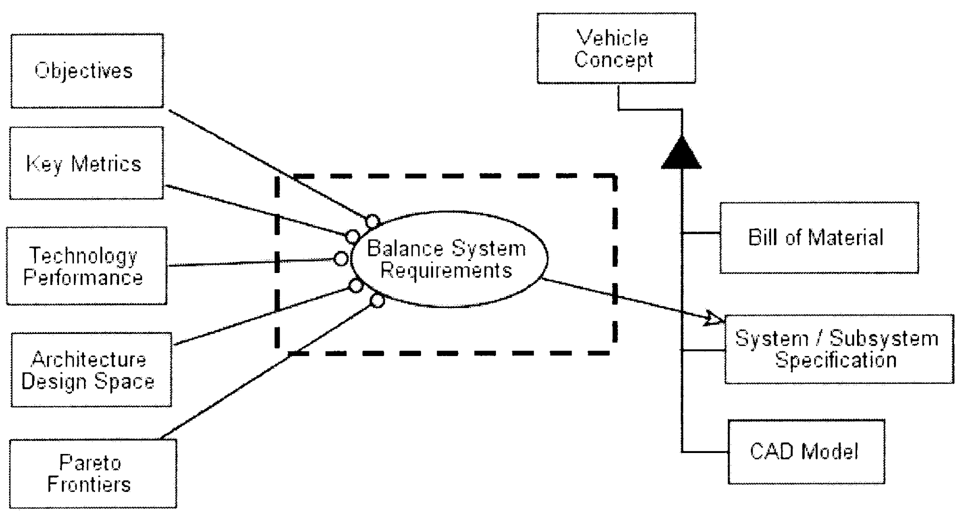

Figure 6-2: Setting balanced system requirements, including supporting instruments and affected deliverables (see Section 2.4 for OPM key)

6.2. Architecture / Technology Downselection

As was previously noted, architecture is "the embodiment of concept". Having solidified the requirements the vehicle system is expected to meet, architectural decisions should be derived based upon their performance across key attributes (Figure 6-3). This could be considered relatively straightforward as the design space exploration should have provided the differentiation necessary for decisions. An outcome might be that one powertrain architecture provides maximum fuel efficiency but carries an unacceptable weight penalty, while another is simply not competitive with other options. An important consideration is that there may be cases of an architectural spectrum in which the optimum lies in a combination of elements from two different "bundles" of technology and function. Ideally the architecture within the design space exploration is decomposed sufficient to support these decisions, (based upon the morphological matrix method in Section 4.1.1), but this may not always be the case.

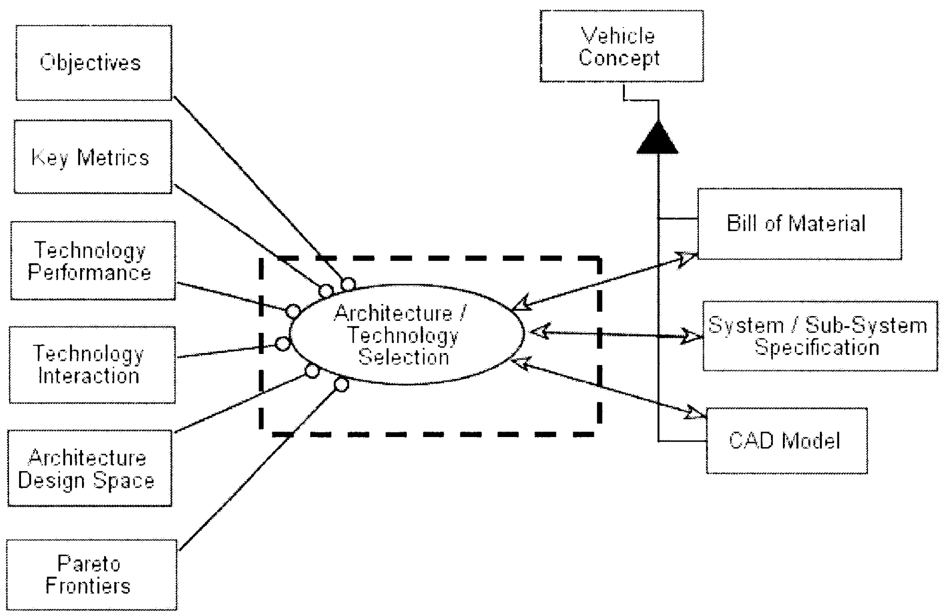

Figure 6-3: Architecture and technology selection, including supporting instruments and affected deliverables (see Section 2.4 for OPM key)

Technology decisions are made in a similar manner. Given the threshold requirements and architecture selected, what technology lies along the Pareto frontier? Consideration should be given to the system objectives. The objective of the FED system was to maximize fuel economy while meeting M1114 HMMWV requirements. However the overarching goal of the program was to improve the fuel efficiency of the DoD ground vehicle fleet. Therefore there are factors less easily quantified, such as the ease of technology insertion into legacy vehicles. This is an example where consideration of the "system-of-systems" should be taken to support the overall objectives.

6.3. System / Subsystem Specification

Having largely determined the vehicle requirements, architecture, and content, it is a relatively straightforward endeavor to optimize subsystem specifications (Figure 6-4). The design space exploration in some cases should have provided some optimization, but it is necessary to develop the specifications to an additional level of detail. The FED design space exploration included only a few possibilities for final drive ratio (driveline gearing), and required an additional parameter sweep within the vehicle simulation software. At first glance this may seem a backward step, moving beyond the usage of the surrogate model environment after having gone through the considerable investment in the process. However, at this stage it is sometimes necessary to return to the more typical engineering methods, but now armed with requirements and technology content derived through systems engineering. The methodology moves now into the application of the systems V-model in which the system requirements are cascaded and decomposed into additional levels of detail.

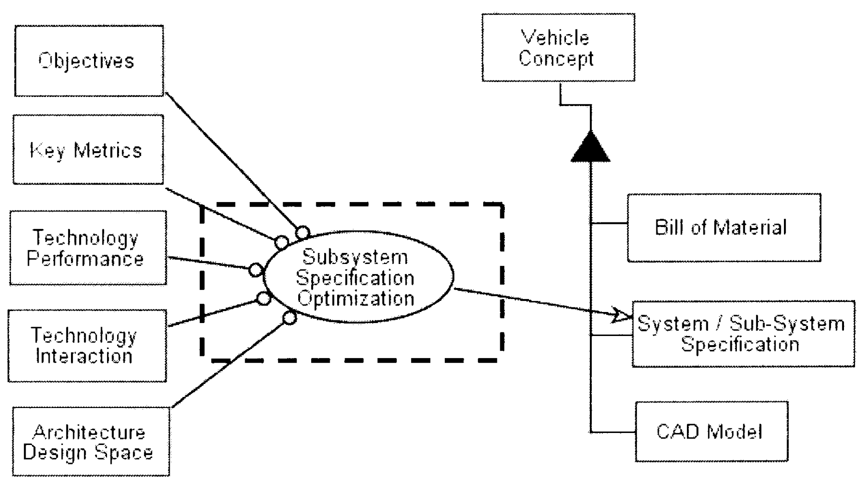

Figure 6-4: Subsystem specification optimization, including supporting instruments and affected deliverables (see Section 2.4 for OPM key)

Thus far the concept development exercise has been focused upon the art of the possible, and it is assumed that systems can be sized as is ideal for the system. This is another area where system-of-systems requirements and limitations must be considered. While FED is a focused demonstrator, customized for its purpose, many vehicles exist within a family where commonization and modularity are very important to support stakeholder needs (e.g. manufacturing complexity or military logistics). It is a principle of systems architecture that commonality and modularity will compromise the performance of the system. That is not to say that the benefit to the system-of-systems will not outweigh the compromise, but it is an additional requirement that will result in a cost to the individual system performance. The end result is that in many cases the vehicle system is likely to use components that are available, rather than those that would be ideal if custom designed. This means that an off-the-shelf differential might be larger and heavier than is required, but could be utilized to meet other requirements such as cost. Customization versus commonality is as much a content decision for the vehicle development as the earlier architecture and technology selection.

6.4. Concept Design

Section 4.1.3 described the development of an initial baseline CAD model in order to inform the development of the performance models and requirements tradespace. At this stage the CAD can be developed into a complete concept design based upon the decisions made thus far. The FED concept model is shown in Figure 6-5. The CAD model will often serve to constrain an attribute difficult to represent within the performance prediction process, that of design envelope or "package space". The performance simulations might identify a Stirling engine as a favorable technology selection, only to find integration into the vehicle design to be difficult or impossible without compromising other attributes.

Figure 6-5: Concept model for FED

Supporting concept definition, as shown in Figure 6-6, is BoM development, first discussed in Section 4.1.2. Earlier stages focused upon a flexible, parametric BoM designed to capture the effects of all possibilities. At this stage the BoM becomes an area of focus for documenting actual component selections. BoM discipline becomes extremely important as it provides predictions for many of the key metrics that drive program decisions, including cost and weight. If for example the BoM predicts a vehicle mass of 10,000 lbs, then a number of subsystem specifications, such as differential sizing, become dependent upon this system specification. Some iteration is to be expected, but if the later detail design process develops a vehicle mass of 15,000 lbs, this will set off a spiral of up-rating subsystem specifications or down-rating payload requirements. Accuracy and discipline within the vehicle concepting will pay dividends in decreased design churn later in development.

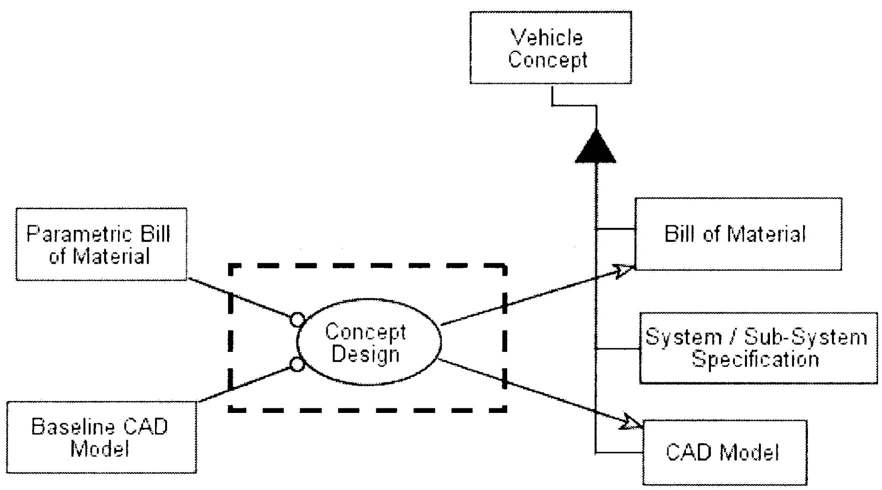

Figure 6-6: Concept design development, including supporting instruments and affected deliverables (see Section 2.4 for OPM key)

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7. Verification Phase

"A model is not reality." (Rechtin, 1991)

Verification and validation is largely outside the scope of this methodology. It is of course still a key element to the discipline of system engineering. The latter half of the systems V-model is entirely devoted to verification and validation. Rechtin gives a heuristic from the early years of the space program, "before the flight, it's opinion. After the flight, it's obvious." The methodology seeks to mitigate some of the prediction risk through the use of a benchmark model for correlation (discussed in Section 4.1.4), as well as the use of well established modeling and simulation tools and subject matter expertise. All of this is subject to limitation, particularly in the implementation of new technology. In some cases it may be that technology simply does not live up to its promise, in others there may be unforeseen aspects not captured within the models. Outright modeling flaws and human error are a possibility as well.

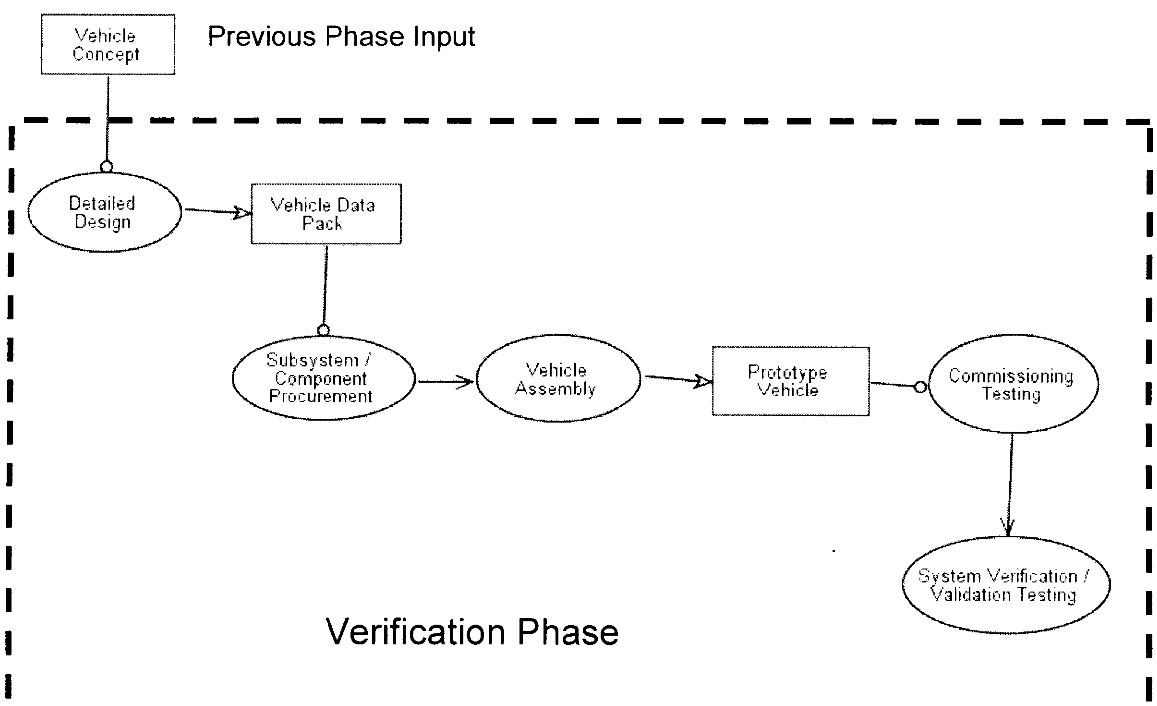

Figure 7-1: Verification Phase process elements and inputs (see Section 2.4 for OPM key)

The construction of prototype vehicles in this instance should strictly be considered as a way of verifying correlation and obtaining data to support modeling and simulation that could not be accomplished previously, rather than a replacement for modeling and simulation within the vehicle lifecycle. Construction of multiple prototype vehicles as a form of design space exploration is inherently very inefficient, with considerable resources devoted to each single point solution, versus the hundreds of thousands of feasible design solutions that can be developed within the modeling and simulation environment.

A wide range of developments are likely to benefit from a robust design space definition executed up front in the product lifecycle. As circumstances change over time, there is always the possibility that requirements will change for future iterations of the system. A classic example is increasing armor requirements over time. As the preferred balance of performance, payload, and protection changes, the surrogate model environment and design space exploration already exist to inform the change. Technology, not being static, is also likely to see the need for insertion later within the product lifecycle. Verification of the modeling and simulation will strengthen the ability to support these actions over time.

8. Conclusions and Recommendations

Section 1 presented the growing fuel consumption of ground vehicles of the U.S. Armed Forces and the problems and costs associated with this issue on the battlefield. The challenge was to reduce this fuel consumption through the development of a tactical wheeled vehicle demonstrator that maximizes fuel economy while maintaining credible tactical vehicle capability, (the Fuel Efficient Demonstrator program). A significant aspect of the FED program was the objective to "document the process of how to build in fuel economy" and expose government engineers to "novel and innovative design, advanced automotive engineering, and systems engineering practices and methodologies." (Mathes, 2008) The methodology presented here is intended to provide a structured systems engineering approach to fulfill those objectives. It is hoped that this methodology was successful in this endeavor, and indeed the results thus far appear very promising. This systems engineering approach however should be considered as more than a method of improving the fuel efficiency of military vehicles. The methodology is a means of developing product concepts and improving any product attribute, whether or not efficiency, military, or vehicle related.

The process demonstrated throughout this document was relatively complex with many interrelated elements. Many of these elements are useful for attribute improvement and concepting initiatives without the application of the methodology as a whole. In fact, the entire methodology can be viewed as an assembly and practical application of a wide range of established systems engineering tools, processes, and methods. The intent is that, in true systems engineering fashion, the assembly of the whole is more than the sum of its parts. If there is any innovation here, it is in the application of surrogate modeling techniques to ground vehicle systems in support of requirements engineering and technology selection, a process in which Ricardo, Inc. in partnership with Georgia Institute of Technology's Aerospace Systems Design Laboratory (ASDL), are leaders in.

In considering application of the methodology, whether in whole or part, several elements stand out in importance:

- **Objectives** – Clear definition of objectives, both at the system and system-of-systems level

- **Usage Cycles (Drive Cycles)** – Effective definition of the aggregate expected usage of the product so that the utility is defined accordingly
- **Requirements Tradespace** – Consideration of product requirements as a balancing of attributes within a feasible design space
- **Energy Balance** – Understanding the process in which all energy passes out of the system
- **Technology Survey** – Structured outreach efforts informed by modeling and simulation, inclusive of lead users/advanced analog industries
- **Surrogate Model Tool** – Mapping of system design space for top-down decision making
- **Sources of Improvement** – Use of requirements, specifications, architecture and technology all for their potential in improving the product system

It is recommended that that all elements of this methodology, but these in particular, be considered in similar endeavors for product improvement.

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