

Military Hybrid Vehicle Survey

by

Denise M. Kramer, U.S. Army RDECOM-TARDEC

Gordon P. Parker, Michigan Technological University

Abstract

Hybrid vehicles are common in the marketplace for passenger cars and commercial applications such as delivery trucks and transit busses. One of the biggest justifications for hybrids is their fuel efficiency. However, the U.S. military has yet to field a hybrid vehicle even though battle field fuel costs can be as much as \$400 per gallon. This is not due to a lack of investment in research and development, since much work has been done. The goal of this survey paper is to summarize past research in both the commercial and government sectors towards achieving a military hybrid vehicle and provide recommendations for a path forward. Special attention is given to drive cycles and the unique requirements that impact military hybrid vehicle design.

Introduction

With ever increasing emission and fuel economy requirements, most of the passenger car (defined as 8500 lbs or less) Original Equipment Manufacturers (OEMs) have conducted extensive research on various types of hybrid vehicles to comply with these new demands. The literature illustrates not only research, but includes product development, which demonstrates that most of the OEMs have a hybrid model in the marketplace or will introduce one in the near future [1]. Furthermore, the use of hybrid powertrain components consisting of power electronics and electric motor drives have established themselves as a means of improving the energy efficiency of passenger cars [1]. Additionally, there has been significant work and progress in the development of hybrid transit busses [2], which also shows that significant energy savings can be realized with hybrid powertrains. This work has also been extended to delivery trucks and garbage trucks, which have a similar application that utilizes the same type of drive cycle.

The U.S. Army is also interested in realizing the potential energy savings from utilizing hybrid vehicles. "Fossil fuel accounts for 30 to 80 percent of the load in convoys into Afghanistan, bringing costs as well as risk. While the military buys gas for just over \$1 a gallon, getting that gallon to some forward operating bases costs \$400," according to Gen. James T. Conway, the commandant of the Marine Corps [3]. In fact, the U.S. Army has been researching hybrid vehicles since 1943[4]. However, from observing the literature, it appears that the U.S. Army is further away from realizing a hybrid ground vehicle. There are very few if any hardware related papers and many of the papers overlook some of the basic requirements of a military ground vehicle, such as 60% grade ability and fording. Furthermore, a standard duty cycle that is accepted for measuring fuel economy does not exist nor does a focus towards a particular technology. This could be for the following reasons:

- (1) Military ground vehicle researchers do not publish as readily as OEM researchers, due to lack of available data, test vehicles and proprietary information.
- (2) The challenge of a military application is much greater due to the ever increasing and mutating threats that translate into continually changing requirements.
- (3) The life cycle of military vehicles is much different than that of passenger vehicles and not enough development has been completed to understand the long-term reliability and maintainability of hybrid components.
- (4) The off-road mobility requirements present a unique challenge and the off-road production hybrid vehicles are only starting to emerge with construction equipment.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 03 AUG 2011		2. REPORT TYPE Journal Article		3. DATES COVERED 23-04-2011 to 23-09-2011	
4. TITLE AND SUBTITLE Military Hybrid Vehicle Survey				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Denise Kramer; Gordon Parker				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Michigan Technological University,1400 Townsend Drive,Houghton,Mi,49931				8. PERFORMING ORGANIZATION REPORT NUMBER ; #22157	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000				10. SPONSOR/MONITOR'S ACRONYM(S) TARDEC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) #22157	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES For IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY					
14. ABSTRACT Hybrid vehicles are common in the marketplace for passenger cars and commercial applications such as delivery trucks and transit busses. One of the biggest justifications for hybrids is their fuel efficiency. However, the U.S. military has yet to field a hybrid vehicle even though battle field fuel costs can be as much as \$400 per gallon. This is not due to a lack of investment in research and development, since much work has been done. The goal of this survey paper is to summarize past research in both the commercial and government sectors towards achieving a military hybrid vehicle and provide recommendations for a path forward. Special attention is given to drive cycles and the unique requirements that impact military hybrid vehicle design.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Public Release	18. NUMBER OF PAGES 16	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

To understand what has been completed and where the challenges are, this paper will summarize the current state of the art, the missing pieces and the future work with regard to military hybrid ground vehicles.

Background on Research

For fifty years, the U.S. military has been considering the use of electric drive technology [5]. To understand the performance of this technology the Hybrid-Electric Vehicle Experimentation and Assessment (HEVEA) program was initiated in 2005 [5]. The goals of this program were to understand how hybrids performed in a military environment, establish a test procedure for evaluating the performance and create a validated simulation tool for evaluating system-level performance [5, 6]. During the course of this program various one-off hybrid vehicles were tested:

- XM1124 – High Mobility Multipurpose Wheeled Vehicles (HMMWV) Series Electric
- Future Tactical Truck Systems (FTTS) – Parallel Electric
- Family Medium Tactical Vehicle (FMTV) – Hydraulic Hybrid
- Family Medium Tactical Vehicle (FMTV) – Series Electric
- Heavy Mobility Expanded Tactical Truck (HEMTT) – Series Electric

With introduction of the Future Combat Systems (FCS) program, a series of conference papers were published [7-15, 44] by various Original Equipment Manufacturers (OEMs) to show capability on current vehicles with OEM specific hardware. Some of the prototype hybrid vehicles were:

- EP-50 – Parallel Hybrid Light Armored Vehicle (LAV-III) and a Refuse Hauler
- Advanced Hybrid Electric Drive (AHED) – 8x8, 20 ton Series Hybrid (new start)
- Hybrid Electric (HE) M113 – Series Hybrid
- Family Medium Tactical Vehicle (FMTV) – Hydraulic Hybrid
- Commercially Based Tactical Truck (COMBATT) – Dodge RAM Hybrid

Additionally, the commercial sector has shown success with hybrid systems for heavy duty vehicles that have a known drive cycle such as city busses and delivery trucks. Some examples include:

- Allison Hybrid EP System™ - Transit buses two-mode parallel hybrid with continuously variable transmission (CVT)
- Azure Balance Hybrid™ - Ford E-450 chassis parallel hybrid post transmission with starter/generator
- BAE HybridDrive™ - Series Hybrid Electric with a fixed gear reduction
- Eaton - Parallel Hybrid Electric integrated motor/generator with automatic transmission

Currently, the three technology demonstrators for the Joint Light Tactical Vehicle (JLTV) all have Integrated Starter Generators (ISGs), which are not used for propulsion, but could be expanded into mild hybrid with the addition of a clutch connecting the generator to the transmission and additional energy storage [16-17]. Additionally, the Fuel Economy Demonstrator (FED) program is creating two demonstrators: one with an ISG only and one that is a full parallel electric hybrid [18-21].

Military Challenges

As illustrated above, there has been years of work with respect to U.S. military hybrids, however, there has not been a military HEV fielded to date. A paper published in 2009, explains in detail the challenges that military vehicles face [4]. In summary, the vehicle performance requirements such as 60% grade ability, speed on grade, cooling and soft soil mobility add challenges that could diminish the gains seen by a hybrid vehicle. In addition, the reliability and maintainability is unknown for the lifecycle of a

military vehicle. Lastly, the continuously changing threat impedes engineers from understanding the duty cycle and use of the vehicle. However, as technology is ever advancing and hybrids are becoming mainstream for commercial applications including some heavy duty vehicles, such as busses and delivery trucks, it appears that the military can leverage the emerging technologies and eventually field hybrid military vehicles.

Opportunity

It is generally accepted that hybrids can provide improved fuel economy, in fact, a study [22] conducted in 1999 concluded that by just looking at an engine fuel map and eliminating the inefficiencies associated with idling, vehicle braking and low engine speed part load efficiency, many improvements can be realized as shown in Table 1.

Vehicle	Vehicle Class	FE Improvement	Cycle
Ford E-Super Duty Truck	III	61%	Average over Central Business District (CBD), New York City Bus Cycle and Commute Phase Truck Cycle (COMM)
GMC C-Series P-Chassis Truck	III	75%	Average over Central Business District (CBD), New York City Bus Cycle and Commute Phase Truck Cycle (COMM)
Navistar 300 Series Bus	VI	35%	Average over Central Business District (CBD), New York City Bus Cycle and Commute Phase Truck Cycle (COMM)

Table 1: Opportunity

Vehicle class is defined the by gross vehicle weight (GVW) of the vehicle [47] and summary of the classifications are as follows:

(1) Medium Duty:

- Class III – 10,000-14,000lb
- Class IV – 14,001-16,000lb
- Class V – 16,001-19,500lb

(2) Heavy Duty:

- Class VI – 19,501-26,000lb
- Class VII – 26,001-33,000lb
- Class VIII – 33,001lb +

While this work does not take into account component integration or optimal controls, it does show the potential for heavy duty vehicles.

Furthermore, one study by Stodolsky et al. [23] showed that class III – IV trucks can obtain an average of 93% fuel economy gains over a number of urban / city cycles and class VI – VII trucks can obtain an average of 71% over the same cycles.

As depicted by these two papers, hybrids show great promise in regard to fuel economy saving.

Therefore, the next two sections will summarize and explain fuel economy improvements that have been shown in literature.

Parallel

Table 2 gives a summary of fuel economy improvements reported in the literature for parallel hybrid systems, which include mild, electric and hydraulic. The different versions are explained in [24-27]. Additionally, the vehicles are sorted from lightest to heaviest for each section and most to least fuel economy improvement. It is important to note for many of the configurations a range of fuel economy improvement was reported and the maximum improvement was chosen for the summary in Table 2, below. Therefore, the values reported in Table 2 can be considered the ‘best case’ or maximum value that could be attained.

Parallel Type	Vehicle	Vehicle Class	Cycle	Fuel Economy Improvement	Method
Mild	HMMWV	III	Composite	4.3%	Integrated starter generator for engine shut down, regenerative braking and avoidance of inefficient engine operation [28].
	FMTV	VI	Composite	6-9%	Fuel cell advance power unit to allow for engine shut down [29].
Electric	HMMWV	III	Urban, Highway, Composite	21%, 35.8%, 26.5%	Parallel electric hybrid vehicle [30].
			Urban	18%	Engine in the loop simulation with stochastic dynamic programming control system optimizing for fuel economy and emissions [31].
			Munson, Churchville B	17.8%, 45.2%	Simulation using optimal design and power management system [32].
				7%, 11.3%	Series - Parallel hybrid with a continuously variable transmission using optimal design and power management system [31].
	FMTV	VI	Munson, Churchville B	2%, 16.7%	Simulation using optimal design and power management system [31].
				-5%, 30%	Series - Parallel hybrid with a continuously variable transmission using optimal design and power management system [31].
	FMTV	VII		7.5%, 11.5%	Simulation using optimal design and power management system [31].
				11.9%, 15.4%	Series - Parallel hybrid with a continuously variable transmission using optimal design and power management system [31].
	HEMMTT	VIII		2.9%, 0%	Series - Parallel hybrid with a continuously variable transmission using optimal design and power management system [31].
				0%, 0%	Simulation using optimal design and power management system [31].
Hydraulic	FMTV	VI	Composite	32%	Simulation using optimal design (2/3) and dynamic programming power management system [33].
			Urban	26.7%	Hydraulic hybrid vehicle testing [34].

Table 2: Summary of Parallel Hybrid Fuel Economy Improvement

In summary, a HMMWV can realize between 4.3 – 45.2% fuel economy improvement depending on technology and drive cycles, where the FMTV can realize between 2-32% and 7-15% for class VI and VII, respectively. Lastly, the HEMMTT can demonstrate between 0 - 2% improvement. This brings to light

the fact that there is more opportunity for lighter vehicles with respect to parallel hybrids to achieve fuel economy improvements versus conventional powertrains.

Notably there are only three different military vehicles used for all of the publications: HMMWV, shown in Figure 1, FMTV, shown in Figure 2, and HEMMTT, shown in Figure 3. However, these three vehicles span a wide range of weights from 10,000lb to 33,000+ lb indicative of class III through class VII vehicles. Furthermore, information and data related to these vehicles are readily available.



Figure 1: High Mobility Multipurpose Wheeled Vehicles (HMMWV)



Figure 2: Family Medium Tactical Vehicle (FMTV)



Figure 3: Heavy Mobility Expanded Tactical Truck (HEMMTT)

The second item to note is that many different drive cycles were used in the studies for these vehicles ranging from a combinations of courses that were intended to represent military driving conditions, to Munson and Churchville courses, which are test courses from the U.S. Army Aberdeen Proving Grounds, to standard courses developed by the federal government to test passenger cars and heavy duty trucks. A detailed discussion on drive cycles is given in Drive Cycle section.

Lastly, a majority of the papers – all but two shaded entries of Table 2 – focus on simulation. Very few military hybrid vehicle prototype studies have been published, which could be due to proprietary information or simply a lack of hardware development.

Series

Table 3 gives a summary of fuel economy improvements reported in the literature for series hybrid systems, which include electric and hydraulic. The different versions are explained in [24-27]. As in the previous section, the vehicles are sorted from lightest to heaviest for each section and most to least fuel

economy improvement. Again, the range of fuel economy improvements was reported and the maximum improvement was chosen for the summary in Table 3. Therefore, the values reported in Table 3 can be considered the ‘best case’ or maximum value that could be attained.

Series Type	Vehicle	Vehicle Class	Cycle	Fuel Economy Improvement	Method	
Electric	HMMWV	III	Urban	49.6%	Simulation with two sliding mode base controllers - one for engine speed control and one for engine/generator torque [35].	
			Urban, Highway, Composite	33%, 27.9%, 49%	General vehicle simulation [30].	
			Urban	19.0%	Simulation and prototype testing of the XM1124 [36].	
			Munson, Churchville B	12.1%, 43.5%	Simulation using optimal design and power management system [31].	
				7%, 11.3%	Series - Parallel electric hybrid with a continuously variable transmission using optimal design and power management system [31].	
	Notional Military Bus	VI	Four different Urban Cycles	19.1%, 15.9%, 22.7%, 12.5%	Simulation using parametric design and an energy management for fuel economy [37].	
	FMTV	VI	Urban	7.1%	Simulation optimized for fuel economy with 60% grade and acceleration constraints [38].	
			Munson, Churchville B	-5.9%, 30%	Simulation using optimal design and power management system [31].	
				-5%, 30%	Series - Parallel electric hybrid with a continuously variable transmission using optimal design and power management system [31].	
		FMTV	VII		11.9%, 15.4%	Series - Parallel electric hybrid with a continuously variable transmission using optimal design and power management system [31].
					-1.5%, 19.2%	Simulation using optimal design and power management system [31].
	HEMMTT	VII	Composite	17.4%	Vehicle simulation without batteries designed using target cascading [39].	
				12.5%	Electric vehicle simulation without batteries designed using target cascading [39].	
	HEMMTT	VIII			15.8%	Vehicle simulation without batteries designed using target cascading [39].
					15.6%	Simulation with in-hub wheel motors designed using target cascading [39].
			Munson, Churchville B	2.9%, 0%	Series - Parallel hybrid with a continuously variable transmission using optimal design and power management system [31].	
				0%, 9.1%	Simulation using optimal design and power management system [31].	

Hydraulic	HMMWV	III	Urban, Highway	68%, 12%	Simulation with optimized supervisory control [40].
	FMTV	VI	Composite	20%	General vehicle simulation [41].

Table 3: Summary of Series Hybrid Fuel Economy Improvements

In summary, a HMMWV can realize between 7-68% fuel economy improvement depending on its technology and drive cycles, where the FMTV can realize between -5.9-30% and -1.5-19.2% for class VI and VII, respectively. The HEMMTT can demonstrate between 12.5-17.4% and 0-15.8% improvement for class VII and VIII, respectively. Last, a notional military bus (class VI) shows a 12.5%-19.1% improvement, again depending on drive cycle and technology. The series hybrid analysis as with the parallel hybrid demonstrates that there is the greatest opportunity with lighter vehicles. However, the series hybrid shows more potential for improvement in the very large class VII-VIII vehicles than a parallel hybrid.

As with the earlier section, the HMMWV, FMTV and HEMMTT were used for all of the analysis with the exception of one study that used a notional military bus and all of the publications were simulation related with the exception of one (shaded). Finally, many different drive cycles were used and a discussion is detailed in the next section.

Drive Cycles

As mentioned earlier a number of different drive cycles were used to predict fuel economy improvements in the published literature. They can be divided into the following two categories:

- (1) Time dependent speed profiles, shown in Figure 4, usually defined by the federal government (EPA) [42]:
 - FTP 75 Cycle
 - Urban Cycle
 - Highway Cycle

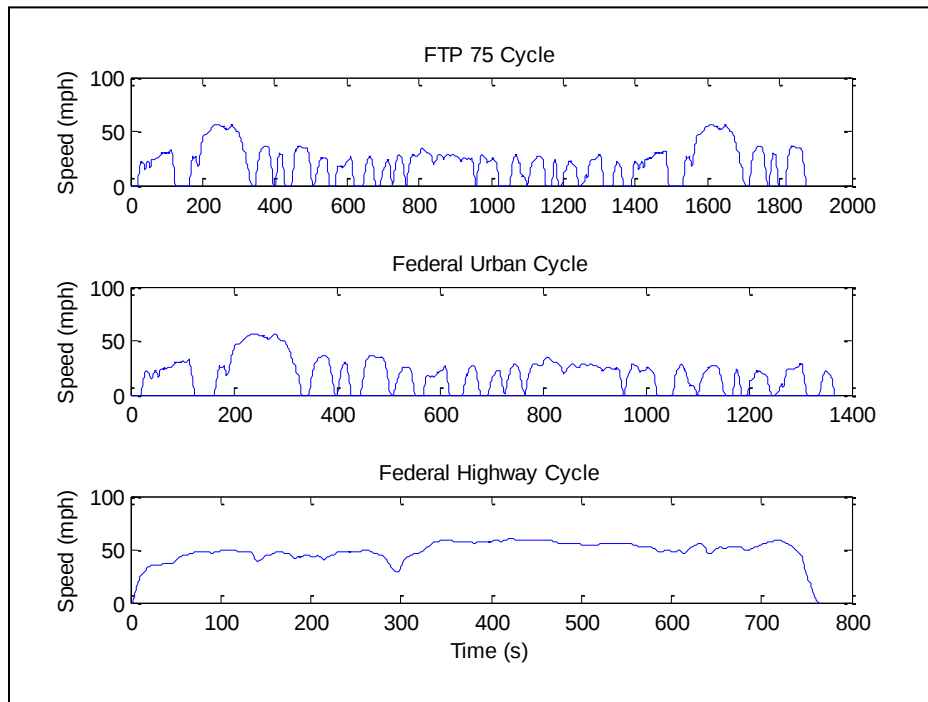


Figure 4: Time Dependent Speed Profiles

(2) Distance dependent grade or elevation profiles (figure 5, below) usually defined by the U.S. Army:

- Churchville Cycle
- Harford Cycle
- Munson Cycle

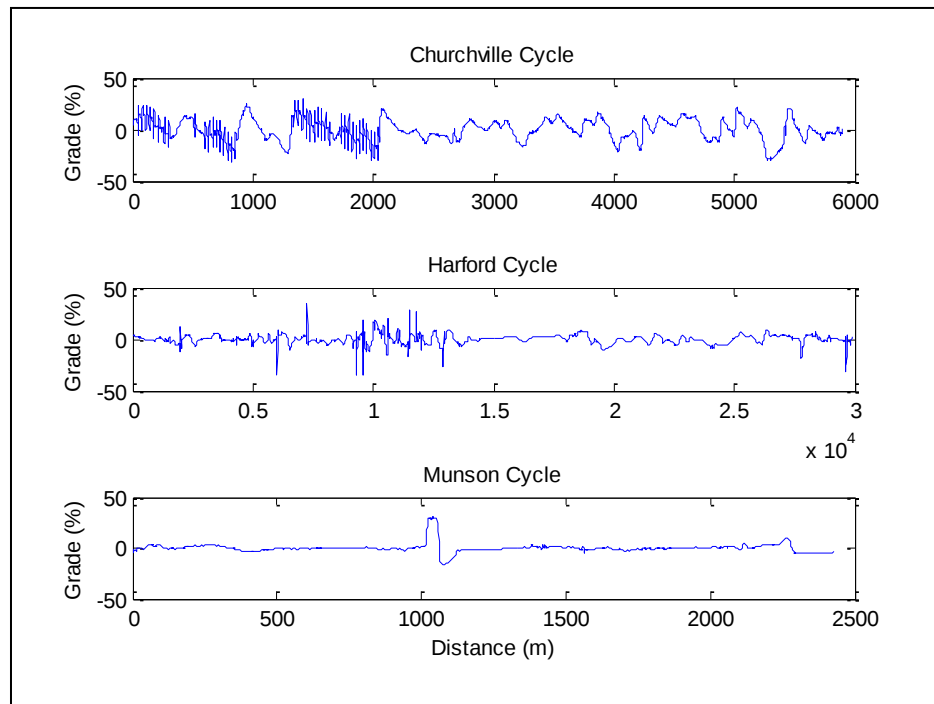


Figure 5: Distance Dependent Grade Profiles

By examining the two figures it becomes apparent that the FTP 75 cycle, which is very similar to the federal urban cycle, and Churchville would show the greatest benefit for a hybrid system. While the highway and Munson would show minimal benefit.

To further illustrate this, figure 6 shows cycle versus percent fuel economy improvement for series, parallel and series-parallel combination for the HMMWV vehicle [28, 30, 31, 32, 35, 36, 40]. While the configuration and methods were different for each of the points on the plot, a general trend shows that the hybrid HMMWVs show more improvement on urban cycles, which is expected. Furthermore, the Munson cycle shows the least amount of fuel economy improvement, which is also anticipated since Munson is basically a flat course without any stops.

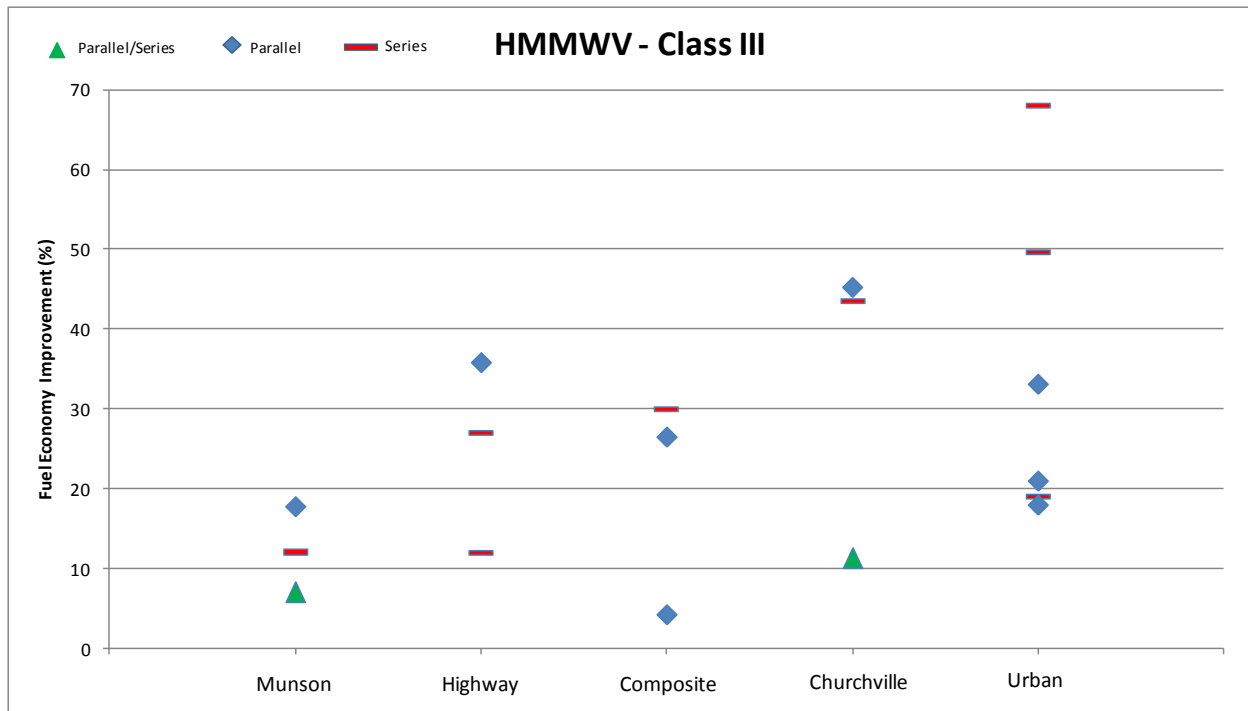


Figure 6: Cycle vs. Fuel Economy Improvement for the HMMWV

Additionally, Figure 7 is a similar plot for the Class VI vehicle [29, 31, 33, 34, 37, 38, 41]. In this plot, a composite cycle is a catch all bin for ad-hoc cycles while the other course are explained by figures four and five. Once more, the urban cycle shows the most improvement, while the Munson cycle even shows degradation in fuel economy.

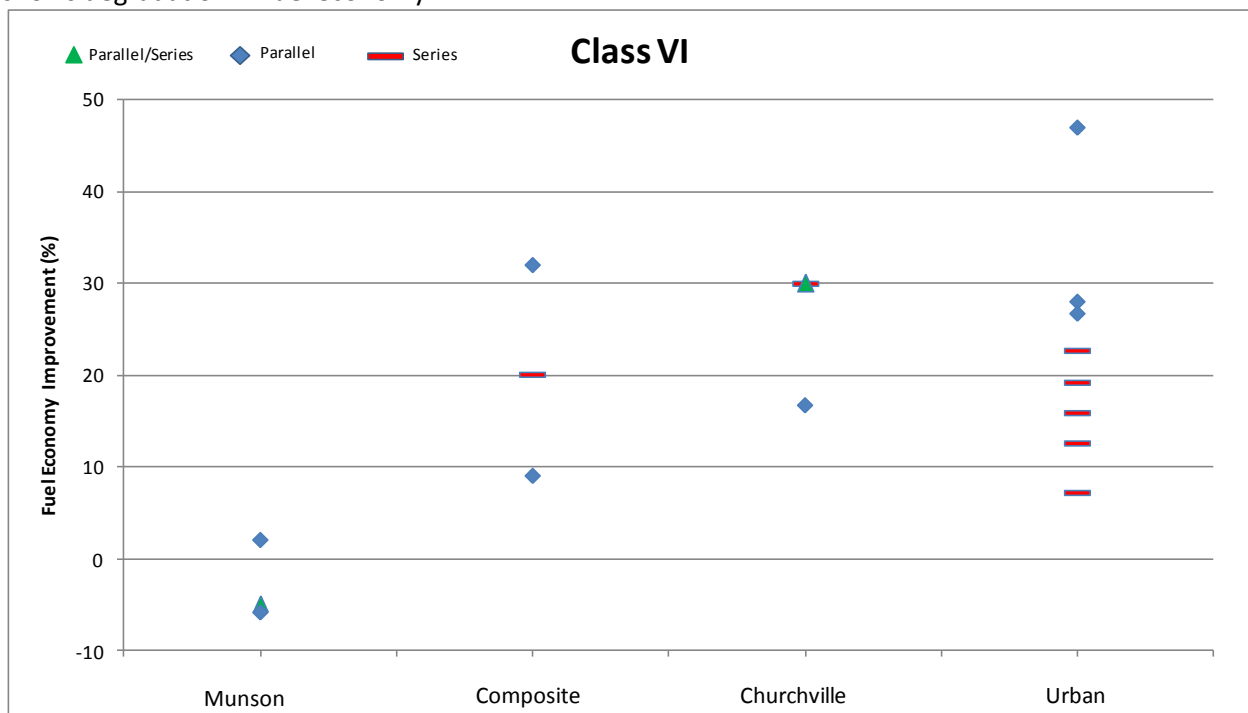


Figure 7: Cycle vs. Fuel Economy Improvement for the Class VI Vehicle

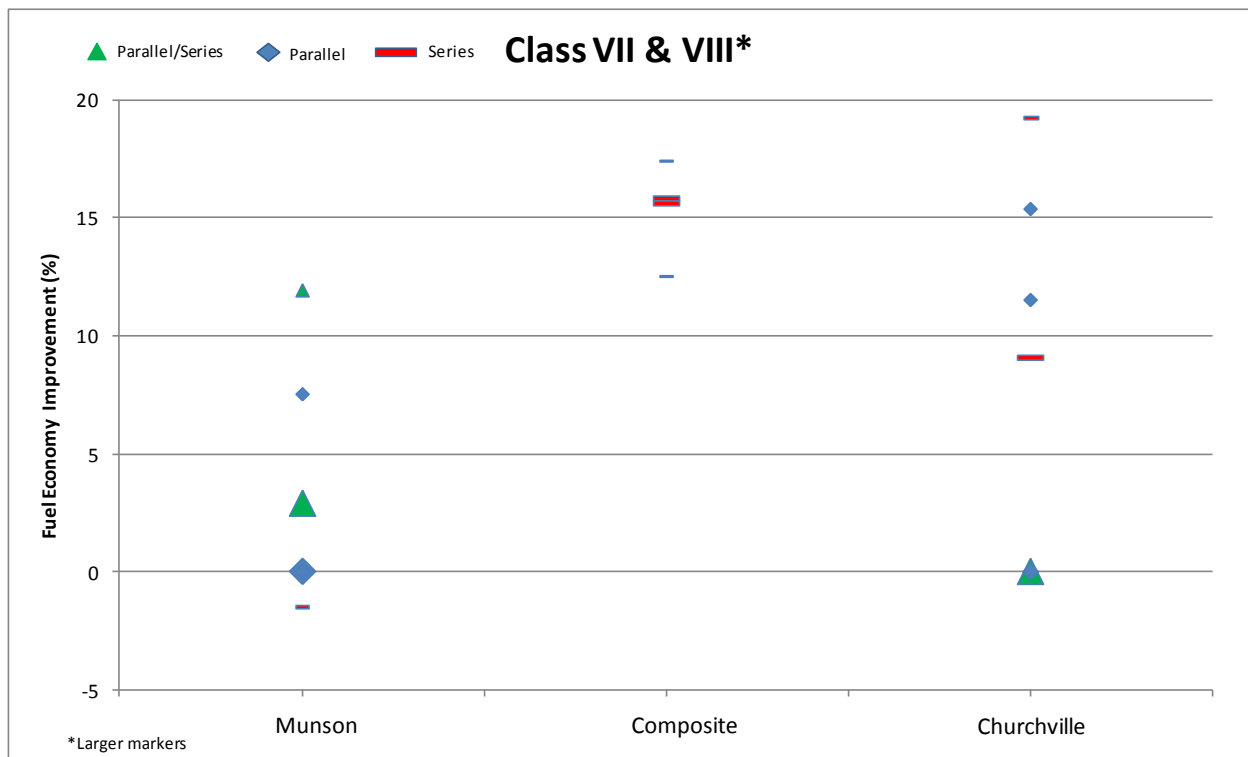


Figure 8: Cycle vs. Fuel Economy Improvement for the Class VII & VIII Vehicle

Figure 8 depicts drive cycle versus fuel economy improvement for Class VII and VIII vehicles [31, 39]. Since an Urban cycle was not used in any of the publications, Churchville, which has some characteristics of an urban cycle, showed the best results. Again, Munson showed the least improvement.

It is important to note that work has been done [45] to develop a true military combat drive cycle to understand real world fuel economy. This study included using soldiers-in-loop in a motion based simulator faced with an actual scenario, such as a convoy escort mission, to determine how a military vehicle would be used. However, based on the surveyed literature, these cycles have not been adopted by the community.

In summary, the fuel economy improvement for military hybrid vehicles is highly dependent on the drive cycle used for the analysis and this research showed a lack of standard drive cycle for analysis, which makes it difficult to judge technologies and understand how the military can benefit from a hybrid vehicle.

Other capabilities

While this paper focuses on fuel economy improvements for military hybrid vehicles, it is important to note that there are other potential payoffs. The first one includes the ability to idle and possibly move without the internal combustion engine. This will not only improve the sound signature, but it will also greatly reduce the thermal signature [5].

The other prospective capability will be the increased onboard electrical power for government furnished equipment. Not only can a hybrid system, such as an engine with an integrated starter generator, provide more electrical power than the typical alternator, but this power can be converted,

conditioned and delivered in any form to and from any load. Some examples included charging the soldiers' batteries or delivering power back into an electrical grid. Additionally, new military vehicles are demanding an excess of 100kW, which can only be provided with an advanced onboard power unit or a hybrid system. Quantifying these capabilities could help the military understand the benefits of hybrid vehicle.

Constraint gaps

Military vehicles typically have clear requirements with regard to grade ability, acceleration times and speed on grade. These requirements will differ from commercial or passenger vehicles and for the different class of vehicles; however, the literature shows that a standard set of requirements is not being used. Fuel economy will be adversely affected when trading off acceleration or grade performance; therefore, it is difficult to determine true fuel economy performance when the various publications use different standards.

Table 5 summarizes the fuel economy improvements for the Class III HMMWV over the urban cycle with the grade and performance requirements used in the analysis. For each of the investigations, a different standard was used for grade or acceleration and in fact some of the publications did not mention the use of any performance requirements. According to the Hybrid Electric HMMWV specification [46] the HMMWV at gross vehicle weight (GVW) shall:

- Be capable of starting and stopping on slopes up to and including 60%.
- Be capable of ascending a 5% grade at 55 mph.
- Accelerate from 0 to 30 mph within 9.0 seconds and from 0 to 50 mph within 24 seconds.

Vehicle	Acceleration	Grade	Fuel economy improvement
Series Electrical	none	none	49.6%
Series Electrical	0-60mph: 16.5s	3.2% grade @ 20mph	33.0%
Series Electrical	none	none	19.0%
Series Hydraulic	0-50mph: 10.8s	2% grade @ 55mph, 3% grade @ 45mph	68.0%
Parallel Electric	0-60mph: 21.7s	0% grade @ 20mph	21.0%
Parallel Electric	none	none	18.0%

Table 5: Summary of HMMWV Urban Cycle Performance and Requirements

The analysis summarized by Dususin et al. [43] noted that 60% grades are achievable, but this type of driving cycle will push motors in a series system to their peak power and the motors can only maintain peak power for a short amount of time. This would indicate that the 60% grade constraint is vital in the design of a military hybrid vehicle.

Another publication [38] used the 60% grade as a constraint in the optimization for a series electric FMTV Class IV vehicle and the fuel economy improvement was 7.1% over the urban cycle, which is the smallest improvement for the Class IV over the urban cycle. The analysis conducted in [31] makes note that all of the vehicle configurations used in their simulations match current acceleration and grade performance targets, but does not provide further details.

Table 6 contains a similar summary for the FMTV Class IV vehicle. The results are similar to the HMMWV where there is an absence of standard performance requirements.

Vehicle	Acceleration	Grade	Fuel economy improvement
Series Electrical	0-37.2mph: 22s	Traverse 25% grade	19.1%
Series Electrical	0-37.2mph: 22s	Traverse 25% grade	15.9%
Series Electrical	0-37.2mph: 22s	Traverse 25% grade	22.7%
Series Electrical	0-37.2mph: 22s	Traverse 25% grade	12.5%
Series Electrical	0-50mph: 25s	Traverse 60% grade	7.1%
Parallel Hydraulic	none	none	26.7%
Parallel Electric	none	none	28.0%
Parallel Hydraulic	none	none	47.0%

Table 6: Summary of FMTV Class IV Urban Cycle Performance and Requirements

Summary

It has been proven that hybrid systems can lead to fuel economy improvement in many types of vehicles and saving fuel in a military environment can save up to \$400 a gallon. A survey of all military hybrid peer reviewed publications illustrates that extensive work has been done with regard to military hybrid vehicle simulations, optimization and controls. All of the literature focuses are three military vehicles: HMMWV, FMTV and HEMMTT, which spans the weight classes for military vehicles. However, there are very few publications with respect to military hybrid vehicle hardware, which could be due to cost, proprietary information or the fact that military hybrid vehicle hardware requires more development time. Additionally, military vehicles provide unique challenges such as, 60% grade ability, speed on grade, cooling and soft soil mobility.

Many different types of duty cycles were used for the fuel economy investigations. They include time speed dependant cycles that are defined by EPA and distant dependant grade profiles that are defined by the U.S. Army. Both types have duty cycles that represent urban style driving (FUDS, Churchville B) and highway style driving (Federal Highway Cycles, Munson). In addition, some of the publications used a mix so that the fuel economy improvements are reported over a composite duty cycle. While the U.S. Army has tried to define an appropriate military drive cycle, overall there is a lack of an accepted duty cycle to estimate fuel economy improvements like the FTP 75, which is used to report miles per gallon for passenger vehicles. This could be due to the fact that military threats are constantly changing and it is generally unknown where a military vehicle could be utilized.

The fuel economy analysis showed that the Class III vehicle had the most potential for fuel economy improvements over an urban cycle and those improvements diminish with composite and highway cycles. The heavier vehicles demonstrate the same trend with respect to cycles and in some cases there was fuel economy degradation over the Munson cycle and the heavier vehicles do not show as much potential as the Class III vehicle. Lastly, fuel economy gains are not the only capability that hybrid system can provide a military vehicle. The hybrid system can be used to provide electrical power for soldiers and allow for an improved noise and thermal signature.

Typically, there is a tradeoff between fuel economy and performance, so it is important to understand the performance constraints, such as acceleration and grade ability. Many of the publications used

performance constraints in their analysis, but some did not. Furthermore, the analysis where performance constraints were taken into account there was a lack of consistency. Most notably, the 60% grade ability was omitted from most analysis even though this is a requirement for all military vehicles. Therefore, it becomes increasingly difficult to compare and contrast different conclusions.

Conclusions

To fully understand the benefits of a military hybrid vehicle and evaluate the research to date with respect to fuel economy benefits a standard drive cycle needs to be created, accepted and widely used so that technologies can be fairly compared to each other. A fuel economy test is a guide that all vehicles are measured by to give an understanding of the fuel efficiency of a vehicle. An example of this is the Federal Test Procedure from 1975 (FTP 75). This is the cycle that is used by all passenger vehicles in the United State to generate the miles per gallon (mpg) that is located on the window sticker of a new vehicle. When a customer reads the sticker mpg they know that this is a number that they may or may not achieve based on driving style and conditions, but it gives them an understanding for how this vehicle compares to other vehicles. Additionally, this standard cycle give researchers a method to compare their work with the work of others. There is no perfect fuel economy test to represent all driving scenarios and drivers. Furthermore, it is impossible to determine a perfect representative fuel economy drive cycle for a military vehicle because the environments and conditions are constantly changing. A mix of known military driving conditions should be used to develop a cycle that would be adopted by the community.

Performance constraints, such as acceleration or grade ability, are parameters that are essential to the development of military vehicle. A hybrid system that can deliver 50% fuel economy improvement but cannot fulfill the acceleration time or grade ability targets is virtually useless to the military. All of the military performance constraints must be used in the research and development of a military hybrid vehicle; otherwise the work will be viewed as inapplicable in a real work environment and dismissed. These constraints should include traversing a 60% grade, acceleration performance, and speed on grade. The absence of consistent real performance targets and a drive cycles used for analysis could be one of reasons that military hybrids have not been fielded date.

Future work should include translating many of the concepts surveyed in this paper with regard to controls and optimization of components into a military vehicle prototype vehicle. As with any system, the simulation provides the best case scenario and translating concepts into hardware provides a unique set of challenges such as repeatability, disturbance rejection and response time. This work will provide particular challenges due to the complex nature of the optimization problem, which includes minimizing fuel economy with stringent performance constraints. Furthermore, the optimization problem is dependent not only on the powertrain 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 ever increasing degrees of freedom on a propulsion system demands an ever increasingly complex control system that must not only run real time, but provide the soldier with required performance when necessary and optimal efficiency when possible. This control system also has to prolong the life of components and protect them from failing due to fatigue or other causes failures.

Other work could include, exploring how a military hybrid vehicle would perform in an off-road situation and how the hybrid system compares to conventional systems under the same condition. Trying to understand the life cycle cost of a hybrid system in a military environment and how this can be offset with fuel costs. Quantifying the non-fuel economy benefits related to silent mobility and power

generation for the warfighter could help the military understand the further payback of fielding a military hybrid vehicle.

Acknowledgements

The authors would like to acknowledge Mike Pozolo, Gus Khalil, U.S. Army RDECOM-TARDEC, and John Beard, Michigan Technological University, for their insight and feedback into to this work.

References

- [1] C.C. Chan, Y.S. Wong, A. Bouscayrol, K. Chen, *Powering Sustainable Mobility: Roadmaps of Electric, Hybrid, and Fuel Cell Vehicles*, Proceedings of the IEEE, Vol. 95, No. 4, April 2009.
- [2] V. Dawood, A. Emadi, *Performance and Fuel Economy Comparative Analysis of Conventional, Hybrid and Fuel Cell Heavy-Duty Transit Buses*, Proceeding of the Vehicular Technology Conference, Vol. 5, pp 3310-3315, October 2003.
- [3] E. Rosenthal, *U.S. Military Orders Less Dependence on Fossil Fuels*, New York Times, October 5, 2010.
- [4] G. Khalil, *Challenges of Hybrid Electric Vehicles for Military Applications*, Proceedings of the IEEE Vehicle Power and Propulsion Conference, pp. 1-3, September 2009.
- [5] G. Khalil, C. E. Allen, M. Pozolo, *Hybrid-Electric Experimentation and Assessment [HEVEA] Program Supports the Army's Need for Increased Power Demand*, Accelerate, pp. 4-7, April-June 2009.
- [6] C. Williams, *Hybrid-Electric (HE) Drive Knowledge Expanded Through Validation Testing*, Accelerate, pp. 20-21, July-September 2009.
- [7] J.W. Hodgson, W. R. Hamel, C.B. Rutherford, J.S. Armfield, *Design of a Low Production Cost Hybrid HMMWV*, Proceedings of IEEE Digital Avionics Systems Conference, Vol. 2, pp. I46/1, 31 Oct-7 Nov 1998.
- [8] M.M. Freeman, *Hybrid Power – An Enabling Technology for Future Combat Systems*, Proceedings of the IEEE Pulsed Power Conference, Vol. 1, pp. 17-22, June 1999.
- [9] R. Crow III, S. P. Cortese, *Dual Use Hybrid Technology for the 21st Century Truck Program*, SAE Paper No. 2000-01-3421, December 2000.
- [10] C. Johnson, L. Dueck, *Hybrid Electric Systems for 20-Ton Platform*, SAE Paper No. 2001-01-2773, November 2001.
- [11] J.S. Ernat, W.G. Harris, T. Trzaska, *Advanced Hybrid Electric Drive (AHED) Technology Demonstrator*, SAE Paper No. 2001-01-2774, November 2001.
- [12] M. A. Kluger, D. Szkubiel, E. A. Bass, *A Dual-Use Hybrid Electric Command and Control Vehicle*, SAE Paper No. 2001-01-2775, November 2001.
- [13] H. Almand, W. Doolittle, G. Klees, *Hybrid Propulsion Truck Platform Dually Developed by the U.S. Army and DaimlerChrysler*, SAE Paper No. 2001-01-2794, November 2001.
- [14] J. M. Paschen, C. Johnson, *Shared Technology/Shared Cost, the Evaluation of the Allison EP-50 Electric Drive for Military and Commercial Vehicles*, SAE Paper No. 2003-01-0271, March 2003.
- [15] P. DiSante, *Hybrid Drive Partnerships Keep the Army on the Right Road*, RDECOM Magazine, June 2003.
- [16] K. Osborn, *3 Firms Win JLTV Contract*, Defense News: <http://www.defensenews.com/story.php?i=3795022&c=AME&s=LAN>, October 2009.
- [17] P. Mcleary, *Army Taking Another Look at JLTV*, Aviation Week: http://www.aviationweek.com/aw/generic/story_generic.jsp?channel=aerospacedaily&id=news/asd/2010/03/03/07.xml, May 2010.
- [18] C. Johnson, *Fuel Savings Design and Engineering Drive the Army's FED Program*, Accelerate: FED Special Edition, pp. 4-9, 2010.
- [19] C. Williams, *Modeling the FED – New Concepts, New Techniques*, Accelerate: FED Special Edition, pp. 10-13, 2010.

- [20] M. Seaton, J. Gardini, *Systems Engineering Approach Crucial for the FED Vehicles*, Accelerate: FED Special Edition, pp. 22-27, 2010.
- [21] P. Luskin, R. Berlin, *Systems Engineering Methodology for Fuel Efficiency and its Application to the TARDEC Fuel Efficient Demonstrator (FED) Program*, Proceedings of the NDIA Ground Systems Engineering and Technology Symposium: Systems Engineering Mini-Symposium, August 2010.
- [22] F. An, F. Stodolsky, J.J. Eberhardt, *Fuel and Emission Impacts of Heavy Hybrids*, Argonne National Laboratory, Report Number ANL/ES/CP-98502, 1999.
- [23] F. An, F. Todolsky, A. Vyas, R. Cuenca, J.J. Eberhardt, *Scenario Analysis of Hybrid Class 3-7 Heavy Vehicles*, SAE Paper No. 2000-01-0908, March 2000.
- [24] A. Emadi, K. Rajashekara, S. S. Williamson, S. M. Lukic, *Topological Overview of Hybrid Electric and Fuel Cell Vehicular Power System Architectures and Configurations*, IEEE Transactions on Vehicular Technology, Vol. 54, Issue 3, pp. 763-770, May 2005.
- [25] M. Ehsani, Y. Gao, J. M. Miller, *Hybrid Electric Vehicles: Architecture and Motor Drives*, Proceedings of IEEE, Vol. 95, No. 4, pp. 719-728, April 2007.
- [26] C.C. Chan, *The State of the Art of Electric, Hybrid and Fuel Cell Vehicles*, Proceedings of IEEE, Vol. 95, No. 4, pp. 704-718, April 2007.
- [27] J. Stecki, P. Matheson, *Advances in Automotive Hybrid Drives*, Proceedings of the 6th JFPS International Symposium on Fluid Power, TSUKUBA. November 2005.
- [28] A. Malikopoulos, Z. Filipi, D. Assanis, *Simulation of an Integrated Starter Alternator (ISA) System for the HMMWV*, SAE Paper No. 2006-01-0442, April 2006.
- [29] Z. Filipi, L. Louca, A. Stefanopoulou, J. Pukrushpan, B. Kittirungsi, H. Peng, *Fuel Cell APU for Silent Watch and Mild Electrification of a Medium Tactical Truck*, SAE Paper no. 2004-01-1477, March 2004.
- [30] A. I. Antoniou, J. Komyathy, J. Bench, A. Emadi, *Modeling and Simulation of Various Hybrid-Electric Configurations of the High-Mobility Multipurpose Wheeled Vehicle (HMMWV)*, IEEE Transactions on Vehicular Technology, Vol. 56, No. 2, pp. 459-465, March 2007.
- [31] D. Milner, J. Goodell, W. Smith, J. Tzau, M. Pozolo, J. Ueda, *Power System Design Optimization for Tactical Wheeled Vehicles*, Proceedings of the EVS24 International battery Hybrid and Fuel Cell Electric Vehicle Symposium, May 2009.
- [32] Z. Filipi, H. Fathy, J. Hagena, A. Knafl, R. Ahlawat, J. Liu, D. Jung, D. Assanis, H. Peng, J. Stein, *Engine-in-the-Loop Testing for Evaluating Hybrid Propulsion Concepts and Transient Emissions – HMMWV Case Study*, SAE Paper No. 2006-01-0443, April 2006.
- [33] A. Filipi, L. Louca, B. Daran, C.C. Lin, U. Yildir, B. Wu, M. Kokkolaras, D. Assanis, H. Peng, P. Papalambros, J. Stein, S. Szkubiel, R. Chapp, *Combined optimization of design and power management of the hydraulic hybrid propulsion system for the 6X6 medium truck*, Int. J. of Heavy Vehicle Systems, Vol. 11, Nos. 3/4, 2004.
- [34] P. Matheson, J. Stecki, *Development and Simulation of a Hydraulic-Hybrid Powertrain for use in Commercial Heavy Vehicles*, SAE 2003-01-3370, November 2003.
- [35] M. Gokasan, S. Bogosyan, D. Goering, *Sliding Mode Based Powertrain Control for Efficiency Improvement in Series Hybrid-Electric Vehicles*, IEEE Transactions on Power Electronics, Vol. 12, No. 3, May 2006.
- [36] H. E. Bargar, J. Li, D. J. Goering, J. H. Lee, *Modeling and Verification of Hybrid Electric HMMWV Performance*, Proceeding of the IEEE Industrial Electronics Society 29th Annual Conference, Vol. 1, p. 939, November 2003.
- [37] C. Liang, W. Weihua, W. Qingnian, *Energy Management Strategy and Parametric Design for Hybrid Electric Military Vehicle*, SAE Paper No. 2003-01-0086, March 2003.
- [38] G. Rizzoni, J. R. Johnson, A. Soliman, C. Huber, C. Cantemir, N. Dembski, P. Pisu, D. Mikesell, L. Serrao, J. Russell, M. Carroll, *Modeling, simulation, and concept design for hybrid-electric medium-size military trucks*, Proceedings of SPIE Vol. 5805, 2005.

- [39] N. Michelena, L. Louca, M. Kokkolaras, C. C. Lin, D. Jung, Z. Filipi, D. Assanis, P. Papalambros, H. Peng, J. Stein, M. Feury, *Design of an Advanced Heavy Tactical Truck: A Target Cascading Case Study*, SAE Paper No. 2001-01-2793, November 2001.
- [40] Y. J. Kim, Z. Filipi, *Simulation Study of a Series Hydraulic Hybrid Propulsion System for a Light Truck*, SAE Paper No. 2007-01-4151, 2007.
- [41] B. Surampudi, A. Nedungadi, G. Ostrowski, A. Montemayor, H. Gruenewald, *Design and Control Considerations for a Series Heavy Duty Hybrid Hydraulic Vehicle*, SAE Paper no. 2009-01-2717, 2009.
- [42] Drive cycle data: <http://www.epa.gov/nvfel/testing/dynamometer.htm>
- [43] M. Ducusin, S. Gargies, C. Mi, *Modeling of a Series Hybrid Electric High-Mobility Multipurpose Wheeled Vehicle*, IEEE Transactions on Vehicular Technology, Vol. 56, No. 2, March 2007.
- [44] W. G. Harris, D. L. Ventimeglia, *Will Hybrid electric Propulsion Drive Future Combat Systems*, SAE Paper No. 2002-01-03052, March 2002.
- [45] M. Brudnak, M. Pozolo, M. McGough, T. Mortsfield, A. Shvartsman, R. Romano, *Motion Based Simulation of a Hybrid-Electric HMMWV for Economy Improvements*, SAE Paper No. 2008-01-0775, April 2008.
- [46] Performance Based Purchase Description – Hybrid Electric High Mobility Multipurposed Wheeled Vehicle, ATPD 2335, 30 May 2003.
- [47] Vehicle Weight Classifications – Emission Standards Reference Guide, Environmental Protection Agency, <http://www.epa.gov/otaq/standards/weights.htm>.

Disclaimer: Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Department of the Army (DoA). The opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or the DoA, and shall not be used for advertising or product endorsement purposes.

As the author(s) is(are) not a Government employee(s), this document was only reviewed for export controls, and improper Army association or emblem usage considerations. All other legal considerations are the responsibility of the author and his/her/their employer(s)