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THESIS

**SYSTEMS ENGINEERING TECHNOLOGY READINESS
ASSESSMENT OF HYBRID-ELECTRIC TECHNOLOGIES
FOR TACTICAL WHEELED VEHICLES**

by

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September 2014

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FOR TACTICAL WHEELED VEHICLES**

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ABSTRACT

The Department of Defense is the largest federal government consumer of fossil fuel. The military has been severely limited by the burden of petroleum-based fuel technologies, which have greatly hindered the military's ability to conduct operational missions in support of worldwide commitments. The military's interoperability is hindered by an insatiable worldwide demand for fuel supply and a profound dependence on other countries, especially hostile nations for fuels. Improvements in technology are critical to meeting energy goals.

One solution could be the use of hybrid-electric vehicles. Hybrid-electric technology (HET) offers significant opportunities for the military to meet the growing demands for reduced fuel consumption and increased combat vehicle performance. With fuel costs as high as \$500 per gallon in the battlefield, according to Gen. James T. Conway, former Commandant of the Marine Corps, it is astonishing that hybrid-electric (HE) military tactical wheeled vehicles have not been deployed.

This study presents a technology readiness assessment of the benefits and challenges relative to cost, maturity and technical complexity of the HE system for military vehicle applications. It describes the potential benefits offered should the military make the leap into HET.

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LIST OF ACRONYMS AND ABBREVIATIONS

2V-ISG	dual-voltage integrated starter generator
A	amps
A _m	materiel availability
A _o	operational availability
AC	alternating current
AECV	all electric combat vehicles
AMC	Army Material Command
API	application programming interface
ATC	Aberdeen Test Center
BCT	brigade combat team
CTA	Collaborative Technology Alliance
DAPS	Defense Acquisition Program Support
DC	direct current
DEER	Directions in Engine-efficiency and Emissions Research
DEW	directed energy weapons
DOD	Department of Defense
DOE	Department of Energy
DSB	Defense Science Board
EFP	explosively formed projectile
EM	electro-magnetic
EMA	electro-magnetic armor
EMI	electro-magnetic interference
ETC	electrical thermal chemical
EV	electric vehicle
FCS	future combat system
FED	fuel economy demonstrator
FMEA	failure modes effects analysis
FMECA	failure modes effects and criticality analysis
FMTV	family of medium tactical vehicles
GAO	Government Accountability Office
GVC	ground combat vehicle
GVPM	ground vehicle power and mobility
GVW	gross vehicle weight

HE	hybrid-electric
HED	hybrid-electric drive (series)
HEMMIT	heavy mobility expanded tactical truck
HET	hybrid-electric technology
HEV	hybrid-electric vehicle
HEVEA	hybrid-electric vehicle experimentation and assessment
HMMWV	high mobility multipurpose wheeled vehicle
HUMS	health and usage monitoring system
ICE	internal combustion engine
IED	improvised explosive device
IFV	infantry fighting vehicle
IGBT	insulated gate bipolar transistor
ISG	integrated starter generator
kJ	kilojoules
km	kilometer
kW/kg	kilowatts per kilogram
KPP	key performance parameter
KSA	key system attribute
kw	kilowatt
LCC	life cycle costs
Li-Ion	lithium-ion
LMP	lithium-metal polymer
M&S	modeling and simulation
M/G	motor/generator
MDA	Milestone Decision Authority
MDAP	major acquisition program
MDS	magneto-dynamic storage
MDT	maintenance down times
MOE	measures of effectiveness
MOP	measure of performance
MOS	measures of suitability
MPG	miles per gallon
MRL	manufacturing readiness level
MTBF	mean time between failures
MTV	medium tactical vehicle
NAC	National Automotive Center
NiMH	nickel metal hydride
NPS	Naval Postgraduate School
NRAC	Naval Research Advisory Counsel

O&S	operation and sustainment
OBVP	onboard vehicle power
P&E	Power and Energy
PCU	power converter unit
PFN	pulse forming network
PHEV	plug-in hybrid electric vehicle
PRT	program readiness for transition
R&D	research and development
RDECOM	Research, Development & Engineering Command
RDT&E	research, development, testing and evaluation
RAM	reliability, availability maintainability
rpm	revolutions per minute
S&T	science and technology
SAS	Studies, Analysis and Simulation Panel
SE	systems engineering
SiC	silicon carbide
SIL	systems integration lab
SOE	system operational effectiveness
TARDEC	Tank Automotive Research, Development, and Engineering Center
TRA	technology readiness assessment
TRL	technology readiness level
TWV	tactical wheeled vehicle
V	volts
V&V	verification and validation
W/kg	watts per kilogram
Wh/kg	watt hours per kilogram
ZEBRA9TM	sodium nickel chloride

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EXECUTIVE SUMMARY

During a gathering at the Pentagon in October 2010, Navy Secretary Ray Mabus addressed a group of leaders about the importance of energy conservation: “Our military and our country rely too much on fossil fuels ... and too much of our oil comes from volatile places...” he said. “Make no mistake—energy policy can be used as a weapon” (Daniel 2010).

The U.S. military’s dependence on foreign fuel is a national security concern (Perez, Hartka, and Veitch 2010). The Department of Defense (DOD) is the largest federal government consumer of petroleum-based fuel (*Defense Update* 2005). The military has been severely encumbered by its dependence on petroleum-based fuel technologies, which has greatly reduced the military’s ability to conduct operational missions anytime, and anywhere, in support of worldwide commitments. The military’s interoperability is hindered by an insatiable worldwide demand for petroleum and a profound dependence on other countries for fuel resources, especially hostile nations (Fields 2009). During operations in the battlefield, it became apparent that alternate energy sources were needed to improve efficiency and decrease fuel consumption of sustainment platforms, the largest battlefield consumers of fuel, which makes it one of the DOD’s top priorities (*Defense Update* 2005).

The majority of the DOD energy spending is being driven by mobility fuel requirements. Fossil fuel transportation in combat zones is too expensive, costs lives, and creates logistical problems related to transportation, storage, and spill response. One improvement could be the use of the hybrid-electric (HE) systems. Hybrid-electric technology (HET) offers significant opportunities for the military to meet the demands for reduced fuel consumption while enhancing combat vehicle performance.

With fuel costs as high as \$500 per gallon on the battlefield, according to Gen. James T. Conway, former Commandant of the Marine Corps, it is quite astonishing that HE military vehicles have not been deployed to date. The DOD has conducted numerous studies and vehicle demonstration projects dealing with electric and hybrid-electric

vehicles (HEVs) since 1943, including electrical transmission technologies, fuel cell drive and hybrid-electric drive (HED) technologies. These studies compare technology requirements and systems for mobility, survivability, and lethality. The analyses included power requirements and the energy storage needed to meet vehicle power requirements and identified enabling technologies that require further development and/or breakthroughs (Kramer and Parker 2011).

This study presents a technology readiness assessment (TRA) of the current state of the technology research and development (R&D), the benefits and challenges relative to cost, maturity, and technical complexity of the HE system for military vehicle applications.

The main conclusions are as follows.

- The TRA of (HED) is currently at the technology readiness level (TRL) between TRL4 to TRL6. HEVs have been built and tested in the labs at the component and system levels. They have been tested in systems integration labs (SILs) at the vehicle level and they have also been evaluated in the field at several proving grounds.
- HED systems provided vastly better fuel economy than their mechanical counterparts.
- The performance of HEVs in terms of speed, acceleration, gradeability and stealthy operations is superior to the performance of mechanically driven vehicles. In addition, energy storage onboard hybrid HEV can support silent watch operations, as well as electric weapons.
- Technologies, such as silicon carbide and lithium ion batteries, will greatly enhance the packaging and integration of the HED systems. The maturity level of these emerging components is at TRL3 (Ding 2011; Mainero 2010; Zanardelli 2010).
- Life cycle cost (LCC) data is not available. Extensive field testing of completed actual production system must be completed and proven through successful mission operations to determine the measures of suitability of HET. Available data shows that development and demonstration costs for HED are currently excessive. Nonetheless, most of these costs are likely to be offset in the long run by the fuel and maintenance savings (NATO RTO 2004).
- While HET is still under development, recent advances lead to an expectation that future military tactical wheeled vehicles will contain HE systems (RedOrbit 2007). This technology is a significant departure from the power package and drive train technology seen on current generation

vehicles. Nevertheless, significant verification and validation obstacles must be overcome before HET becomes widespread. The conclusion is HET for military applications is viable. It is predicted that by the end of this decade, the first production model military HEV will be deployed in the battlefield.

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I. INTRODUCTION

Based on its studies and deliberations, the Defense Science Board (DSB) Task Forces (Perez, Hartka, and Veitch 2010) concluded that tactical mobility operations suffer from the unnecessarily high and growing battlefield fuel demand for the following reasons.

- Compromises operational capability and mission success
- Requires an excessive support force structure at the expense of operational forces
- Increases life-cycle operations and support costs

In an October 2009 *National Energy Awareness Monthly* (Allen, Ghassan, and Pizzolo 2009), the Army stated it is leading the Department of Defense (DOD) and the federal government in sustainability, stewardship of environmental resources and in initiatives to achieve energy security. Through the Army's National Automotive Center Command Chain: Army Material Command (AMC), Research, Development & Engineering Command (RDECOM), Tank-Automotive Research, Development & Engineering Center (TARDEC) to the National Automotive Center (NAC), "this center will serve as the focal point for the development of dual-use automotive technologies and their application to tactical wheeled vehicles (TWVs). It will focus on facilitating joint efforts between industry, government and academia in basic research, collaboration, technology, industrial base development and professional development" (Schramm 2011).

Energy security includes energy assurance by preventing the loss of access, supply by accessing local alternative and renewable energy sources, sufficiency by providing adequate quantities when needed, survivability by providing resilient systems, and sustainability by promoting support for the DOD's mission, community, and environment (U.S. Army RDECOM 2014a).

Energy security is an operational imperative and a top military priority (U.S. Army RDECOM 2014b). Energy dependence creates a logistical trail, which slows operations and makes deployed forces more vulnerable. Military bases and warfighter

training require secure and uninterrupted access to energy. The DOD has adopted a comprehensive energy security strategy, and is investing more than \$1 billion in energy security initiatives, including nearly \$700 million in DOD energy stimulus funds (U.S. Department of Energy 2007) for research.

A. PURPOSE

The purpose of this study is to document the thesis research, which was performed to fulfill the requirement of a master's degree program in Systems Engineering Management. This thesis includes the following chapters.

- Chapter I Introduction
- Chapter II Hybrid-Electric Technology for Military Applications
- Chapter III Challenges of Hybrid-Electric Technology for Military Applications
- Chapter IV Systems Engineering Technology Readiness Assessment
- Chapter V Conclusion and Future Research

B. RESEARCH QUESTIONS

Fuel economy, reduced emissions, modular components, and better performance are common goals shared between the commercial and military sectors. The commercial sector has invested and shown great success through the production of passenger cars and other commercial applications, such as delivery trucks, garbage trucks, and transit buses. These heavy-duty vehicles have similar drive cycles as the military TWVs. Therefore, the research questions analyzed in this thesis are presented in the chapters as follows.

- Are dual-purpose commercial hybrid-electric technology (HET) components available that will work effectively for military TWV applications?
 - Chapter II
 - Chapter III
- Why has no military hybrid-electric vehicle (HEV) been deployed? What are the benefits of HET? What are the challenges of HET in preventing the fielding of a military HEV and going into full production? How and when will the U.S. military overcome these challenges?

- Chapter II
- Chapter III
- HET is a newly developed technology. The DOD acquisition guidance requires that hardware and software systems exhibit an appropriate level of maturity. Based on the technology readiness level (TRL) analysis, what is the TRL of the hybrid-electric drive (HED)?
- Chapter IV
- Can the DOD overcome the challenges of HET and is it the right investment for the military?
- Chapter III
- Chapter V

C. BENEFITS OF STUDY

The majority of the military's energy spending is being driven by mobility fuel requirements; however, as pointed out by the Government Accountability Office (GAO) Defense Management, "the military lacks an effective approach for implementing fuel reduction initiatives" (GAO 2009). A large step in decreasing U.S. dependence on foreign fuels would be the use of HET, which could greatly improve fuel efficiency, as well as vehicle performance of military ground TWVs. HET offers significant opportunities for the military to meet its growing energy demands to reduce fuel consumption and increase tactical vehicle performance.

HEVs are steadily being adopted in the commercial market due to their proven benefits in decreased fuel consumption and lower emissions. These benefits could also be realized for military ground TWVs, as HET is key to generating significant level of electric power on-board the vehicle to meet the demand of the warfighter and the DOD mission. HET could expand mission capabilities in terms of mobility, survivability and lethality. Costs and technical challenges must be addressed effectively before HET can be considered viable for military applications. Many years of work have been invested relative to military tactical HEV applications, but HET for military application is still in its infancy of development, prototyping and demonstration. HET is viewed as having great potential for certain military TWV applications and can justify the continued military investment in HET.

This research provides military planners and requirements developers an assessment of the knowledge, understanding of the benefits, challenges, maturity and impact of the HET for military TWV applications.

D. SCOPE AND LIMITATIONS

This study addresses the military needs, goals, requirements, metrics, and the current state of military hybrid-electric (HE) tactical vehicle development. It addresses why a military ground HEV has yet to be fielded. It describes the benefits and challenges relative to the cost, maturity, complexity and technical challenges of the HE system for military vehicle applications. This study describes a perspective if HET offers a sufficient number of advantages, and whether the military should make the hurdle into hybrid technology for military ground tactical vehicle applications.

E. METHODOLOGY

From an acquisition development process standpoint, HET R&D is at the pre-systems acquisition phase at milestone A (Ryen 2008) of the life cycle of the defense acquisition management system. This research is limited to HET material development assessment and technology development. Figure 1 illustrates the project technical development life cycle from the needs definition to system disposal (Ryen 2008).

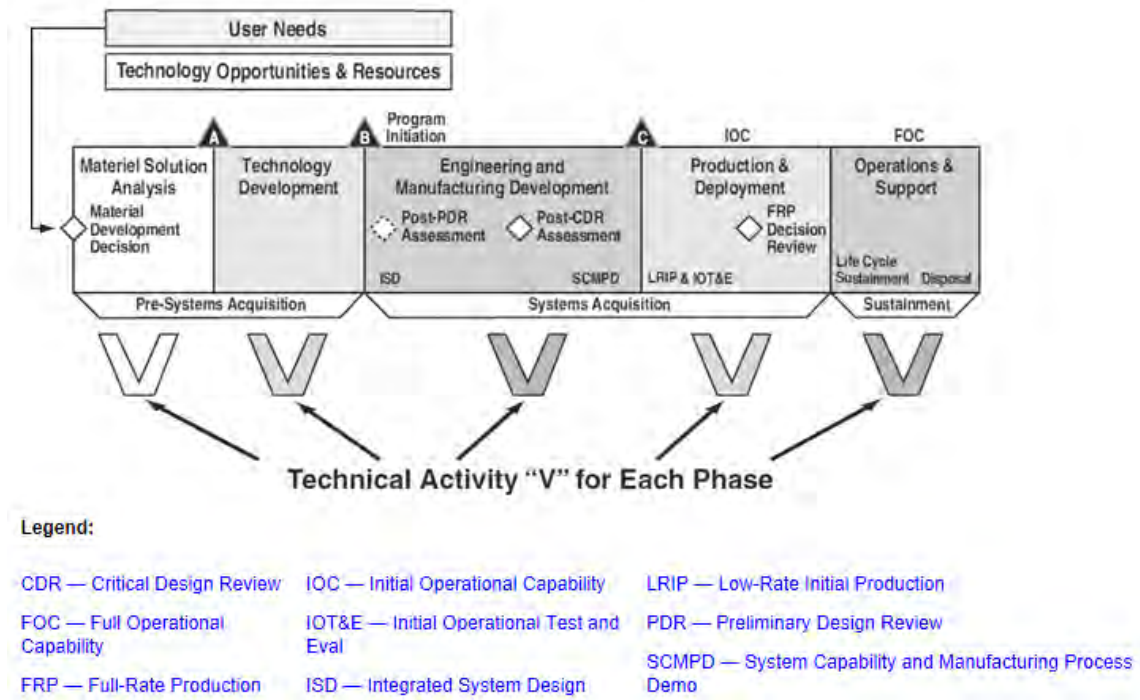


Figure 1. Technical activity "V" for each phase (from Ryen 2008)

The research activities included the following.

- Performed data collection and database development. A broad survey was conducted of available historical data, professional journals, literature reviews, reports, and information published by government agencies (the DOD and Department of Energy (DOE)) on existing and emerging energy, fuels, and technologies. The available data is limited, as much of the effort is either privately funded in industry or classified information in the military.
- The research was focused on DOD initiated efforts in material analysis and to integrate, test, and evaluate sources and technologies in military systems, operations, and logistics.
- Subject matter experts were interviewed, mainly from the U.S. Army's diesel-electric hybrid TARDECs.
- Baseline, benefits and challenges of HET for TWVs were researched. The tradeoffs of a typical tactical vehicle versus HEV tactical vehicles were evaluated.
- Performed a DOD mandated technology maturity-level readiness assessment (TRA) and analysis using the TRL calculator tool.
- Developed a conclusion on whether HET is the right investment for military application with suggested future research opportunities.

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II. HYBRID-ELECTRIC TECHNOLOGY FOR MILITARY TACTICAL WHEELED APPLICATIONS

This chapter describes the needs, goals, requirements, and metrics of the requirement analysis. Figure 2 illustrates the systems engineering (SE) process for the life cycle of the technical management processes. The HET development is at the requirement analysis phase.

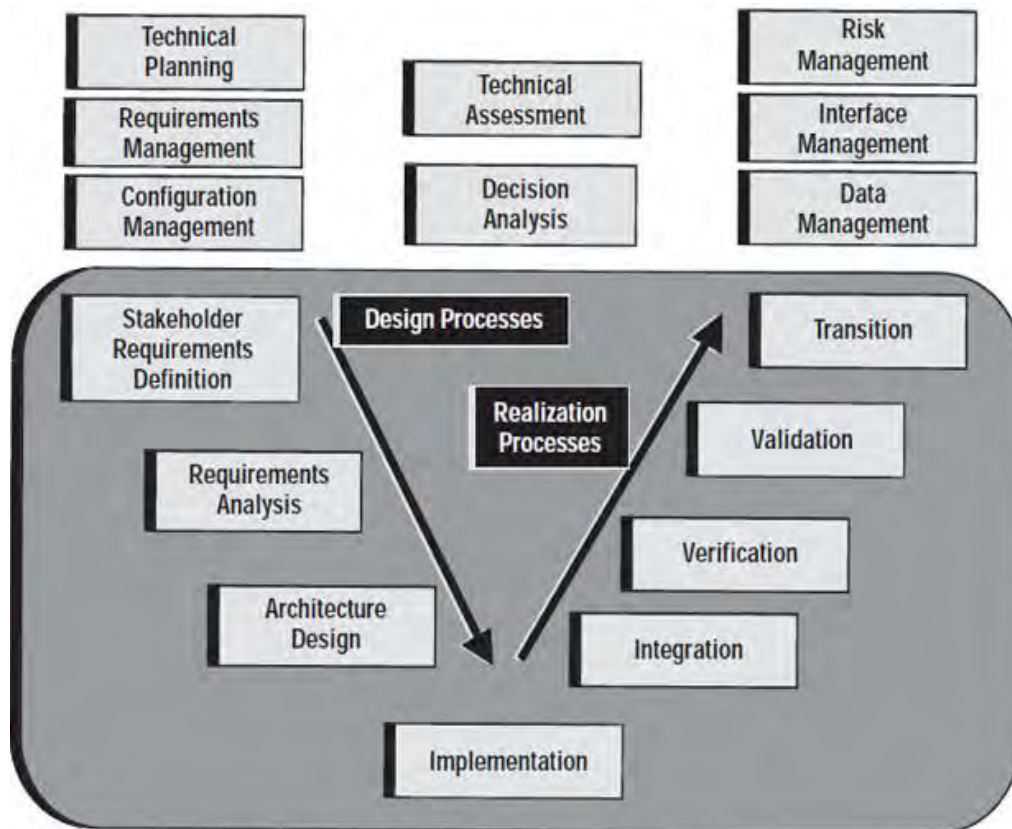


Figure 2. SE process (from Ryen 2008)

A. NEEDS

The primary focus for both the commercial and the military sectors is to reduce fuel consumption and dependence on oil (Kramer and Parker 2011). The commercial sector has shown great success through the production of passenger cars (e.g., Toyota Prius) and other commercial applications including heavy duty vehicles (which have

similar drive cycles as the military TWVs), such as delivery trucks, garbage trucks, and transit buses (e.g., Allison Hybrid EP System, BAE Hybrid Drive series hybrid-electric) (Kramer and Parker 2011).

The operations performed by the military are adversely impacted by ever-increasing battlefield consumption of energy. Energy security is problematic and focuses increased emphasis on system power. Military forces around the world are deeply interested in the potential energy savings from utilizing HEV (U.S. Army RDECOM-TARDEC 2011). Figure 3 illustrates a historical perspective of increasing battlefield fuel consumption and demands per soldier (Fields 2009). Figure 4 presents a historical perspective of the increasing reliance on fossil energy imports.

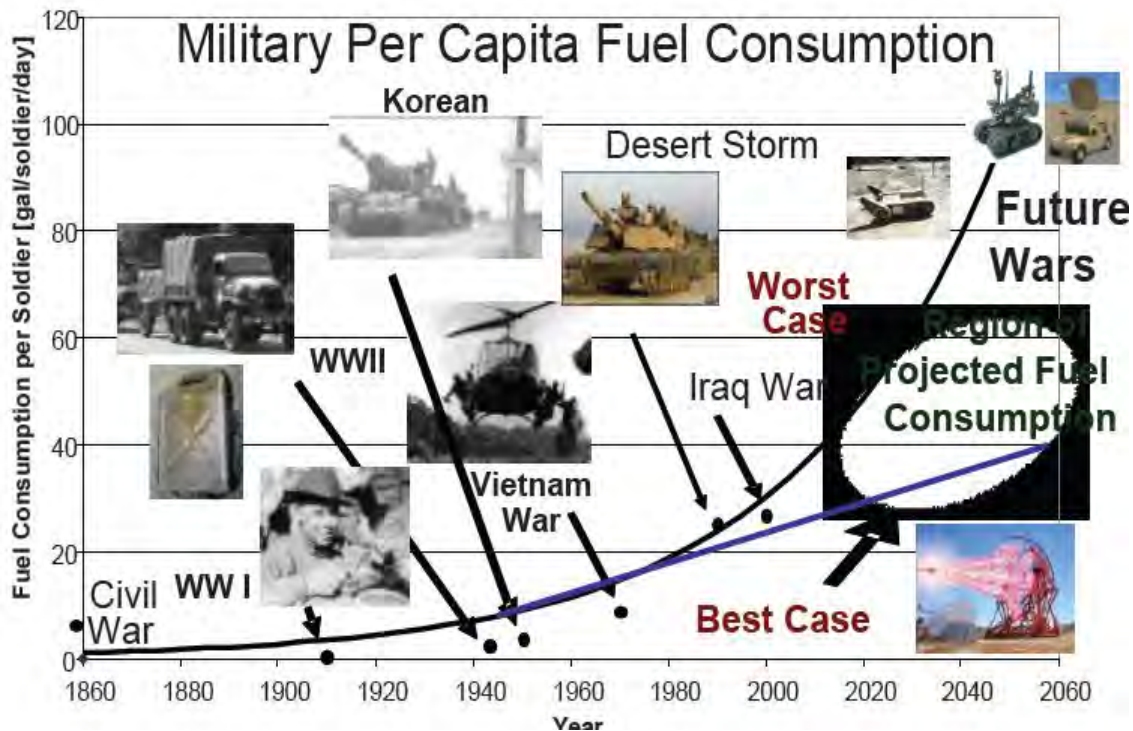


Figure 3. RDECOM TARDEC emerging technologies for the future fight (from U.S. Army RDECOM-TARDEC 2011)

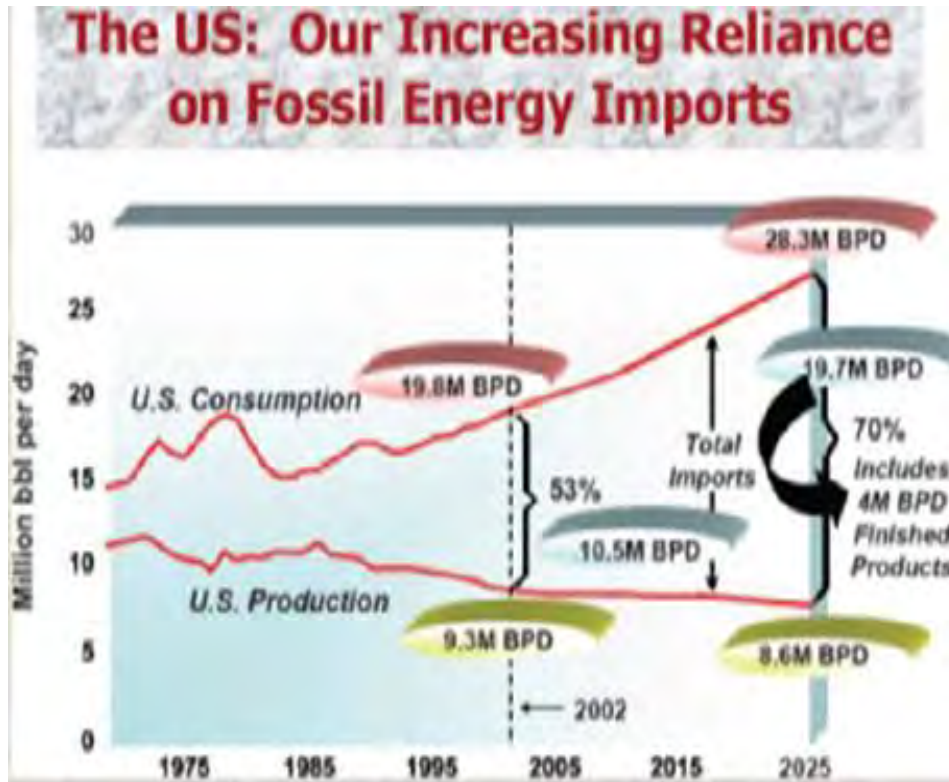


Figure 4. Increasing reliance on imported oil (from TARDEC 2014)

According to Gen. James T. Conway, former Commandant of the Marine Corps, “Fossil fuel accounts for 30 to 80 percent of the load in convoys into Afghanistan, bringing increased costs as well as risk. While the military buys gas for just over \$1 a gallon, getting that gallon to a forward operating bases costs greater than \$500.” (Kramer and Parker 2011). Improving fuel and energy delivery methods will increase soldier survivability by decreasing the number of trips required to transport fuel as illustrated in Figure 5 relative to the exposure risk to potential improvised explosive device (IED) attacks and vulnerability of U.S. supply lines, as well as other logistics support requirements.



Figure 5. Impact of saving 1% fuel (from Schramm 2011)

Since 1943, the DOD has been researching the potential use and the benefits of HET. Program reviews and technology studies occurred roughly once every 15 years without much success and usually resulted in the cancellation of the programs (Khalil 2010) (e.g., Future Combat System). The same conclusion was reached with each progressive program, namely, that HET was too costly and neither mature nor efficient enough to compete with comparable conventional mechanical systems. It was not until around 1995 that the HET program came under serious consideration (Kramer and Parker 2011; Khalil 2011). The military has identified HE power as a potential technology to meet its future needs and provide expanded mission capabilities to the warfighter (Osborn 2009).

B. GOALS

The DOD strategic drivers and energy security goals are illustrated in Figure 6 (U.S. Army RDECOM 2014b).

- **Increase force protection**
 - Fewer fuel convoys means fewer people and systems in harm's way
- **Increase sustainability**
 - Operate for longer / go farther without resupply
 - Reduce O&S costs
 - Crude oil closed at \$96.37/Bbl on 11-7-07; DoD standard (refined) price is additional \$25/Bbl
 - Free up manpower and equipment
- **Reduce Dependency on foreign oil**
 - Reduce revenue flow to unfriendly / unstable nations



"For too long our nation has been dependent on foreign oil...and the way forward is through technology."

President George W. Bush, State of the Union Address, 23 January 2007

"We've also got to address the challenges of energy security and global climate change. We need to harness the power of technology"

President George W. Bush, Speech at the Asia-Pacific Economic Cooperation Business Summit, 7 August 2007



"Reducing the military's dependence on fuel for power generation could reduce the number of road-bound convoys."

U.S. Marine Corps Maj. Gen. Richard Zilmer, Defense News, August 2006



Figure 6. DOD strategic drivers and energy security goals (from U.S. Army RDECOM 2014b)

Programs, such as the cancelled future combat system (FCS), and its replacement program, the brigade combat teams (BCTs), and the ground combat vehicle (GCV), all sought to strike a balance between critical performance factors to include ground platform strategic, operational and tactical mobility, lethality, survivability, and sustainability (Global Security 2011). Through programs, such as BCT and GCV, the military is focused on developing and demonstrating leading technologies that will be ultimately employed for operational uses (TARDEC 2014).

The DOD's strategic drivers and energy goals are stated in Figure 7.

- **Reduce energy consumption.** Reduce the operational fuel/energy consumption of existing sustainment platforms through selective technical retrofit or add new platforms applying technological enhancements.
- **Increase energy efficiency across platforms and facilities.** Make platforms lighter, without increasing their vulnerability. Optimize

maintenance processes (i.e., proper tire pressure, reducing travel speed, using the correct oil in the engine, and using clean air filters).

- **Increase the use of renewable/alternative energy.** Design future systems with more effective fuel/energy efficiencies throughout the drive train. Use more lightweight materials in the manufacturing process to extend operational reach without reducing the capability of the platform.
- **Ensure access to sufficient energy supplies.** Supplement current battery systems with fuel cell technologies, which have the potential to reduce consumption and prolong the life of the battery.
- **Reduce adverse impacts on the environment.** Ensure only items needed for the current mission are carried in the vehicle to reduce the overall weight and increase mileage and fuel efficiency.

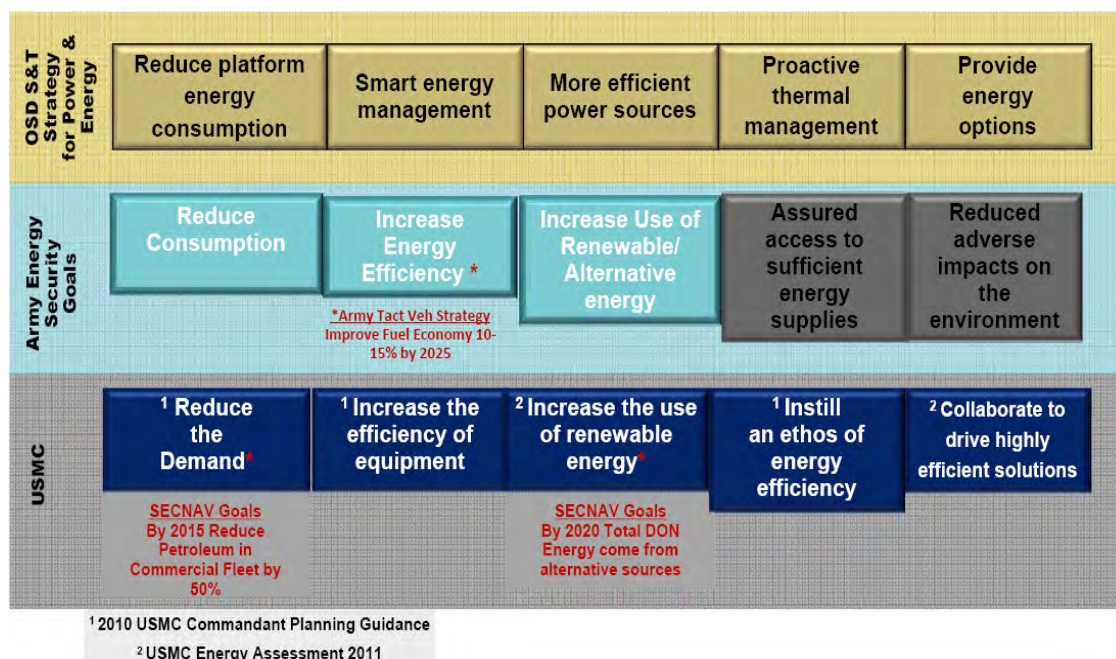


Figure 7. Energy goals for the U.S. military (from Schramm 2011)

C. REQUIREMENTS

The military has unique requirements that impact the military HE tactical vehicle design including mobility, survivability, and lethality. All these systems require electric power that could be generated, stored, and delivered to the different systems in the vehicle within one integrated HE power management and distribution system (NATO RTO 2004).

The requirement for a HET TWV is “to enable lightweight, compact power sources and highly-powered dense components that will significantly reduce the logistics burden, while increasing the survivability and lethality of the soldiers and systems of the highly mobile mounted and dismounted forces of the future” (Hopkins and Acharya 2005; U.S. Army RDECOM 2014b)

The military mission requirements are the “iron triangle” of payload, performance. and protection that include the following (Perez, Hartka, and Veitch 2010).

- Payload includes the operators, supplies, and cargo equipment
- Performance includes fuel economy, acceleration, soil mobility, gradeability, ride, and handling
- Protection includes armor, ground clearance, armaments, and countermeasures

The military transportability requirements for HET are as follows (Perez, Hartka, and Veitch 2010).

- **Survivability:** The electromagnetic armor can be developed to replace the thick armored plates. It includes a combination of active and passive protection, mobility, signature, and operational use. It must be capable of surviving first-round engagements from future armored platforms, shoulder fired AT missiles, and mines (NATO RTO 2004).
- **Mobility:** Active and semi-active suspension systems must be considered to achieve greater cross-country speeds. It should be capable of traversing all anticipated land environments, including urban, complex, and open and rolling terrain. It should possess unsurpassed battlefield agility in terms of maneuverability, cross-country (and hard surface speeds). Strategic mobility is the ability of the vehicle to move or be moved into the operational theatre, which implies that lighter and smaller vehicles have greater strategic mobility. Operational mobility is the ability of the vehicle to move by its power at various speeds. Tactical mobility or battlefield mobility is the ability of the vehicle to move over various terrains and obstacles, such as ditches, trenches, and streams (NATO RTO 2004). The most critical mobility requirements are the following.
 - Vehicle top speed
 - Vehicle top cross country speed
 - Gradeability (60% max)
 - Steering
 - Acceleration

- Braking
- Electric motors in a hybrid-electric drive system can provide two advantages over the mechanical engine and transmission. These are faster acceleration and burst power capability (RedOrbit 2007).
- **Deployability:** Individual platforms must be smaller and lighter, compared to current platforms. The design is to facilitate deployment in units, such as a C-130 or C-17 (NATO RTO 2004).
- **Supportability:** The overall requirement is to reduce drastically operational sustainment requirements compared to the current force. These platforms will include improvements in reliability, availability, and maintainability characteristics. Individual platforms must maintain increased mobility while requiring less external support, such as refuel, re-supply, maintenance, and engineer assistance. Optimum use will be made of embedded diagnostics, prognostics, and repair capabilities to reduce soldier tasks (NATO RTO 2004).

In summary, from the handbook published by the AMC, in 1965, “Military vehicles must have the capacity to operate anywhere in the world, under extreme environmental conditions, from the frigid temperature of the arctic to the intense heat of the deserts, and from the hard rocky and paved roads to hilly and soft soil. They must withstand the vibrations, shocks and violent twisting experienced during cross-country travel over rough terrain, and they must be able to operate for long periods of time with very little or no maintenance” (Kramer and Parker 2011). These basics are still valid today with additional requirements mentioned in this chapter.

D. METRICS

It is vital to the success of this strategy that the DOD develops and tracks metrics that can be used to evaluate both the pace and success of specific projects and initiatives, and to capture aggregate progress in integrating energy factors. Decision makers can compare alternative programs based on their contribution to these metrics (Luskin and Berlin 2010).

- **TRL:** Risk management associated with technology maturity. It is the consideration of successful hardware and software demonstrations, and for the ability of legacy and near-term programs to make use of included technologies.

- **Fuel Efficiency:** Measurement for evaluating alternatives relative to either gallon per mile for a vehicle class or output specific fuel economy (tons-mile per gallon).
- **Vehicle Mass:** Mass is a critical factor that directly affects other attributes including transportability, survivability, and payloads.
- **Promising Technology:** Might be included in spite of a low TRL, and as part of the program's value in increasing TRL through successive demonstration.
- **Drive Cycle:** Shown in Figure 8, it is an example of the measurement of broad usage experienced by TWVs in the field. Elements within this cycle include convoy escort with relatively high speeds, steady state driving, on paved road; urban assault with low speed, stop/start deriving on paved road; cross-country with low speed driving on trails, and tactical idle with operation at zero speed while running accessories. The definition of the drive cycle must be considered to determine the relative effectiveness of any solutions. The elements of the operational and environmental parameters relative to time or distance are vehicle speed, elevation or grade, road surface, accessory usage, and payload, based on data from the battlefield. Several priority considerations exist relative to weight, cost, and complexity (Perez, Hartka, and Veitch 2010).
- **Technology:** The new technology must meet the DOD Instruction 5000 series mandatory maturity level, operational effectiveness, and sustainment requirements to ensure that it meets the expected outcome over the life cycle of the systems including measure of effectiveness (MOE) including measure of performance (MOP) and measure of suitability (MOS), specifically to key performance parameter (KPP), key system attributes (KSAs), and costs (Kageyama 2014).
- **Measures of Operational Effectiveness.** They derive from a hierarchy of component factors. These component factors, and their relationships, are reflected in the system operational effectiveness (SOE) model as illustrated in Figure 9, as discussed in SE 3302 Systems Suitability at the Naval Postgraduate School in 2010. Each component of the model contributes to the ultimate outcome, affordable operational effectiveness. Maximizing operational effectiveness requires proper attention and balance among all the factors included in the SOE model. The stakeholder value system determines the priorities on which the Program Manager relies when making the tradeoffs that system design undergoes, balancing performance, availability, process efficiency, and costs.

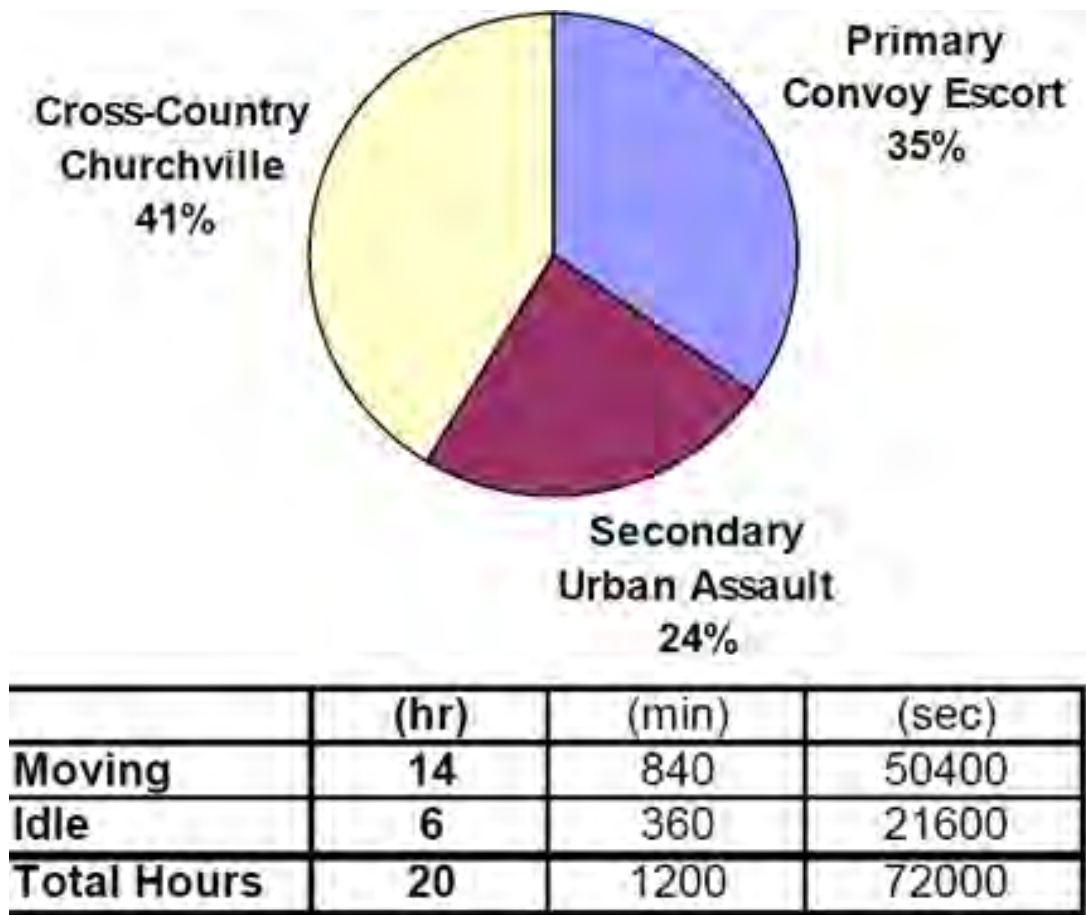


Figure 8. Usage cycle defined for the fuel economy demonstrator (FED) program (from Perez, Hartka, and Veitch 2010)

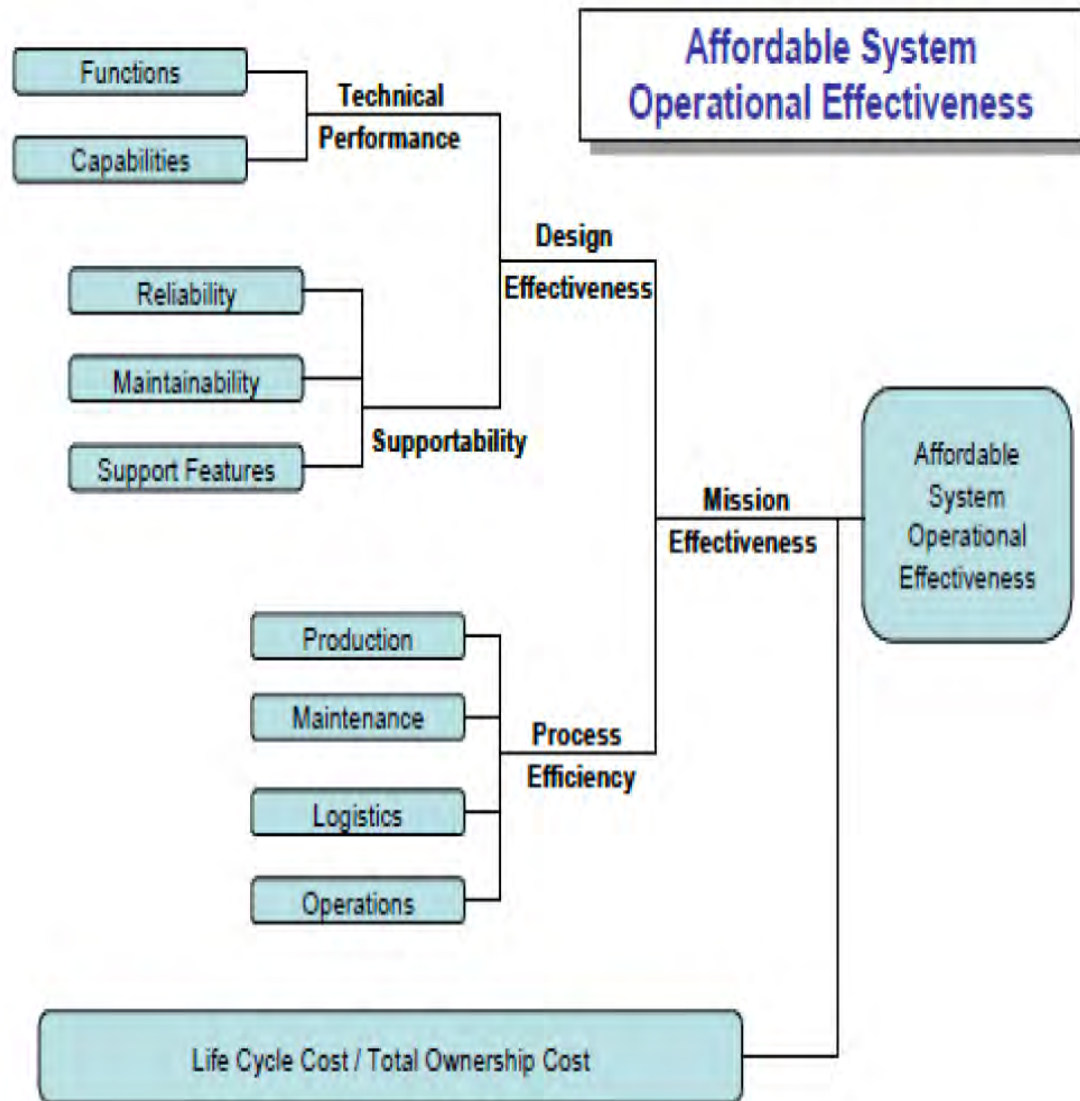


Figure 9. System operational effectiveness diagram (from SE 3302 Systems Engineering Suitability Analysis, Naval Postgraduate School 2010)

E. CURRENT STATE OF DEVELOPMENT AND DEMONSTRATION

The U.S. military has been researching the use of HED technology for over 50 years (Khalil 2011). Extensive work has been done relative to simulation, optimization, and controls of the hybrid power train on three types of military TWVs (Kramer and Parker 2011), namely the high mobility multipurpose wheeled vehicles (HMMWV), family medium tactical vehicle (FMTV), and heavy mobility expanded tactical truck (HEMMIT). These span ranges from class III through class VIII and with a gross vehicle

weight (GVW) of 4536 kg to 14972 kg (*Defense Update* 2005). In demonstrations, the HMMWV, class III vehicle showed the greatest potential for fuel economy improvement with respect to the drive cycle (Sheftick 2011) and is the focus of this study.

To understand the performance of this technology, the hybrid-electric vehicle experimentation and assessment (HEVEA) program was initiated in 2005 (Allen 2007; Allen, Ghassan, and Pizzolo 2009). The goals of this program were to understand how hybrids performed in a military environment, develop standard test procedure and methodology for testing HEVs, and to develop analytical tools for both assessment and evaluation. HEVs also sought to establish credible and quantifiable data for HEVs versus conventional vehicles, i.e., fuel economy and reliability and to develop modeling and simulation (M&S) methods. In four years, the military developed physical and analytical methods for evaluating conventional and HE vehicles that have been accepted by the acquisition community and industries as shown in Figure 10.

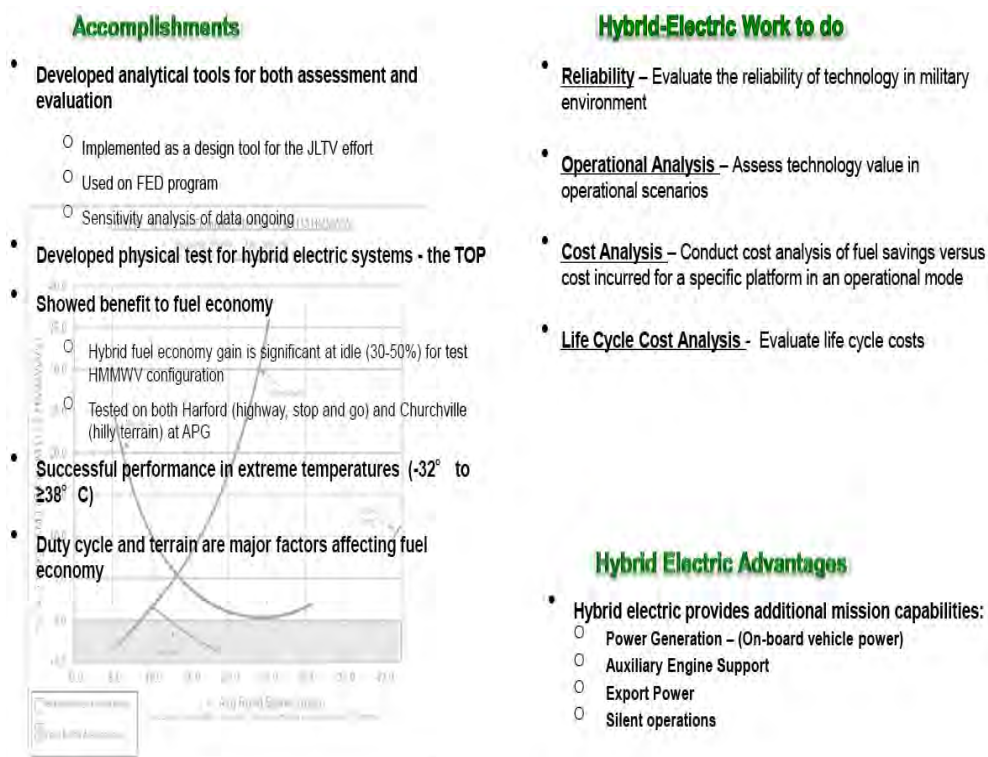


Figure 10. Hybrid-electric vehicle experimentation assessment (HEVA) (from Bochenek 2011)

In addition, the FED program effort is a collaborative effort with industry and subject matter experts to brainstorm and evaluate technologies that increase light tactical vehicle fuel efficiency. The FED program created two demonstrators (Alpha, Bravo). One has an integrated starter generator (ISG) only, while the other is a full parallel electric hybrid (TARDEC 2012a; TARDEC 2013b). TARDEC successfully demonstrated the fuel-efficient ground vehicle FED Bravo vehicle at the SAE World Congress and Exhibition in Detroit in April 2014. The FED Alpha and Bravo demonstrator program represents the DOD's willingness to pursue originality in reducing fuel consumption. This program was initiated to test commercially available fuel-efficient systems on military applications. To design FED Bravo, TARDEC assembled subject matter experts from government, industry, and academia to filter through the most innovative and effective fuel-efficient technologies on the market that could be applied to a military platform. Trade-offs using a top-down, systems-level approach with fuel efficiency and performance as primary requirements were assessed and examined (TARDEC 2008).

The FED Alpha and Bravo demonstrators are concept vehicles funded by the DOD to test and transfer technology. "The vehicle itself won't go into production, but the components, technology and lessons learned will be transitioned to the current fleet and allow for improvement of the future fleet. The FED vehicles were built to evaluate whether existing fuel efficiency solutions will be effective on a military platform" stated Carl Johnson and Rachel Agusti of the TARDEC (TARDEC 2014). The results summarized the FED Bravo vehicle as "This vehicle can perform the same mission as a HUMVEE, but with 90% better fuel efficiency" (TARDEC 2014). Figure 11 shows the FED Bravo vehicle (Schramm 2011).



Figure 11. The fuel-efficient ground vehicle demonstrator FED Bravo vehicle, designed by TARDEC (from Schramm 2011)

The benefits and lessons learned from the FED Alpha and Bravo (TARDEC, 2012b) are illustrated in Figure 12 and the findings are listed as follows.

- The transfer of as many fuel-saving technologies and improved processes to other projects and platforms to make TWVs as efficient, agile, and safe as possible
- Use of the same drive cycles for other military vehicles
- The FED Bravo offers 7.50 combined miles per gallon (MPG), which represents a mixture of urban mission and convoy escort (highway) driving. The current HMMWV model the FED uses for comparison generates about 4.8 MPG. The FED Bravo obtains 90 percent better fuel economy and can travel at 80 MPH. It has both efficiency and protection with the V-shaped hull and the adjustable suspension for blast protection (TARDEC 2014).

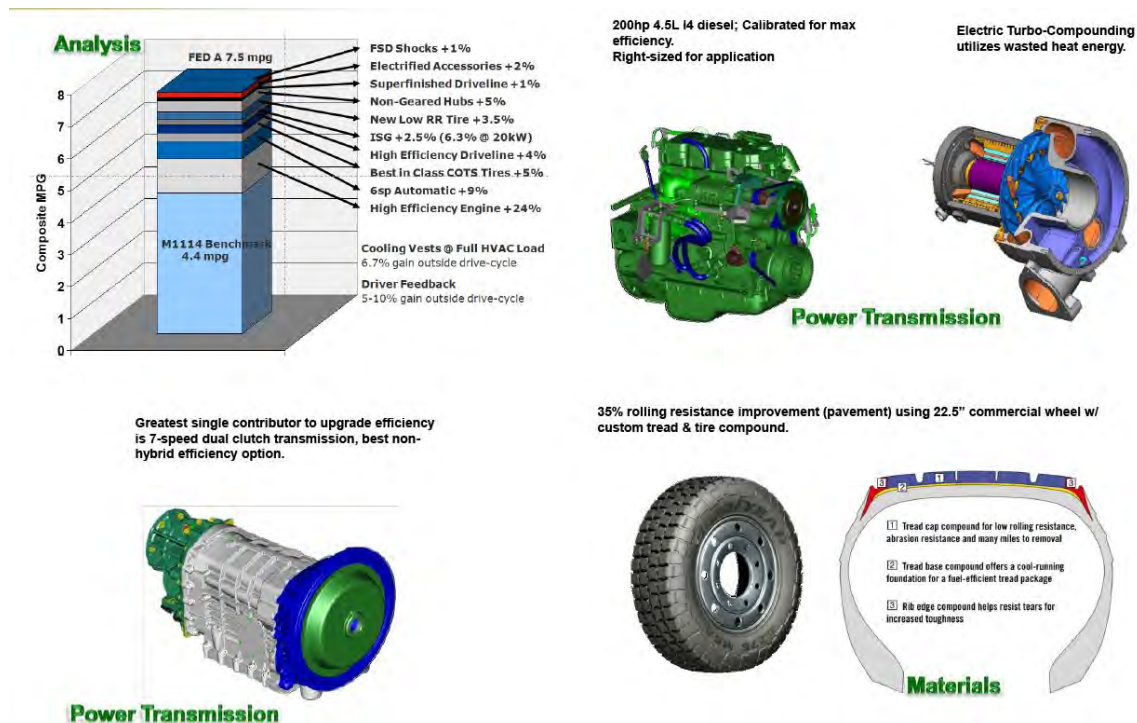


Figure 12. FED findings directions in engine-efficiency and emissions research (from Bochenek 2011)

The DOE and DOD formed an alliance to research advanced vehicle power and energy technologies for use in military application (Bochenek 2011). The goal is to leverage investments around common requirements and leverage industrial R&D to transition technologies and increase efficiency of R&D funding. The opportunities for leveraging HET are shown in Figure 13 for both the DOD and DOE.

Work Groups Convened in Six Technology Focus Areas Identified for initial Joint Activity

Technology Focus Areas	Primary Interest	
	Army	DOE
1) Advanced Combustion Engines & Transmissions	High density, energy efficient powertrain	Extreme gains in engine efficiency
2) Lightweight Structures & Materials	Reduce weight to improve performance	Cost reduction for consumer market
3) Energy Recovery & Thermal Management	Improved efficiency, manage heat generation	Efficiency gains through waste heat recovery
4) Alternative Fuels & Lubricants	Standardization & security	Efficiency gains for the legacy fleet
5) Hybrid Propulsion Systems & Energy Storage	Efficiency improvements	Efficiency improvements
6) Analytical Tools	Assessment/Design Trades	Assessment/Design Trades

UNCLASSIFIED

Figure 13. DOD/DOE joint activity (from Schramm 2011)

The specific technology goals of the partnership include improving diesel engine efficiency, designing a heavy duty (> 8,500 pound gross vehicle weight) HE propulsion-based vehicle, improving aerodynamics, integrating idling-reduction systems, and increasing vehicle safety through collision avoidance technology. Given the operational parallels between commercial trucking industry and military operations, possible opportunity exists for vehicle technology transfer between this partnership and the DOD (Perez, Hartka, and Veitch 2010). The DOD showed that the military is serious about using less fuel and achieving higher MPG ratings for its vehicles. TARDEC, in collaboration with private industry and academic partners, identified and employed feasible, commercially-off-the-shelf technology available to provide fuel savings, and build enhanced aerodynamic and safety features to satisfy the military's requirements for a tactical vehicle (TARDEC 2008).

F. BENEFITS OF USING HET

Projects and programs for the use of HEV combat vehicles mentioned are currently in various development and demonstration phases. These projects are leading to

the main conclusion that HEVs do offer a variety of advantages (NATO RTO 2004). The main benefits for military applications are the following.

1. Improved Fuel Economy

Improvements in fuel consumption are realized through efficient power management, electrical regenerative braking, and reduced mass from decreased volume over armor and reduced engine mass. HET realizes such a large fuel swing since the HED directly supplements the engine power by using stored energy (e.g., batteries, flywheels, and capacitors). The engine power is used mainly during steady-state driving when the least amount of fuel is consumed for mobility. Transient conditions are powered mainly from the energy stored, which is created by regenerating the energy from braking, as well as from the generator. The characteristics of HE propulsion systems, the optimization of engine operation, and the brake-energy recovery system contribute to overall fuel savings, which can be 15 percent to 20 percent better than a conventional mechanical system under certain driving conditions (NATO RTO 2004). Typical results are shown in Figure 14. Improved fuel economy, emissions, and thermal signatures reduction shrink the overall logistics burden of HEVs for military applications (Allen 2007).

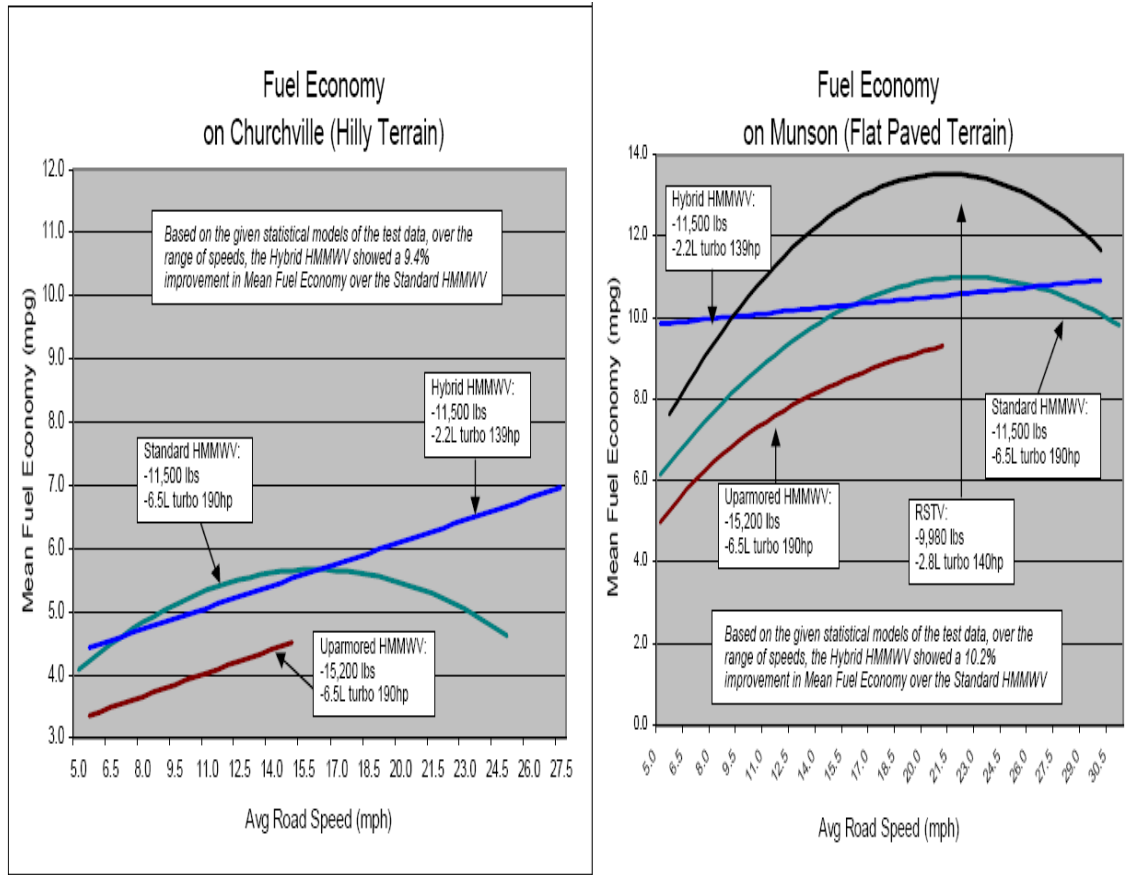


Figure 14. Fuel economy varies with terrain and driving condition (from Allen 2007)

2. Available Onboard Power Generation

The demand for on-board electrical power supplies has increased in the past decade and is expected to continue to increase for future military systems. One of the most tangible benefits of HET for military vehicles is the ability to generate and store electric power. This on-board power can be used for auxiliary loads on and off the vehicle. The HED system has two sources to generate power, the engine generator and the energy storage system. The main power management and distribution system can be designed to meet the electrical power of users within the vehicle, as well as off-vehicle demands. The power management and distribution system is able to supply continuous power adequately to meet the main user propulsion, as well as to supply the intermittent power to drive/charge a pulsed power system for electric weapons (e.g., electrical thermal chemical (ETC) gun and directed energy weapons (DEW)) or electro-magnetic (EM)

armor, while providing thermal management. The availability of these high levels of on-board electrical power may be used to reduce the logistical burden by eliminating, in certain instances, the towed generators normally used to provide electric power in the field (RedOrbit 2007).

Batteries deliver power back into an electrical grid. New military vehicles are demanding an excess of 50 kilowatt (kw) of power, which can only be provided by an advanced onboard power unit or HE system (NATO RTO 2004). An on-board vehicle power (OBVP) study concludes that a 10 KW system would meet most unit energy requirements. A key operational benefit is that it provides backup power for mission-critical systems. Using HET can supplement but would not eliminate conventional generator sets and can provide power where it is normally unavailable. Off-setting the increased operating costs (associated with the use of fuel) with on-board power generation, can augment vehicle power to platforms for more weapons and other onboard systems. Mitigating the separate requirement for vehicles and systems can provide a significant cost savings to the warfighter effort (Raney 2007).

3. Reduced Acoustic and Thermal Signatures

HE systems have the potential to reduce the vehicle acoustic and thermal signatures significantly; however, it is not known if they will increase the electromagnetic signature. A HED has the ability to generally provide a reduced thermal signature by having a more efficient power train and by being able to optimize the power management of the system for reduced emissions. In addition, it offers a temporary mode of mobility, in which the vehicle's main power generators are turned off and the vehicle is powered by a pure electric power source, such as a chemical battery, a flywheel generator, and an ultra-capacitor, or perhaps, even a fuel cell (NATO RTO 2004).

4. Silent Watch and Silent Mobility

A critical benefit of HEV is the ability to idle and move without the noise and thermal signatures produced when its internal combustion engine is engaged (40). The military has been working to define silent watch and mobility requirements for varying load, duration, and mission requirements. HET vehicles are capable of running silently

for a time while the vehicles are moving and a capability to conduct silent reconnaissance operations while in a stationary position. During silent operations, loads vary from one vehicle mission to another, and energy requirements range from a minimal to extensive kw usage. Therefore, the battery pack must be designed and sized to meet each specified silent watch requirements (RedOrbit 2007).

The onboard energy storage system can be used to meet silent watch and silent mobility requirements for extended periods of time to meet various mission requirements. Depending on the power requirements of the silent watch, a mission could be extended by several hours, which exceeds the current silent watch capability (NATO RTO 2004).

Silent mobility over a limited distance is also achievable. The vehicle can move in or out of a hostile territory with a reduced chance of being detected. To obtain a silent watch/mobility capability, however, the energy storage system on the vehicle must be able to provide sufficient power and energy to fulfill the military requirements (RedOrbit 2007).

5. Vehicle Packaging Flexibility

The HEV consists of modular components connected by cables that provide vehicle designers with more packaging flexibility. This system also avoids the constraints of conventional mechanical drive systems, which require the engine to be connected to the wheels via gearboxes and rigid shafts. This flexibility allows the components to be arranged and integrated for the optimum utilization of the available vehicle space (NATO RTO 2004).

In the Series HEV configuration, for example, all the power is transferred from the prime mover to the wheels electrically. This configuration eliminates the rigid connections and the required alignment between different components, which normally results in dead or unused volume in the vehicle. The packaging efficiency of the HEVs is an advantage from which integrators can benefit (RedOrbit 2007).

6. Enhanced Prognostics and Diagnostics

In a HEV, operations are controlled by microprocessors that lend themselves to the provision of a health and usage monitoring system (HUMS). The HUMS is capable of identifying impending failures before they happen and providing data on the faults so that reliability-centered maintenance can be implemented. This proactive maintenance should help reduce operation and maintenance costs over the life of the vehicle, as well as help offset the acquisition costs associated with procuring new vehicles to achieve an improved life cost for the HEV. Currently, the acquisition cost exceeds that of a mechanical system (NATO RTO 2004).

7. Other Benefits

a. Electro-Magnetic Armor

Electro-magnetic armor (EMA) is a supplemental armor solution that is not an integral part of a HE system; however, the infrastructure provided by a HE power train can support EMA, which is an added benefit of the system (Science Applications International Corporation 2013). EMA systems use a high current of energy to disrupt the plasma jet of an explosively formed projectile (EFP). This technology is used to replace some heavier conventional armor on combat vehicles.

Additionally, the battery pack of the HEV can be used to charge a pulse forming network (PFN). A capacitor module in the PFN can store up to 100–200 kilojoules (kJ) of energy. The armor is triggered by an EFP. Upon impact, the stored energy is quickly dissipated in a controlled and shaped pulse, which disrupts the stream, and severely limits its ability to penetrate the vehicle.

Technical challenges to successful EMA development include lightweight battery banks; flywheel energy storage; high capacity, high energy-density conventional polymer capacitors, low impedance buses, and high current, high firing-rate switches. All these components are in advanced development, and system integration issues are being addressed (Science Applications International Corporation 2013).

b. Off-board Power Generation

A potential feature of HEVs is off-board power generation. The vehicle can be used to provide power to other vehicles and systems on the battlefield. Off-board power generation is an application that is very important to the military. HEVs can advance the cause of a highly mobile force by providing power to other vehicles and systems on the battlefield (Science Applications International Corporation 2013).

Figure 15 summarizes the HE benefits described in this chapter. Fuel economy is adversely affected with acceleration or grade performance. It becomes difficult to determine comparable fuel economy performance across studies with different duty cycles increases.

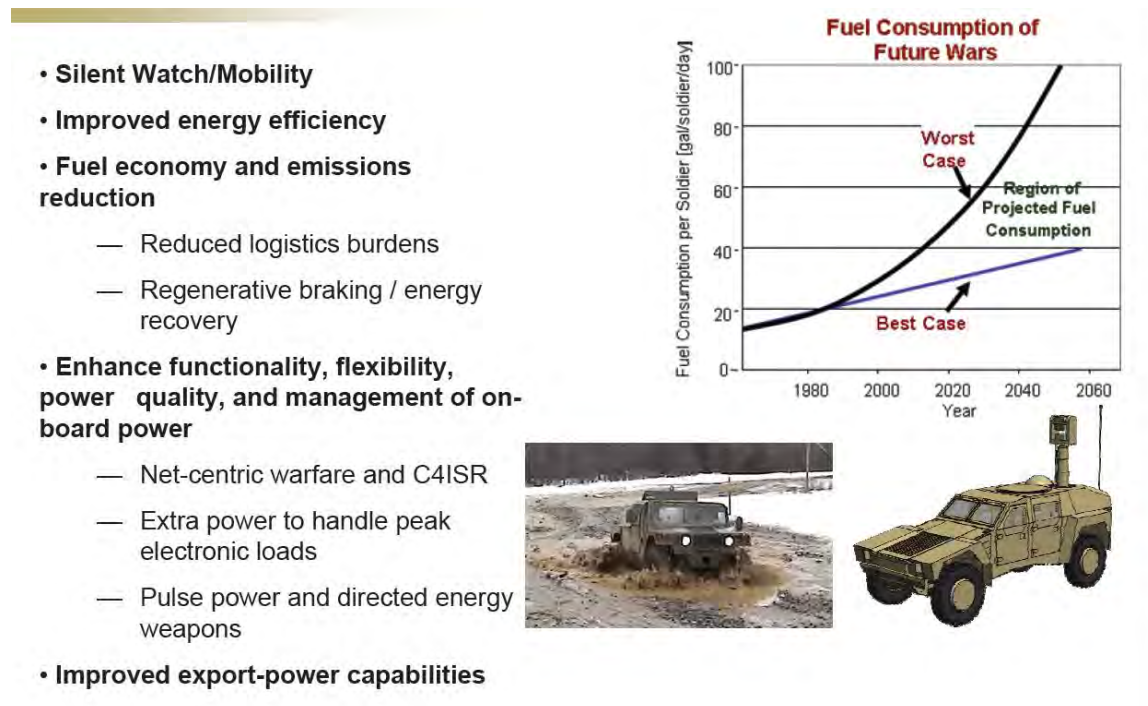


Figure 15. RDECOM TARDEC HE benefits (from U.S. Army RDECOM 2014b)

At the switch level for the power semiconductors, the benefits are lower losses, high reliability, high operating temperature, lower thermal resistance, higher surge capability, and higher frequency operations at higher power levels. At the systems level, the benefits are higher reliability, longer availability, higher efficiency, improved fuel

economy, lower operating cost, lower losses, smaller and lighter components, and reduced signature (NATO RTO 2004).

The design benefits are no mechanical link or drive shaft, which allow for design flexibility that potentially improves maintainability, and provides a lower profile or footprint (U.S. Army RDECOM 2014b). The development costs for HET are currently excessive; however, most of these costs are likely to be offset by the LCC in fuel and maintenance (NATO RTO 2004). Further quantifying these capabilities by the stakeholders and developers could help to define the benefits of HEVs for military applications.

G. CHAPTER SUMMARY

The military recognizes the growing energy challenges of the warfighter, mainly that the HE drive systems are needed to support future military mission applications. The main advantages meeting the energy challenges are the following (NATO RTO 2004).

- Research on advanced vehicle power technologies for vehicle platforms underway with collaborative efforts with industry, academics, and DOD and DOE labs
- Progress has been made in the area of HE propulsion analysis
- HE propulsion strategically aligns with the operational energy strategy
- HE provides additional mission capabilities
- Optimized HE can achieve fuel economy savings over various drive cycles
- Sustainment based on reliability and durability need to be proven, in right applications, with the following.
 - Potentially have good cost-benefit
 - Provides capabilities not otherwise available
 - Fits customers need

Advantages over conventional combat vehicle power train systems include the following (NATO RTO 2004).

- HED systems provide better fuel economy than their mechanical counterparts due to the use of optimum engine performance and energy recovery during braking; however, the fuel economy gain has not yet been quantified and will require extensive field testing before any prediction is

verified and validated. Current predictions range from 20% to 30% improvement based on various mission scenarios.

- HET greatly increased power for the integration for high efficiency electric drives, sensors, and computing systems. Exportable electric power reduces logistics burden for towed generators, enhances low-speed maneuverability; provides a smaller overall vehicle profile for concealment, a low acoustics signature, and a quiet ride. Additionally, it produces a high amount of electrical power that is sufficient to enable the use of future high power technologies.
- The automotive performance of HEVs in terms of speed, acceleration, gradeability, and stealthy operations is superior to the performance of mechanically driven vehicles. In addition, energy storage onboard HEVs can support silent watch when idle, silent mobility operations, and also future electric weapons, such as the ETC gun and DEW.
- Embedded diagnostics and prognostics allow the maintainers to determine the source of faults and advanced planning directly for unscheduled maintenance. The design allows for future improvements by decoupling the power generation unit from the drive train architecture. The existing power generation unit can be replaced by another technology, such as fuel cells, once this technology has matured to further improve fuel consumption, acoustic signature, and mobility performance (RedOrbit 2007).
- Emerging technologies, such as silicon carbide (SiC) and lithium ion batteries will greatly enhance the packaging and integration of the HED systems for both continuous and pulsed power in a combat vehicle. Pulsed power technology, particularly for ETC gun applications, is achievable and can be integrated in combat vehicles (RedOrbit 2007).

The expected HET LCC qualitative advantages include the following.

- **Affordability:** Commonality is the ability to use the same subsystems in multiple vehicle types, which results in economies of scale for basic components and a reduction in maintenance costs and the logistical burden.
- **Dual use:** Electrical and electronics devices, whether developed for the commercial market or for military applications, for the most part can be designed for interchangeability, which is particularly true for solid-state semiconductors. It also implies economies of scale and expected lower development costs.
- **Modularity:** Several subsystems can be assembled from basic modules: i.e., batteries, capacitors, power controllers, generators, and motors. Again, it is an approach that would yield lower production and maintenance costs.

- **Operational Benefits:** These advantages will allow more operational capabilities. The power generating unit and the power controllers can be positioned anywhere in the vehicle to allow several design strategies depending on the established mission of the HEV, such as a reduction of the vehicle profile, and rear crew access for infantry fighting vehicles (IFVs). The electrical energy storage will improve the overall powertrain efficiency, reduce fuel consumption, and thus, increase the range of the vehicle. The electrical energy storage allows the vehicle to operate in silent mode for short distances of about 1 to 2 kilometers (km), which provides considerable reduction of the thermal and acoustic signatures (NATO RTO 2004).
- **Logistical Support:** The realization of modular components leads to fewer part counts, quicker parts replacement, and a reduction in transportation, maintenance costs, and logistical support. The use of electrical technology leads to improved diagnostics, due to the continuous fault detection feature inherent to electric systems, which will predict potential failures, and thus, increase availability by reducing the down time and repair costs by optimizing the scheduled maintenance (NATO RTO 2004).
- **HET:** Much of the HET occurs in the systems requirements and design phase. Therefore, operational requirements analysis, such as reliability; maintainability; availability; sustainability; operational analysis; safety; cost analysis, and LCC analysis has not been evaluated. The technology maturity TRL is between TRL4 to TRL6 and will require further development (NATO RTO 2004).
- **LCC Savings:** Will come from the cost of fuel itself and maintainability. It will also trim volumes off the military's logistical transportation requirements (Daniel 2010).
- **Future Fuels:** According to the Naval Research Advisory Counsel (NRAC) for future fuels, fuel economy is power. No single "silver bullet" exists for a 75% reduction in fuel consumption. The key actions are to commit to HE architecture for TWVs (Hansen 2009), fuel management during combat operations, and long-term commitment to alternatives and renewable fuels from domestic sources. The NRAC recommendation is to establish a HEV development roadmap, initiate SE trade-offs, and invest in on-going HEV development projects (NRAC 2005).

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III. CHALLENGES OF HYBRID-ELECTRIC TECHNOLOGY FOR MILITARY TACTICAL WHEELED APPLICATIONS

The challenge of R&D of a new technology is to determine the impact on cost, space, weight and power needed to meet specific requirement or a set of requirements (Seaton and Gardini 2010). An absence of deployed military hybrid vehicles is NOT due to a lack of investment in R&D but rather because applying hybrid vehicle architectures to a military application has challenges that make fielding such a vehicle technically and cost prohibitive. The span of energy and technologies exists in various phases of commercial, and research and developmental availability. Unfortunately, these efforts are characterized by activities that do not provide for a well-structured and well-understood method to adequately assess the effectiveness of the new technology (Kramer and Parker 2011). Common metrics, methods, and evaluation techniques have not been standardized. Furthermore, technology maturity level and risk assessments have not been adequately evaluated prior to integration into DOD efforts. Also, the investment, availability of support infrastructure, and competitive environment for such technologies must be better understood to determine the cost of research, development, testing, and evaluation of DOD efforts more accurately in migrating to these new energy technologies (Perez, Hartka, and Veitch 2010).

TARDEC is leading some of the DOD's early evaluation and adoption efforts of alternative energy sources, fuels, and technologies for vehicle use. The majority of the grounds vehicle projects focused on prime power sources, non-primary power, energy storage, and power and thermal management. Figure 16 illustrates the challenges of the HET from the increasing reliance on imported fossil fuel to the ever-increasing consumption of energy sources and its effect on the operational issues (U.S. Army Technology and RDT&E 2011). The challenges facing HEV for military applications have two aspects, technical and cost challenges:

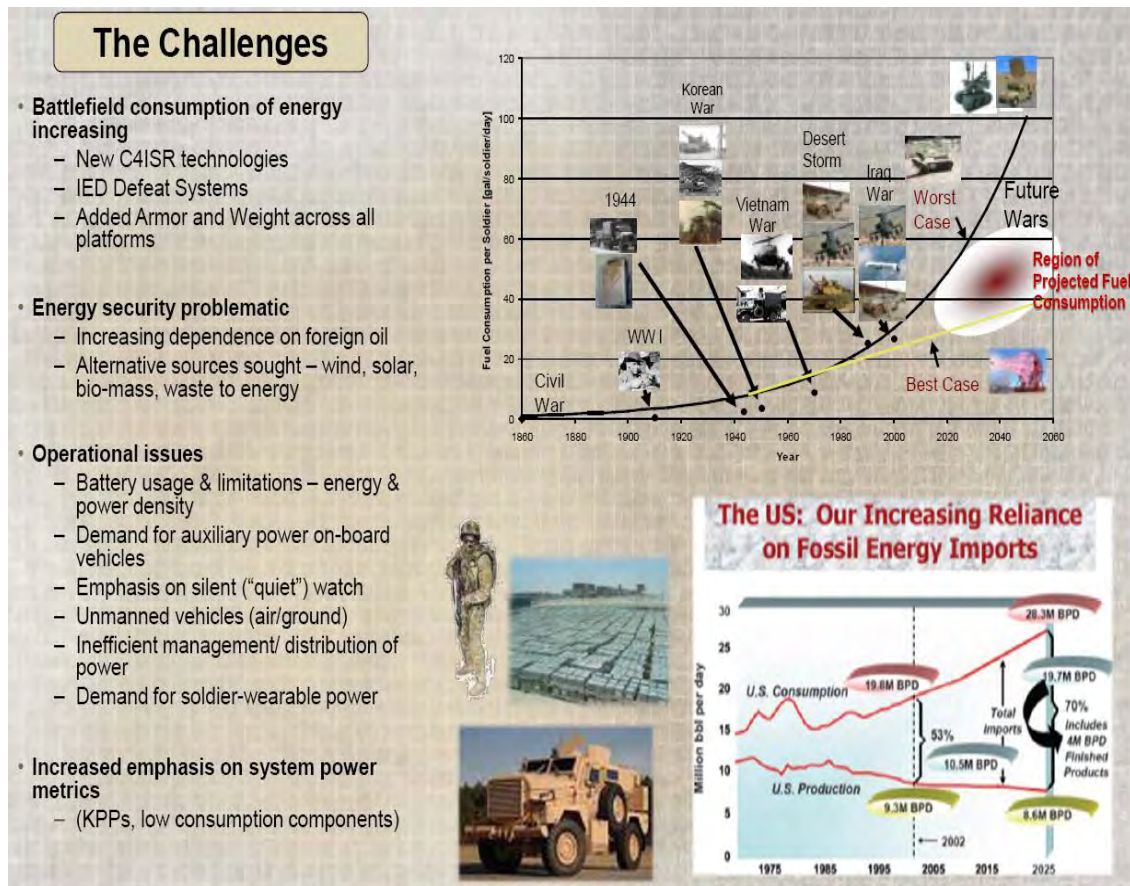


Figure 16. Challenges (from U.S. Army Technology and RDT&E 2011)

A. WHY HAS THE U.S. MILITARY NOT YET FIELDDED HEV?

Many HEV components are maturing, such as motors, alternators, controls, improved semiconductors, cooling systems, and many of the basic components are almost ready for at least pre-production. However, two primary issues are preventing the successful design and demonstration of military HEVs, mainly, the military vehicle driving cycles and suitable energy storage media for a military environment.

1. Drive Cycle

HEV propulsion battery design and life depends greatly on how the vehicle is used in a tactical environment and from field operations. Accurate and well-defined driving cycles are essential to military HEV propulsion battery design. To produce a

design that exceeds the planned driving cycles may result in degraded or inadequate vehicle performance (Raney 2007).

2. Energy Storage

Efforts are on-going to develop large format, energy dense batteries for HEV propulsion. Technical challenges still remain including energy density, charge and discharge cycles, cell balancing, power vs. energy density trade-offs, operating at temperature extremes, and safety. Other issues are charge management, thermal, weight and space claims; that is, military HEVs are much heavier, shock and vibration more extreme, and military temperatures are more extreme (Raney 2007).

The operational issues are battery usage and limitations relative to energy and power density, demand for auxiliary power on-board vehicles, silent watch, inefficient management, distribution of power, and the demand for soldier-wearable power (U.S. Army RDECOM-TARDEC 2011). While substantial investment has been made in technologies that provide improved energy density and specific energy that is safer and cleaner than older technologies, significant obstacles must still be overcome before the HET becomes feasible for full production and deployment. Many of the components that either do or will comprise HE power trains are still in their technological infancy. Specifically, the fuel economy improvement for military hybrid vehicles is highly dependent on the drive cycle used, which makes it difficult to evaluate technologies to prepare the military to benefit from a hybrid vehicle (Kramer and Parker 2011).

Batteries capable of powering HE vehicles are still in development. Without further advances in this area, it is not likely that HE vehicles will gain significant progress in the military market. Battery packs necessary to power these vehicles are large and heavy. Additionally, the space claim of the batteries is significant (Ding 2011). While batteries and energy storage in general is the most significant obstacle, other components present challenges as well. The motors for HE vehicles are still developing and are being produced at low quantities. Furthermore, high power density engines that could alleviate many of the weight and volume concerns are still in development. It is not clear that engine downsizing is viable in a military context. Military vehicles may require the

option of operating at full power at all times. Thus, the development of high power density engines is critical to the development of military HE vehicles (Science Applications International Corporation 2003).

All components will need to be matched with each other, both in terms of their functions and operating methods. The benefits that can be achieved with HEVs depend largely on the approach adopted. Since HET is ever advancing and taking on commercial applications including some heavy duty vehicles, such as buses and delivery trucks, it appears likely that these technologies could be leveraged to field hybrid military vehicles eventually (Kramer and Parker 2011).

The one-of-a-kind prototype and demonstrations vehicles will not go into production but the components, technology, and lessons learned from the development can potentially be transitioned into the current fleet of vehicles and allow for the improvement of future vehicles. These components and systems will require a rigorous verification and validation process to ensure that mandatory sustainment requirements are addressed over the life cycle (TARDEC 2012b).

Lastly, commercial investment, the availability of delivery support infrastructure, and the competitive (foreign and domestic) landscape for HET must be better understood to reflect the cost the research, development, testing, and evaluation (RDT&E) of DOD efforts more accurately in migrating to these new technologies (U.S. Army RDECOM-TARDEC 2011).

B. TECHNICAL CHALLENGES

Selected electric drives can be fielded for selected missions. Some technologies are not ready for pre-production and other technologies that, if they can be realized, will lead to a more efficient vehicle. The technical challenges associated with the integration of components that without further development are characterized as too large, too heavy, and too expensive for use in tactical ground vehicles. These technical challenges are undergoing research; however, the majority of the HET is not expected to be resolved for the next 10 to 15 years (NATO RTO 2004). The main technical challenge involves thermal management, high-energy storage devices, and high torque and power density

traction motors as shown in Figure 17 relative to the increasing demands and operational flexibility of threat, capability, and the different terrain requirement.



Figure 17. Excellence in vehicle mobility and energy efficiency directions (from Bochenek 2011)

1. Thermal Management

The critical temperatures of magnetic materials and the silicon-based power devices are the main criteria for the design of the cooling system (NATO RTO 2004).

The coolant into the base plate must be maintained at 65 degrees C, which leaves a very small margin with the maximum operating temperature of 125 degrees C. Consequently, the cooling system and its power demand are too large to be integrated into the vehicle. Repackaged silicon based insulated-gate bipolar transistor (IGBT) switches have improved the thermal limits by 50 percent. This improvement is still in its experimental stage and requires further development and testing. Development and

fabrication of high temperature and high power density power electronics to meet aggressive space requirements on combat HEVs pose additional technical challenges (NATO RTO 2004). Another challenge is to develop and test a hybrid Si/SiC oil cooled 600 amp/1200 volt silicon based IGBT module, and integrate it into an oil-cooled inverter (Hopkins and Acharya 2005).

The ultimate solution for power electronics is the SiC device. The operating junction temperature can be as high as 500 degrees C, and therefore, the coolant temperature can be easily maintained at 200 to 250 degrees C (Davis and Bochenek 2011). This type of device would allow the cooling system to be much smaller due to its high efficiency and operating temperature. At present, SiC switches are limited to small current ratings due to the impurities of the material, a crystal defect known as “micro pipes.” Significant improvements have been achieved in the last few years in SiC and the technology is expected to reach the required level of power rating in a reasonable yield within this decade. Similarly, the permanent magnet motors, which are desirable for traction due to their high efficiency, must also be cooled below the critical temperatures to ensure they are not partially demagnetized. The temperature for magnets’ operation range is between 140 degrees C and 180 degrees C (RDECOM Public Affairs 2014). Current electric drive vehicles, using permanent magnet motors, have thermal limitations well below the desired levels. Currently, vehicle designers are confronted with the burden of integrating at least two cooling circuits. Coolant requirement alone jeopardizes the space claim for the power train in addition to the cooling system size dictated by the relatively low temperatures for both the motor and its inverter (U.S. Army RDECOM 2014a). The potential benefits are efficiency, pollution-free, low acoustic and thermal signature, and electrical power availability. Technical challenges include achieving power density, cost, and durability (RedOrbit 2007).

2. Energy Storage

In the military sector, energy storage is the most significant obstacle to the widespread integration of HEVs. TWVs require significant energy storage for cooling equipment and crew, and for silent mobility and silent watch. It also consumes a large

proportion of vehicle weight and volume. Energy storage is an essential part of the HE drive application. Thus far, three types of energy storage have been used: batteries, flywheels, and ultra-capacitors.

Advanced batteries are the foundation for HE vehicles and technologies as highlighted in Figure 18. Batteries have been used more extensively than the other two devices due to their higher energy density and lower cost. The most commonly used lead-acid battery has low energy density, limited cycle life, cannot be stored in a discharged condition as the cell voltage must not drop below 2.1 volts, and is environmentally unfriendly due to a toxic electrolyte that must be disposed of safely. Additionally, battery thermal management is required as the battery loses power at low temperatures, and requires preheating and will start deteriorating at elevated temperatures. The lead-acid battery does not have a serious shelf discharge problem but its shelf life is limited (NATO RTO 2004).

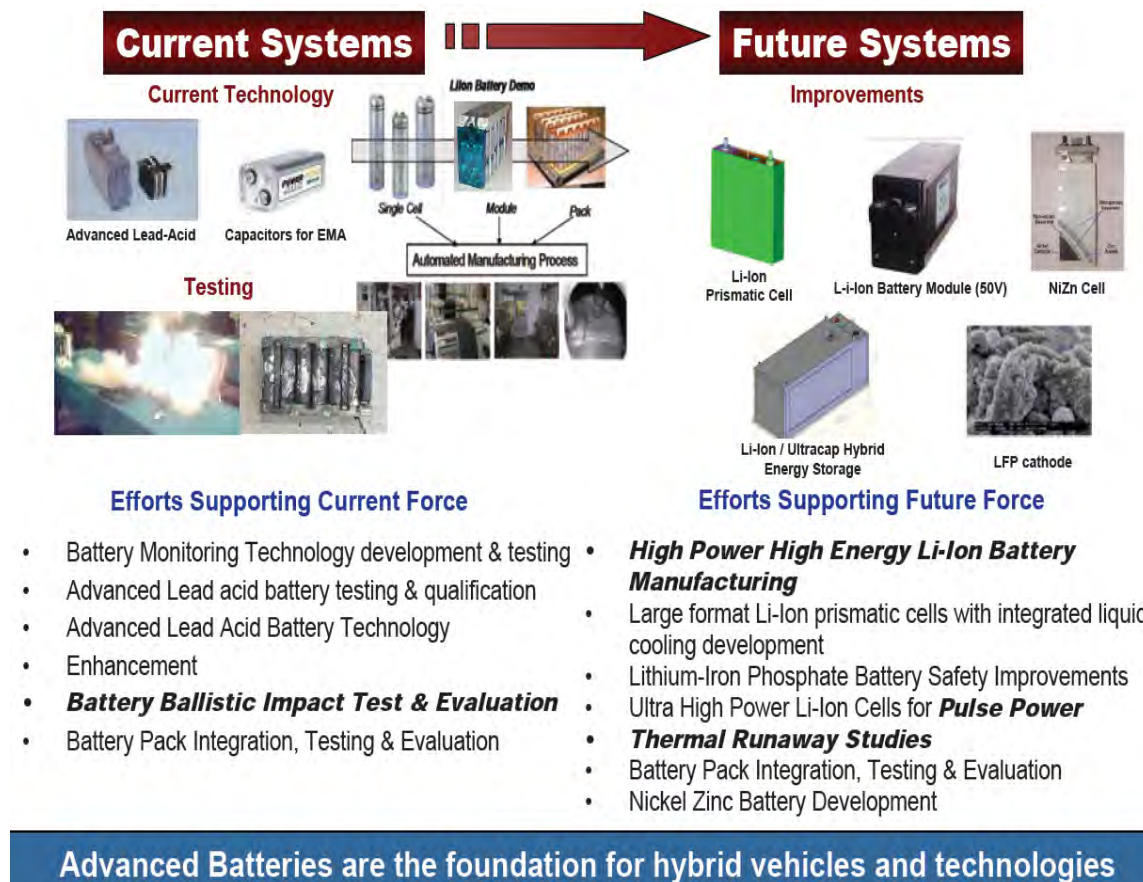


Figure 18. RDECOM TARDEC energy storage investment strategy (from Ding 2011)

The most viable candidates at this time are lithium-ion (Li-Ion), nickel metal hydride (NiMH), sodium nickel chloride (ZEBRA(TM)), and lithium-metal polymer (LMP). All these batteries have higher energy densities than lead-acid batteries but they all present some challenges that must be resolved before they can be considered suitable for military applications. Lithium-based batteries currently offer the most significant potential for HEVs because of their outstanding electrochemical characteristics. Lithium-ion batteries with a liquid electrolyte potentially fulfill the energy storage requirements for traction applications. They can achieve higher specific energies than lead and nickel based technologies, and peak specific powers in excess of 1000 watts per kilogram (W/kg) have been reported for HEV designs (Ding 2011; Mainero 2010; Zanardelli 2010).

At present, the cost of these battery options is high as they are still in research R&D, and prototype production is limited. Energy density, cost, and safety are important concerns when considering any of the next generation batteries, especially for use in military applications. Navigant Research (a smart energy company focused on the R&D of clean energy and energy storage) forecasts that global next-generation advanced battery revenue will grow from \$182.3 million in 2014 to more than \$9.4 billion in 2023.

3. Traction Motors

The traction motors must meet torque/speed curve dictated by mobility requirements of any ground tactical vehicle. The challenge in using traction motors is meeting power requirements with a motor able to integrate into either the chassis or the hub of a wheeled vehicle or behind the sprocket when used as a tracked vehicle. Three types of motors are suitable for meeting these requirements: permanent magnet brushless motors, induction motors, and switched reluctance motors (U.S. Army RDECOM 2014b).

Wheeled vehicles offer the basic option of mounting the traction motor in the chassis or hub. The disadvantage of mounting in the chassis or hub is that drive shafts are still needed to transfer power to the wheels. The in-hub approach offers the optimum solution. The challenge with mounting the traction motors in-hub is keeping the unsprung mass as low as possible and less than in the conventional vehicle. Keeping the unsprung mass low ensures the mobility of the vehicle at high speeds, particularly cross-country. Most traction motors currently available have some type of design limitations, if addressed, would result in more efficient and effective overall designs. Size, weight, and cooling requirements were challenges that the state-of-the-art traction motors have successfully overcome for integration and use in HEVs; however, further improvements to the traction motors are needed to enhance packaging and integration for use in TWVs (RedOrbit 2007).

Other challenges facing the use of HE propulsion and power are requirements for compact and fuel-efficient primary energy conversion subsystems, high cycle temperatures, lubrication system limitations at high speeds, and direct-coupled high-

speed generators (NATO RTO 2004). All these additional challenges are currently in R&D to provide practical options for future use.

C. COST CHALLENGES

Commercial HEVs (e.g., cars, trucks, and buses) are in introductory or limited production, and show great potential for commercial use. Some models are in full production (e.g., Toyota Prius Hybrid). Even after applying subsidies and tax breaks from available federal and state programs, the cost per unit for a commercial unit is still relatively high compared to internal combustion engine (ICE) vehicles. The payback could be as long as 10 to 15 years, depending on the automobile (Kageyama 2014). The military faces the same dilemma that the current configuration of military tactical vehicles is too costly.

As demonstrated with the FED Alpha and Bravo project (TARDEC, 2012b), currently, the commercially available components and subsystems are seldom suitable for military application, and additional R&D is required before integration can occur (NATO RTO 2004). The development of HEV components for military application coincides with technology maturation. Figure 19 illustrates the key technology and components opportunities.

Adv combustion engines & transmissions	Lightweight structures & materials	Energy recovery & thermal management	Alternative fuels & lubricants	Hybrid Propulsion Systems	Analytical tools
Thermal Management	Establish Formal Methods for Exchanging Information	Thermo-electrics	More Fuel Efficient Oils and Lubricants	High Temp Inverters and Converters	Improved Multi-Dimensional Models
In-Cylinder Combustion Control and Sensors	Explore Weight Saving Impacts	Climate Control	Advanced Lubricant Additives	High Power/Energy Li-Ion	Standardization of M & S Processes and Metrics
Predictive Tools and Models	Holistic Design	Heat Transfer	More Fuel Efficient Hydraulic Fluids	Li-Air	Framework for Model Sharing
Fuel Injection System		Analysis and Optimization; Energy Balance	Specification Development	Lead Acid (Deep Charge)	
Advance Boosting Systems				Ultra Capacitors	

Figure 19. Key technology opportunities (from U.S. Army RDECOM-TARDEC 2011)

Consequently, cost factors involved with moving the hybrid vehicles from demonstration phases to pre-production is high, especially when considering that the reliability of the hybrid vehicles has not been fully assessed and cannot accurately be predicted. Figure 20 shows the challenges in cost in terms of components and technology.



Figure 20. Ground vehicle power and energy technology challenges (from Bochenek 2011)

Many HEV system components are in various stages of development, prototypes, and limited demonstrations. Most of these components are either emergent or not tailored to military applications. The limited data available currently does provide an insight into recent and expected trends, technical barriers, and manufacturing challenges that must be addressed to develop basic relationships and factors for prototype, low-rate production,

and production phases (Science Applications International Corporation 2013). The challenges are as follows.

1. Power Generation

HET power generation consists mainly of series or parallel power trains. This section discusses the diesel engines, series and parallel hybrids, gas turbines and fuel cell technologies.

a. Diesel Engines

A hybrid-electric power train incorporates an internal combustion engine, and is comprised of several component technologies (batteries, electrical motors, and power electronics). The difference in the requirements imposed on internal combustion engines used in conventional power trains mean that engines intended for hybrid vehicles must be designed or adapted specifically for that purpose. The incorporation of a standard internal combustion engine into a hybrid vehicle would diminish the full potential offered by hybrid propulsion in relation to providing clean and efficient transport (RedOrbit 2007). TARDEC, at this time, is focused on developing the necessary hardware and engine control strategies to allow for reliable and durable use of JP-8 fuel in the currently available heavy-duty, on-road, commercial-off-the-shelf diesel engines. The potential advantage is the ability to provide peak thermal efficiency of greater than 48 percent on JP-8 fuel, which results in greatly decreased fuel consumption, greater than 20 percent in heat rejection; thereby, effectively reducing costly cooling system requirements and improving durability, reliability, and fuel delivery performance (Blain 2009). It is expected then that the most fuel-efficient commercial engines would be provided at the most affordable cost. The greatest technical challenges facing this technology would be the need to obtain an emissions waiver from current emission standards requirements. If a waiver could not be received, it would have a drastic impact on military technical vehicles, as they would require an after treatment system that is as large as the engine (NATO RTO 2004). It would also require a cooling system that is 30 percent larger than standard and could not use substandard fuels without the implementation of a technological solution (NRAC 2005).

b. Series Hybrid

In the Series hybrid drive system, an internal combustion engine drives a generator, and one or more powerful electric motors use the electric current generated to propel the vehicle. Excess electrical energy and the energy generated during braking are temporarily stored in a large battery and used as needed as supplemental energy for the combustion engine to allow it to operate in steady-state mode. This process creates better energy efficiency than in conventional operation with regard to fuel consumption and exhaust emissions. The Series HED decouples the diesel engine from the wheels so each axel or wheel is directly driven by an electrical motor. Elimination of the heavy mechanical drive train greatly reduces the total weight of the vehicle and enables more flexibility when integrating into a mission system. Another advantage of HED is the ability to be used on “silent watch” for extended periods or driven in “stealth” mode under battery power only. In Series HED power trains, the internal combustion engine drives a generator, which delivers the “average” power demand for a propulsion/movement. Acceleration and regenerative power recovery during braking are accommodated by high-powered batteries as illustrated in Figure 21. A result of this technology is a considerable reduction in the overall engine size. In addition, the engine no longer drives the wheels directly, so it can be employed at a limited number of operating points, which offers an opportunity to optimize fuel efficiency and emissions performance at those operating points. The extent to which this optimization is feasible is limited by practical considerations, most of which pertain to the battery (NATO RTO 2004).

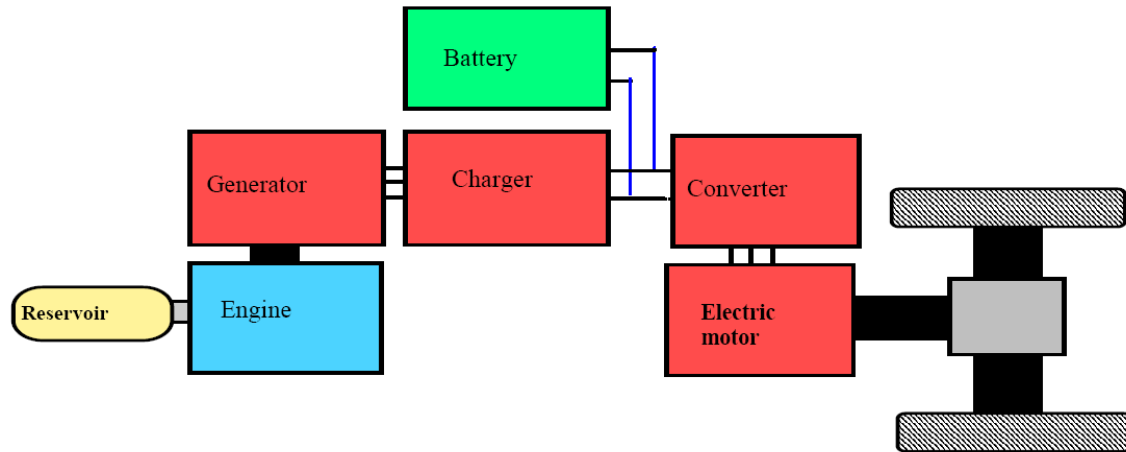


Figure 21. Series hybrid configuration (from NATO RTO 2004)

c. *Parallel Hybrid*

In Parallel Hybrid operation, an internal combustion engine and electric motors receive energy from a large accumulator battery and operate independently of each other. During operation, either both systems or just one of them are engaged depending on the applications and energy requirements. In Parallel Hybrid power trains, the internal combustion engine is mechanically coupled with the wheels in the conventional manner via the transmission as shown in Figure 22. The power train incorporates an electric motor that provides additional torque to the engine. Traditionally, the electric motor and the engine run at proportional speeds, which provide an opportunity to uncouple the engine load from the vehicle load to the extent permitted by the electrical system. The speeds of the internal combustion engine and electrical machine are determined by the vehicle's state. By virtue of this additional electrical power, the internal combustion engine can be downsized as it is mainly used in high-efficiency operating areas. This efficiency is further increased by the use of additional features, such as idle-stop, idle-launch, and boost. Although Parallel HED is heavier than Series HED, it offers the redundancy advantage of a conventional, mechanical link when operating a heavy-duty truck. Weight, as well as production costs of these vehicles, is considerably higher than the standard. Insufficient life of the accumulator batteries still presents an obstacle to large-scale manufacturing. Clearly, the high LCC hinders progress in this matter;

however, progress is advancing as shown in the commercial realm with the heavy trucks and buses (NATO RTO 2004).

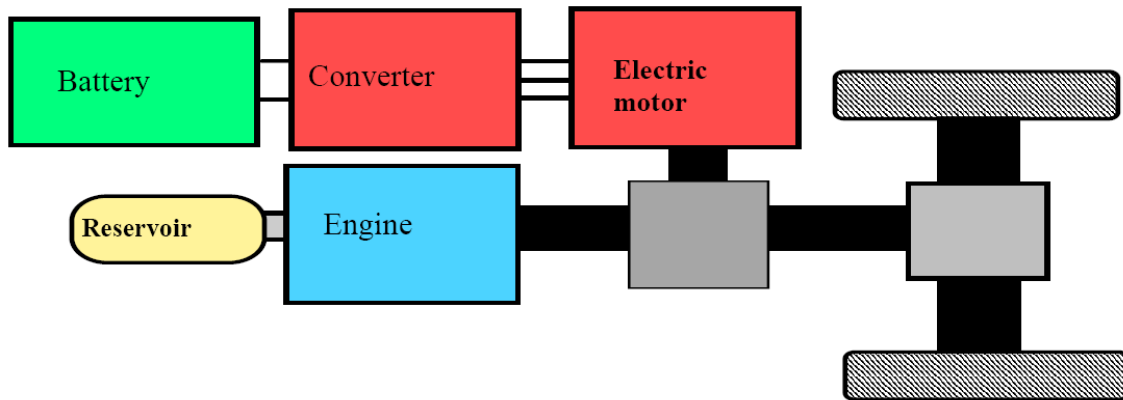


Figure 22. Parallel Hybrid (from NATO RTO 2004)

d. Gas Turbines

The use of gas turbines in ground military vehicles is minimal due to the high cost of manufacturing the turbine and its higher fuel consumption as compared to the diesel engine, its loss of power at higher altitudes, and its high speed. By contrast, gas turbines have several advantages including most notably reduced weight, the ability to operate without a significant cooling system, and its quiet operation compared to diesel engines. Therefore, hybrid applications provide a good opportunity to capitalize on the benefits of the gas turbines while reducing or minimizing any problems associated with their use. In a HE vehicle, the engine must drive an alternating current (AC) generator to produce electric power and deliver that power to the traction motors. A gas turbine output's speed can be as high as 10,000 revolutions per minute (rpm) and can be used with smaller, higher-speed generators to reduce the overall weight and size requirement and eliminate the need for heavy reduction gears (RedOrbit 2007).

Unfortunately, gas turbines realize heightened fuel consumption when operating in the low speed; however, during higher, steady-state speed operation, the turbine is as efficient as a diesel engine. The hybrid operation allows the gas turbines to be operated at its optimum conditions at almost constant speed, while the energy storage devices power

the transient modes of operation. This advantageous power split can be used during most mission operations; thus, maintaining optimum fuel consumption while retaining the low thermal and noise signature (NATO RTO 2004).

e. Fuel Cells

Fuel cells are considered the future of the automobile industry (Science Applications International Corporation 2013). Fuel cells generate electrical energy by an electrochemical reaction as shown in Figure 23. Fuel cells offer a high potential efficiency and emit exhaust gases comprised solely of water vapor.

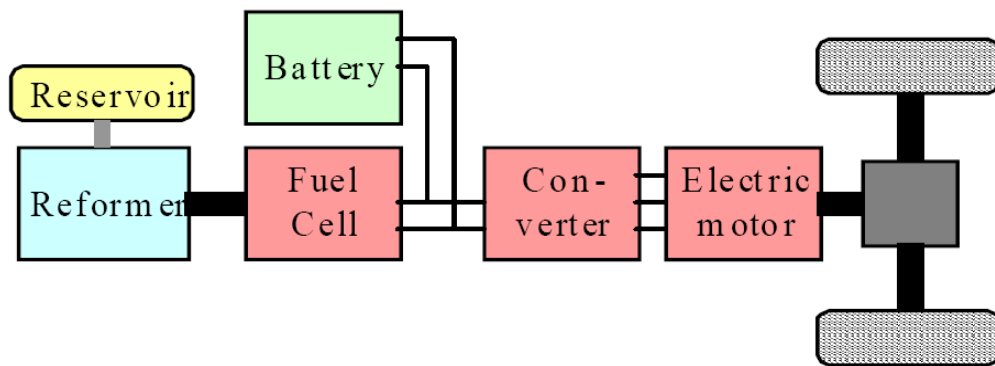


Figure 23. Fuel cell hybrid (from NATO RTO 2004)

The efficiency of fuel cells is at the greatest when used to transport at partial rather than at full loads. Consequently, in contrast to the case of internal combustion engines, it is not beneficial to down-size a fuel cell based solely on efficiency because the available fuel cells are still heavy and bulky, and above all, expensive. Many projects will nevertheless employ a small fuel cell based on its efficiency and smaller carbon footprint (SBA 2009).

It is expected that further development will produce a better fuel cell that offers a reduction in weight, volume, and price. These factors will lead to a trend toward the use of fuel cells as a major component of the future power trains. Research into the use of electricity produced by fuel cells to power vehicles through the recuperation of the braking energy will continue to be of interest, which can be achieved by the use of a

small battery to serve as a buffer. Consequently, these systems will continue to be of an integral component of future fuel cell systems (SBA 2009). Development of the infrastructure support and sustainability will require further R&D.

Potential benefits of fuel cell technology are efficiency, pollution-free, and low-signature. Emissions and electric power availability seem to outweigh the technical challenges of power density, cost, low temperature operation, start-up time, throttle response, and durability. The challenging technical issues for industry and the military include reliability, durability, power output, manufacturing infrastructure, hydrogen related issues, and cost (Science Applications International Corporation 2013).

Toyota will introduce a commercial production fuel cell vehicle in April 2015 in the United States (Kageyama 2014). Even with limited established infrastructure and challenges, the manufacturer is confident a market exists that will grow in significance over time due to quick acceleration, is quiet, takes three minutes to refuel, and runs about 430 miles on a single hydrogen fueling. Currently, fuel cells are unsuitable for use as a tactical mobility fuel; however, fuel cells are regarded as a potential, longer-term (several decades away) likely alternative to the internal combustion engines (RedOrbit 2007).

2. Electric Motors

Electric vehicles employ at least one electric motor in the power train that converts electrical energy into mechanical energy. Virtually all types of electric motors can also convert mechanical energy back into electrical energy. Electric motors are used in almost all currently produced hybrid-vehicles for regenerative braking. In the latter application, the braking-system energy produced normally dissipated in the form of heat is recovered and converted into electricity that can be stored and used by the vehicle, to increase overall efficiency of the power train. Current systems are able to achieve the recovery of up to 30 to 40 percent of the braking energy, with 40 percent lost in the event that the recuperated braking energy is reused in the power train. Higher percentages of usable energy are regarded as feasible in the future by virtue of the development of high-power energy-storage media (flywheels, bipolar batteries, and super-capacitors) (NATO RTO 2004).

Direct current (DC) motors in the past were perceived as the most logical choice for use in HEVs in view of their advanced stage of development and their low costs; however, the disadvantages are that they have relatively large dimensions and high maintenance requirements (RedOrbit 2007).

The asynchronous three-phase electrical motor is a suitable candidate for use in current and future vehicles due to its relatively high efficiency. This efficiency remains high in a relatively large operating range. It is anticipated that the costs of the power electronics will be recovered by the energy savings and expected lower maintenance costs accrued during the lifetime of use. Additional control of vector control and liquid cooling are foreseeable and will achieve a further optimization and cost savings (RedOrbit 2007).

Asynchronous and synchronous motors may also be viable options due to their greater specific performance and their good efficiency, benefits particularly applicable to permanent magnet motors. Synchronous motors with permanent magnets, in combination with a special inverter control, are typically used in HEVs. An added benefit of permanent magnet technology is that it can be used in the construction of more compact, lighter generators, which will be capable of operation at the high rotational speeds required for use when combined with gas turbines. In contrast to the issues with asynchronous motors, the development of permanent magnet motors focused mainly on the actual motor rather than on the motor's electronic components. When a motor is fitted with permanent magnets, synchronous motors are suited for installation in the form of wheel-hub motors. Placing the motors in the wheel hub offers the advantages of overall space savings in the vehicle and removes the requirement for mechanical differential and drive shafts, thereby, increasing efficiency and reducing weight. Additional benefits are that the modular construction method makes it possible to facilitate maintenance and repairs, which will reduce costs. This system enables the ease of integration with the vehicle's dynamic controls, such as electronic traction control, anti-lock braking systems, and steering adaptation, which adds to the weight reduction by eliminating the space taken by the steering angle process required in conventional steering systems.

The advantages of electric motors seem to make this a frontrunner over other types of HET; however, a number of disadvantages may surpass the benefits. Hub motors increase the un-sprung weight and reduce comfort, stability, and road handling. Also, because more motors are required to provide sufficient drive energy, an increased risk of component malfunctions may overcome opportunities for redundancy systems. Neither the use of a gearbox, nor simple final reduction gear, are feasible options to overcome the shortfalls.

In spite of their complexity and associated costs, it is expected that electrical hub motors will play an increasingly important role in the future. With the introduction of a more economical intermediate system between hub motors and a centrally located electric motor (NATO RTO 2004), in this specific application, the electric motors can be located next to the wheels, thereby achieving sufficient space savings that could be used as an advantage, such as, construction of a low-floor bus.

3. Power Electronics

Electric motors cannot be viewed separately from their power electronics (NATO RTO 2004), as power electronics are required in the power train of all HEVs. Some of the most important components required in HET include a rectifier, which converts AC to DC, and an inverter to convert DC power from the battery to AC power for an AC motor, and the reverse. A DC-DC converter is also included and used to increase or reduce the DC voltage. A transformer is used to increase or reduce the AC voltage. Additionally, a controller system for the motor and a controller is used, which converts the inputs from the driver into vehicle operations. These processes of acceleration and deceleration, the flow of energy from the battery to the motor for speed control, and the reversal of the motor's direction of rotation, are regulated by these controls. Essential to energy production are the regenerative braking and on-board charger systems that ensure the battery is continually charged (NATO RTO 2004).

The costs of the power electronics account for a substantial portion of the total costs of the power trains of HEVs, which constitute a major obstacle to mass production of these vehicles. A large number of developments are expected in the power electronics

field to improve efficiency, reduce weight, and dimensions, and above all, considerably reduce costs. These costs will fall as R&D leads to mass production of systems used in both HEVs and other commercial areas. Although not necessarily need to be limited to electric vehicles (EVs), it is expected that prices will be halved within the next 10 years. As the technology and production matures, improvements will need to focus on reducing weight and the volume of the power electronics by producing more compact and lightweight systems. Advancements and new technologies, such as IGBT, and integral cooling, in particular, will result in the achievement of higher power densities (NATO RTO 2004).

4. Electro-Mechanical Transmission

The tracked vehicle must fulfill tasks that far exceed those required for standard wheeled vehicles. Apart from forward and reverse driving, it also assumes the relevant safety functions of braking and steering, and thus, considerably contributes to the mobility performance characteristics of a tracked vehicle. The advantage of the electro-mechanical drive system is its feasibility in use with the continuously adjustable driving and steering operations. Also, the recovery of braking power provides for crawling operations with the combustion engine turned off when the energy storage system is installed and the combustion engine output power is converted into electrical energy. These combined attributes add flexibility for vehicle integration with multi-engine concepts that make it able to integrate into a HE combat vehicle (NATO RTO 2004).

The successful combination of mechanical and electrical components result in better synergy effects over a purely electric drive with respect to safety, weight, design volume, and cost. In particular, an electro-mechanical drive system for tracked vehicles combines the benefits of proven mechanical drive technology with those of the future-oriented electrical drive technology. The specific advantages of this concept include continuously adjustable maximum speed. Furthermore, the requirements for electrical components can be reduced (RedOrbit 2007).

5. Energy Storage System

The use of an energy storage system is a precondition for the initial operation of a HEV and is necessary of its energy optimization. This precondition is required for both the mobility of the vehicle and the operation of its subsystems. As an additional electric element for the power supply, it provides numerous benefits to the vehicle and its functions that include power reserve and power redundancy functions. The ability to provide power adds a decisive improvement to maneuverability especially in heavy terrain. It provides highly increased acceleration, quick-position change ability, and stealth mode operations without the diesel engine running.

The range of tasks required of a vehicle dictates the energy and power that must be provided. In addition, duration energy requirements must be considered for each task. A high level of energy is needed to support long duration applications to meet the power requirement of the subsystems for system initiation/activation or silent watch. This higher-level power requirement is needed to start the prime mover for mobility, acceleration, weapon power supply, active armor, and active suspension. Each of these sub-systems requires a unit type of storage that is currently unavailable and which must be developed and integrated (Ding 2011).

a. Magneto-Dynamic Storage

The magneto-dynamic storage (MDS) uses high-speed flywheel storage with an integrated electric machine that can be used either as a generator in discharge mode, or as a motor in recharge mode via re-accelerating the flywheel rotor, depending on the momentary needs. The energy carrier of the MDS is a cylindrical rotor made of wound carbon fiber. The rotor's axle stands on a vertical plane. The motor/generator (M/G) unit is inside the cylindrical rotor, which accepts or delivers electric power.

The advantages of the MDS compared to other energy storages include the high power ability with respect to weight and volume, and the indefinite cycle number potential since the MDS is an electric machine and is not limited by electrochemical elements. These characteristics open the benefits to use the MDS in military vehicles, or at least as an additional energy and power source.

b. Batteries

The battery requirements for hybrid vehicles are characterized by reduced energy contents and higher power requirements compared to the ICE. For an efficient design, a specific energy of at least 50-Watt hr/kilogram (Wh/kg) and a specific power of at least 500w/kg are required. While the electrical and mechanical components of hybrid vehicles are reasonably mature, the main obstacles for full HED maturation with the military are the batteries. The drawbacks of current batteries are their sensitivity to extreme environmental conditions (heat, cold, and humidity). To prevent freezing, the batteries are contained in an environmental chamber, which maintains the temperature at operational conditions. This method enables the vehicle to operate from -40C to +65C degrees (Ding 2011).

In a rechargeable battery, chemical energy is converted directly into electrical energy by means of the “fuel” and “oxidant” present in the battery. In the lead acid battery, for example, the fuel is lead and the oxidant, lead dioxide. The reaction products of the electrochemical conversions in the battery are converted back into fuel and oxidant by applying a voltage. The battery also functions as a reservoir of fuel and oxidant, when used in an electrical vehicle; therefore, the amount of energy, and consequently, the range of the vehicle, is limited.

Most batteries consist of monopolar cells. In other words, the electrical connection between the positive and the negative plate occurs around the outside in series connections; the electrical current must flow through the whole plate of the connecting strip. Consequently, the specific power, kilowatts per kilogram (kW/kg), is limited due to the necessary electrical conductors. By switching over to bipolar cells, much higher specific powers can be achieved with more or less equal or slightly lower specific energies. The bipolar battery sets higher requirements with regard to sealing because no contact may occur between the electrolytes in the various cells. The bipolar battery is still at a relatively early stage of development (Mainero 2010).

In the development of batteries, the emphasis has traditionally been on achieving a high specific energy, which are usually monopolar batteries. Since the number of

batteries necessary to achieve an acceptable range is relatively large, the limited power requirements of the vehicle are often automatically met. Since flywheels and super capacitors have a very low specific energy relative to most batteries types, they are less suitable for HEVs.

The battery requirements set for HEVs are very different. In this case, the power usually determines the battery specifications to be delivered during acceleration and absorbed during braking, rather than the energy content. Bipolar batteries, and also flywheels and super capacitors, may be more suitable than monopolar batteries. To arrive at a sufficiently long life, the method used for charging the battery from the mains, or in the case of hybrid drive, from the on-board generator or by braking, is very important. Large differences exist between the various types of batteries in this regard. The electrical energy efficiency, as a result of losses during charging and discharging of batteries, depends to a large extent on correct dimensioning and good coordination with the rest of the system. If these factors are optimal, efficiencies of 80% or more are feasible (Zanardelli 2010).

Lithium-based batteries currently offer the most significant potential for HEVs because they can provide twice the energy storage of lead-acid, but only half the power surge. Therefore, they can drive a vehicle twice as far but not as fast. The electrochemistry consists of a carbon negative, a liquid electrolyte typically comprised of carbonate solvent, LiPF₆ salt, and a metal oxide positive. Figure 24 illustrates the available power vs. energy for various storage technologies. Lithium-ion batteries with a liquid electrolyte promise to fulfill the energy storage requirements for traction applications in the near future. They can achieve higher specific energies than lead- and nickel-based technologies, and peak specific powers in excess of 1000 W/kg have been reported for HEV designs. Li-Ion cells promise the highest performance potential but their cost is still prohibitive for mass-production (Zanardelli 2010).

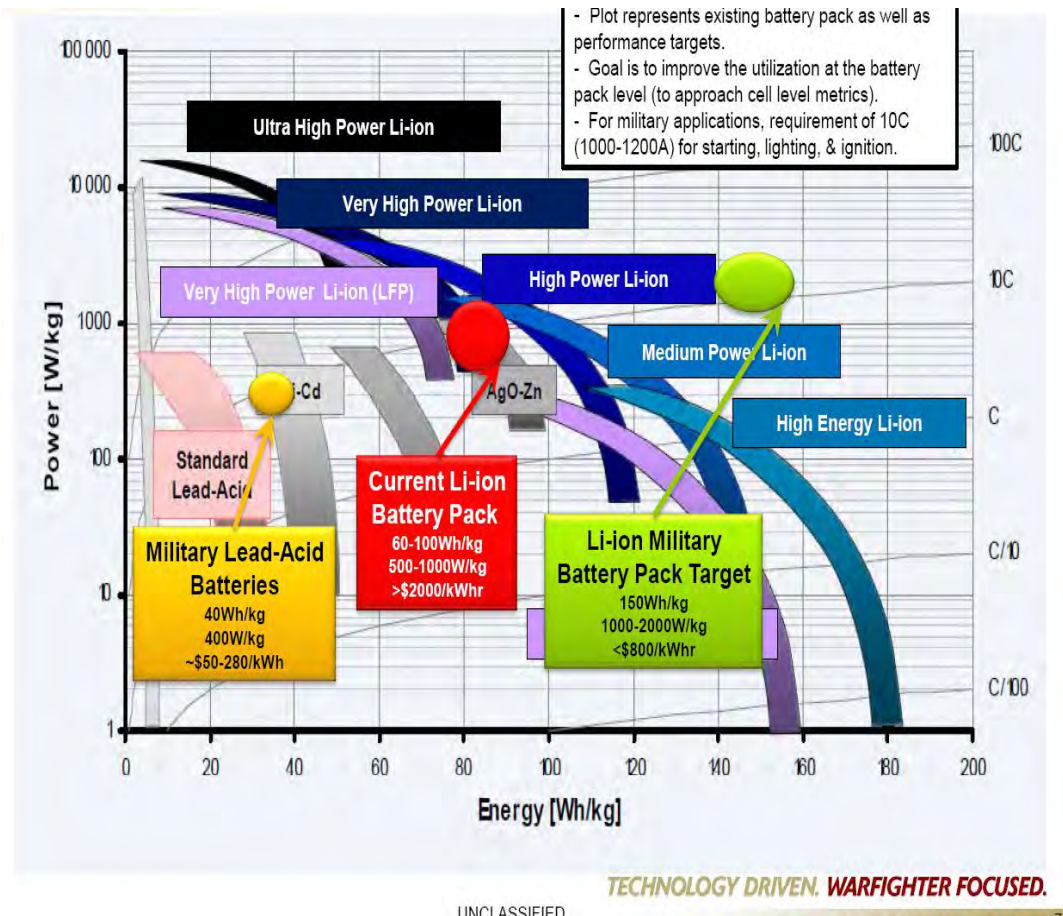


Figure 24. Energy storage team, U.S. Army TARDEC (from Zanardelli 2010)

Significant R&D is still needed for military HEV propulsion. Battery design relies on having accurate and detailed driving cycles. Without operationally derived driving cycles, fuel economy claims cannot be verified. If the battery is undersized for the load, reliability and service life suffers. Therefore, battery life and its reliability are greatly affected by how it is used and/or misused in the driving cycle (Raney 2007).

c. *Super Capacitors*

Capacitors are an alternative to batteries as a power source for HEV. They can be designed for increased power or for increased power storage. Super capacitors are standard capacitors with an internal structure and materials of construction that yield a capacity of 1000 to 3500 farad. The rated voltage is on the order of 2.5 volts (V), which

results in the storage of energy in a range from 3 kJ to 10 kJ. The power density is in the range between 0.7-1 kW/kg (Zanardelli 2010).

As a result of the low internal resistance of 0.5–1 Mohm, the energy can be charged or discharged with a high efficiency, even at high power. However, the efficiency is significantly lower if the voltage drops to half the rated voltage. Consequently, super capacitors are usually not discharged below half the rated voltage, a level at which three-quarters of the stored energy is released. The maximum current is on the order of 300–500 amps (A), and they can then be discharged to yield an average power of 500 watts (W) per capacitor. Consequently, the power/energy ratio is much higher than that of batteries. Thus, super capacitors are ideally suited for use in hybrid vehicles.

Super capacitors can withstand more than 500,000 charge-discharge cycles, and consequently, exhibit a much more linear performance than batteries. Moreover, their performance does not decrease significantly at low temperatures down to 0–40 C degrees. For this reason, super capacitors are a serious alternative to batteries for use as an electrical-energy buffer in hybrid vehicles (Khalil 2011).

Super capacitors can be employed either passively, when the DC voltage of the system depends on the state-of-charge of the capacitors, or in combination with a DC/DC converter, when the DC voltage is independent of the state-of-charge. The latter option simplifies the control of the system, but also increases its cost and weight (Khalil 2011).

d. Combinations of Super Capacitors and Batteries

Super capacitors can also be combined with batteries. The objective is to use a super-capacitor in parallel with a vehicle battery to assist in starting, lighting, and igniting to achieve extended battery performance. The advantage is minimizing the voltage sag and improving the life of the vehicle battery (Blain 2009). The combination can be passive. When the super capacitors are connected in parallel to the battery, the battery will not be exposed to high-frequency pulses. Thus, the life of the battery is increased. Alternatively, the super capacitors can be connected to the battery via a DC/DC converter, in which case, the power flow to the super capacitors can be controlled. This

connectivity offers the opportunity to implement a control strategy focused, for example, on the optimization of the battery life, the system efficiency, or the lowest lifecycle costs. However, the inclusion of the DC/DC converter considerably increases the cost and the weight of the system (NATO RTO 2004).

6. Hybrid Power Management

Although the HEVs will pack significantly more power than current vehicles, they will also consume more power by employing more sensors, radios, computers, active suspension systems, electric gun turrets, nuclear/biological/chemical protective systems, and other mission equipment. Future vehicles could also mount electrical armor protection, which will significantly increase power demands. These future vehicles will require an automatic load management, match power demands with resources, and draw available power from generators, batteries, and other sources. It will be an apparent requirement to move toward the monitoring and control of multiple functions in the vehicle, while considering their mutual interactions, which is “system management” essential for HEVs. Consequently, a great deal of effort and research in the field of systems management is still required for the development of an optimum monitoring strategy to ensure the optimum performance of all the vehicles’ functions in a variety of situations (RedOrbit 2007). The monitoring and diagnosing of all propulsion components within the system are important tasks of the system control electronics. The system control is equipped with microprocessor components that are very insensitive to electromagnetic interference (EMI) to ensure a reliable data communication (NATO RTO 2004).

Other potential challenges are the manufacturing process development, quality and cost control, deployment, and sustainment, which are not yet developed (Khalil 2011; RedOrbit 2007; NATO RTO 2004).

Before fielding military HEVs, HET must be evaluated for its relevance to military operations and must withstand the harsh military environment. In addition, the military HEVs must meet safety, reliability, maintainability, and availability requirements under all shock, vibration, and environmental conditions. The application must be fully

verified and validated through the U.S. government acquisition process. Applying hybrid vehicle architectures to a significant military application has challenges that make fielding such a vehicle technically difficult and costly to date.

Additionally, many future cost projections assume full market penetration of HEVs and components. If this market penetration does not occur, these vehicles may remain prohibitively expensive (Kramer and Parker 2011).

D. POTENTIALS

Many enabling technologies have been identified that are under development and evaluation that directly address the challenges.

1. Combustion Process

To reduce the pollutant effects of combustion, it appears essential to optimize the combustion processes. Four areas are targeted by planned future developments in this domain: (1) the introduction of high-pressure direct injection in combination with turbocharging in the diesel, which has already reduced the fuel consumption of this kind of engines, (2) turbocharging combined with an engine downsizing is also promising for gasoline engines as well, (3) the direct gasoline injection (10% fuel savings), and (4) throttle-free load regulation (Blain 2009) .

2. Silicon-Carbide

SiC has been under development for more than 20 years. Significant progress has been achieved in the fabrication of switching devices at high current; albeit, the production yield is still at a low level. SiC switches and diodes operate at high temperatures and have higher efficiency. Both significantly reduce the cooling burden, which results in reduced system size and power demand and improved vehicle hybrid propulsion system efficiency. It also reduced the size and weight of HE components and improved the integration of HEVs into military vehicles. It has synergy with high auxiliary loads, such as EM armor, EM gun, and DEW (Mainero 2010).

3. Battery Chemistries

Li-Ion, lithium nickel cobalt, lithium iron phosphate, and lithium titanate are being considered. Each of these chemistries provides different characteristics suitable for different applications. The challenge is to improve the current limited manufacturing capability of Li-Ion battery cells and provide affordable Li-Ion battery packs for current and future ground vehicles. The payoff is the reduced cost, size, and weight, while boosting power for faster dash and increased rate capability, extended cycle life, increased operating ranges, survivability, extended silent watch, silent mobility improved safety, as well as the advancement of potential dual-use for both commercial and military cell technology and the manufacturability of the improved designs using the new materials (Blain 2009).

4. Integrated Starter Generator

The ISG is a viable option that can meet expected levels of power demand. The ISG is driven directly by the engine to provide up to 170 kw of electric power. The current and near-term trend is to use a similar power generation system. If a small battery pack is added to the ISG, then the braking energy can be recovered and stored in the battery, and subsequently, used to give a power boost to the vehicle propulsion. This type of ISG/battery combination is a form of mild parallel HE system, which can be considered as a direction toward a full HEV. The dual-voltage integrated starter generator (2V-ISG) and power converter unit (PCU) is capable of meeting current and future TWVs onboard and export power demands. It is expected to contribute to a reduction in space, weight, complexity, and cost of the associated power electronics required for power conditioning of the ISG system.

HE storage systems consisting of batteries, combined with capacitors, are also being considered. Other technologies to increase the power and torque densities of traction motors and their controllers will also improve the integration of HETs in military vehicles (Khalil 2011).

5. Heat Exchangers

The purpose is to advance the heat exchanger core design for use in cooling the ground vehicles power pack, auxiliary power unit, mission equipment, and power electronics that includes increasing heat transfer capability, reducing vehicle volume of the cooling systems claim, and reducing the weight. The payoff is increased vehicle capability at high temperatures, reduction of thermal space claim, weight savings, a flexible form factor, and an improved thermal management system.

6. On-Board Power, Energy and Thermal (OPET)

The purpose is to demonstrate advanced technologies in the area of power generation, energy storage, and power and thermal management as a complete system on a vehicle platform. The payoff is a solution that integrates research technologies onto a vehicle and makes them work together as an integrated system to reduce risk to existing modernization programs and provide validated requirements, design to hardware solutions. Effectively, their TRL is increased and the benefits are moved closer to fielding a tactical HE vehicle. This prototype vehicle can then act as a transition platform for new technologies (Khalil 2011).

7. Power Management

The purpose is to demonstrate advanced technologies in power management onto an existing vehicle platform. The payoffs are reduced power draw, enhanced vehicle situation awareness for electrical loads, state and mode based power management schemes, and power management application that conforms to power management application programming interfaces (APIs) (Khalil 2011).

8. Power Management and Point of Load

The purpose is to demonstrate power management technology and conditioning based on maintaining the military's tactical fleet. The benefits are power management system control loads, reduced power consumption, situational awareness, and reduced logistics burden with preventative measures.

E. CHAPTER SUMMARY

HET for military applications offers significant payoffs and challenges that cannot be overlooked. The DOD acknowledges the advantages of HE military vehicles. At present, the choice of the structure of a hybrid vehicle is an evolving matter because of the steady evolution of the component technology and performance (Kramer and Parker 2011). The fielding of full hybrid vehicles depends on the full implementation of some critical technologies, such as SiC power electronics, lithium batteries, and the other high temperature components. These enabling technologies are under development and evolving into matured products. The ISG is becoming more attractive for applications in combat and TWVs to meet the soldier's electric power demand. Eventually, as silicon carbide and the battery technologies become more viable for military applications, mild hybrid, and later full hybrid, will become acceptable for fielding (Khalil 2010).

Electric drives can potentially be fielded now for certain missions. However, some technologies are not ready for production, and some technologies that, if they can be realized, will lead to a much more efficient vehicle. These technical challenges are undergoing research but they are not expected to be resolved before the end of this decade (NRAC 2005).

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IV. TECHNOLOGY READINESS ASSESSMENT

In evaluating and considering the adoption of the alternative fuels and technologies, it is mandated to conduct a technology maturity-level assessment and analysis. A TRA is required by DOD Instruction 5000.02 (Under Secretary of Defense (AT&L) 2008) for major acquisition programs (MDAPs) or whenever required by the Milestone Decision Authority (MDA) (Under Secretary of Defense (AT&L) 2008) to ensure that a program satisfies its intended purpose in a safe and cost effective manner that will reduce LCC and produce results meeting the requirements (Department of Defense 2011a).

In developing new systems for the military, most of the focus has been on achieving demanding mission performance requirements with relatively little attention paid to the production and sustainment costs. Since HET is at the development and demonstration phases, Operations and Sustainment (O&S) costs and capabilities are unknown for the lifecycle of a military HEV. Therefore, the mandatory sustainment requirements per DOD Instruction 5000.02, such as reliability, availability maintainability (RMA), and operational analysis, have not been evaluated. However, data from modeling and simulation (M&S) for RAM is available to determine predicted or achieved availability throughout the system life cycle. Also, commercial market examples for HEV trucks and buses are available for benchmarks on the potential O&S evaluation for military HEV (Science Applications International Corporation 2013).

A. TECHNOLOGY READINESS LEVEL

The main objective of product development is to deliver systems that meet strict cost, schedule, and performance targets. In a GAO report, “Maturing new technology before it is included on a product is perhaps the most important determinant of the success of the eventual weapon system” (Nolte 2003). The GAO showed that failure to mature new technologies properly in science and technology (S&T) almost consistently leads to cost and schedule over-runs (GAO/NSIAD 1999). Measuring technology

maturity as part of the R&D program can be done for many reasons, such as ensuring best practices, risk management, and program management (*Wikipedia* 2014).

TRLs are measures used to assess the maturity of evolving technologies (e.g., devices, materials, components, software, work processes, and systems) during their development and early operations. Figure 25 shows the DOD definitions for each TRL. It describes the TRLs including the technology assessed, the associated degree of risk, recommended mitigation measures, and whether each was demonstrated in a relevant environment (Department of Defense 2011a). It is derived from the NASA TRL application. When a new technology is conceptualized, it is not suitable for immediate application. Instead, new technologies are usually subjected to experimentation, refinement, and increasingly, realistic testing. Once HET is sufficiently proven, it can be incorporated into a subsystem or systems (*Wikipedia* 2014; Department of Defense 2011). A TRL scale provides a measure of technology toward the operational use of the HET concerned, and compares maturity levels across technologies. The DOD developed detailed guidance for using TRLs in the 2011 DOD Technology Readiness Assessment (Department of Defense 2011b).

- | | |
|---------------------------|-------------------|
| • technology development | levels 1, 2, 3, 4 |
| • exploratory development | levels 5, 6, 7 |
| • full-scale development | level 8 |
| • production | level 9 |

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 (R&D). 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 R&D is initiated. This includes analytical studies and laboratory studies to physically validate the 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 with 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 they 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 a 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 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).
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 (DT&E) 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 (OT&E). Examples include using the system under operational mission conditions.

Figure 25. DOD TRL definitions and descriptions
(from Department of Defense 2011a)

1. Technology Readiness Level Calculator

The DOD mandates TRL measurement, but the published guides do not tell “how” technology maturity is to be measured. The TRL calculator (Defense Acquisition

University 2013) is one tool that can serve to answer the “how to?” The TRL calculator is a tool for applying TRLs to technology development programs. The calculator allows the user to answer a series of questions about a technology project. Once the questions have been answered, the calculator displays the TRL achieved. As the same set of questions is answered each time the calculator is used, the calculator provides a standardized, repeatable process for evaluating the maturity of any hardware or software technology under development.

In applying the TRL concept, the calculator provides a snapshot of what a technology’s maturity level was at a given time. It is a historical view of the technology’s development (Department of Defense 2009b). The TRL calculator can be a useful tool in a risk management program and overall program management of a technology development effort. The calculator’s questions and percent complete feature can assist a program manager in tracking progress toward the accomplishment of required tasks (Nolte 2005).

The structure of the TRL calculator is shown in Figure 26.

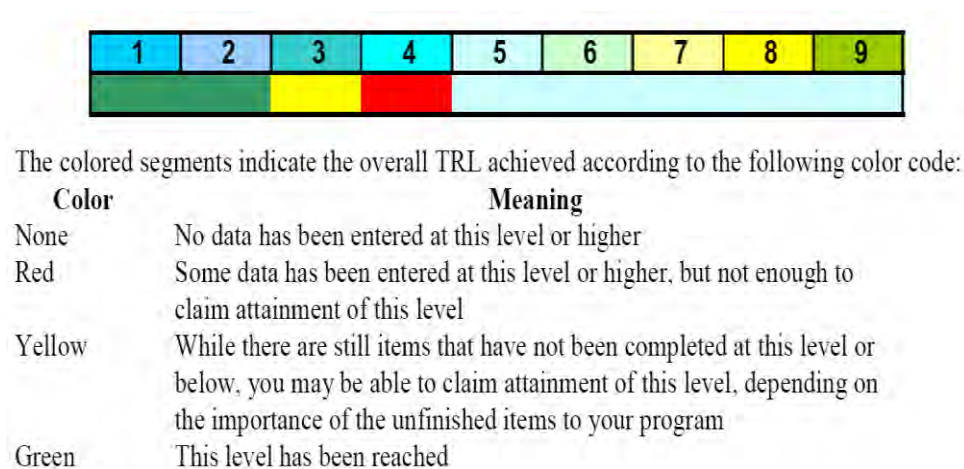
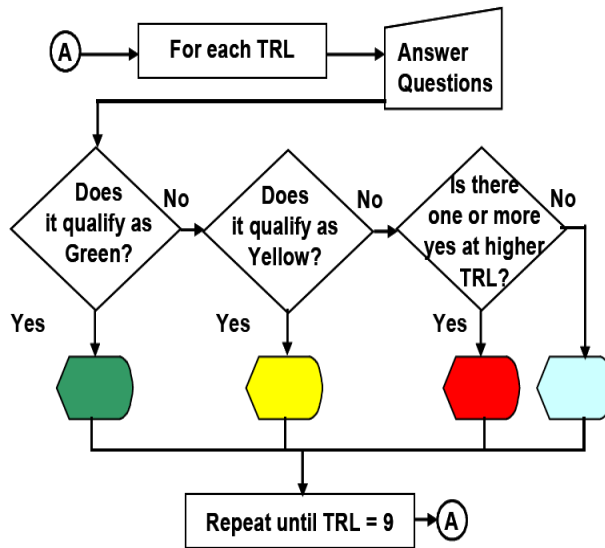


Figure 26. TRL calculator structure (from DAU.mil)

The algorithms of the TRL calculator are shown in Figure 27.



The figure shows the top level decision algorithm used to display the overall TRL graphically, using Red, Yellow, Green, and No Color.

The qualifying algorithm looks at the number of questions checked and the color of the previous TRL, except for TRL1 which has no previous. Checking the previous color keeps the calculator from displaying a green TRL at a higher level than a red or yellow, and keeps a yellow from appearing higher than a red.

The algorithm is:

Display green if everything below this level is green, and there are enough questions at this level checked to justify green.

Display yellow if the previous level is yellow and you have answered enough questions at this level to justify a green or yellow rating. Display yellow if the previous level is green and this level has enough questions answered to justify yellow, but short of the number needed for green.

Display red if there is at least one question answered at this level or higher, but it doesn't meet the green or yellow criteria.

If no question has been checked at or above this level, leave the space blank.

Figure 27. TRL decision algorithms (from Nolte 2005)

2. HET TRL Calculation Results

HET TRL calculation was performed using the TRL calculator ver. 2.2 (Defense Acquisition University 2013). The results are summarized in Figure 28. While the claim is that the HET is at TRL6, as shown in Figure 29, because the HEVs have been built and tested in the labs at the component and system levels. They have been test in SILs at the vehicle level. They have also been evaluated in the field at several proving grounds, such as the Aberdeen Test Center (ATC) in Aberdeen, MD, the Cold Region Test Center, in Ft Greenling, AL, and at the Nevada Automotive Test Center, in Carson City, NV, as stated by the TARDEC subject matter experts. It resulted in red at TRL5 and TRL6 because not

enough tasks were completed to claim attainment of this level. The Appendix shows the calculator's questions and percent complete for TRL1 to TRL6 of the HET development to date. The overall TRL is calculated at TRL4 because sufficient tasks were completed to claim attainment of this level only (TRL Calculator V2.2).

Program readiness for transition (PRT) and manufacturing readiness level (MRL) are two other measures of technology maturity. These topics are not covered in this study because of a lack of data available due to insufficient development to understand the long-term impact of HET.

AFRL Hardware and Software Transition Readiness Level Calculator, Version 2.2

This worksheet summarizes the TRL Calculator results. It displays the TRL, MRL, and PRL computed elsewhere. You may select the technology types and TRL categories (elements) you wish to include here or on the Calculator worksheet. Choose Hardware, Software, or Both to fit your program. If you omit a category of readiness level, (TRL, MRL, or PRL) that calculation is removed from the summary. The box in front of each readiness level element is checked when that category is included in the summary.

You can enter program identification information here, too.
 TRL documentation including discussions of TRL, MRL, and PRL is available from the Main Menu.

	☐	Include Hardware Only
	☐	Include Software Only
X	☒	Include Hardware and Software

X	☒ Use ☐ Omit	Technology Readiness Level
X	☒ Use ☐ Omit	Manufacturing Readiness Level
X	☒ Use ☐ Omit	Programmatic Readiness Level



Green / Yellow set points: Here you can change the default values the spreadsheet uses to determine which color to award at a given level of question completion. System defaults are 100% for Green, and 67% for Yellow. You can change these set points to any value above 75% for Green, and any value from 50% to 85% for Yellow; however, the Yellow set point will always be at least 15% below the Green set point. Use the spinners to set your desired values. The defaults kick in if you try to set a value less than the minimum values of 75% for Green and 50% for Yellow. Start with the "Up" arrow to change defaults.

Green set point is now at:

Yellow set point is now at:

Summary of the Technology's Readiness to Transition

Program Name: Hybrid Electric Technology **Program Manager:** Ed McCown
Date TRL Calculated:

Overall TRL Achieved	3	4
-----------------------------	---	---

1	2	3	4	5	6	7	8	9
---	---	---	---	---	---	---	---	---

Green Level Achieved

TRL 4

MRL 3

PRL 3

Yellow Level Achieved

MRL 4

Overall TRL is an aggregate TRL that includes contributions from each one of the three readiness level elements you have checked above.

If Green and Yellow are at the same level, only the Green result shows.

Figure 28. HET summary of the TRL (from TRL Calculator V2.2)

AFRL Transition Readiness Level Calculator, version 2.2

Summary

Reset All

☒ Use Manufacturing
☐ No Manufacturing

☐ Hide Blank Rows
☒ Use Programmatics
☐ No Programmatics

% Complete is now set at: 100%

Green set point is: 75%
Yellow set point is: 60%
Change set points on Summary sheet.

Hardware and Software Calculator

Technology Readiness Level Achieved

1	2	3	4	5	6	7	8	9
---	---	---	---	---	---	---	---	---

Technical: 4

☐ Only Hardware
☐ Only Software
☒ Hardware & Software

Program Name: Hybrid Electric Technology Assessment
Program Manager: Ed McCown

Date TRL Computed:
16 August 2014

TOP LEVEL VIEW -- Demonstration Environment (Start at top and pick the first correct answer)

☐	Has an identical unit been successful on an operational mission (space or launch) in an identical configuration?
☐	Has an identical unit been demonstrated on an operational mission, but in a different configuration/system architecture?
☐	Has an identical unit been mission (flight) qualified but not operationally demonstrated (space or launch)?
☐	Has a prototype unit been demonstrated in the operational environment (space or launch)?
☒	Has a prototype been demonstrated in a relevant environment, on the target or surrogate platform?
☐	Has a breadboard unit been demonstrated in a relevant (typical, not necessarily stressing) environment?
☐	Has a breadboard unit been demonstrated in a laboratory (controlled) environment?
☐	Has analytical and experimental proof-of-concept been demonstrated?
☐	Has a concept or application been formulated?
☐	Have basic principles been observed and reported?
☐	None of the above

Reset Top Level View

TRL 6

Source: James W. Bilbro, NASA, Marshall SFC, May 2001

Comments:
 Hybrid-electric vehicles have been built and tested in the labs at the component and system levels. They have been test in System Integration Labs at the vehicle level. They have also been evaluated in the field at several Proving Ground like th aATC at Aberdeen, Cold Region Test Center Ft Greekingm AL abd at the NevadaAutomobile Test Center.

Figure 29. HEV is at TRL6 (from TRL Calculator V2.2)

B. RELIABILITY, AVAILABILITY, MAINTAINABILITY

RAM is a mandatory sustainment requirement per DOD Directive 5000.01 to address the KSAs for reliability, costs and KPPs for operational availability (Department of Defense 2011a).

1. Reliability

System reliability is the probability of executing a mission without a system critical failure. It must be sufficient to support the warfighting capability needed in its expected operating environment. It must also support both the achieved and operational availability metric (Department of Defense 2009a). Reliability requirements must meet the user's needs and expectations while also being achievable, reasonable, measurable, and affordable. Reliability is measured using failure modes effects analysis (FMEA), and failure modes effects and criticality analysis (FMECA) as discussed in SE3302, Systems suitability at the Naval Postgraduate School on 2010. Logistics reliability is the ability of a system to perform as designed in an operational environment over time without any failures, which is measured using the mean time between failures (MTBF). Finally, the

reliability analysis requirement can be summarized as shown in Figure 30, which is a KSA requirement and must be demonstrated. Updating reliability modeling and analysis is required throughout the life cycle of the HET (Department of Defense 2009a).

Table 2-1 Sustainment Requirements and Measures by Phase *(continued)*

Metric	Milestone	How Measured	Responsible Activity	When Measured	Program Phase Metric
Reliability (R_M) (KSA)	A	Comparative Analysis with Legacy Systems and/or Engineering Analysis	Program Manager or Program Sponsor if PM Not Assigned	Pre-ASR for All Candidate Systems Post-ASR for Preferred System Selected	MTBF/MTBM derived from warfighter's stated needs and translated into contract-level testable values.
	B	Demonstrated through Testing, Analysis, and Modeling/Simulation	Test and Evaluation Activity	During DT and Early Operational Assessments	Scored failure rate per FD/SC MTBF if all failures classified as critical and MTBM otherwise
	C	Demonstrated through Testing, Analysis, Modeling/Simulation, and Analysis of Early Fielded System Performance	Test and Evaluation Activity and Program Manager	During DT, DT/OT, and Operational Assessments	Scored failure rate per FD/SC MTBF if all failures classified as critical and MTBM otherwise
	FRP and beyond	Demonstrated through Analysis of Fielded System Performance	OTA and Program Manager	During IOT and throughout the Remainder of System Life Cycle	Scored failure rate per FD/SC MTBF if all failures classified as critical and MTBM otherwise

Figure 30. Reliability KSA requirement (from RAM-C Guidebook 2009)

2. Availability

DOD Directive 5000.01 requires program managers to “develop and implement performance based logistics strategies that optimize that availability while minimizing cost and logistics footprint” (Defense Acquisition Program Support Methodology 2008). Availability requirements address the readiness of the system. Availability is a function

of the ability of the system to perform without failure and to be restored to service quickly (Department of Defense 2008). Availability is a measure of the degree to which an item is in an operable state and can be committed at the start of a mission when the mission is called for at an unknown point in time. Availability as measured by the user is a function of how often failures occur and corrective maintenance is required, how quickly indicated failures can be isolated and repaired, how often and how quickly preventative tasks can be performed, and how long logistics support delays contribute to down time, as discussed in SE3302, Systems suitability at the Naval Postgraduate School on 2010. Availability KPP consists of the materiel availability (A_m) and operational availability (A_o). A_m is a sustainment KPP.

Generally, achieved availability is a function of the system's uptimes (MTBF and maintenance down times (MDT) (Department of Defense 2009a). Availability can be augmented by increasing reliability, with a requisite increase in acquisition costs, decreasing MDT, which will increase support costs, or a combination of the two approaches. The program must have a process in place to monitor, evaluate, score, and initiate corrective action when required for all system downtime events. Finally, the availability analysis requirement can be summarized as shown in Figure 31, which is a KPP requirement and must be demonstrated. Updating availability modeling and analysis is required throughout the life cycle of the HET (Department of Defense 2009a).

Metric	Milestone	How Measured	Responsible Activity	When Measured	Program Phase Metric
Availability Materiel Availability (A _M) Operational Availability (A _O) (KPP)	A	Comparative Analysis with Legacy Systems and/or Engineering Assessment	Program Manager (PM) or Program Sponsor if PM Not Assigned	Pre-Alternative System Review (ASR) for All Candidate Systems Post-ASR for Preferred System Selected	$\frac{(\text{number of operational end items})}{(\text{total number of end items acquired})}$ or $\frac{\text{uptime}}{\text{uptime} + \text{downtime}}$ Value is “as planned” given the expected system use and support concept.
	B	Demonstrated through Testing Plus Modeling/ Simulation Where Needed	Test and Evaluation Activity	During DT and Early Operational Assessments	Scored failure rate per FD/SC MTBF if all failures classified as critical and MTBM otherwise MDT* modeled from MTTR, LDT, and ADT values MDT estimates from early in program; Replaced by data as available
	C	Demonstrated through Testing and Analysis of Early Fielded System Performance	Test and Evaluation Activity and Program Manager	During DT, DT/OT, and Operational Assessments	Scored failure rate per FD/SC MTBF if all failures classified as critical and MTBM otherwise MDT* modeled from MTTR, LDT, and ADT values
	FRP and beyond	Demonstrated through Analysis of Fielded System Performance	OTA and Program Manager	During IOT and throughout Remainder of System Life Cycle	$\frac{(\text{number of operational end items})}{(\text{total number of end items acquired})}$ or $\frac{\text{uptime}}{\text{uptime} + \text{downtime}}$

**Note: MDT = MTTR + mean ADT + mean LDT. For the purposes of estimating the value of AM achieved, MTBF and MTTR are determined from test results while mean ADT and mean LDT shall be representative of the fielded system ADT and LDT as planned and implemented. See Section 3.2.3 for a discussion of why the definition for AM is different from definitions of AO.*

Figure 31. Availability KPP requirement (from RAM-C Guidebook, 2009)

3. Maintainability

Maintainability is the ability of the system to be maintained. The requirements address the ease and efficiency with which servicing, preventive and corrective maintenance can be conducted. In other words, the ability of a system to be repaired and restored to service when maintenance is conducted by personnel with specified skill levels and prescribed procedures and resources (Blanchard and Fabrycky 2010). Maintenance is a series of actions taken to restore a system to an effective operational state. The primary objective is to reduce the time it takes a properly trained maintainer to detect and isolate the failure and affect repair as discussed in SE3302, Systems suitability at the Naval Postgraduate School in 2010. The contributing factors to maintainability are

modularity, interoperability, accessibility, minimum preventative maintenance, embedded training and testing, and human factors engineering.

C. CHAPTER SUMMARY

Currently, TARDEC stated that HET vehicles have been built and tested at the component and systems level, and they have been tested in the SIL at the vehicle level. Therefore, by definition, it is at TRL6. However, by using the TRL calculator, the overall TRL is calculated at TRL4 because insufficient tasks were completed to claim attainment to TRL6. Using the TRL calculator minimized the room for interpretation by various stakeholders, and simplified the process of determining the appropriate TRL for a given technology. By presenting a standard set of questions to every user, the calculator makes the process more repeatable. The standard format facilitates the comparison of different technologies, and accommodates both hardware and software development programs.

While the TRL can present a summary of what has been done up until that time, knowing that a program has achieved a certain TRL says nothing about its prospects for future growth. The current TRL gives no information on risk; nor does it say anything about the likelihood of reaching a higher TRL. It is up to the program manager to make these determinations. TRL provides a standard method of judging technology maturity, and thereby, imparts a significant amount of information about the overall program risk (Nolte 2003).

The ultimate goal of an acquisition program is to produce a system that is effective for its intended purpose, suitable for use in the anticipated environment, and affordable to acquire and operate. An acceptable operational effectiveness technology requires that the system be reliable during use (mission reliability), ready when needed (operational availability), have a low overall failure rate (logistics reliability and materiel availability), be easy to repair (maintainability), and require minimal support (reduced logistics footprint) (Blanchard and Fabrycky 2010).

HET has the potential to meet the performance targets and allowable costs provided successful demonstrations, verification, and validation to prove the technology.

V. CONCLUSION AND FUTURE RESEARCH

A. CONCLUSION

Petroleum-based fuels will remain the military's main power source for tactical platforms from now until at least 2024 (TARDEC 2013a). However, alternative fuel and renewable energy options could rapidly mature to a point at which integration of these options may become viable for tactical military operations. The R&D of electric or hybrid combat vehicles led stakeholders to conclude that electric-powered vehicles do offer a number of advantages and are worth investing in further development, mainly that the HET systems can potentially support future military mission applications.

HET is at the initial capabilities development stage involving material solution analysis and technical development phases. From interviews with subject matter experts from TARDEC and using TRL calculations, the maturity level of HET is between a TRL4 to TRL6. In other words, components and basic sub-system technology were validated in the laboratory, representative prototype systems were built and tested in the required environment, and prototypes were demonstrated in a relevant environment. This technology still requires rigorous engineering, manufacturing, full-scale production, and sustainment development before it can be declared a proven technology. Despite seemingly compelling advantages, HET has struggled to move beyond its one-of-a-kind prototypes and demonstrations even after several decades of R&D by the military and its partners. Parallel to the commercial sector, the main driver is cost, and the main operational issues are drive cycles and energy storage. However, many HEV components are evolving through a continued R&D focus. Several of the basic components are almost ready, but others are at best second or third generation prototypes with very limited field testing.

The cost of replacing or outfitting the current fleet of TWVs with this new technology is quite significant and the payoff of seeing a decrease in fuel consumption is modest. Cost is not the only reason why the DOD would want to procure any new emerging technologies. It is based on the capabilities of the technologies. "We've not

been the most cost-conscious culture and there are times in our business that it doesn't matter what it costs, but that's not all the time," stated Gen Norton A. Schwartz, formal Air Force Chief of Staff (Daniel 2010).

Another prospective is that the DOD lacks efficient emerging technologies' management and procurement processes. Even if HET were ready for implementation, it would be bogged down in a slow, inefficient acquisition process. The current acquisition process is too cumbersome to bring new technologies on board in a reasonable, efficient time frame. "If we would have developed it, it would have taken about 20 years to field it and another 14 years to reap the full benefits," stated Gen. Peter W Chiarelli, formal Vice Chief of Staff of the U.S. Army (Daniel 2010). In today's environment in which rapid change is the norm of operation, the current capability development and the relationship between S&T, acquisition, and requirements, is inadequate (United States Air Force 2014). It is entirely possible that technologies burdened with the industrial-era development cycles measured in decades will become obsolete before they reach full-rate production. The acquisition process must be changed to simpler, modular, open architectures, with more distributed participation that will improve the military's ability to coordinate the development and integration of the capabilities. Full production and deployment face significant hurdles, which include overcoming the skepticism of a new technology, verification and validation (V&V), politics, acquisition bureaucracy, and costs. These challenges need to be overcome before HET becomes widespread in the U.S. military.

A commitment by the military to invest and capitalize on the most promising HET breakthroughs will expand future capabilities. Coupling this long-term commitment with a requirements process and acquisition system that accommodates more frequent opportunities to modify a program during its life cycle and rapid prototyping to bring design idea into services will provide the flexibility to address evolving challenges in many ways. The ability to integrate the best technological advances will accelerate development of the capabilities needed to maintain the cutting edge into the future. The pace of change has quickened substantially over the last two decades. The military's

ability to adapt and respond faster than potential adversaries is the greatest challenge over the next 30 years (United States Air Force 2014).

The payoff is not immediate but gradually, in time, the return on investment will potentially be significant, as was demonstrated in the commercial sector with the Toyota HEV (Prius). In the beginning, each unit was sold at a loss but today, with the increased cost in fuels, the HEVs are realizing significant acceptance by the public, as well as enjoying the gains in profit for the manufacturer. Affordability is a key attribute for future acquisitions. The military should look to the commercial industry for insights into innovative acquisition, procurement, and development processes.

Based on the evidence of this study, reliance on fossil fuel is not sustainable in the long run for the U.S. military. HET is the right technology for long-term investment for the future to enhance power generation, provide superior operational capabilities for future military, and potentially reduce the logistical footprint. HET development and demonstration is an iterative process through which the DOD could leverage the lessons learned and experience to realize the benefits if it could start by easily retrofitting system components to current TWVs until full commitment to HET architecture for a TWV is realized. Current HET solutions could start with the varying HEV technology including the Parallel, Series, and a combination of Parallel/Series, plug-in hybrid electric vehicle (PHEV) drives, all-electric vehicles, and finally, fuel-cells technology. The prediction is that by the end of this decade, the first production military HEV will be fielded.

B. FUTURE RESEARCH

As HET for the military is continuously evolving, future research could include the following.

- Translate many of the concepts with regard to controls and optimization of components into a military vehicle prototype vehicle. As with any system, the modeling and simulation provides the best-case scenario and translating concepts into hardware provides a unique set of challenges, such as repeatability and response time.
- Trade-off analysis will be particularly challenging due to the complex nature of the optimization problem, which includes minimizing fuel economy with stringent performance constraints. The optimization

problem is dependent not only on the power train architecture topology design, i.e., parallel vs. series, batteries vs. ultra capacitors, and component sizing, but also the control system plays a vital role in determining optimal performance.

- The multiple degrees of flexibility on a propulsion system demands an ever increasingly complex control system that must not only run in real time, but provide the required performance when necessary and optimal efficiency when possible.
- Other work could include exploring how the hybrid system compares to conventional systems under the same condition, more vehicle demonstrations, verification and validation relative to the operational capabilities including reliability, availability and maintainability. Analysts need to understand and document the life cycle cost of a hybrid system in a military environment and assess reduced fuel costs in such life cycles.
- Quantifying the non-fuel economic benefits related to silent watch and silent mobility. Power generation for the warfighter could help the military to understand the further value of fielding a military hybrid vehicle.
- HEVs are viewed largely as a transition step on the road to fuel cell technology. If fuel cell technology progresses faster than expected, continued development of HEVs could falter. As the technologies mature, cost and performance will change in ways that may not have been predicted. Therefore, it is critical that these cost relationships be updated to keep pace with technological changes within the industry.
- Reliability of HET needs to be evaluated fully. Operational analysis needs to be performed to identify which platform may gain the greatest benefit from HET to assess logistics impact. Cost analysis of costs incurred for a specific platform, related operational requirement, and life cycle cost analysis of the new technology, is needed.
- One particularly important area to pursue further is system integration. Data on system integration is difficult to find. The U.S. Army's NAC sponsored three prototype development efforts under a HE combat vehicle program study. These programs could provide information in the future on system integration costs.

APPENDIX.

AFRL Transition Readiness Level Calculator, version 2.2

Summary

Reset All

☒ Use Manufacturing
☐ No Manufacturing

☒ Use Programmatic
☐ No Programmatic

Hide Blank Rows

% Complete is now set at: 100%

Green set point is: 75% Yellow set point is: 60% Change set points on Summary sheet.

Hardware and Software Calculator

Technology Readiness Level Achieved					Technical:			
1	2	3	4	5	6	7	8	9

☐ Only Hardware
☐ Only Software
☒ Hardware & Software

Program Name: HET emerging Components Program Manager: Ed McCown

Date TRL Computed: 16 August 2014

TOP LEVEL VIEW -- Demonstration Environment (Start at top and pick the first correct answer)

☐ Has an identical unit been successful an on operational mission (space or launch) in an identical configuration?

☐ Has an identical unit been demonstrated on an operational mission, but in a different configuration/system architecture?

☐ Has an identical unit been mission (flight) qualified but not operationally demonstrated (space or launch)?

☐ Has a prototype unit been demonstrated in the operational environment (space or launch)?

☒ Has a prototype been demonstrated in a relevant environment, on the target or surrogate platform?

☐ Has a breadboard unit been demonstrated in a relevant (typical; not necessarily stressing) environment?

☐ Has a breadboard unit been demonstrated in a laboratory (controlled) environment?

☐ Has analytical and experimental proof-of-concept been demonstrated?

☐ Has a concept or application been formulated?

☐ Have basic principles been observed and reported?

☐ None of the above

Reset Top Level View

Source: James W. Bilbro, NASA, Marshall SFC, May 2001

Comments:

Hybrid-electric vehicles have been built and tested in the labs at the component and system levels. They have been test in System Integration Labs at the vehicle level. They have also been evaluated in the field at several Proving Ground like th aATC at Aberdeen, Cold Region Test Center Ft Greekingm AL abd at the NevadaAutomobile Test Center.

H/SW Both Ques Catgry

☐ Do you want to assume completion of TRL 13

TRL 1 (Check all that apply or use slider for % complete)

H/SW	Ques	Catgry	% Complete	
B	T		100	☒ "Back of envelope" environment
B	T		100	☒ Physical laws and assumptions used in new technologies defined
S	T		100	☒ Have some concept in mind that may be realizable in software
S	T		100	☒ Know what software needs to do in general terms
B	T		100	☒ Paper studies confirm basic principles
S	T		100	☒ Mathematical formulations of concepts that might be realizable in software
S	T		100	☒ Have an idea that captures the basic principles of a possible algorithm
B	P		100	☒ Initial scientific observations reported in journals/conference proceedings/technical reports
B	T		100	☒ Basic scientific principles observed
B	P		100	☒ Know who cares about technology, e.g., sponsor, money source
B	T		100	☒ Research hypothesis formulated
B	P		100	☒ Know who will perform research and where it will be done
				☐
				☐
				☐
				☐

Reset Level 1

H/SW	Ques	Do you want to assume completion of TRL 2?		Reset Level 2	
Both	Catgry	% Complete	TRL 2 (Check all that apply or use slider for % complete)		
B	P	100	☒	Customer identified	
B	T	100	☒	Potential system or component application(s) have been identified	
B	T	100	☒	Paper studies show that application is feasible	
B	P	100	☒	Know what program the technology will support	
B	T	100	☒	An apparent theoretical or empirical design solution identified	
H	T	100	☒	Basic elements of technology have been identified	
B	T	100	☒	Desktop environment	
H	T	100	☒	Components of technology have been partially characterized	
H	T	100	☒	Performance predictions made for each element	
B	P	100	☒	Customer expresses interest in application	
S	T	100	☒	Some coding to confirm basic principles	
B	T	100	☒	Initial analysis shows what major functions need to be done	
H	T	100	☒	Modeling & Simulation only used to verify physical principles	
B	P	100	☒	System architecture defined in terms of major functions to be performed	
S	T	100	☒	Experiments performed with synthetic data	
B	P	100	☒	Requirement tracking system defined to manage requirements creep	
B	T	100	☒	Rigorous analytical studies confirm basic principles	
B	P	100	☒	Analytical studies reported in scientific journals/conference proceedings/technical reports	
B	T	100	☒	Individual parts of the technology work (No real attempt at integration)	
S	T	100	☒	Know what hardware software will be hosted on	
B	T	100	☒	Know what output devices are available	
B	P	100	☒	Investment Strategy Sheet	
B	P	100	☒	Know capabilities and limitations of researchers and research facilities	
B	T	100	☒	Know what experiments you need to do (research approach)	
B	P	100	☒	Qualitative idea of risk areas (cost, schedule, performance)	
B	P	100	☒	Have rough idea of how to market technology (Who's interested, how will they find out about it?)	

H/SW	Ques	Do you want to assume completion of TRL 3?		Reset Level 3	
Both	Catgry	% Complete	TRL 3 (Check all that apply or use slider for % complete)		
B	T	100	☒	Academic environment	
H	T	100	☒	Predictions of elements of technology capability validated by Analytical Studies	
S	T	100	☒	Analytical studies verify predictions, produce algorithms	
H	T	100	☒	Science known to extent that mathematical and/or computer models and simulations are possible	
H	P	100	☒	Preliminary system performance characteristics and measures have been identified and estimated	
S	T	100	☒	Outline of software algorithms available	
H	T	100	☒	Predictions of elements of technology capability validated by Modeling and Simulation	
S	T	100	☒	Preliminary coding verifies that software can satisfy an operational need	
H	M	100	☒	No system components, just basic laboratory research equipment to verify physical principles	
B	T	100	☒	Laboratory experiments verify feasibility of application	
H	T	100	☒	Predictions of elements of technology capability validated by Laboratory Experiments	
B	P	100	☒	Customer representative identified to work with development team	
B	P	100	☒	Customer participates in requirements generation	
B	T	100	☒	Cross technology effects (if any) have begun to be identified	
H	M	100	☒	Design techniques have been identified/developed	
B	T	100	☒	Paper studies indicate that system components ought to work together	
B	P	100	☒	Customer identifies transition window(s) of opportunity	
B	T	100	☒	Metrics established	
B	P	100	☒	Scaling studies have been started	
S	T	100	☒	Experiments carried out with small representative data sets	
S	T	100	☒	Algorithms run on surrogate processor in a laboratory environment	
H	M	100	☒	Current manufacturability concepts assessed	
S	T	100	☒	Know what software is presently available that does similar task (100% = Inventory completed)	
S	T	100	☒	Existing software examined for possible reuse	
H	M	100	☒	Producibility needs for key breadboard components identified	
S	T	100	☒	Know limitations of presently available software (Analysis of current software completed)	
B	T	100	☒	Scientific feasibility fully demonstrated	
B	T	100	☒	Analysis of present state of the art shows that technology fills a need	
B	P	100	☒	Risk areas identified in general terms	
B	P	100	☒	Risk mitigation strategies identified	
B	P	100	☒	Rudimentary best value analysis performed, not including cost factors	

H/SW	Ques						Reset
Both	Catgry	% Complete					Level 4
TRL 4 (Check all that apply or use slider for % complete)							
B	T	100	✓		Cross technology issues (if any) have been fully identified		
H	M	100	✓		Ad hoc and available laboratory components are surrogates for system components		
H	T	100	✓		Individual components tested in laboratory/by supplier (contractor's component acceptance testing)		
H	M	100	✓		Piece parts and components in a pre-production form exist		
H	T	100	✓		M&S used to simulate some components and interfaces between components		
S	T	100	✓		Formal system architecture development begins		
B	P	100	✓		Customer publishes requirements document		
B	T	95	☐		Overall system requirements for end user's application are known		
B	P	95	☐		System performance metrics have been established		
S	T	90	☐		Analysis provides detailed knowledge of specific functions software needs to perform		
B	P	100	✓		Laboratory requirements derived from system requirements are established		
H	M	100	✓		Available components assembled into system breadboard		
H	T	100	✓		Laboratory experiments with available components show that they work together (lab kludge)		
S	T	100	✓		Requirements for each function established		
S	T	95	☐		Algorithms converted to pseudocode		
S	T	100	✓		Analysis of data requirements and formats completed		
S	T	100	✓		Stand-alone modules follow preliminary system architecture plan		
H	T	100	✓		Hardware in the loop/computer in the loop tools to establish component compatibility		
S	M	90	☐		Designs verified through formal inspection process		
B	P	90	☐		S&T exit criteria established		
B	T	100	✓		Technology demonstrates basic functionality in simplified environment		
S	P	100	✓		Able to estimate software program size in lines of code and/or function points		
H	M	100	✓		Scalable technology prototypes have been produced		
B	P	100	✓		Draft conceptual designs have been documented		
H	M	100	✓		Design techniques identified/defined to where small applications may be analyzed/simulated		
B	T	100	✓		Controlled laboratory environment		
B	P	100	✓		Initial cost drivers identified		
S	T	100	✓		Experiments with full scale problems and representative data sets		
B	M	100	✓		Integration studies have been started		
B	P	100	✓		CAIV targets set		
S	T	100	✓		Individual functions or modules demonstrated in a laboratory environment		
H	M	85	☐		Key manufacturing processes identified		
B	P	80	☐		Draft Systems Engineering Master Plan (SEMP)		
B	T	95	☐		Low fidelity technology "system" integration and engineering completed in a lab environment		
H	M	85	☐		Mitigation strategies identified to address manufacturability / producibility shortfalls		
B	P	85	☐		Customer commits to transition through ATD commissioning and/or MOU		
B	T	100	✓		Functional work breakdown structure developed		
B	P	85	☐		Integrated Product Team (IPT) formally established with charter		
B	P	85	☐		Customer representative is member of IPT		
B	P	95	☐		Formal risk management program initiated		
B	P	90	☐		Preliminary Failure Mode and Effects Analysis (FMEA) or Risk Waterfall analysis performed		
B	P	95	☐		Technology availability dates established		

H/SW Both	Ques Catgry	% Complete	TRL 5 (Check all that apply or use sliders)	Reset Level 5
B	T	100	☒ Cross technology effects (if any) identified and established through analysis	
H	M	85	☐ Pre-production hardware available	
B	T	95	☐ System interface requirements known	
B	P	95	☐ System requirements flow down through work breakdown structure (systems engineering begins)	
S	T	95	☐ System software architecture established	
H	M	90	☐ Targets for improved yield established	
S	T	95	☐ External interfaces described as to source, format, structure, content, and method of support	
S	T	90	☐ Analysis of internal interface requirements completed	
H	M	85	☐ Trade studies and lab experiments define key manufacturing processes	
B	T	95	☐ Interfaces between components/subsystems are realistic (Breadboard with realistic interfaces)	
H	M	95	☐ Significant engineering and design changes	
S	T	90	☐ Coding of individual functions/modules completed	
H	M	100	☒ Prototypes have been created	
H	M	95	☐ Tooling and machines demonstrated in lab	
B	T	100	☒ High fidelity lab integration of system completed, ready for test in realistic/simulated environments	
H	M	100	☒ Design techniques have been defined to the point where largest problems defined	
H	P	85	☐ Form, fit, and function for application addressed in conjunction with end user development staff	
H	T	85	☐ Fidelity of system mock-up improves from breadboard to brassboard	
B	M	90	☐ Quality and reliability considered, but target levels not yet established	
H	M	90	☐ Some special purpose components combined with available laboratory components	
H	P	95	☐ Three view drawings and wiring diagrams have been submitted	
B	T	90	☐ Laboratory environment modified to approximate operational environment	
H	M	90	☐ Initial assesment of assembly needs performed	
H	P	85	☐ Detailed design drawings have been completed	
H	M	85	☐ Sigma levels needed to satisfy CAIV targets defined	
B	P	95	☐ Draft SEMP addresses integration	
B	P	95	☐ Draft SEMP addresses test and evaluation	
B	P	95	☐ Draft SEMP addresses mechanical and electrical interfaces	
H	M	85	☐ Production processes have been reviewed with Manufacturing and Producibility office(s)	
B	P	90	☐ Draft SEMP addresses performance; translate measured to expected final performance	
B	P	85	☐ Risk management plan documented	
S	T	100	☒ Functions integrated into modules	
B	P	95	☐ Configuration management plan in place	
S	T	100	☒ Individual functions tested to verify that they work	
S	T	100	☒ Individual modules and functions tested for bugs	
S	T	100	☒ Integration of modules/functions demonstrated in a laboratory environment	
S	P	90	☐ Formal inspection of all modules/components completed as part of configuration management	
B	P	95	☐ Configuration management plan documented	
B	P	85	☐ Draft Test & Evaluation Master Plan (TEMP)	
S	T	95	☐ Algorithms run on processor with characteristics representative of target environment	
H	P	95	☐ Preliminary hardware technology "system" engineering report (Draft SEMP) completed	
B	P	95	☐ Customer commits to transition via POM process	
B	P	95	☐ Draft Transition Plan with Business Case	
H	P	90	☐ Failure Mode and Effects Analysis (FMEA) performed	
B	P	85	☐ Value analysis includes analysis of multiple technology and non-material alternatives	
B	T	85	☐ IPT develops requirements matrix with thresholds and objectives	
B	T	95	☐ Physical work breakdown structure available	
B	P	95	☐ Value analysis includes life-cycle cost analysis	

H/SW	Ques	% Complete		TRL 6 (Check all that apply or use sliders)	Reset Level 6
Both	Catgry				
B	T	85	☐	Cross technology issue measurement and performance characteristic validations completed	
H	M	85	☐	Quality and reliability levels established	
B	M	100	☒	Frequent design changes occur	
H	P	85	☐	Draft design drawings are nearly complete	
B	T	100	☒	Operating environment for eventual system known	
B	P	90	☐	Collection of actual maintainability, reliability, and supportability data has been started	
B	P	90	☐	Design to cost goals identified	
H	M	85	☐	Investment needs for process and tooling determined	
B	T	85	☐	M&S used to simulate system performance in an operational environment	
B	P	80	☐	Final Test & Evaluation Master Plan (TEMP)	
H	T	50	☐	Factory acceptance testing of laboratory system in laboratory setting	
B	T	80	☐	Representative model / prototype tested in high-fidelity lab / simulated operational environment	
B	T	85	☐	Realistic environment outside the lab, but not the eventual operating environment	
B	P	70	☐	Final Systems Engineering Master Plan (SEMP)	
S	T	70	☐	Inventory of external interfaces completed	
B	P	85	☐	Technology Transition Agreement has been updated	
B	P	90	☐	Scaling issues that remain are identified and supporting analysis is complete	
S	T	85	☐	Analysis of timing constraints completed	
S	T	85	☐	Analysis of database structures and interfaces completed	
B	P	95	☐	Have begun to establish an interface control process	
H	P	70	☐	Draft production planning has been reviewed by end user and developer	
H	M	50	☐	Critical manufacturing processes prototyped	
H	M	50	☐	Most pre-production hardware is available	
B	P	50	☐	Technology Transition Agreement has been coordinated and approved by end user	
S	T	95	☐	Prototype implementation includes functionality to handle large scale realistic problems	
S	T	95	☐	Algorithms partially integrated with existing hardware / software systems	
H	M	85	☐	Materials, process, design, and integration methods have been employed	
S	T	95	☐	Individual modules tested to verify that the module components (functions) work together	
B	P	80	☐	Technology "system" specification complete	
H	M	95	☐	Components are functionally compatible with operational system	
S	T	90	☐	Representative software system or prototype demonstrated in a laboratory environment	
B	T	90	☐	Laboratory system is high-fidelity functional prototype of operational system	
B	P	95	☐	Formal configuration management program defined to control change process	
B	M	95	☐	Integration demonstrations have been completed	
B	P	95	☐	Final Technical Report	
H	M	50	☐	Production issues have been identified and major ones have been resolved	
S	T	80	☐	Limited software documentation available	
S	P	50	☐	Verification, Validation and Accreditation (VV&A) initiated	
H	M	50	☐	Process and tooling are mature	
H	M	50	☐	Production demonstrations are complete	
S	P	95	☐	"Alpha" version software has been released	
B	T	90	☐	Engineering feasibility fully demonstrated	
B	P	90	☐	Final Transition Plan with Business Case	
B	P	100	☒	Acquisition program milestones established	
B	P	90	☐	Value analysis includes business case	
B	P	100	☒	Technical alternatives include "do nothing case"	
B	P	90	☐	Formal requirements document available	

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