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DRIVE CYCLE MODELING OF SERIES AND PARALLEL HYBRID ARCHITECTURES FOR THE BRADLEY FIGHTING VEHICLE

Courtney Razon, Vikram Mittal, PhD

Department of Systems Engineering, United States Military Academy, West Point, NY

ABSTRACT

The recent climate change plan for the United States Army states that hybridized combat vehicles will enter the fleet by 2050. The Bradley Fighting Vehicle (BFV) and its family of vehicles are prime candidates for hybridization. This paper sets out to perform a drive cycle analysis for the BFV using its traditional powertrain along with hybridized powertrains. The analysis considers both series and parallel hybrid architectures, where the size of the batteries are based on modifications to the existing powertrain. Three different drive cycles are considered – stationary, highway, and off-road. The model accounts for accelerative forces, transmission losses, cooling losses, drag, road grade, tractive losses, and ancillary equipment. The results indicate that both parallel and series hybrids provide reduced fuel consumption and increased range. Of the two, the series hybrid architecture provides more overall benefits. The study concludes by discussion of the technical challenges associated with hybridization.

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1. INTRODUCTION

The US Army's official song, "The Army Goes Rolling Along," praises the power and maneuverability of its vehicle fleet. Indeed, the US Army takes significant pride in its fleet of ground vehicles, many of which have become synonymous with performance. Furthermore, these vehicles are critical for modern combat since they allow Soldiers to maneuver across the battlefield to destroy their enemies.

As such, the U.S. Army modernization effort is pushing for more powerful and versatile vehicles. Meanwhile, the recently released Army climate change plan stresses the need for increased efficiency and a move to electrification. Given the power requirements for the larger combat vehicles, full electrification is not feasible; however, many benefits can be realized through hybridization.

This study sets out to explore the benefits of hybridization for the M2A3 Bradley Fighting Vehicle (BFV) through a drive-cycle analysis on the current and hybrid powertrains. Three different drive-cycles were considered including stationary, highway, and off-road. Additionally, the study analyzes both parallel and series hybrid architectures.

2. BACKGROUND

2.1. Bradley Fighting Vehicle (BFV)

The BFV is an infantry fighting vehicle that functions as both an armored personnel carrier and a tank-killer. It was introduced in 1981 by FMC Corp and manufactured by BAE Systems Land and Armaments [1]. The BFV has a three-man crew consisting of a commander, gunner, and a driver; additionally, it can transport 6 soldiers. The vehicle is armored to provide protection from small arms fire. The main weapon of the BFV is a turreted 25 mm chain gun which can fire over 100 rounds per minute at a range of 3,000 m. It also carries TOW missiles which are capable of destroying a tank [2].

The BFV has a wide range of variants suited for specific missions, including scout, air defense, and engineer missions. The BFV originally had a gross weight of 25 tons; however, vehicle upgrades pushed the vehicle weight upwards to 40 tons. Operationally, the vehicle will also have a crew, passengers, equipment, and ammunition, which will make the vehicle heavier.

Furthermore, several other Army vehicles use the same powertrain and body as the BFV. The M109A7 Paladin self-propelled howitzer is built on the same platform as the M2A3 BFV but with the addition of a 155mm howitzer gun. The requirements for the M109A7 Paladin are significantly more extreme than that of the BFV given the size of the main gun and the requirement for carrying ammunition. Additionally, the M1283 Armored Multi-Purpose Vehicle (AMPV) is basically a BFV without a turret and with minor modifications in the cabin [3].

Although the U.S. Army is designing the replacement for the BFV, this family of vehicles will likely be used for numerous years. Furthermore, there is a high likelihood that the U.S. Army will only replace a portion of the vehicle fleet, opting to modernize the rest, a strategy utilized for the High Mobility Multipurpose Wheeled Vehicle (HMMWV). [4] One modernization strategy that has gained significant traction is electrification of the vehicles.

2.2. Current Power System

The power system for the BFV consists of an engine, transmission, final drive, and sprocket. The engine generates the torque at a given speed. The transmission then modifies the torque and speed to better suit the vehicle needs. The final drive then transfers the torque from the transmission to the sprocket. The rotation of the sprocket turns the vehicle tracks.

As the weight of the BFV increased, so did the demand on the powertrain. The original engine was a repurposed commercial Cummins diesel engine that produced approximately 500 hp. The engine has undergone numerous upgrades, including turbocharging, and can now produce upwards to 650 hp [5].

Meanwhile, the other powertrain components, including the transmission, underwent upgrades as well to account for the additional power requirements. Additionally, the transmission received several upgrades as early versions had significant reliability issues [6].

2.3. Move to Hybridization

In the initial message from the Secretary of the Army to the Force, Secretary Wormuth wrote that one of her main priorities is "climate change [7]." A few days later, the Army released its climate strategy that included the electrification of the non-tactical fleet by 2035. Meanwhile, the Army is hoping to field hybrid-drive tactical vehicles by 2035 and fully electric tactical vehicles by 2050 [8]. While it is unclear as to the scope of the tactical vehicle market, it will likely include vehicles such as the Joint Light Tactical Vehicle and the Infantry Squad Vehicle.

Although it is uncertain as to whether tracked vehicles will undergo electrification as part of the Army climate strategy, there remains a strong desire to achieve some degree of hybridization for larger combat vehicles. The reality is that given the power requirements of these vehicles, full electrification would be difficult. Additionally, there are little sustainability benefits, given that in a deployed environment, the fuel consumption is simply being moved from the vehicle engine to a tactical genset.

However, from a tactical standpoint, hybridization makes substantial sense. First, at low engine speeds, electric motors provide more torque than diesel engines. This has the potential to increase the vehicle acceleration and towing capacity. Additionally, the vehicle would be able to run for extended periods of time without the engine running, allowing it to be quiet and less detectable, especially given that modern infrared cameras can detect the infrared signature of a diesel engine from multiple miles away. Hybridization also minimizes the challenges associated with electrification including charging times.

3. METHODOLOGY

3.1. Hybrid Architectures and Components

Hybrid powertrains are almost as old as the engine itself. However, they achieved commercial viability in the early 2000s due to advances in control systems and battery technology. Hybrid vehicles tend to employ either parallel or series architectures as shown in Figure 1. Both are viable architectures for a hybridized BFV.

The parallel architecture is more common in most modern hybrid-electric vehicles, including the Toyota Prius. The engine and the motor from the batteries are both capable of providing locomotion. In this case, the engine assembly is fairly similar to a standard BFV. In a parallel architecture, the existing powertrain must be downsized to make room for the battery pack, alternators, and motors. However, most designs opt for a more power dense option since the engine is expected to still provide the bulk of the locomotion power at high load. This system benefits from regenerative braking, which recaptures the

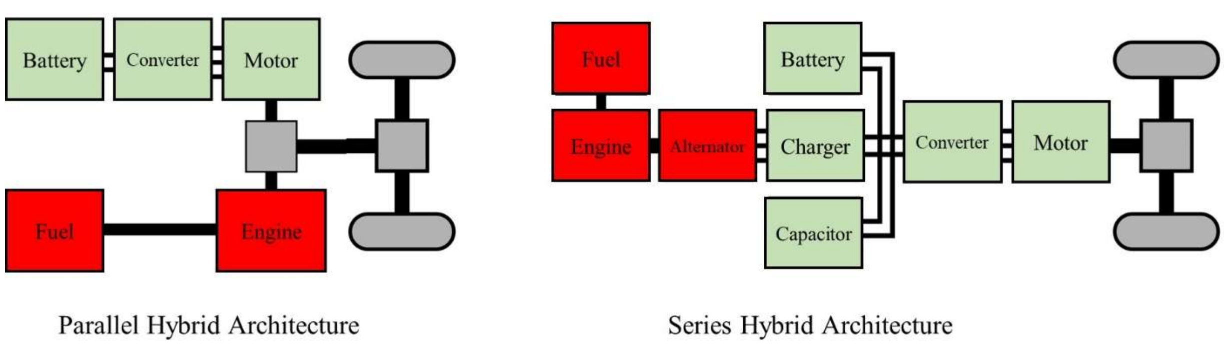

Figure 1. Hybrid Architectures

energy lost typically when the vehicle brakes. Additionally, it includes a large battery bank that can provide for low-speed movement in addition to supplying power to electronics.

The series hybrid architecture relies solely on the motor for locomotion. Although, these vehicles have the opportunity to be much simpler, in practice they seldom are. The most basic series architecture vehicles use the engine and generator as a "range extender" to recharge the battery bank, which solely runs the motors to provide locomotion. However, most series hybrid vehicles maintain the capability to run without the battery banks. In this case, the generator is able to provide power directly to the motor. In the "range extender" case, a less-powerful engine can be used. In the more common case where the generator provides power directly to the motor, the engine must retain much of its original power output. However, there is some weight savings from not requiring a transmission.

For both hybrid architectures, the BFV powertrain would need to be modified to make room for the batteries, motors, and accessories necessary for hybridization. The current powertrain in the BFV is the Cummins VTA-903T which is capable of producing 650 hp. It is coupled to a hydraulic-mechanical continuously-variable transmission. Altogether, the engine and transmission require a considerable amount of volume. Additionally, the BFV carries a 175-gallon fuel tank.

A parallel architecture requires a more power dense engine to create enough room for the other components. A novel opposed-piston engine with an advanced 32-gear transmission was found to provide a volume saving of 16 cubic feet when accounting for the engine, transmission, and cooling system. The motors on a Tesla Model S can provide up to 825 hp, so comparable motors and accessories were used for sizing. The remaining space was allocated for batteries, allowing for approximately 400 kg of batteries. The total vehicle weight increases by 700 kg.

The series architecture can potentially use the same engine. For this architecture, a transmission is not required, freeing up another 25 cubic feet for the generator, motors, and battery banks. The system would have 1500 kg of batteries, and the overall vehicle weight increase would be 1650 kg.

3.2. Drive Cycle Analysis

The traditional, series hybrid, and parallel hybrid powertrains were analyzed over three different drive cycles using an Excel-based model. Figure 2 shows an input/output block diagram for this model, which approximates the energy and fuel consumed for each vehicle to move in accordance with a given drive cycle. The inputs to the model are vehicle specifications and drive cycles. The model outputs the fuel consumption, range, and power requirements.

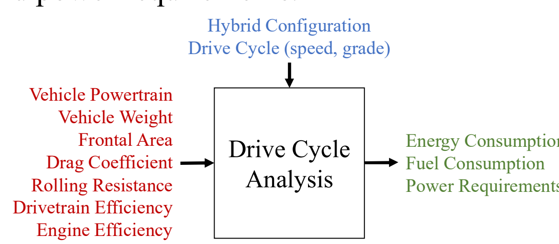

Figure 2. Block diagram depicting the inputs and outputs from the model.

This analysis considered three different drive-cycles. The first assumes that the BFV is stationary for 1 hour while powering 5 kW of electronics, which would provide enough power for air-conditioning, weapon systems, and radios. The second uses the distance profile for the EPA highway drive-cycle but modified to set the maximum speed to 30 mph. This drive-cycle replicates the vehicle driving on a highway as part of a convoy. This drive cycle lasts for 26 minutes and is shown in Figure 3. The third drive cycle uses data collected for a tactical maneuver performed with a BFV at the National Training Center. In this case, the vehicle is also moving on a graded surface. Figure 4 illustrates the speed and elevation profile for this drive cycle.

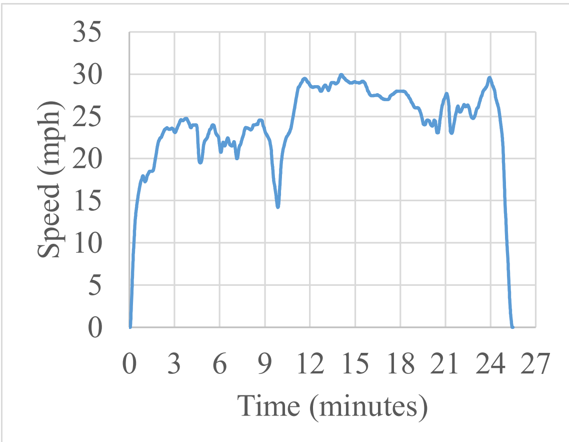

Figure 3. Speed Profile for the Highway Drive Cycle

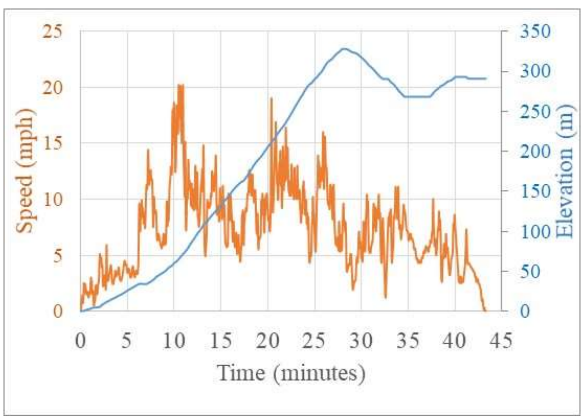

Figure 4. Speed and Elevation Profile for the Off-Road Drive Cycle

The model breaks the drive-cycle into 1 second increments and determines the power necessary for the vehicle to increase/decrease in velocity, change the inertial energy of rotating bodies in the vehicle, provide cooling, overcome air drag, overcome rolling resistance, overcome an incline, and power accessories [9]. The following variables were required to be defined for each vehicle:

- v : instantaneous velocity (m/s)
- m : mass of vehicle (kg)
- q: incline (rad)
- C_d: drag coefficient of vehicle
- ρ: density of air (kg/m^3)
- A: frontal area of vehicle (m^2)
- C_R: coefficient of rolling resistance (N/kg)
- h_d: transmission efficiency
- h_e: engine efficiency as a function of load

With these parameters defined the model performed the following steps:

1) Calculate the power required to change the velocity of the vehicle:
$$P_{accel} = m\frac{\Delta v}{\Delta t}v$$
2) Approximate the power required to overcome inertial changes of rotating bodies
$$P_{rotation} \approx 0.1P_{accel}$$
3) Calculate the power required to overcome an incline (set at a 1 percent grade)
$$P_{incline} = mg\sin\theta\ v$$
4) Calculate the power required to overcome drag
$$P_{drag} = 0.5\ C_d\rho\ v^3$$
5) Calculate the power required to overcome rolling resistance
$$P_{rolling} = C_R m$$
6) Approximate the power required for accessories to include engine components and vehicle electronics, radios, and air conditioning
$$P_{accessories} \approx 5000\ W$$
7) Calculate how much of the total power is required by the engine (P_{engine}) and battery ($P_{battery}$)
8) Calculate the power required for cooling the engine
$$P_{cooling} = 0.15\ P_{engine}$$

The model makes the following assumptions:

- Air properties at sea-level
- Coefficient of rolling resistance is set to 90 lb/ton
- Accessory power is set at 5 kW to provide power for engine accessories (not including cooling), radios, vehicle electronics, and air conditioning

Furthermore, the model used the following parameters for the vehicle properties:

- The base vehicle weight was set to being 40,000 kg (approximately 44 tons). This weight included the crew, passengers, equipment, and ammunition. The hybrid vehicles accounted for the increased weight for the battery packs.
- Constant drag coefficient of 0.5, a value that is commonly used for larger pick-ups which have similar shapes to these military vehicles. Note that due to the low speed of the vehicle, the drag effects are often negligible.
- An engine efficiency was based solely on the engine load using the curve in Figure 5. Note that in Figure 5, the blue line indicates the losses associated with running at part-load. The red line further accounts for losses from the engine associated with engine cooling. These values are comparable to larger turbocharged diesel engines. A more thorough analysis could use the actual engine map to determine the efficiency as a function of speed and load.

The total power required from a powertrain at a given time is then the sum of the power components (P_{accel}, $P_{rotation}$, $P_{incline}$, P_{drag}, $P_{rolling}$, $P_{accessories}$, $P_{cooling}$). The power from the engine can then be calculated by accounting for the efficiency of the transmission, which is a function of the vehicle speed. The model then approximated the efficiency of the engine based on its load.

Upon establishing the efficiency of the engine and the power draw, the model then calculated the amount of fuel consumed during that time interval. By summing across all time steps in that drive cycle, the model then calculated the total fuel consumption.

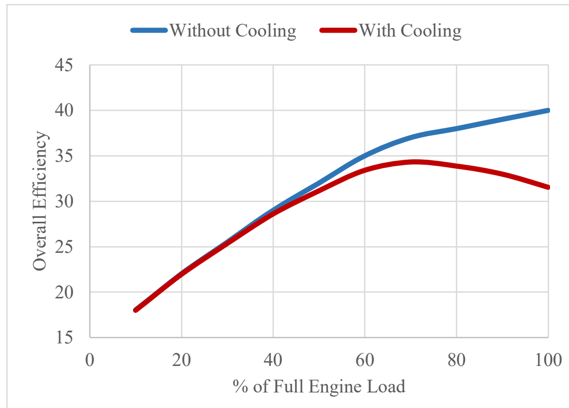

Figure 5. Engine efficiency as a function of engine load

The model used a similar approach to determine the amount of energy dissipated from the batteries. In this case, the energy consumed is pulled from the battery, as opposed to from burning fuel. The batteries are not allowed to reach a discharge state below 20 percent to ensure battery health and longevity.

Note that for the power required for acceleration, as the vehicle decelerates, energy is lost from braking for the traditional model. However, the electrified vehicles can take advantage of regenerative braking, where the motor uses the vehicle's momentum to recover energy that would otherwise be lost to the brake discs as heat. Though the efficiency of this process varies based on the vehicle and design, the model assumes a 65 percent regenerative braking efficiency [10].

The model assumes that the vehicles are at a forward deployed location; therefore, the batteries are recharged from diesel genset. As such, there is fuel consumed by even the pure electric vehicle option. This analysis assumes that the genset is running at 40 percent efficiency, and that the battery recharging process is 90 percent efficient.

3.3. Comparison to Other Models

The model presented in this paper is not the only hybrid drive-cycle analysis model. Most hybrid drive-cycle models have their roots in predicting fuel consumption in a standard powertrain. One of the more prominent models is the ADvanced VehIcle SimulatOR (ADVISOR) developed by the National Renewable Energy Laboratory [11]. ADVISOR was developed in 1994 and included a graphical user interface and web interface that allowed users to model vehicle performance. Several researchers have used ADVISOR to study the trade-offs between series and parallel architectures [12].

More recently, Matlab, Simulink, GT-Power, and other common simulation software packages have been used for modeling hybrid powertrains for different vehicle types ranging from dump trucks [13] to motorcycles [14].

The model presented in this paper is intended to be somewhat simplistic and open to show the driving factors underlying hybridization. While other models are somewhat more intricate, this model traces its roots to first-order vehicle dynamic principles. As such, the model was developed in Microsoft Excel in such a way that any researcher can reconstruct this model using a spreadsheet. The use of a spreadsheet further allows users to have fully visibility into the inner workings of the model.

4. ANALYSIS AND RESULTS

4.1. Fuel Consumption

The model was run for the baseline BFV along with the two hybrid alternatives. Figures 6-8 illustrate the resulting cumulative fuel consumption throughout the stationary, highway, and off-road drive cycles. In all cases, the hybrid options consumed less fuel than the current BFV powertrain.

Figure 6 shows the on-board fuel consumption for the BFV while stationary. Given the constant power draw for electronics and accessories, the fuel consumption linearly increases in time with the conventional engine. However, for the hybrid alternatives, much of the requisite electricity can be provided by the battery bank. For the series hybrid, the engine turns on at 2500s to recharge the battery bank and maintain the battery state of charge. For both the parallel and series hybrid systems, the batteries would need to be recharged following the mission. The plot includes the total amount of fuel required over the drive-cycle including the fuel required to bringing the battery bank back to its initial state of charge.

Figures 7 indicates the on-board fuel consumption for the different alternatives for the highway drive cycle. For this drive cycle, the vehicles are moving at high load to maintain their speed; as such, the parallel hybrid system is relying heavily on its engine, resulting in a fuel consumption comparable to the non-hybrid BFV. Note that the blip in the highway drive cycle for the parallel hybrid solution at 600 s is related to a period of deceleration and regenerative braking.

The series architecture consumes less fuel that the other alternatives over the highway drive-cycle. The data points on the far right indicate the total fuel required for each powertrain alternative after recharging the battery banks. The parallel system does not heavily rely on its battery bank, so it requires minimal fuel for recharging.

Figure 8 shows the similar plot for the offroad drive-cycle. In this case, the low vehicle speeds result in similar on-board fuel consumption for the series and parallel alternatives. However, the state of charge of the parallel system is somewhat less than the series system at the end of the drive-cycle. As such, although the parallel hybrid alternative uses less on-board fuel, it uses more fuel than the series hybrid alternative when factoring in recharging the batteries.

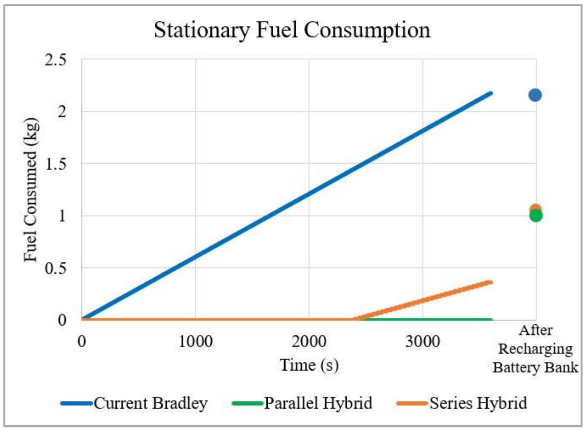

Figure 6. Stationary Fuel Consumption

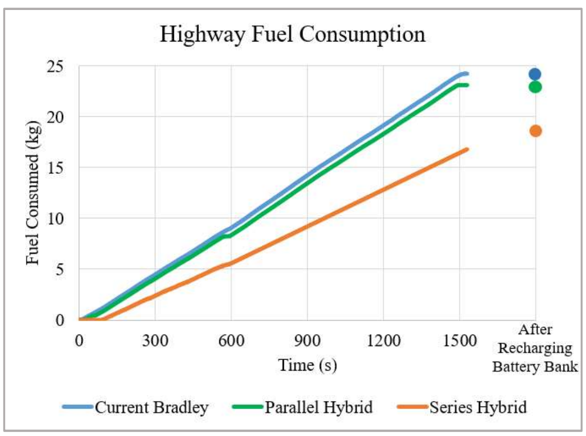

Figure 7. Highway Fuel Consumption

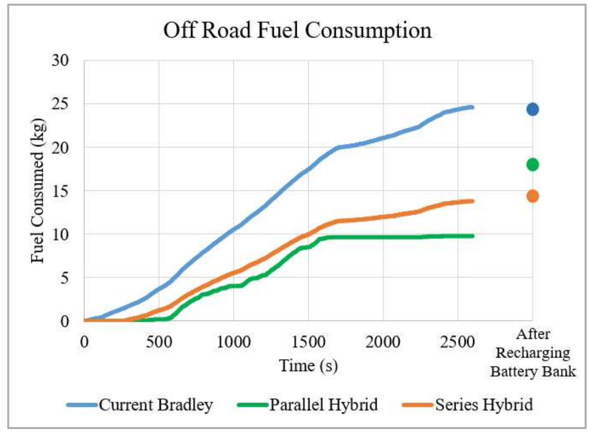

Figure 8. Off Road Fuel Consumption

The total fuel consumed for locomotion and to recharge the battery pack to its initial state of charge is given in Figure 9 for the different alternatives. The results indicate a decrease in fuel consumption can be realized through both parallel and series hybridization. The models further indicate that between the two alternatives, the series hybrid architecture results in a larger decrease in fuel consumption.

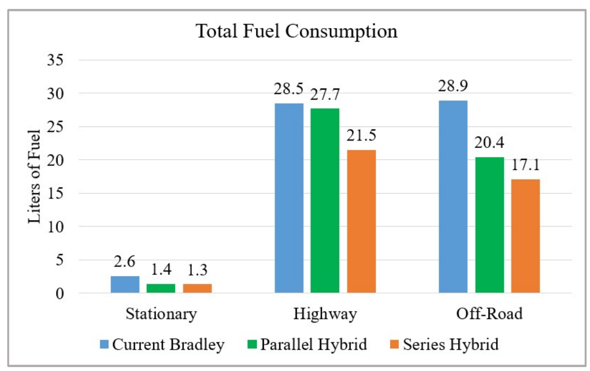

Figure 9. Fuel Consumption for Locomotion and Battery Recharge

4.2. Fuel Efficiency

Using the fuel consumption obtained from Section 4.1 and the distance per drive cycle, the model determined fuel efficiency as measured in miles per gallon. Results are shown in Figure 10. Note that the current BFV powertrain is expected to get approximately 0.7 mpg, which is similar to the value shown in Figure 9 for the BFV in an off-road condition.

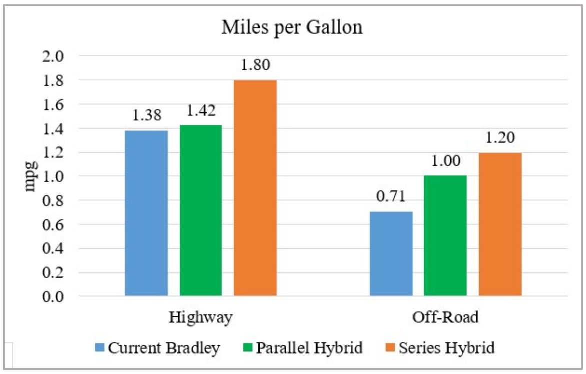

Figure 10. Fuel Efficiency

In a multi-domain operational environment, an increased vehicle range gives a substantial tactical advantage. Given a BFV contains a 175-gallon fuel tank, Figure 11 shows the maximum range for each configuration. For both the off-road and highway drive cycles, a series hybrid architecture provides the maximum range before refueling is required.

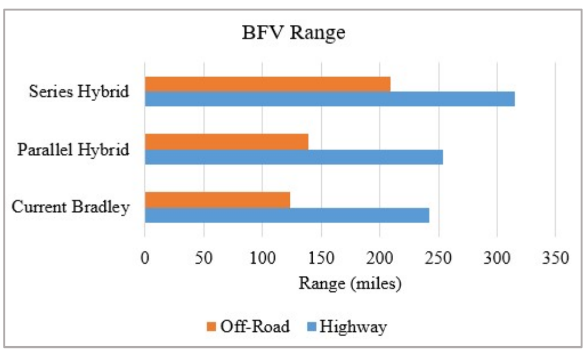

Figure 11. BFV Range Given Full Fuel Tank

The results from the model somewhat conflict with other work done comparing parallel and series hybrid alternatives, many of which show parallel hybrid vehicles as having a better fuel economy than series hybrid [15-17]. However, many of these studies are limited to passenger and light-duty vehicles. Moreover, the optimal architecture is heavily dependent on the drive-cycles considered. This model indicates that the large power demand and low speeds of the BFV appears to favor the use of a series hybrid architecture.

4.3. Other Considerations

The analysis shows that for the BFV there are numerous benefits that can be realized from hybridization of the vehicle. Indeed, the series and parallel alternatives showed increased range and decreased fuel consumption across all three drive cycles. However, there are numerous other factors that must be considered prior to the hybridization of the BFV.

The largest issue with hybridization would be repackaging the engine cavity to allow for all the required components. In particular, for the parallel hybrid vehicle, the opened space from switching engines may not allow for fitting in motors to turn the sprockets. Additionally, the transmissions would likely require additional modification to allow for the electronic input. This issue will be significantly less for the series hybrid architecture, since there is no transmission, and the engine does not need to be packaged near the output sprocket.

A second large issue is related to the vehicle braking and steering. In particular, as a tracked vehicle turns, the torque from the internal track is transferred to the outer track. As such, a parallel hybrid drivetrain would require a complex control system to allow for smooth and tight steering. Moreover, a parallel or series hybrid solution would require more powerful motors to produce an adequate amount of torque on the outer track.

The third issue is safety given that lithium burns quickly and aggressively. Additionally, a small amount of physical damage to an individual battery cell can result in the thermal runaway, resulting in the entire battery pack catching fire. A small roadside bomb or a well-placed bullet aimed at the battery pack could cause the entire vehicle to rapidly catch fire. Given the combat applications of these vehicles, a more stable battery chemistry would help ensure the safety of the soldiers.

A fourth issue is related to security, especially in the cyber domain. As vehicles undergo hybridization, there is an increased reliance on computation to control the vehicle powertrain. These computers are vulnerable to cyber-attacks and electronic warfare. Even if the computer is a closed system, such that it does not access a network, its performance can still be degraded or disrupted through electronic warfare.

A fifth issue is related to environmental factors that affect battery and motor performance. In particular, cold weather slows down the underlying chemistry in the batteries, resulting in sluggish performance and inefficient discharge [18]. Meanwhile warmer weather can result in the motors to operate less efficiently due to copper and magnetic losses [19].

While these challenges must all be overcome to see hybridization of military vehicles, most will eventually be resolved by the commercial sector. In particular, the commercial vehicle market is investing heavily in new battery chemistries to support the widespread usage of electric vehicles.

5. CONCLUSIONS

Given Secretary Wormuth's climate change initiative, rising fuel prices, and an increase in powertrain demands, the DoD must consider hybridizing its current and future combat vehicle fleet. The model presented in this study reduced BFV total highway fuel consumption by 24% and off-road fuel consumption by 40% by utilizing a series hybrid architecture. Additionally, this resulted in increased fuel efficiency and extended the highway for a fully fueled BFV by 30% and extended the off-road range by 68%.

Once implemented, a hybrid architecture offers the additional benefit of stealth operations as the vehicle can run for extended periods of time without the engine running. Furthermore, at low engine speeds, electric motors provide more torque than diesel engines which offers the potential to increase vehicle acceleration and towing capacity.

Despite the benefits, implementing a hybrid architecture in existing BFVs would incur cost, logistical considerations, and introduce risk as discussed in Section 0. The model developed provides the ability to analyze BFV power requirements and fuel consumption given varied driving conditions. With this analysis, this study provides decision makers the data to contemplate the tradeoffs with the benefit gained from implementing a hybrid architecture is a necessary investment to ensure "the Army keep rolling along."

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