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SYSTEMS ENGINEERING METHODOLOGY FOR FUEL EFFICIENCY AND ITS APPLICATION TO THE TARDEC FUEL EFFICIENT DEMONSTRATOR (FED) PROGRAM

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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. This article provides an overview of a systems engineering methodology for maximizing fuel efficiency and its application in concept development for the FED program. Engineering tools and methods used include tradespace definition, provisional baseline product models, decomposition of energy expenditure over the product usage cycle, structured technology market surveys, complex systems modeling & simulation tools, and design space exploration / Pareto optimization. The methodology explores the impact of technology on fuel efficiency along with other aspects of vehicle development including drive cycle definition, operational requirements, subsystem specifications, and architecture.

INTRODUCTION

The issue of fuel efficiency within the Department of Defense (DoD) is one of increasing importance. As the largest single consumer of energy in the United States, in 2006 the 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).

In addition to petroleum prices, the U.S. Armed Forces also have a number of unique issues related to fuel consumption. Operational effectiveness of military forces is affected by endurance as vehicles are forced to spend time transiting to fuel sources and refueling. All manner of military assets are also required to move and protect fuel within the battlespace, reducing the ratio of “tooth” (resources devoted to combat operations) to “tail” (resources devoted to support of combat resources). This logistics tail of U.S. forces is particularly vulnerable within asymmetric conflicts like Afghanistan, where adversaries will attempt to strike soft targets exposed along mountainous transportation routes.

These resources and vulnerabilities result in a fully burdened cost of fuel well above the price paid by the DoD for diesel fuel. This fully burdened cost includes the delivery costs of the Military Sealift Command, Air Mobility Command, refueling vehicles used by the Army and Marine Corps, and the assets used to protect the fuel in transit. Efforts to quantify this cost vary widely, but estimates for forces deep within a battlespace may be up to several hundred dollars per gallon. [1]

Adding to the issue of fuel cost is the increasing consumption of fuel by the U.S. Armed Forces, as shown in figure 1. One culprit is weight, as many ground systems have seen mass increases far in excess of initial requirements through the addition of armor protection. The Humvee for example, has variants operating at 17,900 lbs, more than double the 7700 lbs it was fielded at in 1984. [2] Also contributing to fuel consumption is the increasing demand for electrical power. Vehicles now carry a variety of C4ISR technologies (Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance), along with survivability systems such as IED defeat solutions.

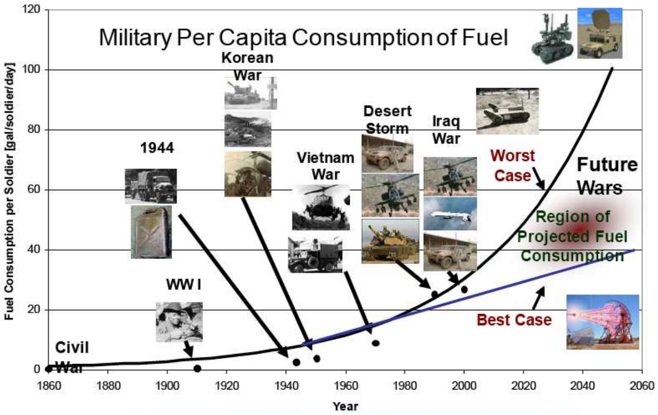


Figure 1: Growth of per capita fuel consumption of U.S. Armed Forces [3]

Fuel Efficiency ground vehicle Demonstrator (FED) Program

The Fuel Efficiency ground vehicle Demonstrator (FED) Program was initiated by the Office of the Secretary of Defense 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. The FED is a vehicle level system demonstrator focused on fuel efficiency.

The technical objectives of the FED program include demonstrating a tactical vehicle with significantly greater fuel economy than a M1114 High Mobility Multipurpose Wheeled Vehicle (HMMWV) while maintaining tactical vehicle capability, integrating emerging fuel efficient technologies to demonstrate potential capabilities for next generation vehicles, and consider higher risk/higher payoff technologies to attain the most fuel efficient vehicle possible. [4]

The eventual outcome of the FED program is the validation of models and engineering tools developed for the FED program. Validation will be achieved by testing a demonstration vehicle beginning in early 2011.

Systems Engineering

Systems engineering is “an interdisciplinary approach encompassing the entire technical effort to evolve and verify an integrated and total life cycle balanced set of system, people, and process solutions that satisfy customer needs. Systems engineering is the integrating mechanism across the technical efforts related to the development, manufacturing, verification, deployment, operations, support, disposal of, and user training for systems and their life cycle processes. Systems engineering develops technical information to support the program management decision-making process”. [5]

Critical to achieving the stated goals of the FED program is the use of a systems engineering approach to solve technical challenges. Systems engineering practices have become very important to Department of Defense (DoD) in streamlining acquisition cycles and improving the end product of development efforts. The complexity of modern military systems has made vehicle development efforts extremely complicated. A disciplined planning and management approach must be applied to yield optimal system level performance without significantly impacting schedule and cost.

The FED program executed two different systems engineering approaches to create fuel efficient concepts. One approach, discussed in this paper, was devised by an industry partner and U.S. Army Tank-Automotive Research Development and Engineering Center (TARDEC). This team focused on a data driven approach to include requirements analysis, detailed modeling and simulation of the design space, and concept refinement. The contractor utilized several systems engineering methods and tools. TARDEC engineers embedded with the contractor engineering team were exposed to many of these tools and have brought new systems engineering skills and knowledge back to TARDEC for use on current and future programs.

DEFINITION PHASE

The initial phase of the methodology 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.

Key Metric Definition

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. [6] Therefore, a set of appropriate metrics must be determined which are aligned with the program objectives. Obviously for the Fuel Efficient Demonstrator program, the measurement of fuel efficiency is going to be the foremost criterion for evaluating alternatives. While fuel economy in miles per gallon was used, arguments exist for the use of fuel consumption (gallons per mile) or output specific fuel economy (ton-miles per gallon). Another key metric is vehicle mass. Not only is this a driver for potential fuel consumption, but for military ground vehicles, mass is a critical factor for other attributes including transportability, survivability, and payload. The other key metric for the program is Technology Readiness Level (TRL), as risk management is an essential element of systems engineering, and a significant proportion of risk can be associated with technology maturity. For a demonstrator program like FED, TRL must be considered both in terms of a successful hardware demonstration, and for the ability of legacy and near term programs to make use of included technologies. In addition, as a demonstrator program, a promising technology might be included not only in spite of a low TRL, but because of a low TRL, as part of the program's value is increasing TRL through successful demonstration.

Drive Cycle Definition

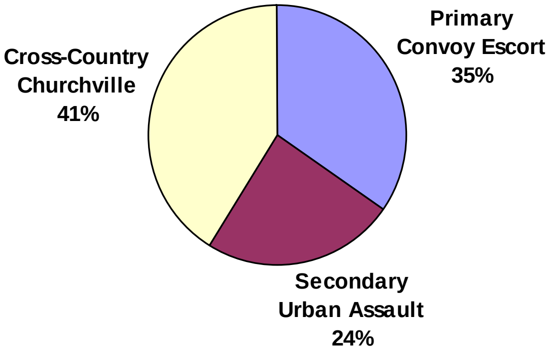
The vehicle drive cycle or usage cycle can be defined as a characterization of the manner in which the vehicle is expected to be operated or driven, used in order to assess performance. Fuel economy can only be derived according to the usage of the vehicle, and the relative effectiveness of any particular solution will be cycle dependent. A high speed drive cycle may for example drive a focus on aerodynamic improvements, while high frequency of braking will highlight the benefits of regenerative braking. Parameters within the drive cycle may include vehicle speed, elevation/grade changes, road surface, accessory usage, and payload.

The FED program sought to define a drive cycle, shown in figure 2, which came as close as possible to capturing the broad usage experienced by tactical vehicles in the field. Elements within this cycle included:

- convoy escort missions (relatively high speed, steady state driving on paved roads)
- urban assault missions (low speed, stop/start driving on paved roads)
- cross country missions (low speed driving on trails)
- tactical idle (operation at zero speed while running accessories).

These drive cycle elements were developed by TARDEC's Analytical Modeling and Simulation Team using a process they call Duty Cycle Experiments (DCE). The drive cycles are based on actual terrain maps collected from areas such as Iraq and Afghanistan. To create a cycle soldiers are asked to drive the simulated courses on one of TARDEC's motion based simulators. From all of the data collected, TARDEC engineers then build a realistic duty cycle to represent different missions such as driving in an urban area or in a highway convoy.

While variability between theatres will mean that the missions used and their proportions are subject to debate, the key consideration is that this is a robust cycle that includes many different operational modes. The intent is that the cycle will reward technologies that demonstrate improvement across usage types, rather than rewarding those that show promise only within a single type of operation. It should also be noted that the cycle deliberately focuses on combat operations. A peacetime or state-side cycle will show different characteristics, and while a significant proportion of fleet mileage might be of this type, it does not entail the risks and fully burdened cost of fuel inherent to battlespace operations.



	(hr)	(min)	(sec)
Moving	**14**	840	50400
Idle	**6**	360	21600
Total Hours	**20**	1200	72000

Figure 2: Usage cycle defined for the Fuel Efficient Demonstrator Program

Requirements Engineering

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. Whether within the government's requirement setting process, or the contractor's development process to meet those 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." [7] Commonly referenced is the "iron triangle" of payload, performance, and protection, all attributes that must be traded-off. Rather than setting a strict set of requirements at this stage however, a tradespace should be 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. This is so that data might be generated to understand the cost and compromises inherent in every requirement.

Contributing to this requirements tradespace definition should be a benchmarking exercise of other program requirements and legacy vehicles in order to establish the range of existing operation performance. The low end benchmark of any attribute might show the minimum of what would be acceptable, while the high end 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.

The FED program utilized the M1114 HMMWV as its primary benchmark, setting expectations that the demonstrator vehicle would perform no worse than the legacy fleet, and would use the advantages of modern design and new technology to maximize fuel efficiency. Some HMMWV requirements used included:

- Payload
- Ride & Handling
- Mobility
- Gradeability
- Performance
- Transportability
- Ballistic Protection

Other vehicle programs were also benchmarked including the Joint Light Tactical Vehicle (JLTV). This drove certain additional increased requirements for FED, such as:

- Electrical Power Generation
- Underbody Blast Protection
- Human Factors

While outside the scope of improving fuel efficiency, these increased requirements ensured the vehicle design would be relevant to current and future new vehicle programs.

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 using modeling and simulation can provide design alternatives.

Model Development

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. Unfortunately, it is impossible to complete the requirements for a complex system without some idea of what the resulting system is likely to be. [8] Therefore one or more baseline architectures must be selected, not as a specific vehicle designs, but as a design space to be evaluated against a range of specifications, requirements, and technologies within the modeling and simulation environment. For the FED program, vehicle architecture was defined for a four wheeled, front engined, four passenger, high mobility armored tactical vehicle, similar to its M1114 HMMWV benchmark. Several alternative baseline powertrains, as shown in figure 3, were selected for evaluation, including parallel hybrid electric, series hybrid electric, and conventional. Early selections such as these must be made by subject matter experts based on suitability for the requirement tradespace that has been defined, the drive cycle, and likelihood of maximizing key metrics to meet program objectives.

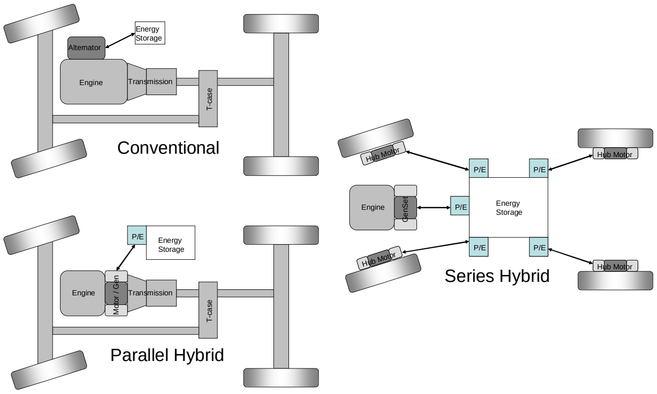


Figure 3: Baseline powertrain architecture alternatives for FED

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. While it is possible to simulate vehicle performance at any vehicle weight, the BoM provides a method of evaluating feasibility, as the mass of every subsystem or component must be accounted for. This drives discipline into the concept development process, and provides a useful decomposition of key vehicle metrics such as cost or weight. BoM accuracy during concept development can be an issue, but can be offset through the use of benchmark BoM's and focus on complete accounting of components.

A baseline CAD model should be developed as a design representation of the vehicle concept architecture. This, like the BoM, 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. 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. [8] This model is also used to support the development of performance simulations.

While many provisional baseline models should be developed, perhaps the most important in this case is the performance prediction models, which for FED drove the technology selections. The contractor uses commercially available vehicle performance modeling and simulation software for this purpose, along with proprietary powertrain libraries. 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. 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 and specifications. This flexibility is crucial to the methodology, allowing eventual design space definition through design of experiments (DoE).

Prioritization

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. 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 simulation operation over the drive cycle. Areas of expenditure might include aerodynamics 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. The engine energy balance diagram represents all of the chemical energy contained in every gallon of diesel consumed and losses in its conversion into usable energy (brake power) by the engine. The vehicle energy balance diagram represents the consumption of all of the brake power produced by the engine. The complete energy balance diagram represents “tank to wheels” fuel consumption.

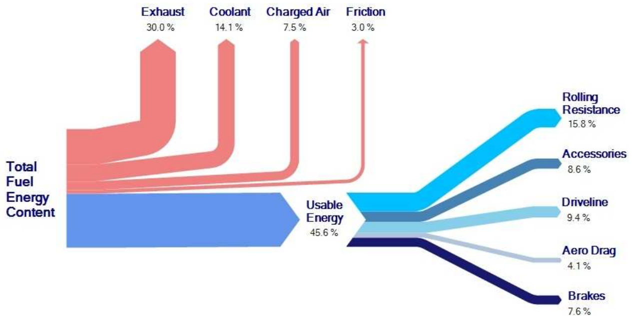


Figure 4: FED energy balance diagram

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. Technology and architecture will also drive differences in the energy balance. Automatic transmissions for example 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 Quality Function Deployment (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. While figure 4 shows 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 missing elements within the model.

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.

Ideation / Technology Market Survey

At this point in the process, the engineering team has a number of sources of information at their disposal including objectives, key performance metrics, drive cycle, and energy balance. Teams of subject matter experts in various vehicle systems can now effectively generate leads for methods of increasing fuel efficiency. 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. 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, including requirements (e.g. max speed on 5% grade), architecture (e.g. body-on-frame structure), and subsystem specifications (e.g. engine horsepower).

Proposed fuel efficiency improvements can be organized within a "mind map" format, as shown in figure 5. 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. 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.

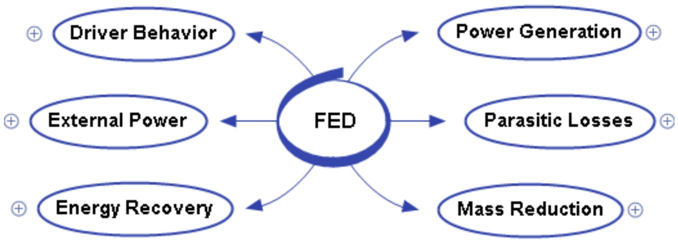


Figure 5: Technology mind map for fuel efficiency measures

In order to 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.

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. The efficiency mind map provides 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. [9] 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. 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. This approach of looking outside the defense supply base identified many interesting improvements including efficient lightweight electrical power (lift truck technology), isotropic superfinishing of gears (helicopters), haptic driver feedback (automotive), and low rolling resistance tires (commercial trucking).

ANALYSIS PHASE

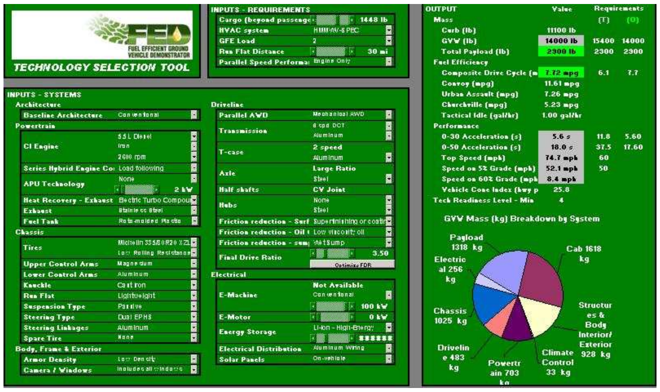
Up to this point in the methodology, all modeling and simulation has been based upon single point analysis. The energy balance exercise for example is based upon running a single version of each benchmark or baseline model, with an assumed set of technology and specifications intended to meet some or 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. A 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.

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 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.

Vehicle Performance Tool

The modeling and simulation DoE is intended to support the development of an integrated performance prediction and technology selection toolset. Shown in figure 6, this tool includes inputs related to vehicle requirements, specifications, technology, and architecture. Through the use of surrogate modeling techniques, real time outputs are available, including curb weight, payload, fuel efficiency over the complete drive cycle and each drive cycle element, acceleration, top speed, and sub-system TRL. This tool is not a replacement for commercially available performance prediction software, but rather a decision making tool that integrates results from several simulations and tools, and makes multi-attribute tradeoff results instantly available to the systems engineer.



INPUTS - REQUIREMENTS
Cargo (beyond passenge 1448 lb
HVAC system HMMWV-S PEC
GFE Load 2
Run Flat Distance 30 mi
Parallel Speed Performa Engine Only

INPUTS - SYSTEMS
Architecture
Baseline Architecture Conventional
Powertrain
CI Engine 5.5 L Diesel
Iron
2600 rpm
Series Hybrid Engine Co Load following
APU Technology None
2 kW
Heat Recovery - Exhaust Electric Turbo Compou
Exhaust Stainless Steel
Fuel Tank Roto-molded Plastic
Chassis
Tires Michelin 335/80R20 XZL
Low Rolling Resistance
Upper Control Arms Magnesium
Lower Control Arms Aluminum
Knuckle Cast Iron
Run Flat Lightweight
Suspension Type Passive
Steering Type Dual EPHS
Steering Linkages Aluminum
Spare Tire None
Body, Frame & Exterior
Armor Density Low Density
Camera / Windows Includes all windows
Driveline
Parallel AWD Mechanical AWD
Transmission 6 spd DCT
Aluminum
T-case 2 speed
Aluminum
Axle Large Ratio
Steel
Half shafts CV Joint
Hubs None
Steel
Friction reduction - Surf Superfinishing or coatin
Friction reduction - Oil (Low viscosity oil
Friction reduction - sum Wet Sump
Final Drive Ratio 3.50
Electrical
E-Machine Not Available
Conventional
100 kW
E-Motor 0 kW
Energy Storage Li-Ion - High-Energy
######
Electrical Distribution Aluminum Wiring
Solar Panels On-vehicle

OUTPUT	Value	Requirements (T)	Requirements (O)
Mass			
Curb (lb)	11100 lb		
GVW (lb)	14000 lb	15400	14000
Total Payload (lb)	2900 lb	2300	2900
Fuel Efficiency			
Composite Drive Cycle (m	7.72 mpg	6.1	7.7
Convoy (mpg)	11.61 mpg		
Urban Assault (mpg)	7.26 mpg		
Churchville (mpg)	5.23 mpg		
Tactical Idle (gal/hr)	1.00 gal/hr		
Performance			
0-30 Acceleration (s)	5.6 s	11.8	5.60
0-50 Acceleration (s)	18.0 s	37.5	17.60
Top Speed (mph)	74.7 mph	60	
Speed on 5% Grade (mph)	52.1 mph	50	
Speed on 60% Grade (mph	8.4 mph		
Vehicle Cone Index (hwy p	25.8		
Tech Readiness Level - Min	4		

Figure 6: Integrated Performance Prediction Toolset

As was already noted, the first step toward developing the vehicle performance & technology selection tool is a DoE of the relevant vehicle simulations. The process can be computationally intensive, so it is necessary to carefully consider parameters to include as well as the boundary conditions. Techniques were used for the automatic execution of simulations, minimizing time and human resources, a necessity as 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.

The next step toward tool development is the construction of parametric surrogate models. These are, as outlined in figure 7, fast-running approximations of physics-based simulations that can be analyzed almost instantaneously using most standard desktop computers. [10] Properly constructed, surrogate models exhibit negligible (but measurable) loss of fidelity compared to actual engineering codes. FED surrogate models were built using response surface methodology, equation regression representations of physics-based modeling and simulation DoE results. This includes a combination of polynomial-based surrogate models and neural network-based surrogate models. Neural networks are used when polynomial response surface equation (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." [11]

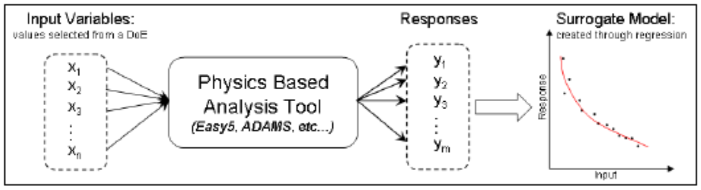


Figure 7: Surrogate model development of physics based analysis tools [11]

A critical system within the toolset is a parametric BoM. 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 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. 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 and the magnitude of impact.

The completed integrated modeling and simulation environment provides the opportunity to 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." [12]

Design Space Exploration

The principle limitation of the vehicle performance and 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". 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 performance tool, 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 8 & 9), and a comprehensive view of the design space.

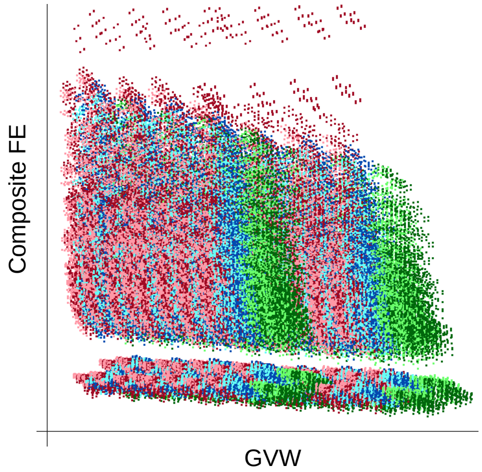


Figure 8: Example design space exploration, design configurations color coded according to engine selections

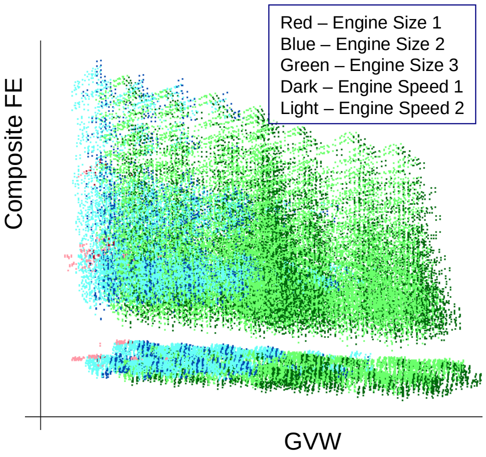


Figure 9: Example design space exploration, filtered to meet performance requirements

Through the use of statistical modeling & simulation software, the clouds of possible solution points can be filtered according to various requirements scenarios. The key benefit to this approach is that it forces an "apples to apples" comparison between design configurations. It also provides a clear quantitative understanding of the relative cost of any selection or requirement. Cost in this case being the trade-off or benefit to all of the attributes modeled. One can explore questions such as the cost of increasing the maximum speed on 5% grade requirement. What is the reduction in maximum fuel economy as a result? What is the increase in minimum curb weight due to engine size increases? What is the decrease in survivability (as measured by armor areal density) in order to still maintain transportability targets?

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." [8] The Pareto frontier allows an evaluation of potential performance against competing objectives. As shown in figure 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. [13] 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.

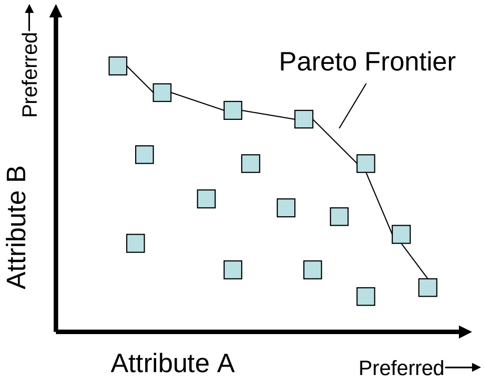


Figure 10: Example Pareto frontier – multiple design configurations are compared on the basis of two attributes

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 is to use modeling and simulation results to develop more focused vehicle concepts. 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

Requirements

To set requirements, the methodology must revisit the assessment of user needs. At this stage, there is now 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.

Technology & Architecture

Having solidified the requirements the vehicle system is expected to meet, architectural decisions should be derived based upon their performance across key attributes. 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, but this may not always be the case.

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.

Specifications

Having largely determined the vehicle requirements, architecture, and content, it is a relatively straightforward endeavor to optimize subsystem specifications. 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.

Design

The Characterization Phase 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 model can be developed into a complete concept design based upon the decisions made thus far. The FED model is shown in figure 11. 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 favorable technology selection, only to find integration into the vehicle design to be difficult or impossible without compromising other attributes.

Figure 11: CAD model for FED

Supporting concept definition is BoM development. 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.

VERIFICATION PHASE

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, 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.

RESULTS

The FED program is still ongoing at this time, with the demonstration vehicle build underway. Therefore, verification of improvements has not yet occurred. However, modeling and simulation results indicate that fuel economy for the FED should exceed a 70% improvement versus the M1114 HMMWV benchmark. Additional features and technology that were identified as potential improvements to the vehicle, but were outside the program cost and timing constraints, would allow improvements of over 110%.

Technology Features

Vehicle improvements selected by the FED team for implementation into the demonstrator vehicle represent a broad spectrum of sub-system technologies. These technologies also fall within a broad range of TRL and implementation hurdles. A significant portion of the content is intended to be feasible for near term insertion into the legacy tactical vehicle fleets, while others are candidates for new vehicle programs. The list of features and technologies for the FED vehicle includes:

- Re-calibrated turbo-diesel engine
    - Clutched supercharger for electrical power generation at idle
- 6-speed automatic transmission
- 28V Integrated Starter-Generator (ISG)
- Isotropic Superfinishing (ISF)
- Spiral bevel differentials
- Non-geared wheel hubs
- Low rolling resistance tires
- Low viscosity oil
- CV-joint prop-shafts & half-shafts
- Low-drag foundation brakes
- Electrified / smart controlled accessories
    - Powertrain cooling fans
    - Hydraulic steering (EPHS)
    - Pneumatic system
    - Climate control system
- Frequency Selective Damping (FSD)
- Accelerator Force Feedback Pedal (AFFP)
- Liquid Circulating Garments (LCG)
- LED lighting
- Integral solar panel
- Aluminum space frame
- Carbon fiber composite body panels
- Aluminum suspension
- Composite 10-mile run-flats
- Aluminum rims
- Aluminum brake calipers
- Coalescing filter air dryer
- Aluminum wire harnesses
- Titanium coil springs

Additional technologies were not included in the initial demonstration, but are candidates for a planned upgrade path for the vehicle.

- Parallel hybrid electric powertrain
- Dual clutch transmission (DCT)
- Regenerative damping
- Electric turbo-compounding (ETC)

Requirements Sensitivity

Beyond technology insertion, an important aspect of the program was understanding requirement sensitivities on fuel efficiency in order to influence tradeoffs on other vehicle programs. For example, reducing the maximum speed on 5% grade requirement by 10 mph was shown to improve potential fuel economy by 7%. This sensitivity can be seen in figure 12. The results reflect that as the speed requirement increases, the engine power and size increases.

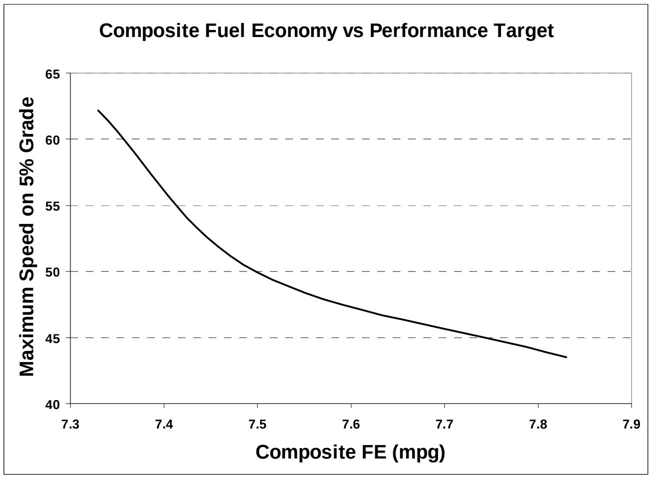


Figure 12: Fuel economy sensitivity to performance requirements

Powertrain Architecture

An obvious topic of interest for fuel efficiency is the selection of hybrid electric powertrain architecture. In fact, the selection of a 28V ISG system for the FED could be seen as an unconventional choice for an efficiency focused vehicle program.

In the case of light tactical vehicles, hybrid electric powertrain do have mixed results. Series hybrid systems, while able to improve upon the legacy fleet, are not competitive with the most efficient conventional systems for fuel economy. A full parallel hybrid system is the most efficient architecture, but does not see the benefits typical in automotive applications. Factors working against parallel systems seeing their full potential in tactical vehicle applications include:

- Unable to use torque assist to downsize the engine due to infinite maximum speed requirements
- Drive cycle less suited to regenerative braking improvement compared to automotive cycles
- High rolling resistance (tires and soft soil) further reduces brake usage
- Increased weight against transportability and payload requirements

It should be noted however that there were significant factors favoring hybrid technology.

- Increasing electrical power demands requiring increasing and more efficient electrical power generation
- “Silent watch”/”silent drive” capability

Due to the competing advantages and compromises of hybrid architecture, FED proceeded with a unique approach. The approach was intended to provide significant efficiency benefits, while minimizing technical risk, cost, and mass compromises. The 28V ISG includes the following advantages:

- Provides efficient electrical power generation significantly better than current alternator technology and comparable to high voltage ISG systems
- Provides 30 kW, sufficient to meet JLTV requirements for onboard power, as well as power for accessory electrification (cooling fans, etc)
- Significantly lighter weight and more compact than comparable high voltage ISG systems
- Avoids weight penalties associated with hybrid power storage
- 28V power is compatible with current standard military systems, avoiding weight, efficiency, and space claim penalties associated with high voltage power conversion
- Allows start/stop hybrid capability

CONCLUSIONS AND RECOMMENDATIONS

Several outputs from the FED program will influence the design of current and future military programs. The program will demonstrate a wide range of fuel efficient technologies by fabricating and testing fuel efficient vehicles, increasing technology TRL and credibility for tactical vehicle applications. Analytical models and tools created during the program will be validated through testing of the hardware demonstrators. Verification planning includes a DoE that will allow FED engineers to correlate the impact of individual subsystems for modeling and simulation.

Lessons learned during the FED program will inform requirements developers as to how particular requirements affect the fuel efficiency of a vehicle system. The FED program can also inform OEM engineers about best practices for designing vehicles more fuel efficiently. TARDEC and the contractor will gain knowledge through these models that will be directly applied to new modeling and simulation efforts.

Follow-on projects may be initiated based on the results of the FED vehicle testing. Promising technologies can be further developed for integration into existing vehicle platforms.

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