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Feasibility of Hybrid Diesel-Electric Powertrains for Light Tactical Vehicles

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Abstract

Hybrid-electric vehicle technologies have gained significant traction in the passenger vehicle market in recent years. The combination of efficient electric drive with the range and power density of internal combustion fuels provides significant advantages. In a military context, a hybrid-electric drive for off-road vehicles might provide reduced fuel consumption, silent drive/silent watch, camp power, and vehicle reconfiguration for improved payload and crew protection. This paper highlights recent prototype hybrid light tactical vehicles, and discusses the technological limitations.

Résumé

Au cours des dernières années, les technologies électriques hybrides ont gagné en popularité dans le marché des véhicules à passagers, grâce aux avantages importants procurés par l’efficacité des moteurs électriques et par la portée et la densité de puissance des moteurs à combustion interne. Dans un contexte militaire, la présence de moteurs électriques hybrides dans des véhicules hors route pourrait permettre une réduction de la consommation de carburant, des déplacements et une surveillance silencieux, une alimentation électrique de camp et une modification de la configuration aux fins d’accroissement de la charge utile et de la protection des équipages. Le présent document porte sur de récents prototypes de véhicules tactiques légers hybrides, ainsi que sur les limites technologiques connexes.

1 Introduction

Hybrid-electric drivetrains have been in commercial production on passenger vehicles for several years, and are now an established, proven technology. They power the vehicle through both electric motors and an internal combustion engine, combined in a variety of configurations discussed below. The primary motivation is to take advantage of the strengths of each: the efficiency of electric power with the energy density of fossil fuels. This report considers the feasibility of acquiring off-road vehicles with a hybrid-electric drivetrain in several categories, including light tactical vehicles such as the HMMWV, ultralight combat vehicles such as the Polaris Dagor, and small single or multi-rider all-terrain vehicles.

Purely electric vehicles have a number of advantages over the use of internal combustion engines: they are quiet, energy efficient, and mechanically simple. Electric motors are generally more efficient than internal combustion engines, have a higher power to weight ratio, and provide torque over a wider variety of speeds reducing the reliance on geared transmissions. However, for off-road military applications, where a vehicle may be deployed to remote locations, the limited range and inability to recharge easily is a major liability. Even with recent advancements, battery technologies do not have nearly the energy of petroleum fuels for the same space and weight. Also, for a deployed operation, there would be no way to quickly resupply an electric vehicle in the same manner that extra jerry cans of fuel can be air-dropped or strapped to the back of a vehicle.

Due to the development of the commercial market over the last several years, technological advancements in motors, batteries, and electronics have been improving the performance of electric and hybrid vehicles. The main motivations for hybrid power in the passenger vehicle market are reduced emissions and lowered costs from reduced fuel consumption. However, there are other compelling military advantages [1]:

- Stealth – Most hybrid configurations offer the potential to operate in pure electric mode for some short period of time, resulting in low-noise, low thermal signature operation, which has obvious tactical benefits [2].
- Logistics – Over most types of driving patterns, hybrids offer better fuel economy (on the order of 15-20% [3, 4]), especially with the use of regenerative braking. In addition, internal combustion engines are generally most efficient when operated at a specific constant speed, possible with series hybrid designs for further efficiency gains. This can increase vehicle range and reduce the logistical requirements for supporting missions [5, 6].
- Silent Watch – A large-capacity on-board battery pack charged by the electric generator and the internal combustion can be used to power electronic equipment silently for a number of hours.
- Camp Power – The electric generator driven by the internal combustion engine can provide several kilowatts of electric power for other non-silent external uses, removing the need for a towed generator.

However, there are also several drawbacks to hybrid-electric drivetrains, particularly in a military context:

- Although hybrid drives may offer similar or even better acceleration, top speed, and gradability performance, with a large battery pack required for silent drive capability, they will almost always weigh more, resulting in reduced payload for a given vehicle [3, 5].
- Depending on vehicles size, there may also be difficulty in physical space for the components, especially for smaller vehicles such as ultralight combat vehicles or single rider ATVs [7] .
- The nature of batteries generally means reduced performance in cold weather [8, 9], and charging and thermal management issues in both hot and cold weather.
- The complexity of having both electric and internal combustion components, as well as the associated power electronics, will generally increase up front cost and make long-term maintenance more difficult and expensive.
- Depending on the type of chemistry and the potential for combat use, there is a safety risk from most types of battery packs. At the very least the use of lead-acid batteries could potentially spread acid to the occupants, while at worst lithium-ion battery packs are at risk of fire when punctured.

This report will describe some of the design criteria for a military diesel-hybrid vehicle, highlight some prototype systems that have been developed, and conduct an analysis of the effect of the positive and negative factors. Summaries of hybrid-electric vehicle technology for military application can be found in [2, 4, 5, 6].

2 Hybrid Vehicle Design

There are many variations of hybrid-electric vehicles, each with their own strengths and weaknesses, and the hybrid-electric architecture should reflect the performance and mission requirements of the vehicle. Hybrid-electric vehicles generally have the following components:

- An internal combustion engine used to generate electric power, and sometimes to provide tractive power. Depending on the design, this engine will generally be smaller than that used for an equivalent pure internal combustion vehicle.
- One or more electric motors which may be located at a central location, at the vehicle axles, or at the wheels. Recent developments in controller technologies have allowed the use of higher voltage/higher power systems.
- A method of combining the internal combustion and electric power sources, such as an electric generator for series hybrids, or some sort of mechanical transmission for parallel hybrids.
- A battery pack for storing electric power. Size and capacity is based on the type of hybrid configuration and the requirement for endurance of the silent watch/silent drive capability. This component is omitted for some hybrid designs, but is necessary for silent drive/silent watch applications.
- Power electronics for controlling the electric part of the drivetrain, including motor controllers to regulate the current to the motors, a battery management unit to regulate charging and discharge of the batteries, and power converters to change voltage levels for generators, batteries and accessory power. These components can be physically quite large due to the magnitude of the electrical power involved, and can be a significant part of the cost of an electric vehicle.

2.1 Hybrid Configuration

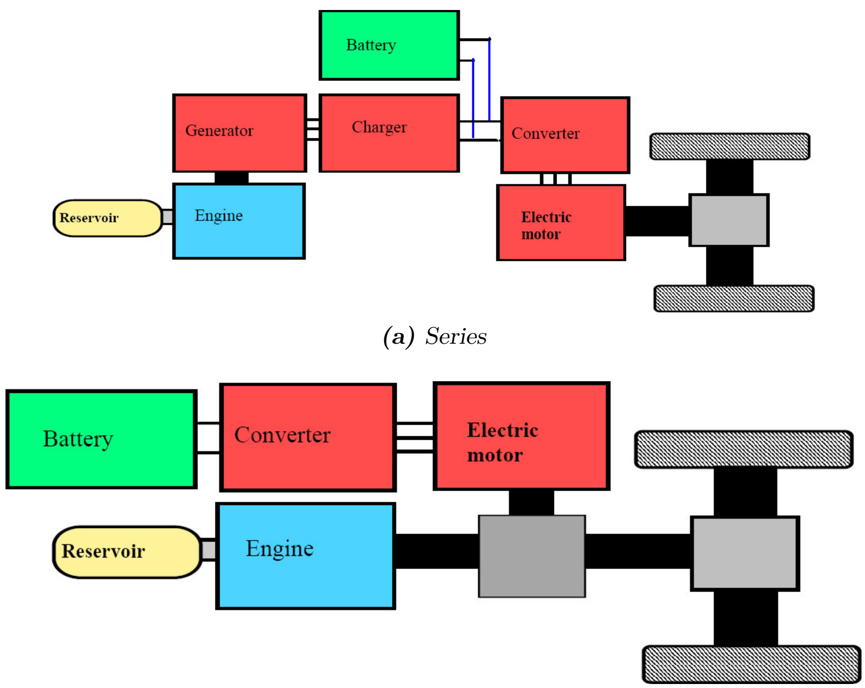
2.1.1 Series Hybrid Design

In a series hybrid configuration [10], the internal combustion engine is only used to create electrical power for the electric motor and batteries, with tractive power supplied solely by the electric motor (Figure 1). This is basically an electric vehicle with a generator. This configuration has the advantage of decoupling the instantaneous power for the drivetrain from the diesel engine, with surge power capacity provided by the battery pack. This allows for a smaller size internal combustion engine than in a pure internal combustion vehicle, as the engine only needs to accommodate the “average” power consumption. Further, series hybrids can be simpler, allow the engine to be operated at its highest efficiency point, and easily accommodate regenerative braking. Most of the prototype military hybrid-electric vehicles have been of the series hybrid type.

However, series hybrids generally require larger electric motors, and higher current battery packs, as there is no power assist from the internal combustion engine for acceleration or hill climbing. A further complication is that if the electric drive becomes disabled, the vehicle is immobile, unlike in other hybrid systems.

In a series hybrid using one electric motor, four wheel drive is still possible by using much of the existing drivetrain, without the original transmission. However, series hybrids also allow for flexibility to the physical layout of the vehicle by moving power around the vehicle with flexible electrical cables. Often two electrical motors are used, one at each axle. This further eliminates the driveshaft and transfer case, allows for smaller electric motors, and provides for system redundancy. Finally, it is also possible to use "in wheel hub" motors which totally eliminates transmissions, transfer case, driveshafts, axles, differentials, etc. This can free up considerable physical space for other vehicle components or payload, and can also can simplify traction control, antilock brakes, and all wheel drive systems.

In-hub systems increase the expense and complexity of motors (having four instead of one). Although suspension travel is generally greater with in "in-hub" setup, it also increases the unsprung mass of the vehicle, reducing suspension response. There is also often difficulty with startup torque of electric motors for in-hub configuration while still providing torque at high speeds, meaning that gearsets are often also included "in-hub". So far, the advantages of "in-hub" electric motors have not outweighed the drawbacks, but it is expected that this will provide a promising technological path for the future [11, 12].



(a) Series

(b) Parallel

Figure 1: *Basic Hybrid Configurations (from [1]).*

2.1.2 Parallel Hybrid Design

In parallel hybrid configurations (Figure 1), the power to the drive wheels can be provided by either the electric motor, the diesel engine, or both. The diesel engine can be used to power the wheels, recharge the batteries, or both simultaneously, with a clutch or other mechanism using to disconnect the two sources of power. Since maximum power can be supplied by the total power from the diesel engine and the electric motors, neither has to be as large. Most parallel configurations also remain operational if either the electric motor or diesel engines become inoperative, allowing for limp home functionality. However, parallel hybrids still require a transmission for the internal combustion engine. When compared with series hybrids, parallel systems are slightly more complex, but provide less demand on the vehicle battery pack for peak performance. Weight and production costs of a parallel hybrid will almost certainly be more than a standard internal combustion vehicle, which isn't necessarily true for a series hybrid vehicle.

There are several variations of these configurations. A power-split or series/parallel hybrid uses an epicyclic geartrain or other mechanism is used to combine engine and electric motor power in a more flexible manner [13]. A mild hybrid design use a primary internal combustion engine with a much smaller electric motor which functions as a starter/generator to provide some power assist when driving or to generate electric energy for batteries. A mild hybrid cannot provide for pure electric drive (silent drive), but could be used to charge a battery pack for silent watch.

Another version which has seen use for military prototypes is the "through the road hybrid", or "road-coupled hybrid", where the internal combustion engine drives one set of the front or back wheels, with the electric motor driving the other wheels [14]. This setup provides a complete back-up drivetrain, as well as four wheel drive power. It also allows for parallel hybrid if both axles are used, or series hybrid if only the electric axle is used. Several light tactical prototypes of this style have been developed.

2.2 Energy Storage

The requirements of the hybrid vehicle will drive the design of a battery pack and electric motors. The battery's energy capacity (i.e. size and weight) will be determined by the driving profile (i.e more silent drive and more silent watch required means more vehicle payload will be used by the batteries). Furthermore, the power capacity of the battery (ability to produce current) and the size of the electric motor will be determined by acceleration and climbing requirements. Finally, there is also the longevity in terms of number of cycles of the battery to be considered.

In general, battery packs can be the weak points of a hybrid electric system. Most modern packs require battery management to maintain proper charging and discharging of the individual cells, and to monitor temperature and state of charge.

Batteries for electric and hybrid vehicles have moved from mature but heavy lead-acid types to more energy dense lithium-ion types, which provide greatly improved energy density for both weight and volume. Lithium-ion batteries also provide longer cycle life and shorter charge times [1]. For hybrids not requiring silent watch capability, supercapacitors have been used instead of batteries to provide surge power to the electric motors.

3 Light Tactical Prototype Vehicles

The commercial passenger vehicle market has steadily increased its adoption of hybrid-electric technology. However, there are very few diesel-electric pickup trucks on the market, and the commercialization of gas hybrid pickup trucks has been limited to a couple of examples.

The requirements of military operations adds an extra burden to the technology readiness of hybrid technology. Prototypes and technology development was conducted for larger armoured military vehicle under the cancelled US Future Combat Systems program, as well as other International programs such as the UK Future Rapid Effects System, and the Swedish SEP program. For light tactical vehicles, several prototypes have also been developed by both military and commercial entities which will be discussed in this section.

A table of the design and specifications of several prototype military hybrid-electric vehicles is shown in Table 4.

3.1 Hybrid-Electric Vehicle Development at TARDEC

The US Army Tank Automotive Research Development and Engineering Center (TARDEC) has been a leader in the development of prototypes and the experimentation of hybrid-electric vehicles for decades, with the goals of advancing technology and understanding performance in military environments [15, 6]. In the light tactical vehicle category, TARDEC has developed several prototypes:

- HMMWV XM1124 – A first prototype was built in 1998 by PEI Electronics, which consisted of a standard HMMWV chassis fitted with a hybrid drivetrain. TARDEC has continued with several additional prototypes and improvements over the years [2, 3]. Improvements have included different battery technologies, hybrid configurations, faster acceleration, improved fuel economy, water resistance for fording, etc. The vehicles were series hybrids with either 1, 2 or 4 electric motors. Testing has been conducted at a variety of locations including Fort Benning, GA, and Fort Greely Alaska. The conclusion from testing is that the XM1124 met or exceeded the performance of the stock HMMWV and has a significantly better fuel economy for certain driving cycles.

- Clandestine Extended Range Vehicle (CERV) – Built for TARDEC in 2011 by Quantum Technologies, this vehicle was intended for reconnaissance, targeting and rescue missions, being somewhat smaller, lighter and faster than other prototypes with a 130kph top speed [16]. It is also small enough to fit inside the V22 Osprey aircraft.

- Fuel Efficient Ground Vehicle Demonstrator (FED Bravo) – Built by ASRC Primus in 2012 from the ground up as a concept vehicles to examine fuel efficiency, the FED demonstrator included a custom vehicle chassis and the protection of v-shaped hull [17, 18]. The second version (Bravo), was a "road-coupled" hybrid, having the front axle driven by electric power only, and the rear axle coupled to the diesel engine generator system.
- Ultra Light Vehicle (ULV) – This vehicle was developed in 2013 with lightweight armour materials, lightweight wheels, and of course a lightweight series hybrid drive-train, while improving reliability and maintaining blast protection [19]. Hardwire LLC was the prime contractor for this prototype. This vehicle is a pure series hybrid design using new lithium-iron-phosphate batteries.

3.2 Other Military Hybrid-Electric Prototypes

In addition to research sponsored directly by TARDEC, there has also been some independent R&D conducted by military suppliers or funded by other sources. There was some activity to develop larger hybrid-electric combat vehicles as part of the US Future Combat Systems program, as well as research on other larger vehicles such as the US ARMY Heavy Mobility Expanded Tactical Truck (HEMTT), the Advanced Hybrid Electric Drive (AHED) 8x8 20 ton truck, and the EP-50 LAV III parallel hybrid.

In the light tactical vehicle category, some prototypes of interest include:

- Reconnaissance, Surveillance and Tactical Vehicle (RST-V) – Funded by DARPA and the Office of Naval Research, built by General Dynamics Land systems, and delivered in 2002, this vehicle was intended for use by the US Marine Corps and special forces, including V-22 Osprey internal carriage [20, 21, 22]. Applications included forward observer, forward air control, reconnaissance, light strike, battlefield ambulance, air defense, logistics, personnel carrier, anti-armor and mortar weapons carrier. Extensive testing was conducted including at Yuma and Aberdeen proving grounds.
- Hybrid Defense Reconnaissance Assault Vehicle (Hy-DRA) – Built by Raytheon in 2007, specifically for special forces applciations [23], this vehicle managed to pack a lot of capability in a small package. It was even small enough to be slung-load by a BlackHawk helicopter.
- Zero-South HMMWV – This vehicle was built from 2009-2014 by a non-profit organization that seeks to travel to the south pole using no fossil fuels. The vehicle is mounted with Mattrack kits which reduce its performance, but provide for mobility on ice and snow. In winter 2016 the vehicle travelled almost 2000km from Prudhoe Bay to Barrow, Alaska. One of the interesting accomplishments of this project is

the thermal management of the battery and electronic systems to maintain adequate temperature for charging lithium-ion batteries (i.e. above 0 degrees Celsius) [24].

Significant recent activity on smaller tactical wheeled hybrid vehicles has been spurred by the Joint Light Tactical Vehicle program to replace the HMMWV. Several companies developed prototypes, including the following:

- Advanced Ground Mobility Vehicle (AGMV) – This 2007 demonstrator was developed by General Dynamics Land Systems and AM General, and was based on the technology used for the AHED 20 ton vehicle. This included 4 "in-hub" electric motors, which made adjustable ride height easier for transport inside CH-47 helicopters.

- Millenworks Light Utility Vehicle – This vehicle was built in 2007 as a parallel "through the road" hybrid, including a custom electric transaxle with 2 speed gearbox and electric motor on the front axle, and a custom rear transaxle with has an integrated generator to interface with the diesel engine [25].

- OshKosh Light Combat Tactical All-Terrain Vehicle (L-ATV) – This company, which won the JLTV program (although not with a hybrid powertrain), has developed several prototypes that use their ProPulse hybrid powertrain, including HEMTT 8x8 trucks and the US Marine Corps MTVR truck. Using this drivetrain they claim an efficiency improvement of 20%. As publicized, this drivetrain only uses supercapacitors for energy storage, and thus does not enable silent drive capabilities. The company also used one of their hybrid prototypes, the Light Concept Vehicle to participate in the 2010 Baja 1000 race.

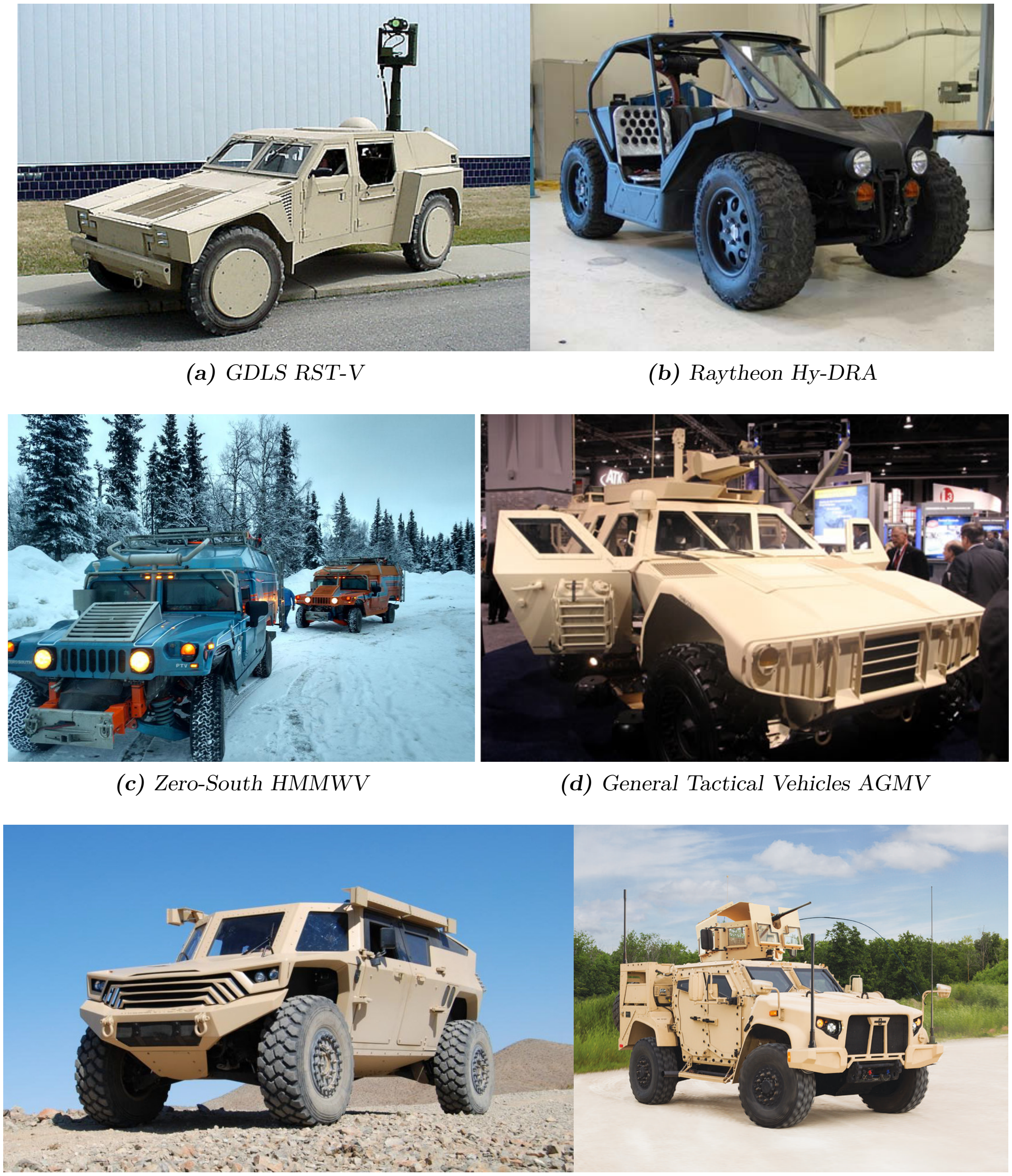
(a) XM1124

(b) CERV

(c) FED Bravo

(d) ULV

Figure 2: *TARDEC Prototype Vehicles.*



(a) GDLS RST-V *(b) Raytheon Hy-DRA*

(c) Zero-South HMMWV *(d) General Tactical Vehicles AGMV*

(e) Millenworks L-UTV *(f) Oshkosh L-ATV*

Figure 3: *Other prototype hybrid-electric vehicles.*

Name	Year	Company	Sponsor	Type	Gross Weight	Payload	Battery Voltage	Battery Capacity	Battery Type	Battery Range	Accessory Power	Engine	Electric Motor	Speed	Acceleration
Reconnaissance, Surveillance, and Tactical Vehicle (RST-V)	2002	GDLS	DARPA/ ONR	Series/In-hub	10000lb			20kWh	Li-Ion	20 miles	30kW	2.5L/152hp	40x 50kW	112kph	
XM1124 HMMWV (specs from 2009)	2003	PEI Electronics	TARDEC	Series/At-axle	9100lb	1700lb	288V	24kWh	Li-Iron-Phosphate		33kW	134hp		80mph	0-50mph/7s
HY-DRA	2007	Raytheon	USAF	Series/In-hub	3400lb	1000lb			Li-Ion	18 miles	30kW			60mph	
Light Utility Vehicle	2007	Millenworks	TARDEC	Parallel Road-Coupled	18500lb	4000lb	330V	15kWh	Li-Ion			215hp	2x 100kW	76mph	0-50mph/15s
Advanced Ground Moblity Vehicle	2007	GDLS/ AM General		Series/In-hub	16000lbs	5000lbs			Li-Ion		30kW	2.8L		70mph	0-30mph/5s
Zero-South HMMWV	2009	Zero-South	Various	Series/At-axle	9740lb (curb)		388V	24kWh		32 miles		218hp	2x 150kW	93mph	0-60/7s
Light Concept Vehicle	2010	Oshkosk		Series/At-axle					Ultracapacitors only		70kW	6.6L/400hp			
Clandestine Extended Range Vehicle (CERV)	2011	Quantum Fuel Systems	TARDEC	Series	6500lbs	3000lbs	380V	22kWh	Li-Ion	12 miles	50kW	1.4L	100kW	80mph	
Fuel Efficient Ground Vehicle Demonstrator (FED) Bravo	2012	N/A	TARDEC	Parallel Road-Coupled	16760lbs	4260lbs		22.5kWh	Ultracapacitors + Li-Ion		30kW	4.4L/325hp	145kW	80mph	0-50mph/15s
Ultra Light Vehicle	2013	Hardwire LLC	TARDEC	Series/At-axle	18500lb	4500lb		14.2kWh	Li-Iron-Phosphate	21 miles	65kW	6.5L/175hp	2x 200kW	74mph	0-50mph/16s

Figure 4: *Available specifications of prototype diesel hybrid-electric tactical vehicles.*

4 Analysis

Given the number of prototype vehicles indicated above that have undergone significant real-world testing, diesel-hybrid technology has reached a certain level of advancement for military applications. However, to date, they have not been fielded operationally. This section will analyze the underlying factors.

4.1 Tactical Benefits

It is clear that hybrid-electric vehicles can provide for enhanced mission capabilities such as reduced fuel consumption, silent watch, camp power, and silent drive. However, the benefits realized will be very mission dependant.

Hybrid-electric vehicles can certainly improve fuel economy. This benefit should allow for longer range missions, and longer time between resupply, an obvious tactical benefit. On some test cycles this may be up to a 60% reduction in consumption, but for most driving profiles, improvement of 15–20% is more realistic [26, 6, 17, 5, 1, 27]. The benefit is largely based on the amount of acceleration/deceleration, hill climbing/descending, and idling. The reduced consumption is largely based on maintaining constant internal combustion engine speed despite hills or changing speeds, and recouping power through regenerative braking. For a straight cross-country drive, a hybrid vehicle offers very little benefit over a conventional vehicle.

Silent drive/silent watch is a tactical benefit that cannot be offered by any other technology other than pure electric vehicles, which are still currently extremely range limited. This capability is obviously very useful on missions where the operator wishes to approach with a very low acoustic and thermal signature [2], allowing a vehicle to get much closer to a target than a normal internal combustion vehicle. For targets that previously needed to be approach soley by dismounted soldiers for reasons of stealth, this may allow much greater sensor capabilities and firepower, and would allow much quicker undetected ingress and egress.

Studies at DRDC for an electric snowmobile indicated a 6dB–10dB reduction in sound pressure level, meaning that you could approach to half the distance of an equivalent internal combustion vehicle without being heard. In addition, for a series hybrid, even with the internal combustion engine running, it operates at a lower, constant speed, greatly reducing the vehicle noise signature.

If a hybrid tactical vehicle were designed with the electric power generation and battery storage for silent drive, this capacity could also easily be used for silent watch applications. Given the on-board electrical systems, it is very easy to generate a variety of AC and DC power sources to power sensors, remote weapon stations, communications, or other future technologies like high-energy lasers. Referring to Figure 4, the prototype vehicles developed to date are able to produce 30 to 70kW of accessory power. With the internal combustion engine running, this amount of power generation capability would also be handy for long duration missions or as a source of camp power, eliminating the need for towed generators.

The biggest limitation of the silent drive/silent watch capability offered is the size and weight of the battery pack. For the JLTV program, power requirements for silent watch were estimated to be in the 7–10kW range. Of the prototypes listed in Figure 4, the battery capacity is in the range of 14–24 kWh, offering a silent watch on the order of 2 to 3 hours. These prototypes also offered silent drive capability on the order of 30km, which would be probably be enough to offer silent ingress and egress to most targets.

However, this energy storage capacity is probably not adequate for some missions that would require long-range silent drive coupled with a period of silent watch. The current technical difficulty is in trying to combine a battery that has high current output for vehicle performance, while at the same time high capacity for silent drive and silent watch. It also needs to be light, small and cheap. The longer the duration required, the more payload and space that will be taken up by batteries, or the greater the amount of time the internal combustion engine needs to be running.

4.2 Technology Challenges

A technology readiness assessment was conducted by McCown [5], who concludes that hybrid-electric technology for tactical vehicles is currently at a TRL 4 to 6, meaning that there would still be significant development needed before operational deployment. It has system prototypes demonstrated in a simulated operational environment, but has not quite been proven to work in its final form and all expected conditions. No one configuration has emerged that would be the ideal system for a production operational vehicle. It also has not been actually used in an operational role.

This assessment would be somewhat at odds with the fact that commercial diesel-hybrids are available for passenger vehicles and commercial trucks. However, the military performance criteria, such as speed, usage cycles, gradability, temperature ranges, and soft soil mobility limit the advantages of hybrid systems compared to commercial urban driving.

Performance is probably not a limiting factor. A NATO panel concluded that in terms of speed, acceleration, gradeability and stealth hybrid vehicles can be considered superior to conventional drivetrains [1]. Referring to Figure 4, the prototype vehicles listed seem to have very good performance in terms of payload, acceleration, speed, etc., and from this point of view would be ready for military use. In addition, for small all-terrain vehicles, there are already several pure electric vehicles on the market which could relatively easily be given extended range through the attachment of a generator. If specifications are to be believed, the yet to be released Nikola Zero four-seat UTV will have a 100–200 mile range, with 0–60mph in 4 seconds and 1400lbs of payload. In a paper on hybrid vehicle cost and performance [27], German discusses the year over year performance increase in hybrid vehicles, and the expected continuation of this trend.

4.2.1 Component Size, Weight, Packaging and Placement

A definite benefit of hybrid vehicles, particularly series hybrids, is the design flexibility that they offer. With in-hub motors it is possible to eliminate many rigid drivetrain components, which eliminates dead space in the vehicle for improved cargo capacity. In-hub motors also allow alternate suspension configurations and increased ground clearance [2, 28]. Furthermore, not having driveshafts and other suspension components could improve blast protection because they don't act as projectiles [29]. However, in-hub motor configurations are less technologically mature, and most of the prototypes produced thus far rely on electric motors at the axle.

To quote a TARDEC researcher [2]:

"the packaging of the other components inside the vehicle space and weight constraints is not trivial. There are limitations in the power density and torque density of the motors and generators and for power and energy densities of the batteries".

There is the previously mentioned tradeoff between the size and weight of batteries, and the amount of silent drive/silent power required. There is an additional tradeoff between the overall energy capacity of the batteries and the instantaneous power they can produce for a given space and weight.

There are also issues with the space, robustness and safety concerns of routing of high-power cables around the vehicle, and issues with the packaging and robustness of power electronics, generators, and batteries including protection from shock, and from water from rain and fording [15, 2].

These problems become more challenging for smaller ultralight vehicles and ATVs [30]. There are several pure electric ATVs and UTVs on the market that could have extended range through the use of a generator, but this would not be an integrated package[1]. For small vehicles, it will be difficult to match the performance of a standard internal combustion vehicle, as the designer needs to integrate an engine, batteries, generator, and electric motors on small chassis. In addition, for a small vehicle the increased weight will have a marked increase in ground pressure, reducing performance in soft terrains.

4.2.2 Thermal Management

The extremes of temperature required for military operations is probably the biggest technological challenge for hybrid and electric vehicles. The issue of reduced battery capacity at low temperatures is well known [31]. To make this problem worse, unlike lead-acid, lithium-ion batteries have problems charging below 0 degrees C at all. Some systems have included battery heaters powered off the internal combustion engine to compensate, but this adds an

[1] Examples of electric ATVs include the Polaris Ranger EV, Textron Recoil, TORQ Suppressor VLE, HuntVe Switchback, etc.

additional layer of complexity to the system, and further drains electrical power. Research on this aspect is ongoing [8, 9].

A lesser known, but more problematic issue is high temperature management [5, 2, 1, 32]. This issue is a problem for almost all the components of a hybrid vehicle. Battery packs if allowed to overheat during discharge become dangerous and must be cooled or reduced in power output. Electric motors also have issues with excess heat under high current loads, and permanent magnet motors can actually be partially demagnetized. Finally, all of the power electronic components have restrictions on the upper temperature of their operation as well without being damaged (typically only 65 degrees Celsius at the baseplate).

Commercial vehicles and the hybrid-electric prototypes discussed have cooling systems installed for thermal management of all these components. However, this adds significantly to the space claim and complexity of the hybrid system, while greatly reducing efficiency. This is a critical consideration for a small, light, tactical vehicle that is to be used in remote areas in hot climates. Research is underway on silicon carbide electronics that can be operated at much higher temperatures, but these are still under development [17, 1].

4.3 Safety and Operational Issues

Although safety is a priority for passenger vehicles, the difficulties of a military environment make this an even more difficult problem. Lithium-ion batteries are in common use on electric vehicles for good reason: they offer 2 to 3 times the power output and energy density of lead-acid batteries, with greatly improved cycle life, making electric and hybrid vehicles for off-road use practical. However, other than temperature issues, they chemistry is more volatile and requires careful management [20].

Lithium-ion cells require a battery management system to protect from charging or discharging too quickly, from over-voltage or under voltage, and from operating outside their temperature range [15, 2]. Failure to protect from these conditions can damage the battery pack or lead to thermal runaway and fires. This battery management system also needs to offer graceful degradation of performance, rather than a sudden halt of the vehicle.

In addition to the necessary management electronics, lithium-ion batteries need to be protected from shock and puncture, as internal or external short circuit can also cause thermal runaway [20]. As has been seen in passenger vehicles, accidents can cause damage to the batteries and catastrophic fires. This is a serious concern for tactical vehicles intended to cross rough terrain and may be subject to gunfire or explosions, which will require significant protection for the battery pack, placement far away from passengers, and automatic fire extinguishers. Newer Tesla vehicles separate the battery into smaller compartments and surround them with cooling fluid. Although probably effective, this is another level of complexity not desirable on a light tactical vehicle. One must also consider the safety consequences of having high voltage wiring running through a combat vehicle.

Research is ongoing to make these battery packs safer, but there will always be a risk in storing a large amount of energy in a small package. One promising technology is lithium-iron-phosphate batteries, which are inherently safer, but have lower storage capacity compared with other lithium-ion chemistries[33].

All this being said, the battery pack may still pose less of a risk than a large tank of gasoline or diesel being ruptured, and electric and hybrid vehicles don't seem to be at higher risk than standard automobiles [34].

4.4 Cost and Procurement

As evidenced by the commercial market, there is no doubt that hybrid systems will be more expensive than an standard internal combustion vehicle, even when considering mass production and economies of scale. Hybrid vehicles are simply more technically complex and have more subsystems. It is probable that the lack of fielded hybrid-electric vehicles is most likely not due to a technology gap, but rather the fact that it is cost prohibitive. The power electronics and battery packs are a significant cost [5] of a hybrid vehicle, but are quickly getting cheaper. Unfortunately, current commercial components for electric and hybrid vehicles are not suitable for military off-road applications [2].

It is possible that the reduced cost of operating a hybrid vehicle may offset the higher purchase price that is often seen in commercial passenger vehicles [1]. However, the life cycle of military vehicles is much different than a commercial vehicle, and much work is needed to understand the long-term reliability and maintainability of hybrid vehicles [6]. More extensive programs of field testing are required to determine the cost-effectiveness of this technology.

In one interesting study, the US Navy demonstrated and tested diesel-electric hybrid trucks for non-tactical roles [35] with improved fuel economy on the order of 30%, reduced noise by 40% and reduced brake wear. However, the vehicles would only achieve cost payback on 6 hours of daily use with regular stops, and the purchase of hybrid vehicles would be difficult to justify on cost alone.

Maintenance is also an issue for a vehicle that is much more complex. Field access to easily replace battery packs or other electronic components is not a consideration required on passenger vehicles. It would be difficult to provide training for field maintenance on a vehicle so electrically complicated. However, according to one TARDEC study, hybrid trucks have proven to have longer maintenance intervals with lower cost than conventional vehicles, based on reduced engine and brake wear, and reduced complexity of the electric portion of the drivetrain [36].

As an emerging technology, reliability of hybrid technology is still in question. In theory, for a series-hybrid design, the removal of many moving parts and the operation of an engine at constant speed has the potential to improve reliability and durability. In passenger vehicles, although hybrid vehicles have not had the same time to mature as internal combustion vehicles, some all-electric models and hybrid models are starting to achieve better than average reliability [37, 38], although results are mixed [39, 40, 41, 42].

5 Recommendation for Technology Demonstrator

To address the technological concerns indicated above (including size, weight, safety, and thermal management), a prudent approach for the design of a light off-road tactical vehicle could have two key features:

1. A series-hybrid design, with a diesel engine driving an electric generator, powering electric drive motors at the axle or wheel hub.

2. An ultracapacitor bank to provide peak power for acceleration or hill-climbing, with no battery pack and no silent watch/silent drive capability.

Such a series-hybrid design would eliminate many drivetrain components such as the transmission, torque converter, transfer case, and drive shafts. The diesel engine, electric generator and energy storage module could be sized just large enough for adequate peak power, storing some small amount of energy from regenerative braking. Such a zero-battery (or minimal battery) design could have a number of benefits over traditional drivetrains, or even other hybrid designs:

- Increased flexibility in design, allowing for better crew cab placement, better blast protection, and better payload storage.

- A reduction in weight and space taken up by the drivetrain components and battery system, resulting in better performance and payload.

- The elimination of the safety, maintenance, and temperature management concerns of battery technologies.

- Improved fuel efficiency, as the diesel engine can operate at its most efficient speed, independent of vehicle speed.

It is unclear exactly how much added crew protection could be achieved, but the removal of many components under the vehicle chassis could result in a better blast protected hulls, as well as much better protected crew module. This was one of the key benefits tested with the TARDEC Ultralight Combat Vehicle [19], and design goal of the DARPA GXV-T [43]. An extreme example of possible hybrid-electric vehicle configuration is the Autonomous Platform Demonstrator [44] (Figure 5a). Although this vehicle was designed as an unmanned vehicle, it demonstrated the performance and reconfiguration possible with a series diesel-hybrid design.

A series, no-battery, diesel hybrid should be entirely feasible with existing technology, and has already been demonstrated in the Oshkosk ProPulse system. In particular, with their

HEMTT A3 prototype (Figure 5b) the company claims a 20% gain in fuel efficiency, a 40% roomier cab, improved crew safety, increased on-board electrical generation capacity, and a 3000lb weight reduction [45].

(a) *Autonomous Platform Demonstrator* ***(b)*** *OshKosh HEMTT A3*

Figure 5: *Series Diesel-Electric Hybrid Prototypes.*

Such a series-hybrid design could be built with either an in-hub motor configuration, or an in-axle configuration. The in-hub option would provide the best blast protection by eliminating the wheel axles altogether, but is a higher risk technology, and has increased unsprung weight which reduces suspension performance. This aspect would need to be studied carefully to understand the best course of action based on technology available.

Supercapacitors also have been demonstrated in hybrid vehicles. When compared with similar battery technology, they offer more efficient drive, work better over temperature extremes, and may have fewer problems with aging [46, 47]. There ares some barriers to the use of supercapacitors, such as cost and lack of energy density. However, if the required capacity is limited their use should be feasible.

6 Conclusion

A hybrid-electric light tactical vehicle with a full battery system and silent drive would probably be heavier, more expensive, and more technically complex than an equivalent internal combustion vehicle. Because it is not clear that the fuel savings would compensate for the increased up front costs over the lifespan of the vehicle, in order for them to be employed there would need to be a compelling operational reason. This may include the longer vehicle range or the silent drive capability that is not offered by any other technology.

As mentioned earlier, the benefit derived from the use of a hybrid vehicle would be very mission specific. How much tactical benefit could be achieved by a silent drive or silent watch capability? Would the accessory power be useful for either sensors or camp power? Would the driving profiles of the mission produce significant improvements in range and fuel economy? There are also the limitations of this technology to consider, including the safety of the battery packs and high voltage electric systems, the thermal management required of the components, and the unknown reliability and maintenance issues.

There are currently no hybrid-electric tactical light vehicle in production, and only a handful of companies with mature prototypes. As such, the employment of this technology would require an up-front investment to work out the systems engineering and technical difficulties discussed. Their absence on the battlefield is probably a result of the technical problems that are tractable for commercial passenger vehicles but much harder for military applications, particularly on a light vehicle platform.

Despite the production of several prototypes for the US army Joint Light Tactical Vehicle program, no hybrid-electric vehicles were purchased. However, it is expected that the benefits of electric vehicle technology will mean that it will eventually overtake internal combustion vehicles, even in a military context [5, 1].

Through the pursuit of a no-battery series-hybrid design, a number of the technological hurdles of hybrid vehicles could be side-stepped, and several benefits could be achieved, including:

- Improved blast protection by removing under-chassis components
- Improved payload through weight reduction and space reconfiguration of an electric drivetrain.
- Improved fuel efficiency by operating an engine at optimal speed and using regenerative braking.
- Increase electrical generation capacity for sensors or camp power.
- Possible maintenance and reliability improvements through the reduction of moving components (with the maturation of technology), and the modularity of the electric motor components.

In general, the possibility of such important benefits warrants the development of a technology demonstrator incorporating these design principles.

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Hybrid-electric vehicle technologies have gained significant traction in the passenger vehicle market in recent years. The combination of efficient electric drive with the range and power density of internal combustion fuels provides significant advantages. In a military context, a hybrid-electric drive for off-road vehicles might provide reduced fuel consumption, silent drive/silent watch, camp power, and vehicle reconfiguration for improved payload and crew protection. This paper highlights recent prototype hybrid light tactical vehicles, and discusses the technological limitations.

Au cours des dernières années, les technologies électriques hybrides ont gagné en popularité dans le marché des véhicules à passagers, grâce aux avantages importants procurés par l'efficacité des moteurs électriques et par la portée et la densité de puissance des moteurs à combustion interne. Dans un contexte militaire, la présence de moteurs électriques hybrides dans des véhicules hors route pourrait permettre une réduction de la consommation de carburant, des déplacements et une surveillance silencieux, une alimentation électrique de camp et une modification de la configuration aux fins d'accroissement de la charge utile et de la protection des équipages. Le présent document porte sur de récents prototypes de véhicules tactiques légers hybrides, ainsi que sur les limites technologiques connexes.