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APPLICATION OF PHYSICS-BASED MODELS TO PREDICT REAL-LIFE DUTY CYCLE PERFORMANCE AND FUEL SAVINGS OF HYBRID ELECTRIC DRIVE ARCHITECTURES

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ABSTRACT

There is continued demand for military vehicles to provide increased fuel economy. Recent trends have appropriately turned to the development of duty cycles that better represent the real-life usage of vehicles. The advent of hybrid electric propulsion and power system architectures offer opportunities for reducing fuel consumption and greater power generation flexibility. The challenge is to effectively quantify the predicted performance for the architectures under consideration using tools that are applicable to shorter development schedules.

This paper discusses the importance of using multidomain physics-based computer simulations to perform the fuel consumption analyses. The models used include mechanical, electrical, magnetic and thermal effects, and their intimate interaction in order to predict the fuel consumption for a tracked vehicle traversing courses at varying speed, up and down hills, and negotiating turns.

This paper also compares the fuel consumption performance of two tracked vehicles having the same overall characteristics but different propulsion systems; one has a series hybrid electric drive; the other has a conventional mechanical drive. During a 72-hour mission, the series hybrid electric drive consumed ~6% less fuel than a comparable mechanical drive. During the 180-day campaign duty cycle, the fuel savings increased to ~10%.

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Introduction

U.S. Army ground vehicle acquisitions identify improved fuel economy and power management as a priority to reduce fuel cost and reduce the exposure of supply line personnel during battle operations. This emphasis,—combined with overall increased performance requirements in survivability, mobility, power generation, space claim, reliability, logistics burden, and development schedule, results in remarkable design challenges. TARDEC research has extensively characterized commercial analysis tools that enable realistic dynamic duty cycles to replace traditional steady state criteria [1]. Compressed program development schedules necessitate the application of advanced tools and improved methodologies. Exploration and application of advanced architectures is possible without settling for legacy-type arrangement based on the use of oversimplified steady state requirements. The successful demonstration of a method for rapid maturation and insertion of these highly valued systems is long overdue.

Our best practice method relies on high fidelity, physics-based models that are calibrated based on prior work. The use of proven scalable solutions and detailed collaboration with suppliers produce innovative integrated system designs with superior performance while simultaneously meeting aggressive development timelines.

In this paper we explore the fuel performance characteristics of a series hybrid electric drive tracked vehicle and a comparable conventional 7-speed mechanical drive tracked vehicle. We use a flexible model architecture to integrate vendor-specific component models. Our control and power management strategies manage the interaction of the subsystems as the vehicle operates over the prescribed synthesized duty cycle. This approach enables rapid exploration of design alternatives.

We demonstrate the application of the methodology in the design of a sample combat vehicle performing a representative 72-hour mission and a 180-day campaign. When compared to traditional mechanical designs, our simulations show that the series hybrid electric drive architecture provides greater fuel economy over the duty cycle with a component architecture offering an unprecedented level of available electrical power. The new design approach demonstrates an integrated system with better overall automotive performance, fuel efficiency, and power management while reducing program risk by using subsystem and component models based on proven technology.

Methods

Simplified models using tools, such as spreadsheets, provide relatively accurate results for steady state conditions such as top speed and performance on grade. Even dynamic conditions that are based on well defined conditions such as full power acceleration and maximum braking events can be explored using basic equations to achieve a force balance ($\sum F=ma$) by equating rolling resistance, grade, and air drag forces to the inertial mass and acceleration of the vehicle. However, when a metric such as fuel efficiency is calculated, so many factors interact that a more sophisticated model is required. For example, for moderate acceleration, steering and other dynamic maneuvers, the added complexity of gear shift points, battery boost, power transfer during steering, thermal management effects and specific control systems need to be included to gain an accurate prediction of the vehicle capabilities in a relevant environment and operating mode. BAE Systems uses an analysis tool known as the Integrated System Model (ISM), created in the Matlab/Simulink environment, to achieve the necessary higher fidelity results. The ISM uses a multidomain, physics-based model for the vehicle that captures the mechanical, electrical, thermal interactions and controls aspects of the applicable vehicle mobility and power subsystems. The high fidelity component models are augmented with experimental parameter data when available and appropriate for the required fidelity of the investigation.

Figure 1 is a block diagram of the general interaction between the Vehicle Model, Automated Drive Commands, and the Environment Interaction. The environment corresponds to the thermodynamic properties of air surrounding the vehicle and a specific three-dimensional terrain with varying elevations, grades, and turns. Each course has a corresponding speed profile that an automated driver uses to generate input commands (accelerator, brake, and steer) to the vehicle model. This is similar to how a real driver adjusts his inputs based on desired speed, heading and feedback on how the vehicle is performing.

Each subsystem within the Vehicle Model is implemented as a library element in the Simulink environment. Library elements use defined common interfaces that include electrical, mechanical, and thermal domains for the inputs and outputs. The use of Simulink's library functionality allows the reuse of subsystem elements multiple times within a model and in an object oriented sense such that the specific input parameters can be varied. Elements include motors, generators, fans, their inverters and controllers, engines, thermal circuits and pumps, heat exchangers, vehicle dynamics, and terramechanics. In addition to system level design and component design, the fidelity of the controller models is such that they can be automatically converted into C-code (through RTW toolbox) for use in actual hardware. **Figure 2** shows a representative interconnection of component models to depict the interaction of the mechanical, electrical and thermal systems.

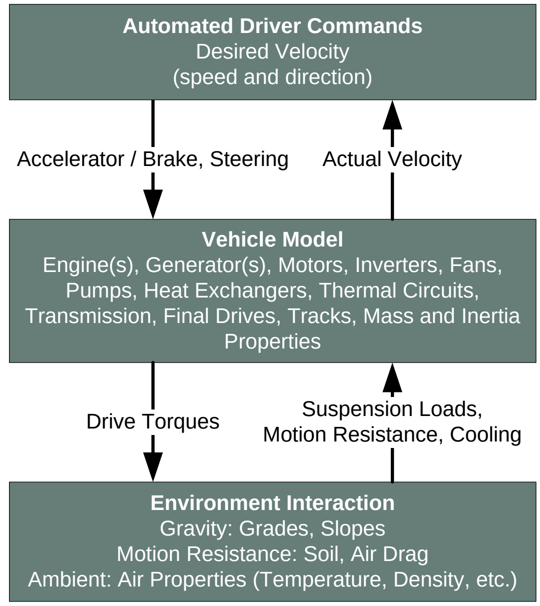

Figure 1. Top Level Integrated System Model. *The generic block diagram for the vehicle provides great flexibility to how the vehicle interacts with a variety of driver commands and the environment in which the vehicle is operated.*

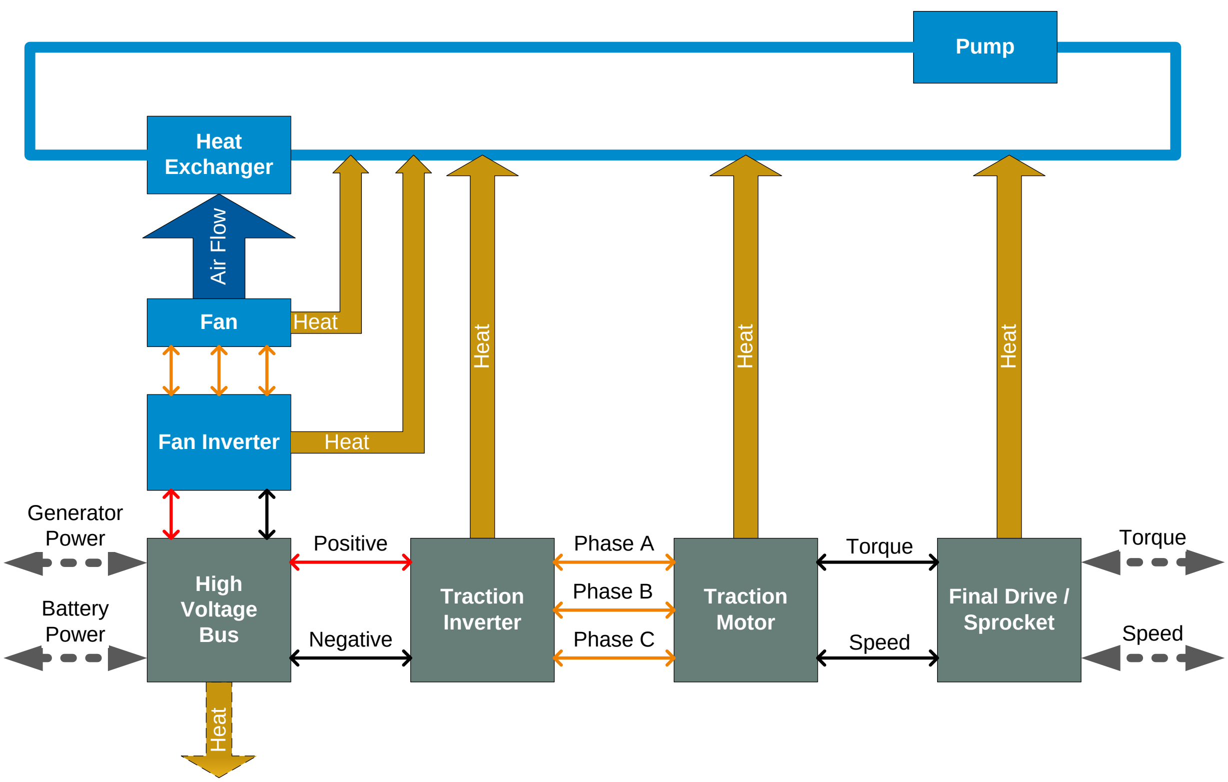

Figure 2. Component Model Interaction. *The multidomain physics-based component models capture mechanical, electrical and thermal interaction using well-defined interfaces.*

The greater level of detail in **Figure 3** highlights the interdependence between subsystems of a 3-Phase AC permanent magnet traction motor. Parameters used correspond to a specific motor. To provide the accuracy required for a high fidelity model, even these parameters are functions of state variables. An example of this is the rotor magnetic flux linkage that accounts for temperature dependency inherent in the magnet material and flux saturation as related to the specific geometry. The model captures the interaction of operating temperature as determined by the cooling system's ability to remove heat at prevailing ambient conditions and required current as a function of torque demand. It can be seen that the three major losses—core, copper, and windage—are functions of frequency, resistance, current, voltage, speed and machine specific parameters, which further shows the oversimplification that would result from using a single efficiency value or even a table lookup created under a specific set of conditions. It is important to have a multidomain model that manages the energy balance between mechanical, electrical, magnetic and thermal components, and the interdependencies of these in order to improve the accuracy of the results.

Duty Cycle Synthesis

At a high level, it is possible to calculate fuel consumption at a predetermined steady state condition or sets of steady state conditions. While this serves as a first order indication of a system's fuel consumption, it does not provide a good indication of the fuel economy that will be seen in the field because it ignores the dynamic and transient events that are part of normal operation. For passenger cars and trucks, the duty cycle is the EPA driving cycle [2]; for military vehicles it is described to some level of detail in the Operational Mode Summary/Mission Profile (OMS/MP) for that particular vehicle. The OMS/MP consists of a variety of conditions that include idle, primary roads, secondary roads, and cross country roads that contain various grades, speeds, and turning maneuvers. Typically, for each of these terrains, an average speed is defined over a given distance (or duration). These high level descriptions represent required course the average speed. In order to capture the inherent transient in such operations, we develop a speed profile (as a function of location on terrain) taking into consideration grades, turns, and straight sections of the course such that the total average speed meets the specified requirement.

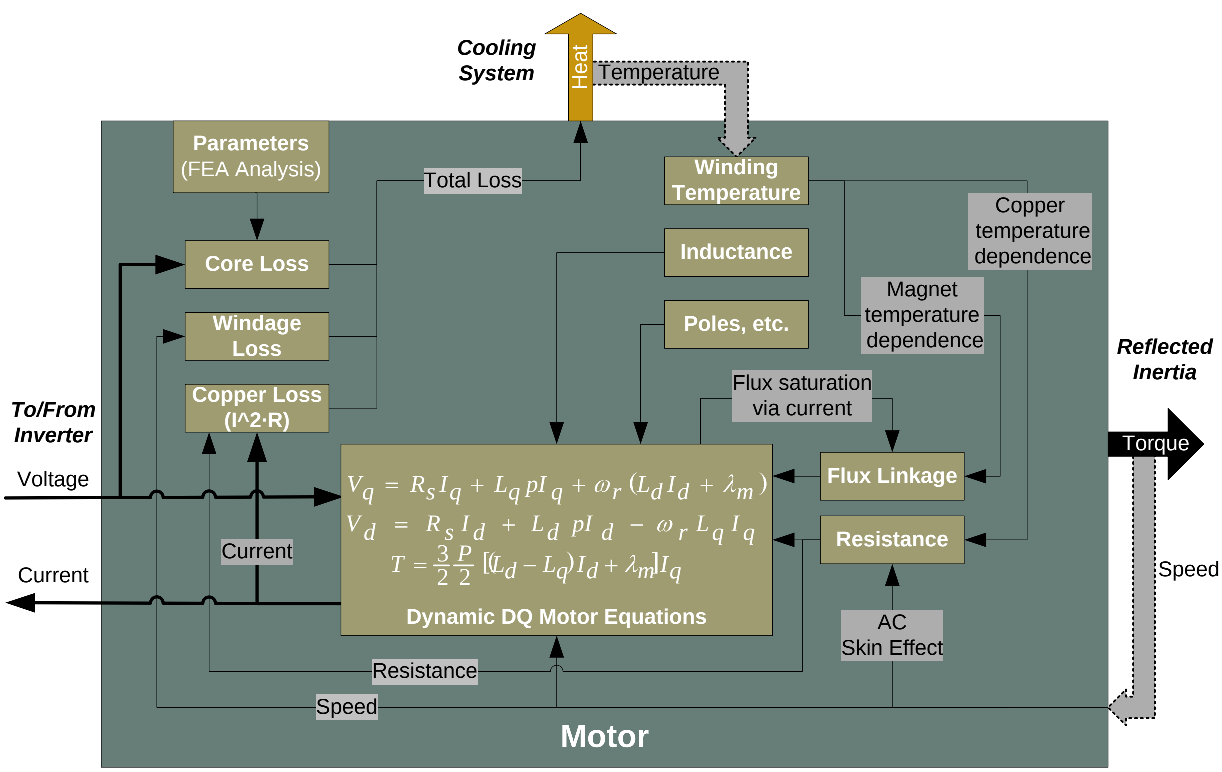

Figure 3. Detailed Component Model Interaction. *The element models capture the multidomain interactions such as how the resulting component temperatures affect the component's performance characteristics to more accurately predict performance and losses.*

Mission Profile	BAE Systems Implementation	Average Speed (kph)	Rolling Resistance (lb/ton)
Primary Road	BAE Systems Primary Road	56	90
Secondary Road	Munson Course	36	115
Cross Country, Wartime	Churchville B Course	15	134
Cross Country, Peacetime	Churchville B Course	6.5	134
Engine Idle	Stationary Idle Operation	0	n/a
Auxiliary Power	BAE Systems Quiet Watch	0	n/a

Figure 4. 180-Day Campaign. *Selected course segments with representative rolling resistance factors and desired operating speeds are mapped to customer-specified mission profiles that comprise the total vehicle distance travelled and operating hours.*

High level descriptions such as “cross country” are mapped to three-dimensional courses with turns, grades and higher rolling resistance values that are characteristic of this type of terrain.

Figure 4 depicts one possible mapping of an OMS/MP to our ISM model courses.

Figure 5 shows a graphical representation of a terrain model for the Churchville B cross country course at the U.S. Army’s Aberdeen Proving Grounds.

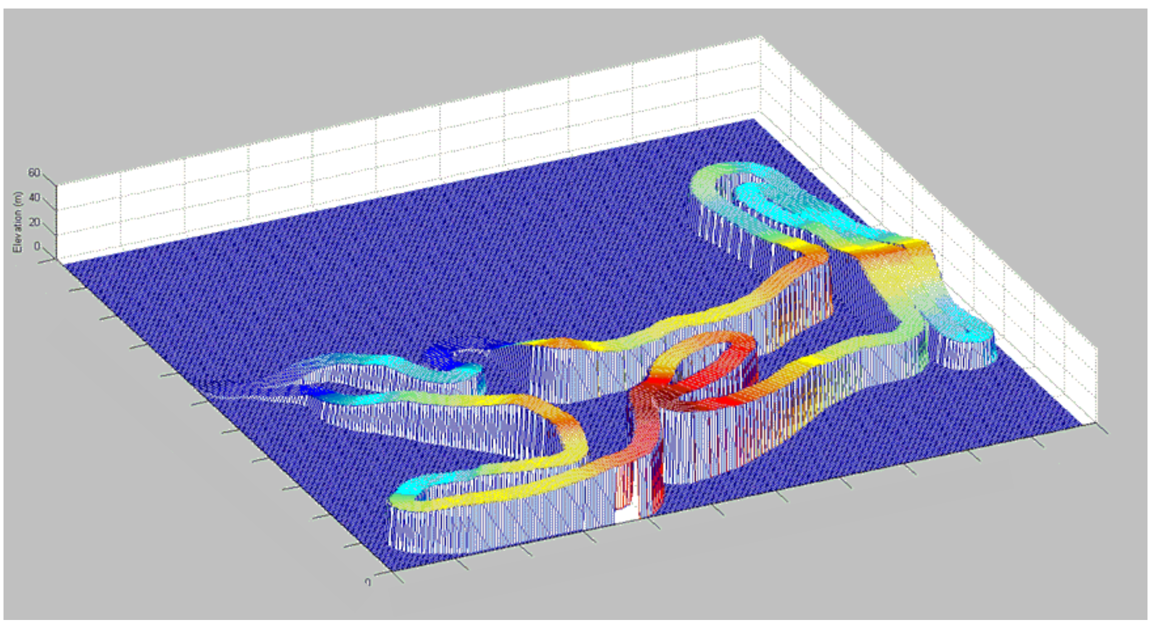

Figure 5. Three-dimensional Churchville B Cross Country Course Profile. *Selected segments of this hilly profile with turns are used to represent portions of the total mission profile.*

Unique Tracked Vehicle Characteristics

Unlike wheeled vehicles, tracked vehicles steer by imparting differential torque and speed to the inside and outside tracks. This means that when turning, there is a significant amount of lateral (across the track) slipping and corresponding frictional losses. This imposed track scrubbing during turns requires significantly more power than straight line driving. Accurately modeling the power needed requires track and vehicle geometry, along with soil parameters and the use of terramechanics equations. Terramechanics is a branch of engineering that uses dynamics and strength of materials to understand the interaction between tracks/tires and various soils [3]. The ISM model uses an experimentally validated terramechanics model. **Figure 6** compares the model predictions to the published Jaguar tracked vehicle experimental results.

Representative Motor Efficiency Map

The calculation of fuel consumption is naturally related to the efficiencies of all the components in a vehicle (engine, generator, inverters, motors, transmission, final drive, etc.), motion resistance (grade, soil deformation, rolling friction, air drag, etc.), as well as other loads supported by the prime mover (accessory loads, cooling fans, export power, etc.). These parameters have substantially different physical relationships to fuel consumption and even interrelate to one another. Using single point values or even a manageable number of selected operating points quickly becomes impractical and can result in compounded error. As an example, the efficiencies in the ISM model are functions of pertinent variables as a result of their physics based construction. **Figure 7** shows a traction motor efficiency as a function of torque and speed at a specific temperature; the thermal model provides a temperature feedback that factors into the efficiency of the traction motor.

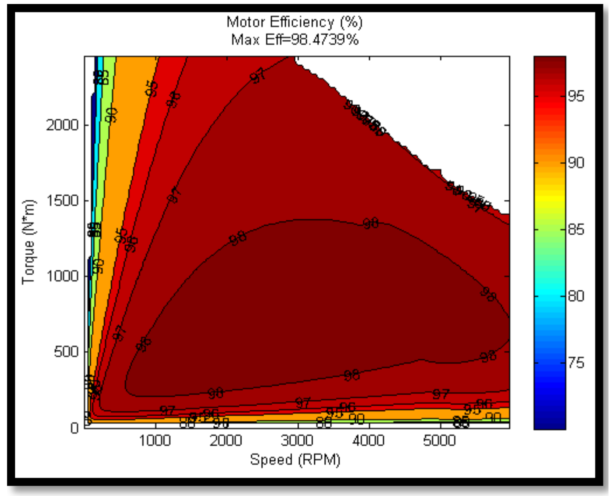

Figure 7. Motor Efficiency Map. *Motor efficiency over the entire operating torque and speed range as a function of temperature is used to more accurately capture losses while operating over the duty cycle.*

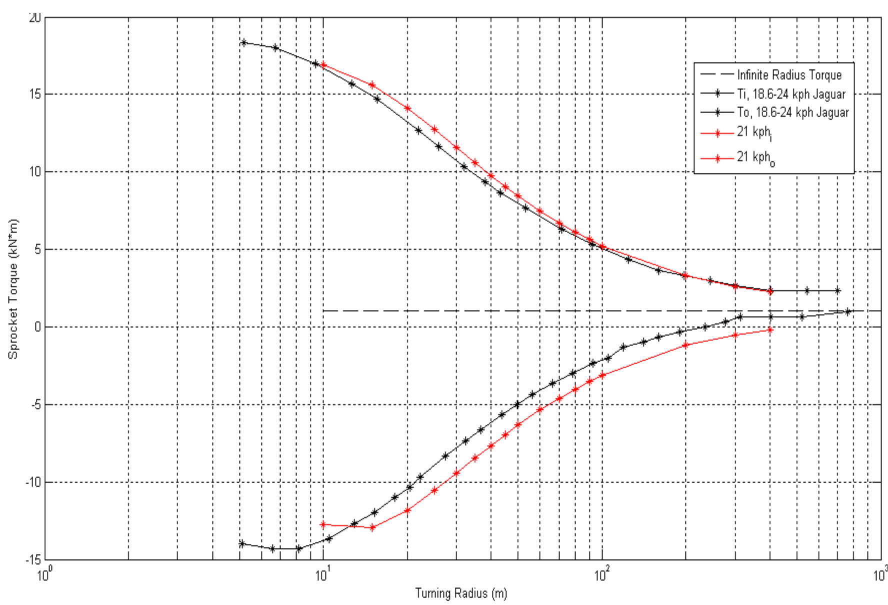

Figure 6. Sprocket Torque vs Turning Radius. *The ISM terramechanics model is validated against Jaguar tracked vehicle experimental data.*

Controls Impact Efficiency

The efficiency of a motor and its inverter is not determined uniquely by specifying a torque and a speed; it is a strong function of how it is controlled. A motor could be controlled, for example, with a simple Volts-per-Hertz (V/Hz) strategy or a more sophisticated Field Oriented Control (FOC) strategy which brings the benefits of increased efficiency and response by directly controlling the torque producing current [4]. Likewise, inverter efficiency will be heavily influenced by switching frequency and choice of switching techniques such as regular PWM or a variety of Space Vector Modulation (SVM) methods [5].

Another example of controls impact relating specifically to certain hybrid architectures is the freedom to choose the operating speed of the engine at a given power level (in contrast, in a conventional mechanical drivetrain, the engine speed is directly related to road speed through the torque converter speed and transmission gear ratio). The use of specific and optimized control strategies that align with the expected real life implementation allows for the accurate determination of both the efficiency and the automotive performance of the vehicle.

Acceleration and Braking

Acceleration and braking are key performance points in their own right; they are also an important part of a realistic duty cycle in the determination of vehicle fuel economy. The ISM accurately models acceleration with its gear shifting controls in both hybrid and mechanical architectures. An important feature of hybrid vehicles is regenerative braking, the ability to instantaneously reverse the torque output of the traction motors to create a braking torque. In this mode, the traction motors act as generators and direct power to the high voltage bus to power other loads, reduce engine fuel burden, or for storage in the battery system. The recovered energy is energy that would otherwise be dissipated as heat in the brakes of a conventional vehicle. Energy stored in the battery is then later used during acceleration events reducing the amount of fuel that would otherwise have been used. A battery system also offers performance advantages in that its power augments the engine's output and is available virtually instantaneously compared to the response time of a large engine.

Competing Architectures

For the purpose and scope of this paper, we narrowed our selection down to two tracked vehicle architectures. **Figure 8** shows a conventional mechanical drive and **Figure 9** shows a series hybrid electric drive arrangement. We held the top level vehicle characteristics constant. We used a Heavy Brigade Combat Team 70-ton weight class platform to fix parameters such as the total Gross Vehicle Weight

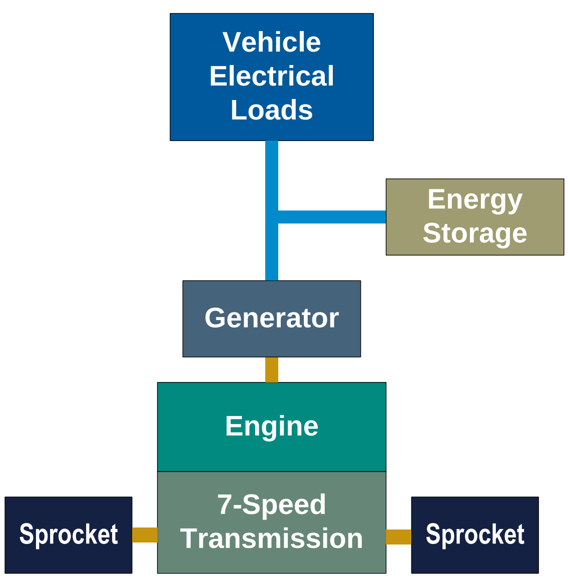

Figure 8. Mechanical Drive. *A 7-Speed transmission is used to represent mechanical drive attainable performance.*

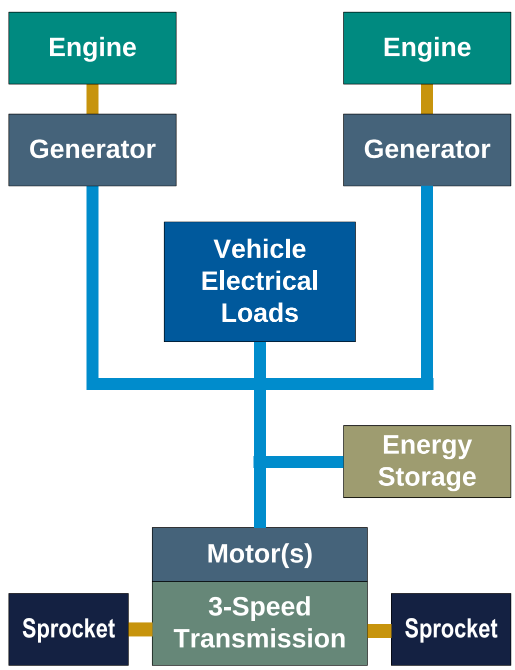

Figure 9. Series Hybrid Electric Drive. *A 3-speed transmission with dual engines is used to represent series hybrid electric drive attainable performance.*

(GVW), the overall vehicle physical dimensions, track dimensions, sprocket radius, running gear component characteristics and so on. Fan load is function of ambient temperature and engine power. Both architectures use identical electric fans so that the typically less efficient hydraulic fans of a mechanical architecture would not blur our focus on drivetrain efficiency over a duty cycle. One unavoidable area of difference is the engine installation due to the nature of the architectures themselves; the hybrid electric vehicle was architected with two smaller engines whose total power is equal to the power of the single engine in the mechanical architecture. The hybrid electric allows the use of two engines because there is no mechanical connection between them and the sprockets. The fuel map and full throttle curve were linearly scaled. The mechanical vehicle uses a conventional seven-speed transmission with torque converter. The series hybrid electric uses a three-speed gearbox. For Quiet Watch, mechanical drive uses an Auxiliary Power Unit (APU) given 25% efficiency (fuel energy to electrical energy delivery) which is typical for a military vehicle APU.

As seen in **Figure 10**, the low fuel efficiency (high brake specific fuel consumption – bsfc) of a large engine in the mechanical architecture during Quiet Watch mode would present a significant disadvantage. Design optimization for the mechanical drive would likely result in the selection of an APU to overcome this weakness. For our analysis, an APU with appropriate fuel consumption characteristics was used for the mechanical drive to reduce fuel usage.

Architectures for Producing 60 kW Electrical Power	Brake Specific Fuel Consumption (bsfc) (g/kW-hr)
Mechanical Drive (Single large engine)	392
Mechanical Drive (with an APU)	300
Series Hybrid Electric Drive (1 of 2 smaller engines)	254

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Figure 10. Quiet Watch Efficiency. *An APU was used with the mechanical drive to overcome the high fuel consumption rate for a single large engine during low power operation.*

Results

Figure 11 tabulates the model results of the two vehicle architectures when operated over the various courses at normal and / or hot conditions. The large differences in the Road March performance is attributed to the mechanical drive operating in the unlocked torque converter mode to maintain the required slow speed. On the Primary Road Course and the Munson Course, the mechanical drive outperforms the series hybrid electric drive since it is able to operate quite efficiently on these relatively benign courses. When the vehicle is operated on the hilly Churchville B course with many turns, the series hybrid outperforms the mechanical drive by benefitting from braking power regeneration, efficient steering and engine speed/load fuel map optimization. On the Steady State Rated Speed run, the mechanical transmission experiences significant spin losses and

Driving Fuel Consumption	Units	Road March	Primary Road Course	Steady State Rated Speed	Road March (Hot)	Churchville B Course	Churchville B Course	Munson Course
Temperature	°C	25	25	25	49	49	49	49
Speed	kph	2.5	56	72	2.5	6.5	15	36
Fan Load (Electric Power)	kW	8.3	75	75	20.7	150	150	150
Auxiliary Load	kW	60	60	60	60	60	60	60
Series Hybrid Electric Drive	mpg	0.196	0.518	0.683	0.177	0.158	0.249	0.333
Mechanical Drive	mpg	0.0778	0.528	0.668	0.0687	0.146	0.242	0.339
Percentage Improvement (Hybrid over Mechanical)	%	**152%**	**-1.9%**	**2.2%**	**158%**	**8.2%**	**2.9%**	**-1.8%**

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Figure 11. Steady State Driving Fuel Consumption. *The series hybrid electric drive is significantly better (~3% to ~158%) on several steady state courses while mechanical drive is minimally (~2%) better on two of the courses, which exemplifies the need for a representative duty cycle to accurately predict field fuel consumption.*

suffers from the engine not being able to adjust its speed to operate at the optimal fuel efficiency point in its fuel map.

Figure 12 tabulates the model results of the two vehicle architectures when operated in a Stationary mode producing auxiliary power to maintain vehicle functions (e.g., export power, air conditioning, communication, etc.). The dual engine architecture selected for the series hybrid electric drive provides great benefit for this type of operating scenario by operating one of its two engines to fully supply the power demands. A significant byproduct of the series hybrid electric drive architecture is it offers the potential for an unprecedented level of electrical export power. The mechanical drive, on the other hand, needs to operate its one larger engine low in its power band which is less efficient due to the increased frictional losses inherent in a larger engine.

Stationary Fuel Consumption	*Units*	*Stationary*	*Stationary (Hot)*
Temperature	°C	25	49
Fan Load (Electric Power)	kW	6.2	15.5
Auxiliary Load	kW	60	60
Series Hybrid Electric Drive	gph	5.47	6.24
Mechanical Drive	gph	7.88	8.62
Reduction in Fuel Burn Rate (Hybrid over Mechanical)	%	**30.6%**	**27.6%**

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Figure 12. Stationary Fuel Consumption. *During stationary operation the series hybrid electric drive consumes less fuel by using fuel at ~30% lower rate than the mechanical drive.*

As we showed previously in **Figure 4**, the 180-day campaign is comprised of representative operation on various courses at varying speeds to synthesize a comprehensive duty cycle that accounts for how the vehicle is operated over that duration. The results of summing the fuel consumed by the two drive systems is presented in **Figure 13** and shows that the series hybrid electric drive consumes ~10% less fuel than the mechanical drive.

180-Day Campaign Fuel Consumption	*Units*	*Fuel Consumption*
Series Hybrid Electric Drive	gal	8,931
Mechanical Drive	gal	9,955
Fuel Saved	gal	1,024
Percentage Improvement (Hybrid over Mechanical)	%	**10.3%**

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Figure 13. 180-Day Campaign Fuel Consumption. *During a 180-day campaign the series hybrid electric drive consumes ~10% less fuel than the mechanical.*

Similarly, the 72-hour mission which is comprised of representative operation on various courses at varying speeds to synthesize a comprehensive duty cycle that accounts for vehicle operation during this period. The results of summing the fuel consumed by the two drive systems is presented in **Figure 14** and shows that the series hybrid electric drive consumes ~6% less fuel than the mechanical drive.

72-Hour Mission Fuel Consumption	*Units*	*Fuel Consumption*
Series Hybrid Electric Drive	*gal*	*727*
Mechanical Drive	*gal*	*773*
Fuel Saved	*gal*	*46*
Percentage Improvement (Hybrid over Mechanical)	*%*	***6.0%***

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Figure 14. 72-Hour Mission Fuel Consumption. *During a 72-hour mission the series hybrid electric drive consumes ~6% less fuel than the mechanical.*

Discussion

We have shown that while basic equations may give first order approximation of a vehicle performance, a model with sufficient detail and interaction between the many elements is necessary to accurately predict fuel consumption. The difference in fuel consumption by the two architectures for steady state operation provides motivation to use improved models for the prediction of fuel used to better correspond to the real world transient operation over a specific duty cycle at the prevailing ambient conditions. Because a realistic duty cycle includes turns, grades, acceleration and braking events, a model is needed that can handle these types of events along with the controllers and algorithms required by the subsystems involved. It has been shown by example, using a traction motor, that efficiency in many subsystems such as motors, generators and inverters are complex functions of multiple variables from the nature of the physics involved in the operation of such devices.

From our work comparing the performance of the different architectures, we can make the following observations.

- At constant speeds and highway conditions such as primary roads, a conventional mechanical vehicle will typically have a slightly greater driveline efficiency than a hybrid electric and therefore gets better fuel economy under these conditions. Although electric motors and inverters, especially with advanced controls, have very high efficiencies, the conversion losses from mechanical to electrical and back to mechanical results in nominally greater total loss.
- Braking and turning events that occur during a real duty cycle enable the hybrid to recapture energy through regenerative braking instead of dissipating heat in the mechanical brakes.
- Energy that is recovered and stored in the battery system has a compound effect of not only recovering that energy for reuse but also not having to expend energy for additional fan power to cool the brake elements had that energy been rejected as heat.
- The hybrid can operate the engine at its most fuel efficient point for a given required power or completely shut down the engine when loads can be otherwise supported by the battery.
- Fuel efficiency gains are realized when hybrid drive component efficiencies are high, the battery system is sized large enough to recapture sufficient energy, and the expected duty cycle contains a reasonable amount of braking and turning events.

Summary/Conclusions

U.S. Army ground vehicle acquisitions have identified improved fuel economy and power management as a priority to reduce fuel cost and to reduce the exposure of supply line personnel during battle operations. Exploration and application of advanced architectures is possible without settling for legacy-type architectures based on the use of oversimplified steady state requirements.

This paper outlines a flexible model architecture and how to integrate vendor-specific component models suitable for rapid exploration of design alternatives. The importance of how control and power management strategies manage the interaction of the subsystems as the vehicle operates over the prescribed synthesized duty cycle is briefly discussed to encourage adaptation and further exploration in this area.

We demonstrate the application of the methodology in the design of a representative combat vehicle to predict fuel consumption on various steady state runs, a 72-hour mission and a 180-day campaign. When compared to traditional mechanical designs, our simulations show up to a 10% fuel economy improvement over the longest duration duty cycle. In some cases, the performance was as high as 158% better; in a few instances it was nominally worse by ~2%.

The ability to integrate high TRL hardware on a platform to verify all critical performance requirements early in a program reduces risk. This design approach arrives at an integrated system model to optimize overall automotive performance, fuel efficiency, and power management. The outlined approach reduces program risk by using multidomain physics-based component models representing high TRL hardware to increase the accuracy and confidence of the performance predictions at the system level in a relevant operational duty cycle.

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Definitions/Abbreviations

180-day campaign ....A notional deployment lasting 180 days

72-hour mission ....A notional mission lasting three days, 72 hours

APU...............Auxiliary Power Unit

Aux................Auxiliary

bsfc ....Brake Specific Fuel Consumption

Churchville B .A course profile maintained at U.S. Army's Aberdeen Proving Grounds

EPA ....Environmental Protection Agency

FOC................Field Oriented Control

GVSETS.........Ground Vehicle Systems Engineering and Technology Symposium

GVW ....Gross Vehicle Weight

HED ....Hybrid Electric Drive

ISM ....Integrated System Model

Matlab/ Simulink ....MATLAB® is a high-level language and interactive environment that enables you to perform computationally intensive tasks faster than with traditional programming languages such as C, C++, and FORTRAN. Simulink® is an environment for multidomain simulation and Model-Based Design for dynamic and embedded systems. Ref: http://www.mathworks.com

NDIA.............National Defense Industrial Association

OMS/MP ....Operational Mode Summary/Mission Profile

P&M..............Power And Mobility

RTW..............Real-Time-Workshop

SVM ....Space Vector Modulation

TARDEC........United States Army Tank Automotive Research, Development and Engineering Center

TRL ....Technology Readiness Level