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Current state of military hybrid vehicle development

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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. With fuel costs as high as $100 per litre in the battle field it is remarkable that there are no deployed hybrid military vehicles. 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 summarise 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.

Keywords: hybrid vehicle; military.

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1 Introduction

With ever increasing emission and fuel economy requirements in the USA, Europe and Asia, most of the passenger car (defined as 3,850 kg 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 in Europe and the USA have a hybrid model in the marketplace or will introduce one in the near future (Bouscayrol et al., 2009). 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 (Bouscayrol et al., 2009). Additionally, there has been significant progress in the development of hybrid transit busses worldwide (Emadi and Dawood, 2003), which also shows that energy savings can be realised with hybrid powertrains. This work has also been extended to delivery trucks and garbage trucks, which have a similar application that utilises the same type of drive cycle.

Militaries worldwide are also interested in realising the potential energy savings from utilising 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 US Marine Corps (Rosenthal, 2010). In fact, the US Army has been researching hybrid vehicles since 1943 (Khalil, 2009). However, from observing the literature, it appears that the USA and other countries are further away from realising 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 military ground vehicles, such as 60% grade ability and fording. The lack of literature related to European and Asian military vehicles conveys that armies worldwide are also facing the challenge of fielding a hybrid military vehicle. Furthermore, a standard or universally accepted duty cycle 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 off- road production hybrid vehicles are only recently starting to emerge in the construction equipment sector.

To understand what has been accomplished and where the challenges are, this paper[1, 2] will summarise the current state of the art, the missing pieces and suggest future directions to aid development of military hybrid ground vehicles.

2 Background on research

For 50 years, the US military has been considering the use of electric drive technology (Pozolo et al., 2009). To understand the performance of this technology, the hybrid-electric vehicle experimentation and assessment (HEVEA) programme was initiated in 2005 (Pozolo et al., 2009). The goals of this programme were to understand how hybrids performed in a military environment, establish a test procedure for evaluating their performance and create a validated simulation tool for evaluating system-level performance (Pozolo et al., 2009; Williams, 2009). During the course of this programme various one-off hybrid vehicles were developed and tested:

- XM1124 high mobility multipurpose wheeled vehicles (HMMWV) series electric
- future tactical truck systems (FTTS) parallel electric
- family medium tactical vehicle (FMTV) hydraulic hybrid
- FMTV series electric
- heavy mobility expanded tactical truck (HEMTT) series electric.

With the introduction of the future combat systems (FCS) programme, a series of conference papers were published (Rutherford et al., 1998; Freeman, 1999; Cortese and Crow, 2000; Dueck and Johnson, 2001; Trzaska et al., 2001; Bass et al., 2001; Klees et al., 2001; Johnson and Paschen, 2003; DiSante, 2003; Ventimeglia and Harris, 2002; Fatemi et al., 2008) by various OEMs to show capability on current vehicles using OEM specific hardware. Some of the prototype hybrid vehicles developed under the FCS programme were:

- EP-50 parallel hybrid light armoured vehicle (LAV-III) and a refuse hauler
- advanced hybrid electric drive (AHED) 8 × 8, 20 ton series hybrid (new start)
- hybrid electric (HE) M113 series hybrid
- 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 US Army's joint light tactical vehicle (JLTV) all have integrated starter generators (ISGs), which are not used for propulsion, but could be expanded into mild hybrid capability with the addition of a clutch connecting the generator to the transmission and additional energy storage (Osborn, 2009; Mcleary, 2010). Additionally, the US Army's fuel economy demonstrator (FED) programme is creating two demonstrators: one with an ISG only and one that is a full parallel electric hybrid (Johnson, 2010; Williams, 2010; Gardini and Seaton, 2010; Berlin and Luskin, 2010).

3 Military challenges

As illustrated above, there has been years of work with respect to US 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 (Khalil, 2009). 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, their 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 these technologies could be leveraged to eventually field hybrid military vehicles.

4 Opportunity

It is generally accepted that hybrids can provide improved fuel economy, in fact, a study conducted in 1999 concluded that by just considering an engine fuel map and eliminating the inefficiencies associated with idling, vehicle braking and low engine speed part load efficiency, many improvements could be realised as shown in Table 1 (Eberhardt et al., 1999).

Table 1 Fuel savings for class III and IV trucks predicted by the study of Eberhardt et al. (1999)

Vehicle	*Vehicle class*	*Fuel economy improvement*	*Method*
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	III	35%	Average over central business district (CBD), New York city bus cycle and commute phase truck cycle (COMM)

A vehicles class is defined by its gross vehicle weight (GVW) summarised below (Environmental Protection Agency, 2009):

1 medium duty
  - *class III:* 4,536–6,350 kg
  - *class IV:* 6,351–7,257 kg
  - *class V:* 7,258–8,845 kg

2 heavy duty
  - *class VI:* 8,846–11,793 kg
  - *class VII:* 11,794–14,969 kg
  - *class VIII:* 14,970+ kg.

While this work does not take into account component integration or optimal controls, Table 1 shows the potential for medium and heavy duty vehicles.

The study by Todolsky et al. (2000) showed that class III–IV trucks can obtain an average of 93% fuel economy gains over a number of urban/city cycles while class VI–VII trucks can obtain an average of 71% over the same cycles. As illustrated by these two papers, hybrids show promise in regard to fuel economy savings. Therefore, the next sections will introduce military vehicles and drive cycles as well as summarise and explain fuel economy improvements that have been shown in the literature according to the powertrain configuration used, parallel and series.

5 Vehicle overview

While many different vehicles are used in the battlefield worldwide, 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 4,536 kg to 14,970+ kg 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 vehicle (see online version for colours)

Figure 2 Family medium tactical vehicle (see online version for colours)

Figure 3 Heavy mobility expanded tactical truck (see online version for colours)

6 Drive cycle overview

To determine fuel economy improvement it is necessary to test a vehicle or run a simulation over a specified drive cycle. A review of the literature showed that many different drive cycles were being used to evaluate vehicle performance. These cycles can be divided into the following two categories:

1. time dependent speed profiles, shown in Figure 4, usually defined by the federal government (EPA, 2010):
   - FTP 75 cycle
   - urban cycle
   - highway cycle
2. distance dependent grade or elevation profiles, shown in Figure 5, usually defined by the US Army:

- Churchville cycle
- Harford cycle
- Munson cycle.

In general, hybrid vehicle fuel savings are realised when the vehicle undergoes frequent speed or load changes. A qualitative examination of Figures 4 and 5 shows that the FTP75, federal urban, Churchville and Hartford cycles all have significant speed or load frequency content. Conversely, the federal highway and Munson cycles have very few speed or load changes. The influence of these different drive cycles will be further analysed in the drive cycle impact section.

Figure 4 Time dependent speed profiles (see online version for colours)

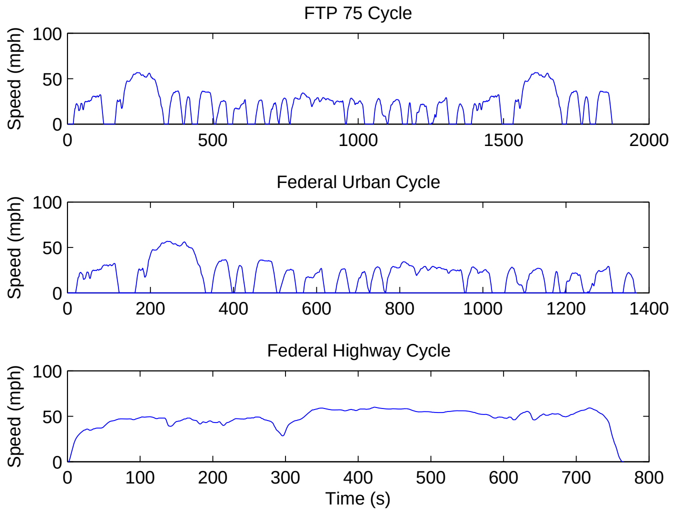
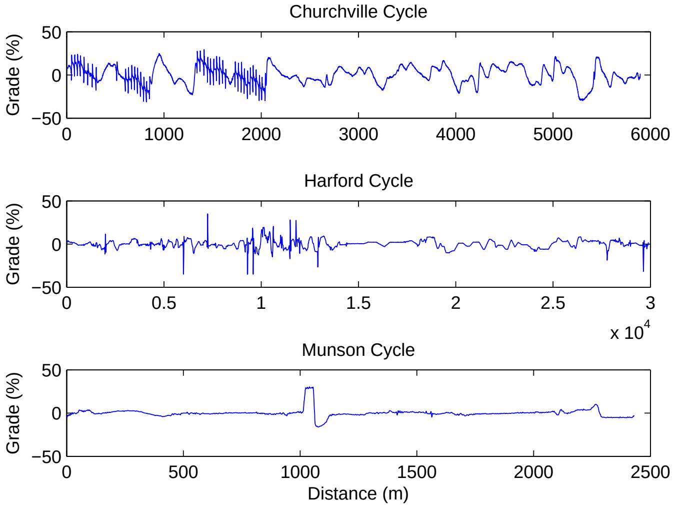


Figure 5 Distance dependent grade profiles (see online version for colours)



6.1 Parallel powertrain

A parallel hybrid powertrain is a configuration where both the internal combustion engine and another power source can drive the wheels. The other power source can be an electric motor or a hydraulic accumulator. The system is described by the term parallel because the power to move the vehicle can come from two different paths. A detailed description of the different powertrain versions are explained Williamson et al. (2005), Miller et al. (2007), Chan (2007), and Matheson and Stecki (2005). Table 2 gives a summary of fuel economy improvements reported in the literature for parallel hybrid systems, which include mild, electric and hydraulic. 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 fuel economy improvement range was reported with only the maximum improvement shown in Table 2. Therefore, the values reported in Table 2 are the best case or maximum value that could be attained.

In summary, a class III HMMWV can realise between 4.3% to 45.2% fuel economy improvement depending on technology and drive cycles, whereas the class VI and VII FMTV can realise between 2% to 32% and 7% to 15% respectively. Lastly, the class VIII HEMMTT only demonstrates an improvement between 0% to 2%. The results of these studies indicate that for parallel hybrid powertrains there exists more opportunity for smaller class vehicles

As noted earlier, 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 US Army Aberdeen Proving Grounds, to standard courses developed by the US Government to test passenger cars and heavy duty trucks. A detailed discussion on drive cycles is given in drive cycle impact section.

Lastly, a majority of the papers all but the 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.

6.2 Series powertrain

A series powertrain is where the internal combustion engine drives a second power source, which drives the wheels of the vehicle. The second power source can be an electric motor or a hydraulic accumulator. The system is called a series system because the power flows on one path in a serial fashion. A detailed description can be found in Williamson et al. (2005), Miller et al. (2007), Chan (2007) and Matheson and Stecki (2005). Table 3 gives a summary of fuel economy improvements reported in the literature for series hybrid systems, which include electric and hydraulic. 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.

Table 2 Summary of published fuel economy benefits of three types of parallel hybrid powertrain configurations for class III, VI, VII, and VIII vehicles

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 (Assanis et al., 2006).
	FMTV	VI		6% to 9%	Fuel cell advance power unit to allow for engine shut down (Stefanopoulou et al., 2004).
Electric	HMMWV	III	Urban, highway, composite	21%, 35.8% 26.5%	Parallel electric hybrid vehicle (Bench et al., 2007).
			Urban	18%	Engine in the loop simulation with stochastic dynamic programming control system optimising for fuel economy and emissions (Smith et al., 2009).
			Munson, Churchville B	17.8%, 45.2%	Simulation using optimal design and power management system (Hagena et al., 2006).
				7%, 11.3%	Series-parallel hybrid with a continuously variable transmission using optimal design and power management system (Smith et al., 2009).
	FMTV	VI	Munson, Churchville B	2%, 16.7%	Simulation using optimal design and power management system (Smith et al., 2009).
				–5%, 30%	Series-parallel hybrid with a continuously variable transmission using optimal design and power management system (Smith et al., 2009).
		VII		7.5%, 11.5%	Simulation using optimal design and power management system (Smith et al., 2009).
				11.9%, 15.4%	Series-parallel hybrid with a continuously variable transmission using optimal design and power management system (Smith et al., 2009).
	HEMMIT	VIII		2.9%, 0%	Series-parallel hybrid with a continuously variable transmission using optimal design and power management system (Smith et al., 2009).
				0%, 0%	Simulation using optimal design and power management system (Smith et al., 2009).
Hydraulic	FMTV	VI	Composite	32%	Simulation using optimal design (2/3) and dynamic programming power management system (Daran et al., 2004).
			Urban	26.7%	Fuel cell advance power unit to allow for engine shut down (Daran et al., 2004).

Notes: Shading indicates a prototype study. All others were simulation only.

Table 3 Summary of published fuel economy benefits of two types of series hybrid powertrain configurations for class III, VI, VII, and VIII vehicles

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 (Goering et al., 2006).
				19.0%	Simulation and prototype testing of the XM1124 (Goering et al., 2003).
			Urban, highway, composite	33%, 27.9%, 49%	General vehicle simulation (Bench et al., 2007).
			Munson, Churchville B	12.1%, 43.5%	Simulation using optimal design and power management system (Smith et al., 2009).
				7%, 11.3%	Series-parallel electric hybrid with a continuously variable transmission using optimal design and power management system (Smith et al., 2009).
	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 (Qingnian et al., 2003).
	FMTV	VI	Urban	7.1%	Simulation optimised for fuel economy with 60% grade and acceleration constraints (Soliman et al., 2005).
			Munson, Churchville B	–5.9%, 30%	Simulation using optimal design and power management system (Smith et al., 2009).
				–5%, 30%	Series-parallel electric hybrid with a continuously variable transmission using optimal design and power management system (Smith et al., 2009).
		VII		11.9%, 15.4%	Series-parallel electric hybrid with a continuously variable transmission using optimal design and power management system (Smith et al., 2009).
				–1.5%, 19.2%	Simulation using optimal design and power management system (Smith et al., 2009).
	HEMMIT	VII	Composite	17.4%	Vehicle simulation without batteries designed using target cascading (Kokkolaras et al., 2001).
				12.5%	Electric vehicle simulation without batteries designed using target cascading (Kokkolaras et al., 2001).
		VIII		15.8%	Vehicle simulation without batteries designed using target cascading (Kokkolaras et al., 2001).
				15.6%	Simulation with in-hub wheel motors designed using target cascading (Kokkolaras et al., 2001).
			Munson, Churchville B	2.9%, 0%	Series-parallel hybrid with a continuously variable transmission using optimal design and power management system (Smith et al., 2009).
				0%, 9.1%	Simulation using optimal design and power management system (Smith et al., 2009).
Hydraulic	HMMWV	III	Urban, highway	68%, 12%	Simulation with optimised supervisory control (Filipi and Kim, 2007).
	FMTV	VI	Composite	20%	General vehicle simulation (Ostrowski et al., 2009).

Notes: Shading indicates a prototype study. All others were simulation only.

In summary, a HMMWV can realise between 7% to 68% fuel economy improvement depending on its technology and drive cycles, where the FMTV can realise between –5.9% to 30% and –1.5% to 19.2% for class VI and VII, respectively. The HEMMTT can demonstrate between 12.5% to 17.4% and 0% to 15.8% improvement for class VII and VIII, respectively. Last, a notional military bus (class VI) shows a 12.5% to 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 analyses with the exception of the study of Qingnian et al. (2003) that used a notional military bus. All of the studies were simulation only with the exception of one [shaded reference (Goering et al., 2003)]. Finally, many different drive cycles were used and a discussion is detailed in the next section.

7 Fuel economy improvement vs. drive cycles

To further understand the effect of drive cycles, Figure 6 shows cycle versus percent fuel economy improvement for series, parallel and series-parallel combination for the class III HMMWV vehicle based on the results provided in Assanis et al. (2006), Bench et al. (2007), Smith et al. (2009), Hagena et al. (2006), Goering et al. (2006, 2003), and Filipi and Kim (2007). 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, vehicles tested on the Munson cycle show the least amount of fuel economy improvement, which is also anticipated since the Munson drive cycle is nearly a flat course without any stops as shown in Figure 5.

Figure 7 is a similar plot for class VI vehicles where the data is extracted from Stefanopoulou et al. (2004), Smith et al. (2009), Filipi et al. (2004), Qingnian et al. (2003), Soliman et al. (2005), and Ostrowski et al. (2009). In this plot, a composite cycle is a catch-all bin for ad-hoc cycles. Once more, the urban cycle shows the most improvement, while the Munson cycle shows a degradation in fuel economy in some cases.

Figure 8 shows the drive cycle versus fuel economy improvement for class VII and VIII vehicles from Smith et al. (2009) and Kokkolaras et al. (2001). Since an urban cycle was not used in either of these 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 (McGough et al., 2008) to develop a true military combat drive cycle to understand operational fuel economy. This study used a motion simulator with soldiers-in-the-loop facing military scenarios, such as a convoy escort mission, to determine typical speed and load profiles that could be used for a drive cycle. 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. The existing literature shows the lack of a standard drive cycle for analysis, which makes it difficult to judge technologies and understand how the military can benefit from a hybrid vehicle. This is likely one of the reasons for the delay in fielding a military hybrid.

Figure 6 Cycle vs. fuel economy improvement for the HMMWV (see online version for colours)

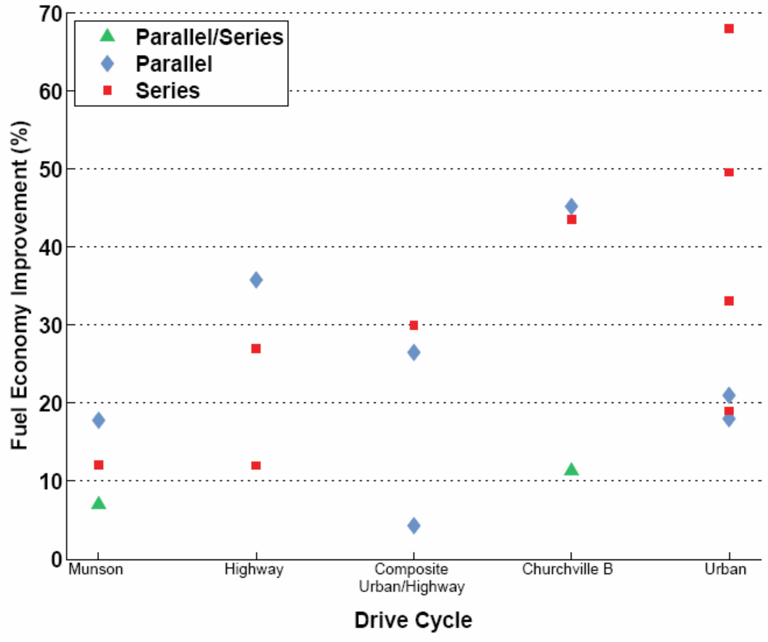


Figure 7 Cycle vs. fuel economy improvement for the class VI vehicle (see online version for colours)

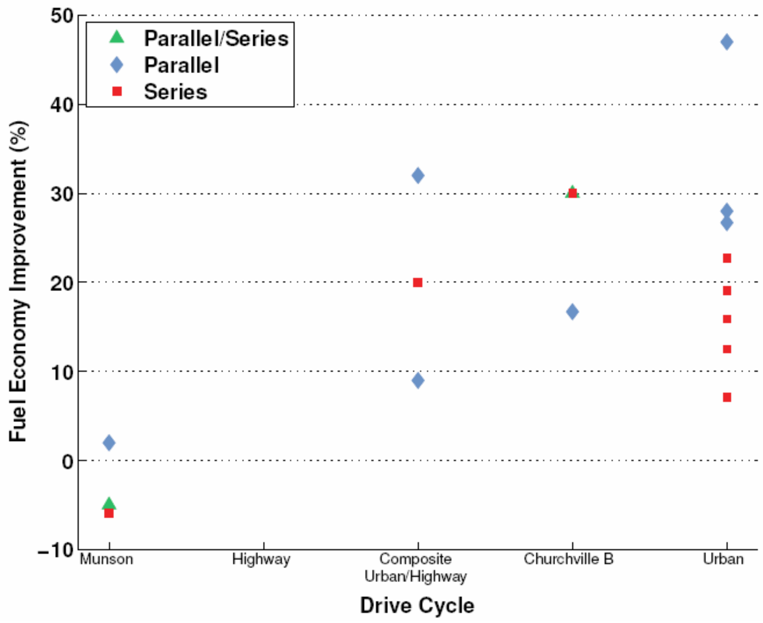
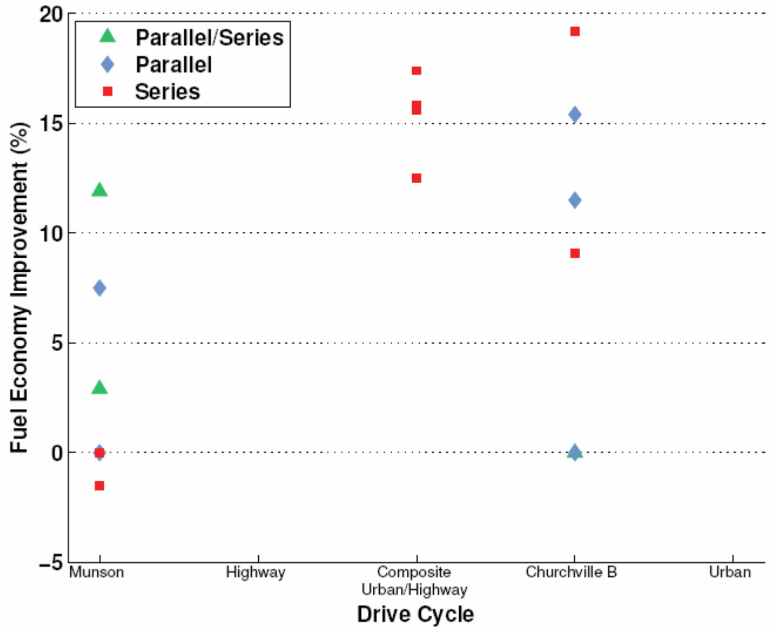


Figure 8 Cycle vs. fuel economy improvement for the class VII and VIII vehicle (see online version for colours)



8 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 benefit is the ability to idle and possibly move without the noise and thermal signatures of its internal combustion engine (Khalil, 2009). Another benefit is the increased onboard electrical power for auxiliary 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 50 kW (Desmond, 2011), which can only be provided with an advanced onboard power unit or a hybrid system. Quantifying these capabilities could help governments understand the benefits of military hybrid vehicles.

9 Constraint gaps

Military vehicles typically have clear requirements with regard to grade ability, acceleration levels 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 comparable fuel economy performance across studies using different requirements.

Table 4 summarises the fuel economy improvements for the class III HMMWV over the urban cycle with different grade and performance requirements used for the analyses of Bench et al. (2007), Smith et al. (2009), Goering et al. (2006, 2003), and Filipi and Kim (2007). For each of the studies, a different standard was used for grade or acceleration. In three cases, no information was given regarding these requirements. According to the hybrid electric HMMWV specification (ATPD 2335, 2003) 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.

The analysis summarised by Mi et al. (2007) 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 indicates that the 60% grade constraint is one of the challenging requirements in the design of a military hybrid vehicle.

Table 4 Summary of HMMWV urban cycle performance and requirements

Vehicle	*Acceleration*	*Grade*	*Fuel economy improvement*
Series electrical	None	None	49.6%
Series electrical	0–60 mph: 16.5 s	3.2% grade at 20 mph	33.0%
Series electrical	None	None	19.0%
Series hydraulic	0–50 mph: 10.8 s	2% grade at 55 mph, 3% grade at 45 mph	68.0%
Parallel electrical	0–60 mph: 21.7 s	0% grade at 20 mph	21.0%
Parallel electrical	None	None	18.0%

Table 5 Summary of FMTV class IV urban cycle performance and requirements

Vehicle	*Acceleration*	*Grade*	*Fuel economy improvement*
Series electrical	0–37.2 mph: 22 s	Traverse 25% grade	19.1%
Series electrical	0–37.2 mph: 22 s	Traverse 25% grade	15.9%
Series electrical	0–37.2 mph: 22 s	Traverse 25% grade	22.7%
Series electrical	0–37.2 mph: 22 s	Traverse 25% grade	12.5%
Series electrical	0–50 mph: 25 s	Traverse 60% grade	7.1%
Parallel hydraulic	None	None	26.7%
Parallel electrical	None	None	28.0%
Parallel hydraulic	None	None	47.0%

The study of Soliman et al. (2005) used the 60% grade as a constraint in the optimisation for a series electric FMTV class IV vehicle where the fuel economy improvement was predicted to be 7.1% over the urban cycle, which is the smallest improvement for the

Class IV over the urban cycle of all the studies considered in Tables 3 and 4. The analysis conducted in Smith et al. (2009) 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 5 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.

10 Summary

Many studies have shown that hybrid powertrains can yield fuel economy improvement in many types of vehicles. A survey of all military hybrid peer reviewed publications illustrates that extensive work has been done with regard to their simulation, optimisation and controls. All of the literature focuses on three military vehicles: HMMWV, FMTV and HEMMTT, which spans the class III through class VIII. However, there are very few publications with respect to military hybrid vehicle hardware (Smith et al., 2009; Stecki and Matheson, 2003; Goering et al., 2003), which could be due to cost, proprietary information or the fact that military hybrid vehicle hardware requires more development time than passenger vehicles. Additionally, military vehicles provide unique challenges such as a 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 and speed dependent cycles that are defined by the US EPA and distant dependent grade profiles that are defined by the US 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 US 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 such as the FTP 75 used to report miles per gallon for passenger vehicles in the USA. This could be due to the fact that military threats are constantly changing and it is generally unknown where a military vehicle will be needed.

The fuel economy analyses showed that the class III vehicle had the greatest potential for fuel economy improvements over an urban cycle and those improvements diminish with composite and highway cycles. Heavier vehicles demonstrate the same trend with respect to drive cycles. In some cases there was even a fuel economy degradation over flatter cycles, such as the Munson cycle. In general, heavier vehicles do not show as much fuel economy potential as the class III vehicles. 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 trade-off 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.

11 Conclusions

To fully understand the benefits of a military hybrid vehicle and evaluate the research to date with respect to fuel economy a standard military vehicle using a mix of known military driving conditions. A fuel economy test is a guide that all vehicles are measured by. 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 USA 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 gives designers and 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.

Performance constraints, such as acceleration or grade ability, are parameters that are essential to the development of military vehicles. A hybrid system that can deliver 50% fuel economy improvement but cannot fulfil the acceleration time or grade ability requirements 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 to date.

Future work should include translating many of the concepts surveyed in this paper with regard to controls and optimisation 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 optimisation problem, which includes minimising fuel economy with stringent performance constraints. Furthermore, the optimisation 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 solider 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 war-fighter could help the military understand the further payback of fielding a military hybrid vehicle.

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