12-20-2019

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Abstract: A hybrid electric tracked ground vehicle (HETGV) can reduce military fuel usage, however a review of current tools determined they are not suitable to estimate HEGTV performance. Based on topographic data and vehicle attributes, this research developed an estimation tool by creating a model to determine tracked vehicle energy and fuel requirements, and using these requirements, created a HEGTV cost and performance optimisation for the Bradley fighting vehicle energy system. The optimised design reduced fuel consumption by 15%, and met the vehicle's peak power requirement of 365 kW, with a recommended configuration of a 135 kW generator and 100 kWh battery, and an estimated drivetrain and fuel cost of $155,000. This analysis concludes by articulating the operational and tactical impacts of increased fuel efficiency.

Keywords: EVs; conventional HEVs; series hybrid electric vehicle; energy transmission; battery technology; DoD; Department of Defense; tracked vehicle.

Reference to this paper should be made as follows: McWhirter, T.E., Wagner, T.J., Stubbs, J.E., Rizzo, D.M. and Williams, J.B. (2020) 'Tracked vehicle physics-based energy modelling and series hybrid system optimisation for the Bradley fighting vehicle', *Int. J. Electric and Hybrid Vehicles*, Vol. 12, No. 1, pp.1–14.

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Torrey J. Wagner is an Assistant Professor within AFIT's Department of Systems Engineering and Management, and earned his PhD from AFIT in 2010. His current research interests include finding optimised solutions to meet

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John E. Stubbs is the Director of the Environmental Engineering and Science program within the AFIT Department of Systems Engineering and Management. As it relates to this work, his research interests are in sustainable lifecycle design and how alternative energy options may impact both non-renewable resource depletion and environmental emissions over the life cycle of the design, use, and disposal stages.

Denise M. Rizzo is a Senior Research Mechanical Engineer for the Vehicle Performance Modelling and Team at the US Army Ground Vehicle System Center (GVSC). She specialises in modelling, simulation and control of propulsion systems of ground vehicles. She received her PhD from Michigan Technological University in 2014. From 2000 through 2008 she was a controls Research and Development Engineer in the Powertrain Group at Chrysler LLC. She joined GVSC in November of 2008 and was promoted to her current position in 2017. She has published 20 papers in archival journals, 32 papers in refereed conference proceedings, 4 technical government reports, and holds two patents.

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1 Introduction

The Department of Defense's (DoD) rapid transition to more fuel-efficient vehicles will be prompted by limited fuel availability and environmental considerations. As the DoD is the largest single consumer of energy in the world, small changes in fuel prices can have significant impacts on the DoD budget (Warner and Singer, 2009). As the global human population increases towards 9.8 billion by 2050, rates of petroleum consumption will continue to increase (United Nations, 2017). Despite advancements in technology and efficiency, projections estimate that mankind will exhaust global oil reserves between 2050 and 2112 (Conti et al., 2016; Wagner et al., 2016). Taira et al. (2017) conclude that a hybrid drive system is feasible for a military vehicle and can reduce overall fuel consumption. Due to the lack of tools available to design and evaluate HETGV performance (Mahmud and Town, 2016), we developed a Matlab-based model that predicts vehicle energy requirements which are then used to optimise the energy system design for a Bradley fighting vehicle. The model developed in this research can be adjusted to predict energy requirements and input factors that influence the physics of a wide range of tracked ground vehicles, including grading resistance, rolling resistance, and vehicle weight.

2 Literature review

Within the past few years, the DoD has formally acknowledged areas of improvements to save costs, advance their technical capability, and reduce energy use and vulnerability in security (Office of the Assistant Secretary of Defense for Energy Installations and Environment, 2016). Regarding energy use, a strategic decision to lower fuel consumption was executed in anticipation of rising fuel costs; expectations are to decrease the amount of fuel used across the department by lowering fuel consumption in vehicles. The HEGTV is proven to reduce overall fuel consumption, when connected in series to appropriately sized components, and this research advances prior work by predicting and optimising HETGV energy use in a realistic environment.

2.1 DoD fuel use

The 2014 Quadrennial Defense Review identified a need for energy improvements to "enhance range, endurance, and agility, particularly in the future security environment where logistics may be constrained" (Hagel, 2014). As a result of the review the DoD energy strategy has focused on decreasing energy consumption and increasing energy efficiency, with three main objectives (Office of the Assistant Secretary of Defense for Energy Installations and Environment, 2016):

- increase future warfighting capability by including energy throughout future force development
- identify and reduce logistics and operational risks from operational energy vulnerabilities
- enhance the mission effectiveness of the current force through updated equipment and improvements in training, exercises, and operations.

In response to energy strategic objectives, each service branch has initiated installation and operational energy reduction initiatives. The demand for ground vehicles to reduce energy consumption will exist if there are sudden sustained increases in fuel cost. Government and other agencies will increasingly turn to computer models in order to reduce reliance on lengthy and expensive field trials (Wong, 1995). The capability to model vehicle performance is increasingly important when screening ground vehicles for acquisition.

Implementing HEVs is desirable for military applications to reduce the high logistics cost of transporting fuels to front line units. Within the DoD the fully burdened cost of fuel (FBCF), including logistics and force protection, can range as high as $600 per gallon for airborne delivery of fuel (Dimotakis et al., 2006; Burke, 2012; Kramer and Parker, 2011).

2.2 Tracked vehicle energy requirements

Fuel economy impact factors for off-road vehicles consist of three broad categories: external resistance, internal resistance, and operator driving habits. External resistance factors typically include resistance due to vehicle-terrain interaction, obstacle resistance, grade resistance, and aerodynamic drag (Wong, 2008). For this model, external resistance was primarily determined from the grade profile of the Churchville Test Area B (CTA B) track, which is shown in Figure 1. Internal resistance is defined by the vehicle characteristics, fuel consumption characteristics of the engine, transmission characteristics, and internal resistance of the running gear. Weight, velocity, and engine displacement are the most crucial internal resistance design features impacting fuel consumption, with modelled parameters shown in Table 1. Operator driving habits are another substantial factor that can have a significant effect on fuel economy. If an operator operates the vehicle in a manner that is not fuel efficient, the overall range can be significantly reduced (Murrell, 1975). Due to the wide range of uncertainty associated with operator driving habits, their effect is not considered in this model.

Figure 1 Churchville test area B grade profile (see online version for colours)

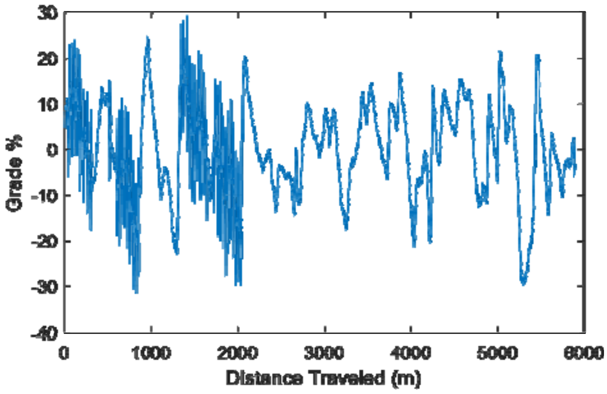


Table 1 Internal and external resistance input parameters

Vehicle inputs/internal resistance		*Terrain inputs/external resistance*	
Input	*Value*	*Input*	*Value*
M – Vehicle weight (kg)	27,600	*d* – Distance travelled (km)	5.9
V – Velocity (m/s)	2.5	*RR* – Rolling resistance coefficient (unitless)	0.06
ES – Engine size (kW)	450	*g* – Grade traversed (degrees)	*
Internal track resistance (N)	*	Engine idle (gph)	*

*Denotes factors calculated in Matlab.

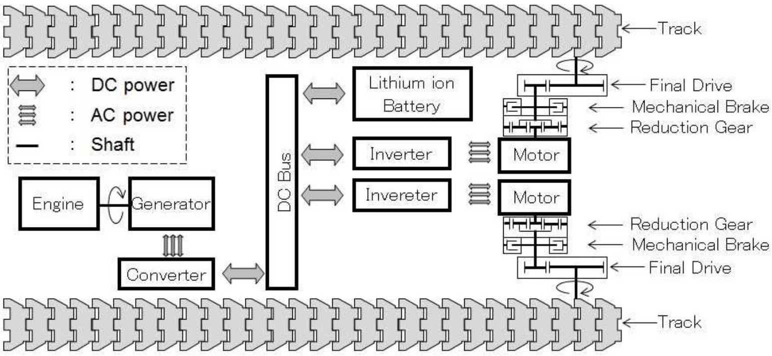
The tracked M2/M3 Bradley fighting vehicle (BFV) was selected to evaluate fuel consumption due to the availability of performance data. Its fuel consumption average is 0.75 mpg (McDade, 1986), and additional vehicle physical characteristics are detailed in Table 1.

2.3 Tracked HEV power train characteristics and limitations

Hybrid electric powertrains have multiple advantages when applied to military applications, and HETGVs demonstrate up to 40% improvement in fuel economy performance on unprepared surfaces, have smoother acceleration, increased available torque, and are more powerful than conventional vehicles with mechanical drivetrains

(Taira et al., 2017). HEV systems can be broadly classified as series or parallel. A series system uses a generator to convert the output of an internal combustion engine into electrical energy, which charges the batteries or propels the wheels through an electric motor and transmission. Figure 2 displays the component structure for a series tracked hybrid electric vehicle.

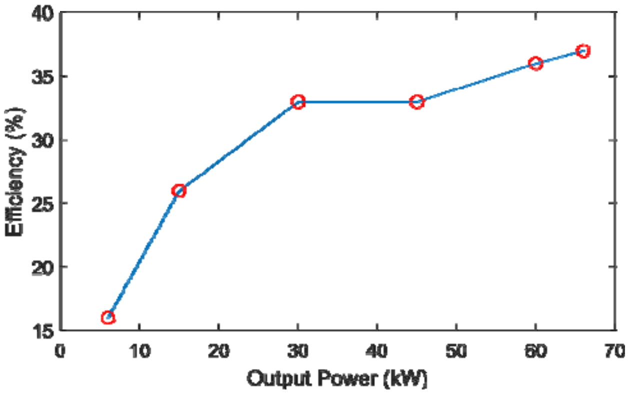
Figure 2 Tracked HEV series hybrid drivetrain



Source: Taira et al. (2017)

A substantial advantage of the series hybrid drive train is the mechanical decoupling between the ICE and driven wheels. Decoupling reduces the overall fuel requirement for the vehicle system by enabling high-efficiency operation of the generator (Sivakumar et al., 2017). When sizing a generator for a series system, it is important to select a generator that will meet the power demand while operating at its maximum efficiency. Figure 3 displays the efficiency profile of a 60 kW generator, which highlights the advantage of operating a generator near its rated output (Sprague, 2015).

Figure 3 60 kW generator efficiency vs. output power (see online version for colours)

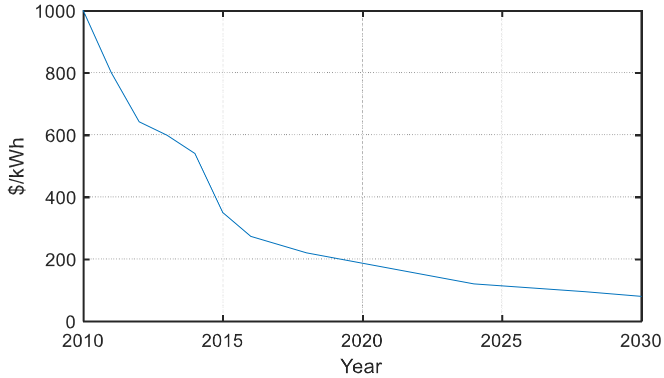


Source: Sprague (2015)

Current technologies have continued to rapidly improve, however the availability of high energy density storage devices is identified as an obstacle in developing HETGVs (Sivakumar et al., 2017). Battery selection is a significant decision in developing HETGVs, and large batteries charging and discharging near their rated power limits possess a sizeable thermal management requirement. The accompanying cooling systems require energy that offsets efficiency gains from hybridisation (Sivakumar et al., 2017). Battery advances have reduced the need for cooling systems (Lambert, 2018), which helps to save energy but requires heat management within the battery system. One commercially available example is a 100 kWh battery pack with 311–451 kW maximum power, a charge rate of $C > 1$, an integrated thermal management system, and degradation limited to 5–10% throughout its lifespan (Lambert, 2018).

Battery performance and cost have historically limited HEV potential, however as battery performance has increased, production cost has decreased. In 2017, the production cost for batteries was estimated at $162/kWh with a projection of $72/kWh in 2030 (Curry, 2017). Figure 4 details battery cost projections utilising historical data from 2010 to 2016. At the time of writing this paper, an acquisitions program for military HEVs took six years to implement from start to project completion. If a program were started based on the present work, battery costs are estimated to be at or less than $100/kWh when production starts.

Figure 4 Battery cost projection (see online version for colours)



Source: Curry (2017)

3 Methodology

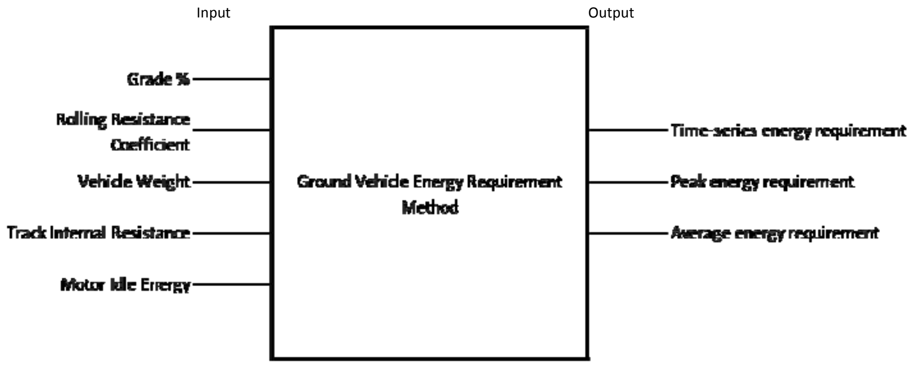
This research developed a physics-based approach to determine energy requirements along a specified route, and a model to optimise a HETGV energy system for the BFV. A model was developed in Matlab to analyse and determine the time series energy requirement. Then, an energy system optimisation is performed using one-dimensional variable sweeps and two-dimensional surface plots for a generator and battery size to understand system dynamics and determine the optimal system design.

3.1 Energy requirement modelling

The route input is a terrain profile (measured in grade percent) which is used to calculate both grading and rolling resistance. Average fuel economy data from the BFV was utilised to validate model results for the Bradley off-road tracked vehicle, and vehicle characteristics can be adjusted to predict energy requirements across a wide range of tracked ground vehicles.

Input parameters are shown in Figure 5 and include considerations for external resistance and internal resistance. External resistance factors typically include resistance due to vehicle-terrain interaction, obstacle resistance, grade resistance, as well as aerodynamic drag (Wong, 2008). The primary external resistance factors utilised in the model are vehicle-terrain interaction and grading resistance. Obstacle resistance is excluded due to the varied and unknown potential obstacles an off-road-vehicle might encounter. Aerodynamic resistance is excluded from the model as it is insignificant at the velocities studied in this work (Wong, 2008). Operator driving habits are also omitted from the model due to the complexity and uncertainty involved with individual driving behaviours.

Figure 5 Energy requirement model input and output diagram



Internal resistance is defined by vehicle characteristics, fuel consumption, transmission and internal resistance of the running gear. The features that have the most impact on fuel consumption are weight and engine displacement, as previous studies show that a 10% change in weight or displacement can create an inverse fuel economy change of 3% to 6%. Since weight changes are typically accompanied by engine displacement changes; the fuel economy influence of these changes have attributed to weight alone (Murrell, 1975). Parameters and units used in modelling are described in Table 1.

The energy required to navigate up or down a grade was calculated using equation (1). If the grade is negative, an empirical relationship for engine idle energy is utilised, which is presented in Figure 6. A linear relationship for idle fuel consumption is determined using data obtained from generator suppliers for generators sized 2–400 kW, which is presented in Figure 6 and equation (2) (Coulson, 2019; Diesel Service Supply, 2018).

The Churchville course terrain consists of moderate to rough soil and stone ranging from muddy to dusty, contingent upon environmental conditions. As a result, the rolling resistance coefficient used within the model is 0.06 (U.S. Army Tank Automotive Command, 1967), and the energy required to overcome rolling resistance is calculated using equation (3). Due to the complex nature of the internal resistance within the track-suspension system, it is difficult to accurately predict internal resistance. As a result, an empirical relationship for modern lightweight tracked vehicles was used, which is shown in equation (4) (Wong, 2008).

$$Energy_{grade} = M \times Gravity \times g \times d \quad (1)$$

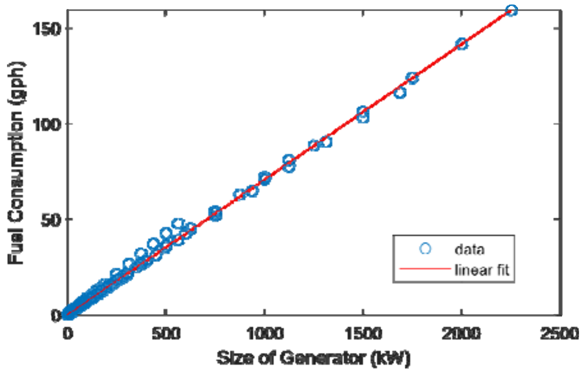
$$Energy_{idle} = 0.0704 \times ES + 0.6954 \quad (2)$$

$$Energy_{rolling} = M \times Gravity \times RR \times g \quad (3)$$

$$Energy_{internal} = \frac{Mass_{vehic}}{1000} \times (133 + (2.5 \times velocity)) \quad (4)$$

Using the factors from Table 1, track grade, internal and rolling resistance values were calculated at each interval and summed to determine the total energy requirement.

Figure 6 Linear relationship for engine idle fuel consumption (see online version for colours)



3.2 Energy system optimisation

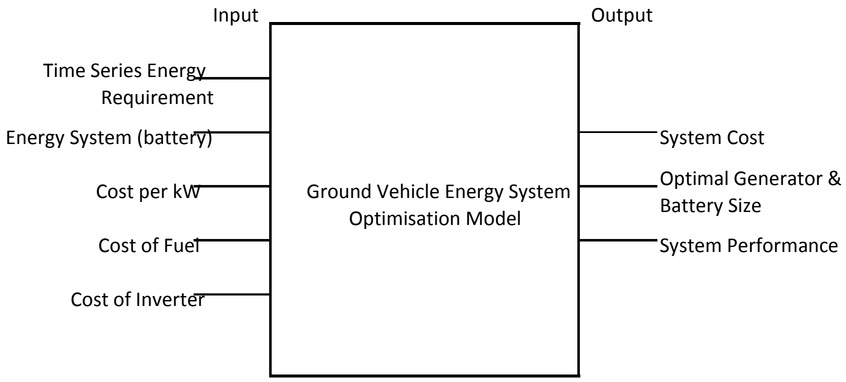
Using the series hybrid architecture shown in Figure 2 and the energy requirement developed in Section 3.1, we optimise the cost of the energy system while incorporating a penalty function to translate a performance shortfall into cost. Figure 7 describes the input and output parameters for the optimisation model. The generator operates at full power in order to recharge the battery and meet the energy requirement, and once batteries are fully charged, the generator shuts off to minimise fuel consumption and excessive deterioration. When the batteries are discharged to a minimum-allowable level, the generator turns back on to recharge the battery. This configuration ensures the generator operates at the highest efficiency as shown in Figure 3.

Table 2 describes the values used in cost and performance modelling within the system. The optimisations are compared to a baseline case, which is specified as 35 laps of the CTA B track, which is the endurance from the baseline BFV 175 gallon fuel tanks.

Table 2 Ground vehicle system cost and performance parameters

	Generator	*Battery*	*Inverter/charger*
Component cost	\$100/kW	\$100/kWh	\$80/kW
Fuel cost	\$3/gal	–	–
Peak efficiency	26%	95%	–
Max power output (steady state/max)	Varies	4 kW/kWh	–

Figure 7 Energy optimisation model input and output diagram



In order to extend the performance margin, a 50% depth of discharge was selected for the battery. Generator parameters are based on the average cost of commercial generators, with an inverter cost of $80/kW (Fu et al., 2017; Sprague, 2015).

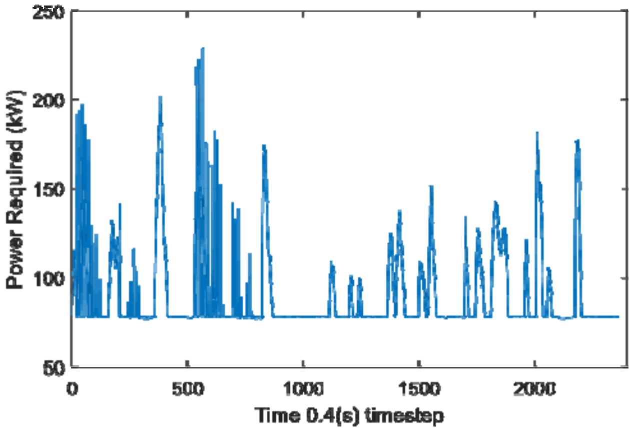
4 Analysis and results

The course energy requirement was determined using equations (1)–(4) for grading, idle, rolling and internal energy. Then, using the requirement and the parameters shown in Table 1, the BFV energy system was optimised for performance and cost.

4.1 Energy requirement modelling

The resulting power requirement for one lap of the CTA B track is shown in Figure 8. The peak power requirement for the CTA B course is 229 kW, the average power requirement is 91 kW and the energy required is 38.9 kWh. When considering the peak BFV gradeability requirement of 60%, the resulting vehicle peak power requirement is 385 kW.

Figure 8 Modelled energy requirements on CTA B at 9 km/h (see online version for colours)



Additionally, this tool determines the minimum amount of energy required to traverse a course, which can be beneficial to verify manufacturer claims of efficiency. For example, 5.6 gallons of fuel is the minimum amount required to navigate the CTA B course at a velocity of 9 km/h, when accounting for the engine's efficiency and dividing by 33.7 kWh of energy per gallon of diesel fuel (Goldenstein, 2011; United States Department of Energy, 2018). The modelled energy requirements were slightly less than the average fuel consumption. We believe the difference is due to the additional load required for electronics, air conditioning and initial acceleration, which are not accounted for within the model.

4.2 Ground vehicle system optimisation

Using the energy requirement obtained in Section 3.1 and the model parameters from Table 2, the BFV energy system design was optimised in a 35-lap scenario. One-variable sweeps are first performed to understand system dynamics, and then a battery and generator optimisation is performed to obtain the final system design. The first one-variable sweep varies generator size with a fixed 100 kWh battery. The results are shown in Figure 9, where the "Timesteps not met" line delineates battery/generator configurations that result in insufficient amounts of energy required for 35 laps on the CTA B track. The sweep in Figure 9 suggests that a 100 kWh battery and generator sized at approximately 65 kW is sufficient to support the BFV for 35 laps. However, this would provide an insufficient performance margin for the grade profile of the CTA B track.

Figure 9 Generator optimisation with fixed battery size, showing cost parameters (left) and performance (right) (see online version for colours)

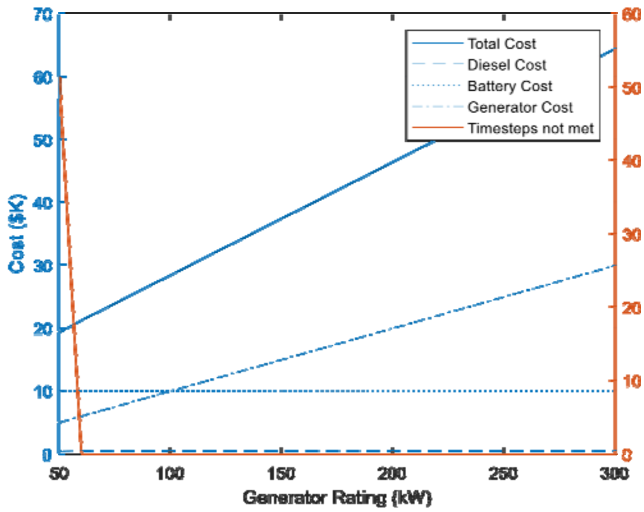
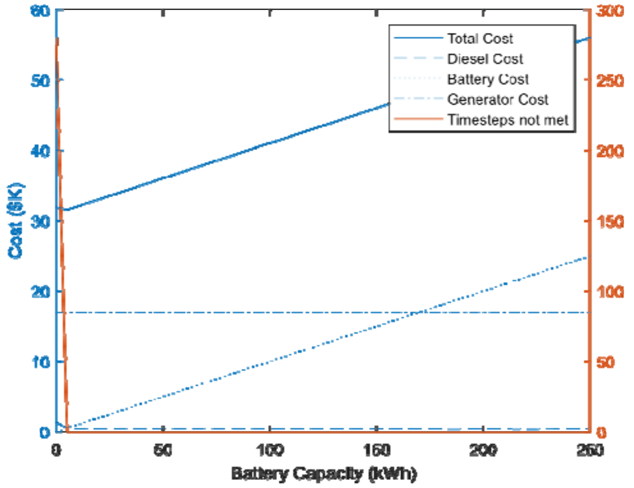


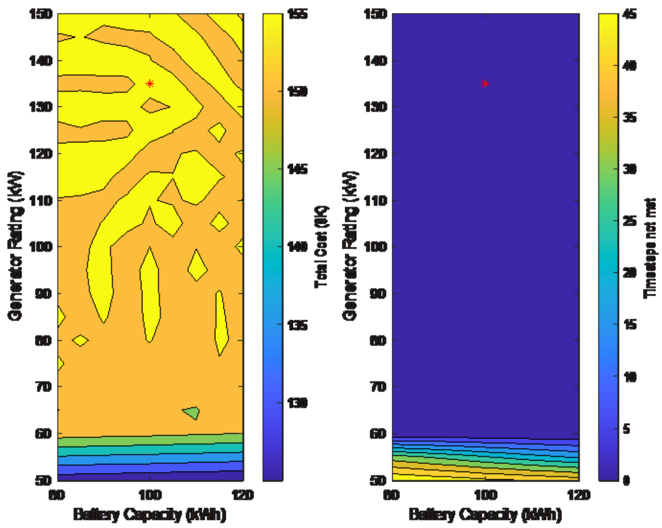
Figure 10 presents the next sweep, which varies battery size with a fixed 135 kW generator, and suggests that a battery sized at approximately 25 kWh is sufficient for 35 laps. However, even with 4 kW/kWh battery peak power, the system power would be insufficient to meet the 385 kW peak gradeability requirement.

Figure 10 Battery optimisation with fixed generator size, showing cost parameters (left) and performance (right) (see online version for colours)



The two-dimensional domain that results from varied generator size and battery capacity is shown in Figure 11, the resulting cost shown on the left, and performance metric “Timesteps-not-met” shown on the right. The irregular shapes on the left graph result from the complex energy requirement. The cost of fuel is currently a small contributor to overall cost, however changes in either policy or fuel availability have the potential to increase the cost of fuel. The estimated cost to meet the energy requirement is $155K, including the costs for the generator, battery, inverter, and fuel for 35 laps. The optimal battery and engine configuration are distinguished by red asterisks, which include a 100 kWh battery and a 135 kW generator.

Figure 11 Generator and battery trade space, showing total cost (left) and timesteps-not-met (right) (see online version for colours)



Referencing Figure 9, at a fixed battery capacity of 100 kWh, a 65 kW generator provides sufficient energy required to propel the BFV for 35 laps. Although this seems appealing, a larger generator is required to ensure the BFV endurance relies on fuel availability, not battery capacity. Additionally, a smaller generator contains a risk of maintaining battery charge despite fuel availability. Due to these risks, a 135 kW generator was selected to meet the maximum charge rate of the selected battery while providing a reduction in fuel consumption.

Figure 10 suggests that a 135 kW generator and a 25 kWh battery can sufficiently support the BFV for 35 laps, however this battery size is unrealistic due to the previously mentioned peak power requirement of 385 kW.

For the optimal system design, the resulting time-series generator output, battery state-of-charge and power requirement for 3.5 laps of operation is shown in Figure 12. This time-series chart allows verification of model parameters including battery capacity, depth of discharge, generator size and model logic. The battery size allows approximately 30 min of engine-off operation when the velocity is 9 km/h.

Figure 12 Optimal configuration power demand, 135 kW generator power production, and 100 kWh battery state of charge (see online version for colours)

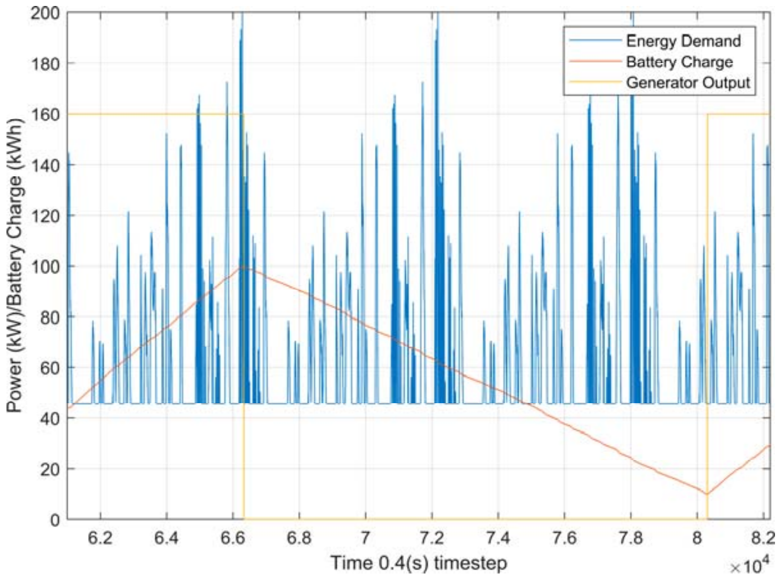


Table 3 Comparison of baseline and optimised fuel efficiency

Speed (km/h)	*Baseline model* (mpg)	*Optimised model (mpg)*	*Difference*
9	0.69	0.83	+21%
15.6	0.78	0.87	+12%
21.3	0.81	0.87	+8%
24.1	0.81	0.89	+12%
26.2	0.83	0.89	+7%
Average	0.78	0.86	+15%

A baseline generator-only model was created for comparison, which uses a 310 hp (230 kW) engine, the generator efficiency curve shown in Figure 3, and no battery. For various velocities, fuel efficiency for the baseline model and the optimised design (135 kW engine supplemented with a 100 kWh battery pack) is presented in Table 3. Regardless of velocity, fuel efficiency was improved with the optimised model.

5 Conclusions and recommendations

If predicted global warming impacts are realised, fuel prices increase, and carbon emission reduction becomes a global initiative, the DoD will have a requirement to implement more fuel efficient systems. HEV technology has matured to a point in which HETGVs are now a viable option to increase fuel efficiency. The model presented in this work reduced fuel consumption by 15% or greater with an optimised system design of a 135 kW generator and 100 kWh battery that can navigate 130 miles of terrain with grades up to 60%. Although the engine size was reduced, the total power capability remained the same due to the augmented power from the battery. A 15% average increase in efficiency is possible when using a smaller engine augmented with a 100 kWh battery.

Once implemented, HEVs will allow for greater endurance and energy flexibility for troops in the field. Additionally, reduced acoustic and thermal signatures will increase survivability, and the reduced logistics burden will save time, money and personnel risk. The models developed provide the ability to analyse tracked ground vehicle performance, assist in decision making and predictability in fuel reduction, and optimise a HETGV energy system.

Acknowledgements

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