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Power System Design And Optimization For Tactical Wheeled Vehicles

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Abstract

The U.S. Army TACOM-TARDEC is conducting a trade study on improving the design of next-generation Tactical Wheeled Vehicles (TWV) with the use of optimized hybrid-electric power system architectures. The objectives for this effort include reducing the overall fuel consumption and thus cost of operation for the military's fleet of tactical wheeled vehicles, optimizing the mobility performance to mass and space claims of the vehicles' power systems, and enabling those vehicles with enhanced electrical power generation and storage capabilities useful for field operations. The trade study involves the creation and utilization of high-fidelity vehicle models each with many permutations of power system model to evaluate the relative capabilities of several variations of hybrid-electric architectures to determine the ideal power system and corresponding control scheme to select for the next-generation of tactical wheeled vehicles.

This study focused on evaluating the potential power system designs for Classes III, VI, VII, and VIII tactical wheeled vehicles. Several power system architectures were chosen for analysis including a traditional diesel engine for the baseline system, and three hybrid-electric power systems: series hybrid, parallel hybrid, and series-parallel hybrid. The hybrid-electric power systems provide the same vehicle mobility capabilities as the traditional diesel engine, but incorporate secondary power sources and energy storage components that enable the use of smaller more fuel-efficient power components that can incorporate controls management tools to further optimize the system's fuel economy. The generator and battery components in these hybrid-electric architectures further enhance fuel economy by allowing the system to store energy during vehicle braking that would otherwise be lost with the traditional diesel engine architecture.

Detailed models of these power systems and corresponding power management algorithms were developed and integrated with the high fidelity vehicle models in a front-end simulation tool built upon a standardized domain neutral, object-oriented, multi-domain modeling language that was established for component-oriented modeling of complex systems. All power systems were developed to either meet or exceed typical vehicle mobility requirements for existing Classes III, VI, VII, and VIII vehicles. Power management algorithms were developed and implemented for optimal control of each power system. The trade studies involved the evaluation of variables including the engine, transmission, battery, power management algorithm, and electric machines. The first phase of the trade study was to determine an optimal set of power system components for each architecture (such as series, parallel, series-parallel, or conventional) along with optimal power system control schemes to apply accomplish this. The second set of trades was to determine which architecture provides the best performance in terms of fuel economy, utility, and mass/space savings while considering currently available hardware for these power system architectures.

Keywords: HEV (hybrid electric vehicle), mobility, modeling, powertrain, regenerative braking

1 Introduction

The next generation of tactical wheeled vehicles will require new and improved power system designs. As fuel prices continue to rise and as power draws become larger on tactical wheeled vehicles, the performance of the power system becomes more important. Further, the state-of-the-art hybrid-electric power systems provide power generation and storage capabilities that provide for considerable added functionality for vehicles military field operations. For these reasons, the U.S. Army TACOM-TARDEC is investigating the means to improve the design of numerous Tactical Wheeled Vehicles (TWVs) with the use of new hybrid-electric power system architectures.

An extensive set of high-fidelity models were developed with advanced modeling and simulation software for use in determining and evaluating the merits of hybrid-electric power systems for TWV power systems. Sixteen six-degree-of-freedom vehicle models were developed to represent each class of vehicle of particular interest to TACOM including classes III, VI, VII, and VIII. Four primary power system architectures were modeled for each class of vehicle; these architectures include a conventional diesel, series-hybrid, parallel-hybrid, and series-parallel.

The vehicle and power system models allow direct calculation of each configuration's capacity requirements for the vehicle's to meet the relevant mobility performance requirements, determination of the power system configurations that provide optimal results in mass/volume savings onboard each vehicle, and any respective gains in fuel efficiency that may result from each design. This continues the work described in Milner [3]. The study will culminate in the determination of the viability and value of implementing hybrid-electric power systems in tactical wheeled vehicles.

2 High-Fidelity TWV Models

The study focused on the design and evaluation of vehicle models for four classes of tactical wheeled vehicles: Classes III, VI, VII, and VIII. These classes include vehicle weights in the following respective gross vehicle weight ranges: Class III- 4,535 to 6,803 Kg, Class VI- 8,618 to 7,257 Kg, Class VII- 11,793 to 15,875 Kg, Class VIII- 28,122 to 32,658 Kg.

The vehicles models are comprised of fully integrated vehicle component systems including the vehicle chassis, independent wheels with pneumatic (compressible) tires, suspension systems, driveline, autonomous path navigation controls, and complete power systems with relevant power management control systems. The vehicle models are simulated over detailed terrain geometries with various soils and paved surfaces, and include gravitational and air drag forces. Four power system architectures were modeled to represent each variation of power system design: conventional diesel, series hybrid-electric, parallel hybrid-electric, and series-parallel hybrid-electric combination.

The models' simulated forces and motion include calculations for lateral and longitudinal wheel slip, traction and normal terrain-wheel forces and moments, suspension forces and deflections, power system forces, 6-DOF chassis movement, etc. The model accounts for all force and motion interactions between the wheels, suspension system, and the chassis. Fig. 1 shows the top level of one vehicle model with representations for the complete vehicle structure, power systems, and path navigation control systems. The figure also shows a sample 3-D graphical rendering of one vehicle model for the FMTV 1083 A1 (Class VII) vehicle.

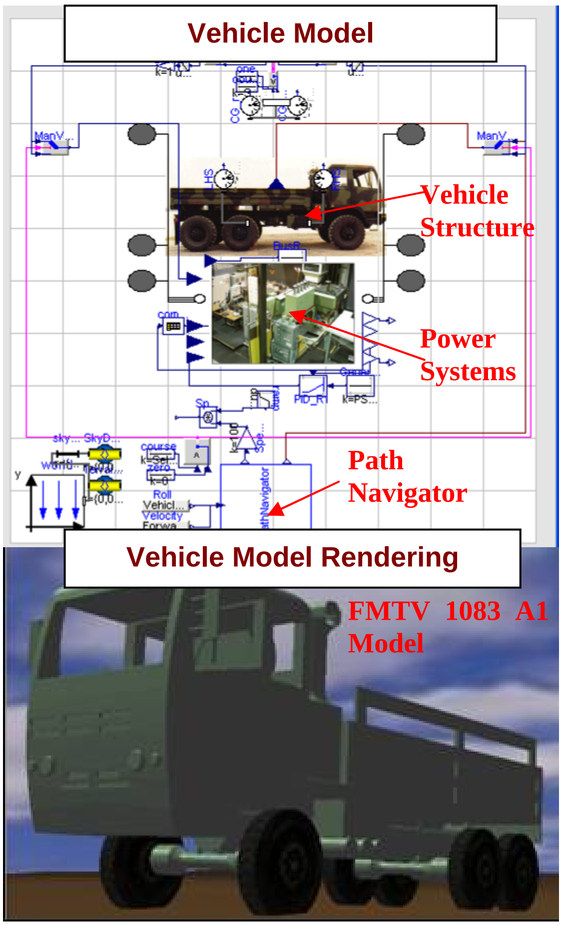

Figure1: Top-Level View of Vehicle Model (top) & Graphical Rendering of Vehicle (bottom)

2.1 Vehicle Structure

The vehicle structure models were modeled for three common primary configurations of tactical wheeled vehicle chassis including two, three, and four axle vehicles (four, six, and eight wheeled vehicles respectively) that fall within these vehicle classes. Specifications were applied to each of these respective configurations from actual vehicle data of tactical wheeled vehicles within those classes. Thus representative setups were applied to all permutations of the models to enable an analysis of the performance of class of vehicle with each power system studied. Figs. 2-4 show the three variations of vehicle structure models and the vehicles that were loaded into each of those models. The Class III HMMWV M1113 and Class VI FMTV M1078 A1 were included in the 4-Wheeled (2-axle) Structure. These are shown in Fig.2. Both of these vehicles employ Ackerman steering of the wheels on the front axle, but propulsive power to all four wheels.

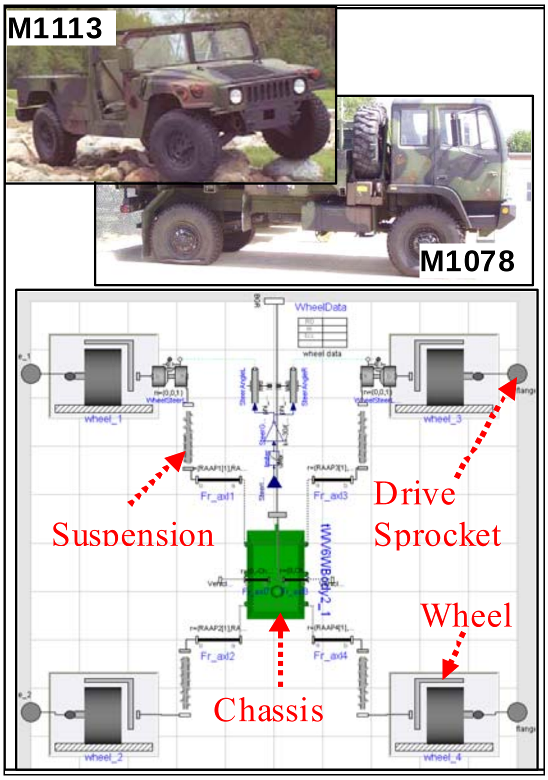

Figure2: HMMWV M1113 (Class III) and FMTV M1078 A1 (Class VI) Vehicles (top) & Vehicle Structure Model for 1-Axle Vehicles (bottom)

The FMTV M1083 A1R was included in the 6-Wheeled (3-axle) structure. This heavier duty version of the FMTV line of tactical wheeled vehicles employs Ackerman steering on the front wheels and power to all wheels. The vehicle and its corresponding model are shown in Fig.3.

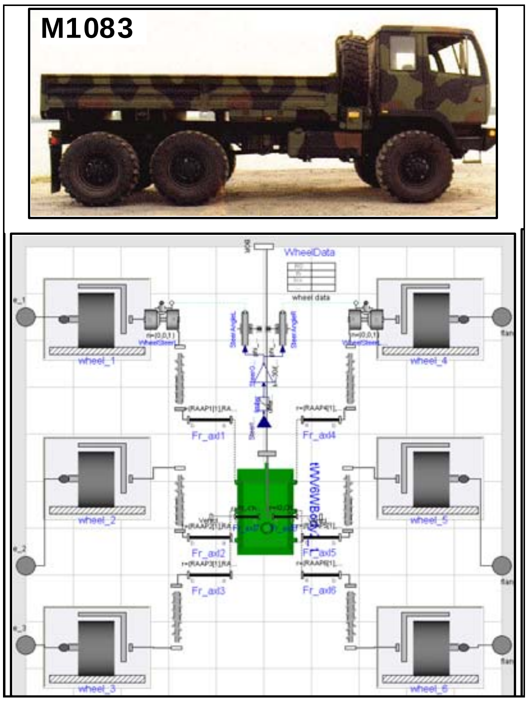

Figure3: FMTV M1083 (Class VIII) Vehicle (top) & Vehicle Structure Model for 3-Axle Vehicles (bottom)

The HEMMT M1120 A4 was included in the 8-Wheeled (4-axle) structure. This vehicle employs Ackerman steering on the two front axles, and powers all wheels. The vehicle and its corresponding model are in Fig.4.

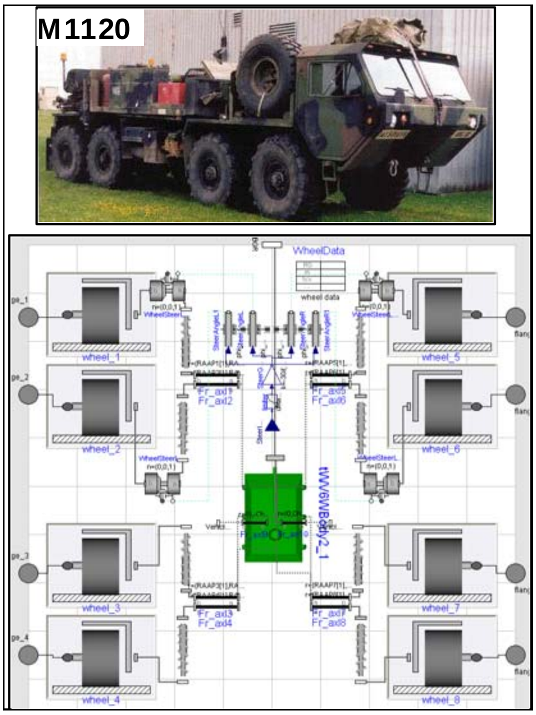

Figure4: HEMMT M1120 A4 (Class VIII) Vehicle (top) & Structure Model for 4-Axle Vehicles (bottom)

2.2 Power Systems

The vehicle models included four variations of power system architectures including: conventional diesel, series hybrid-electric, parallel hybrid-electric, and series-parallel hybrid-electric. These power systems provide power to the wheels to impart sufficient tractive effort to move the vehicle per driver inputs. The hybrid-electric power systems provide additional paths with which the power is routed to the wheels. The advantages of the hybrids include flexibility in the sizing and placement of the power system components, the capability to recover energy normally lost when braking, and capacity to store substantial amounts of energy in the vehicle's battery for a variety of functions.

2.2.1 Power System Architectures

This conventional diesel power system essentially contains a diesel engine with a direct mechanical link through a transmission and other driveline components to the vehicle's wheels. This power system is commonly used in most vehicles today and serves as the baseline power system design for this study. The conventional diesel power system is shown schematically in Fig.5.

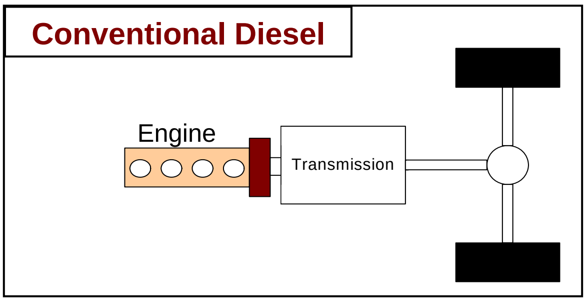

Figure5: Conventional Diesel Power System

The parallel hybrid-electric power system has two sources of primary power supplied to the wheels: a generator/motor and the diesel engine. This system typically includes an engine with speed management controls that can be run more fuel-efficiently than its conventional diesel counterpart, and a battery system for storing energy during vehicle braking further enhancing the vehicle's fuel efficiency. The engine and generator/motor in the parallel hybrid-electric power system are mechanically connected to the vehicle's wheels as shown in Fig.6.

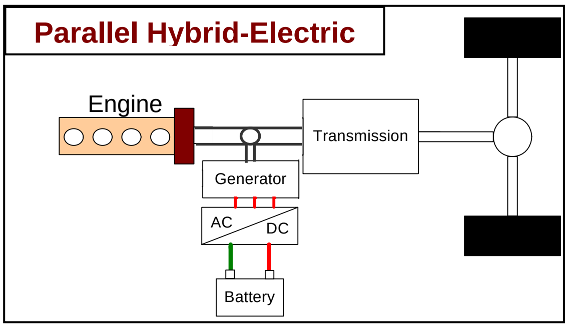

Figure6: Parallel Hybrid-Electric Power System

The series hybrid-electric power system also includes two primary sources of power, a diesel engine and a battery, which are electrically connected to motors that provide power to the vehicle's wheels. The series hybrid's engine can be maintained at its point of optimal fuel efficiency during operation, and its motor/generator system can store energy normally lost during braking to provide better fuel efficiency than that of the conventional diesel power system. The series hybrid-electric power system is shown in Fig.7.

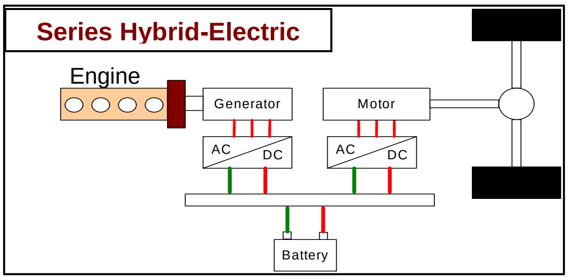

Figure7: Series Hybrid-Electric Power System

The series-parallel (combination) hybrid-electric power system has the same two sources of power but with the engine mechanically connected through a planetary gear set and motor(s) to provide power to the wheels. The series-parallel engine can be maintained close to its point of optimal fuel efficiency by control of its speed through direct commands to the relative speeds of the planetary gear set through control of the accompanying generator. The series-parallel hybrid-electric power system is shown in Fig.8.

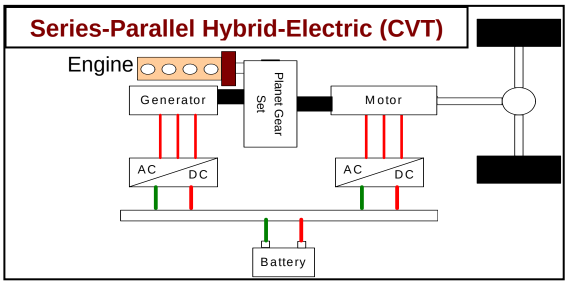

Figure8: Series-Parallel Hybrid-Electric Power System

All of the hybrid-electric power systems could potentially provide improved mass and space savings relative to the conventional diesel by allowing use of more efficient power components. They can also employ advanced system controls that can provide improved fuel efficiencies for vehicles.

2.2.2 Power System Models

The power systems architectures were modeled with electric component libraries and custom code including batteries, engines, generators, motors, transmissions, and brakes. The conventional diesel power system model includes the diesel engine, a multi-speed transmission, gears, and brake systems as shown schematically in Fig.9.

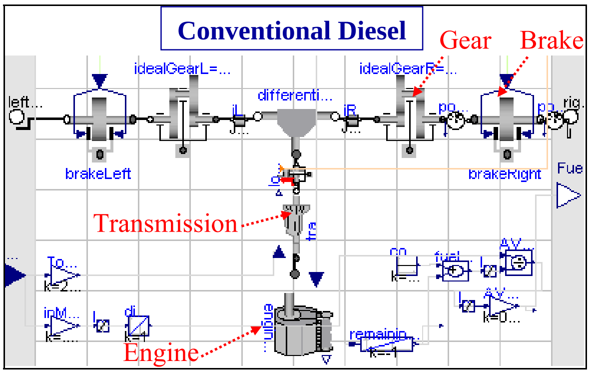

Figure9: Model of Conventional Diesel Power System

The series hybrid-electric power system model includes the same gears and brake systems but connected to a traction motor that is electrically connected to a bus including the diesel engine, generator, and battery system as shown schematically in Fig.10. Power is transferred from the engine or battery through the generator to either the vehicle's wheels for propulsion, or from the wheels to the battery for energy storage.

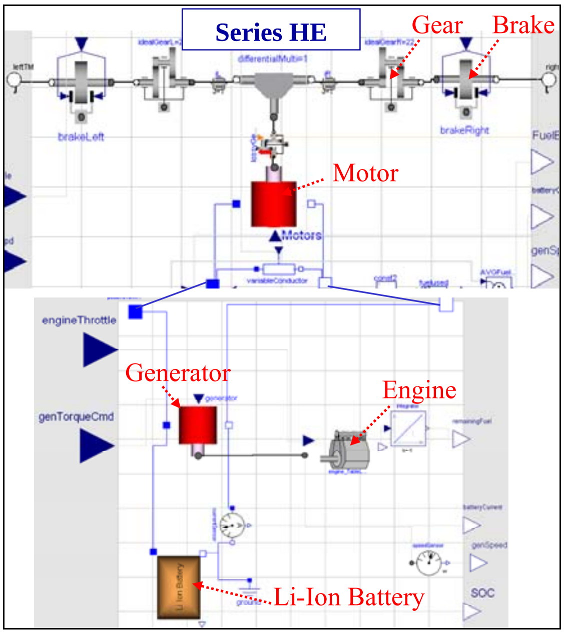

Figure10: Model of Series Hybrid-Electric Power System

The parallel hybrid-electric power system model includes the same transmission, gears and brake systems, but they are mechanically connected to both a generator/motor and a diesel engine as shown in Fig.11. Power is transferred from either the battery or engine to the wheels for propulsion, or from the engine or wheels to the battery for energy storage.

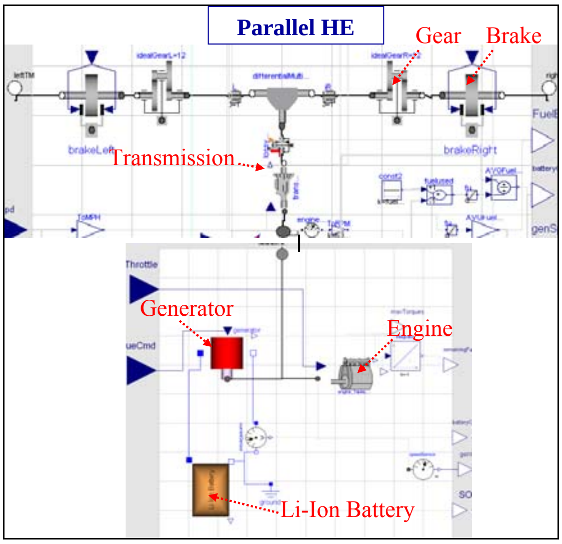

Figure11: Model of Parallel Hybrid-Electric Power System

The series-parallel hybrid-electric power system model is essentially built as a combination of the series and parallel power systems. It includes the same transmission, gear, and brake components but connected to two main power sources: one is the traction motor and the other is the engine and generator set linked via a planetary gear set as shown in Fig.12. The battery is electrically connected to both the generator and the traction motor. Power is transferred from either the battery or engine through either the generator or motor to the wheels for propulsion. Power is routed from the engine or wheels to the battery for energy storage.

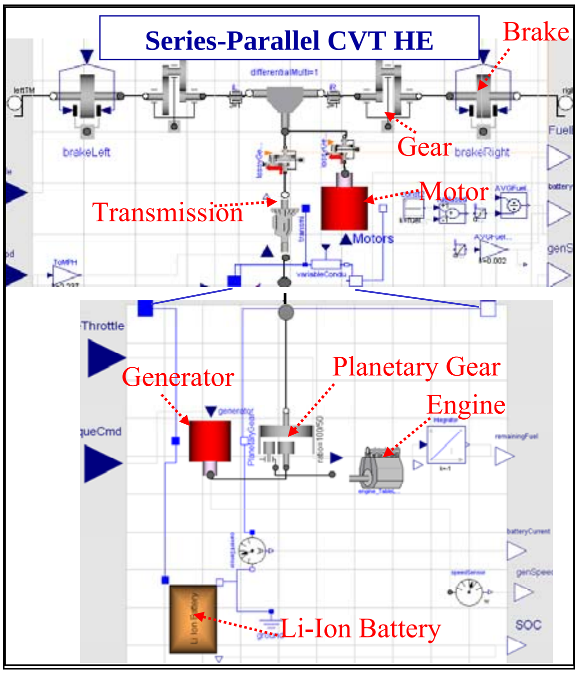

Figure12: Model of Series-Parallel Hybrid-Electric Power System

The battery in all three hybrid-electric power systems is designed as an equivalent circuit of a Lithium Ion battery, and includes state-of-charge (SOC) and temperature-dependence functions for its resistors, capacitors, and voltage source parameters. The engine is comprised of a torque-speed lookup table linked to an engine shaft and lookup table calculations for engine brake specific fuel consumption. The motors and generators calculate electromotive torques and apply them to rotational inertias that are linked to the final drives of each wheel. The transmission provides torque and speed scaling between drive train components. The brakes provide rotational friction for controlled braking when necessary.

2.2.3 Power Management System

The power management system provides throttle or braking commands to the relevant power systems including the engine, generator, motor, and brakes based upon the driver's commands and upon the power and energy available in the vehicle's power system. This system controls the conversion of chemical, electrical and mechanical energies in the hybrid power systems to yield optimal fuel economy while sustaining the vehicles requisite performance. Preliminary versions of such power management systems have been developed for and integrated into each hybrid power system in the vehicle models for this purpose, but further investigations are underway to refine them.

For all hybrid-power systems, the power management system is principally designed to operate the vehicle's engines as close to the minimum brake-specific-fuel consumption (BSFC) for the specific torque, speed, and power levels at which the engine is operating. Fig.13 shows a power vs. speed plot and the sample engine and BSFC for which the power management system would command the engine to operate near.

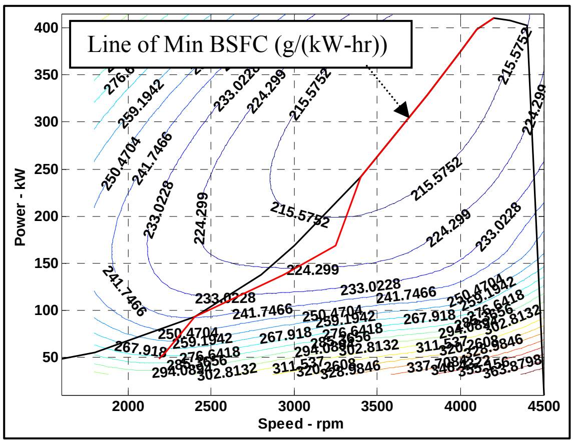

Figure13: Fuel Consumption Map and Minimum BSFC Line

This power management system for the parallel hybrid-electric power system is designed to alternate between operation with the engine-only, with the generator/motor only, or with both the engine and the generator based on seven primary states of operation. These states of operation include:

- <u>Wide-open throttle</u>: Maximize acceleration by applying maximum engine and motor power to drive the wheels.
- <u>Braking</u>: Quick deceleration. Prioritizes braking with electrical regenerative braking, but supplements it with conventional hydraulic braking when necessary.
- <u>Cruising (engine-only powered)</u>: Maintain a steady high speed where energy usage is optimal using the engine only.
- <u>Cruising (motor-only powered)</u>: Maintain a steady low speed where energy usage is optimal using the engine only.
- <u>Cruising (motor + engine powered)</u>: Transition period between the motor-only and engine-only states. Blends the use of the engine and motor to maintain speed.
- <u>Regeneration</u>: Prioritizes recharging of the battery from a low SOC level. Some energy is drawn from the engine to the battery.
- <u>Discharge:</u> Prioritizes discharging of the battery from a high SOC level. Will shut off the engine when possible.

These states are dependent upon the power system's designed capabilities and status along with the driver's demands. These include the accelerator pedal position α, brake pedal position β, vehicle speed V, and the battery's state-of-charge SOC as depicted in Table 1.

Table1: Power Management States for Parallel Hybrid-Electric

Operational State	α	β	SOC	V
Wide-Open Throttle	>0.95	0	--	--
Braking	--	>0	--	--
Cruising (Eng-only powered)	<0.95	0	$>SOC_y$	$>V_e$
Cruising (Gen-only powered)	<0.95	0	$>SOC_y$	$<V_g$
Cruising (Eng + Gen powered)	<0.95	0	$>SOC_y$	$>V_e$ & $<V_g$
Discharge	<0.95	0	$>SOC_g$	$>V_e$ & $<V_g$
Regeneration	<0.95	0	$<SOC_y$ or ($<SOC_s$ & course complete)	--

The table includes several variables used to determine the power system's state of operation. These include the velocity upper limit for generator-only operation V_e, velocity lower limit for engine-only operation V_g, the starting state-of-charge SOC_s, the minimum (yellow) desired state-of-charge for operation SOC_y, and the maximum (green) desired state-of-charge for operation SOC_y.

The series and series-parallel hybrid-electric power systems were designed to operate the engine at its most efficient regime of high-speed and torque to produce the power required for propelling the vehicle or charging the battery. The battery was maintained between an upper and lower limit of state-of-charge (SOC). The system is commanded to charge the battery when the SOC drops below the lower limit, but discharge the battery when the SOC rises above the upper limit. The series-parallel's controls combine this with some aspects of the parallel's control system.

2.3 Wheels

The wheel models consist of hub, wheel, and pneumatic tire components. The tire mass has a primary rotational degree of freedom about its hub mass that is affixed to the suspension. The model calculates and exerts upon these components all forces and moments associated with the ground-to-vehicle interactions and propulsion torque provided from the power system during the simulation.

The forces and moments acting upon the wheel model's components include empirically derived formulations of terrain-wheel forces for both on-road and off-road terrains. An equivalent contact point was determined on the tire surface based upon the deflection of the equivalent terrain-wheel contact point, the stiffness/damping characteristics of the tire surface, tire slip, and soil deformation.

The longitudinal and lateral on-road forces for each wheel were based upon the interpolation within empirically derived force-slip curves for normal truck tire loads. The force-slip curves were defined based upon a curve-fit for specific features of the curves including zero slip, slip of the maximum tire force, maximum longitudinal tire force, slip at sliding, and tire force at sliding as indicated in Fig.14. The slip is the negative difference between the speed of the center of the wheel and the speed of the wheel at the point of contact with the road all divided by the speed of the wheel, or wheel rotational speed multiplied by the wheel radius.

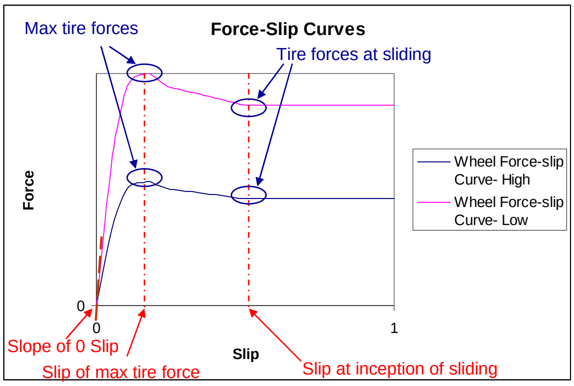

Figure14: Model of Series-Parallel Hybrid-Electric Power System

The off-road forces and moments were based upon off-road terrain-tire force calculations presented in Wong [5], with simplifications based upon equations from Shibly [4]. These primary soft-soil resistive forces included longitudinal and lateral off-road forces, and off-road moments due to soil compression, shear, and bulldozing forces. These were calculated based upon the approximation of the pressure distribution acting upon the tire due to the sinkage of the wheel into the ground.

Shibly [4] defined the normal pressure σ and shear force τ acting upon the tire with respect to the ground sinkage as determined based on the normal load on the wheel and the characteristics of the off-road terrain as described in Wong [5] for terrains such as dry sand, sandy loam, clayey dirt, and snow. This assumed a linear pressure distribution across the wheel-ground surface to allow a closed form solution to be applied for the calculations as described in Milner [2].

The model performs all transformation calculations included for all forces & coordinate frames of the wheel's connection points. The resultant forces are propagated through the suspension to the integrated vehicle structure.

2.4 Path Navigator

The automated path navigator simulates driver inputs suitable for automated negotiation of courses. This navigation system tracks the vehicle's position with respect to a predetermined course described by waypoints that define the desired trajectory for the vehicle to follow. The navigation system allows the vehicle to successfully navigate a course by tracking and actively minimizes the vehicle's body-fixed lateral and heading errors with respect to the desired path by providing closed loop controlled throttle commands to the power system and steer

commands to the front wheels for these Ackerman-steered vehicles.
The model maintains smooth and stable steering inputs by using look-ahead functions to apply torque commands/steer angles to minimize heading error and lateral error as indicated in Fig.15. The model is currently loaded with six options of courses: Churchville B, Perryman A, Perryman 3, Perryman 1-Outer, Munson, a Combination Churchville/Perryman/Munson course, a Flat plane course; the Churchville course is shown in the Fig.15.

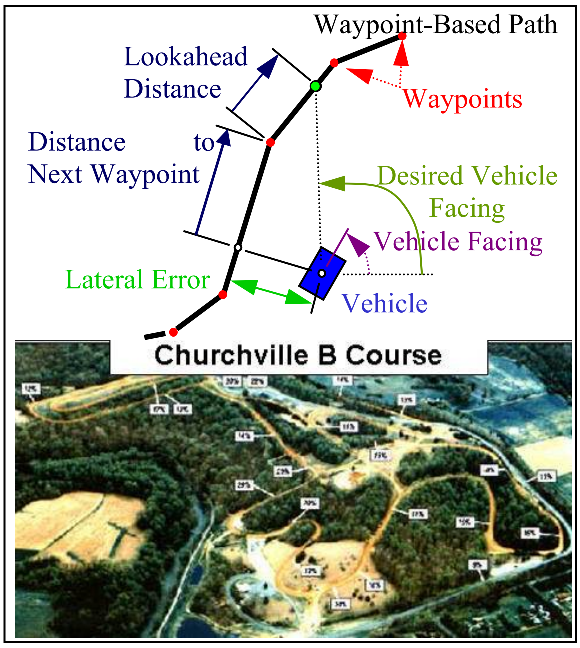

Figure15: (a) Discretized Waypoint-Based Path For the Desired Path (b) Churchville B Course

2.5 Graphics

Open source software was utilized to provide the graphical output for the simulation for the executable version of the model. For this purpose, the vehicle was visually rendered, converted to a mesh, and inserted in a graphics rendering tool. The tool shows the vehicle traversing the terrain based upon direct data inputs ported from the output of the executable simulation. The graphics script was setup with the rendered vehicle, and all courses.

3 Results

3.1 Model Validation

The vehicle models were validated relative to experimental data. The FMTV 1083 A1 vehicle model was specified per the actual vehicle data and then run on a flat, dry, hard road with a full-throttle straight-line acceleration from 0 to 50 mph. The performance results were then compared with data for the actual vehicle's identical acceleration run. The FMTV 1083 A1 is a conventionally powered diesel power train including a 330 hp diesel engine, an Allison MD3070 automatic transmission, and a final drive ratio of 7.8. No accessory loads were applied. Fig. 16 shows the modeled and actual vehicle speeds for the full acceleration test aligned well.

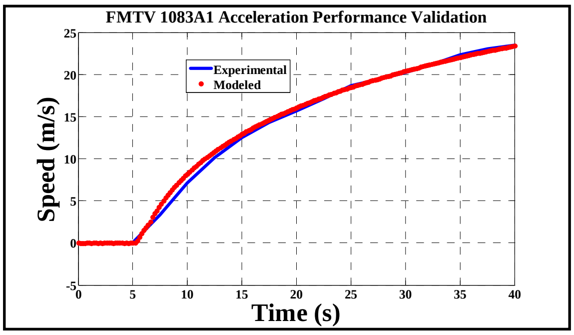

Figure16: Conventional FMTV 1083A1 Validation

The FMTV 1083 A1 vehicle model with the conventional power system was also run on the Churchville-B off-road course for comparison with the fuel economy of the actual vehicle traversing the same course. This course is a 3.7 mile (6 km) closed loop, off-road course including grades up to 29% and many turns; it is an accepted standard course for vehicle power train testing. The simulation used the clayey soil parameters per Wong [5].
The actual and modeled vehicles both traversed the Churchville-B course at an average speed of 20 kph and achieved average fuel efficiencies for the course of 2.7 mpg (or 1.15 km/l) and 2.6 mpg or (1.11 km/l) respectively. This confirmed both the modeled and actual FMTV 1083 A1 vehicles required similar energy usage to traverse the Churchville terrain. Thus the modeled and actual FMTV 1083 A1 were verified to have both comparable acceleration and fuel usage performance and thus could provide usable results for the trade study.

3.2 Model Power System Sizing

The hybrid-electric technology allows for increased options on engine to use in the power system. This was possible in the hybrid-electric vehicles with the inclusion of motors, generators, and batteries that provide supplemental power for the vehicles. These components were sized uniquely for each class of vehicle and type of power system such that every hybrid-electric vehicle matched or exceeded the performance of the conventional diesel power system for the same weight class of tactical wheeled vehicle. For example, the FMTV 1083 A1 vehicles with each power system including the conventional and all three hybrid-electric vehicles were modeled with appropriately sized power systems that provided comparable acceleration performance results in a full-throttle acceleration test as shown in Fig.17.

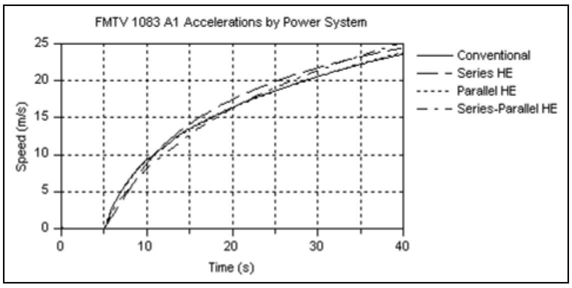

Figure17: Conventional FMTV 1083A1 Validation

In addition to matching the baseline performance of the conventional vehicles, sizing of the hybrid electric components was influenced by other commonly used requirements for military vehicles. Engine sizes were determined by requirements for maximum vehicle speed and speed on grade. Electric machine sizes were determined by maximum grade or 70% tractive effort requirements. Finally, generators were sized to match the power capability of the engines used.

3.3 Preliminary Simulation Results

All sixteen vehicle models, four classes of vehicles each with four variations of power systems, were simulated over the two well known test courses: Churchville-B and Munson. The Munson course is a 2.4 km course with few small hills and minimal turning unlike the Churchville-B course, but it is programmed as a three-lap run in simulations to help improve the accuracy of the calculations. The vehicles were run on these courses at an average velocity of 20 km/h and 30 km/h on the Churchville-B and Munson respectively.

The plot shown in Fig. 18 shows the average fuel economy vs. time for the FMTV 1078 (Class VI vehicle) over the Churchville-B course. The wiggle in the fuel economy measurements vs. time is indicative of the varying loads from traversing the hilly terrain. The exception is the series hybrid-electric which provided most of its propulsion by initially discharging its battery, but the sharp decline in the fuel economy over time is due to the engine recharging the batteries when the SOC is low. All the hybrid-electric vehicles were programmed to idle and recharge their batteries to their original state-of-charge if necessary after completing the courses so the fuel efficiencies could be directly compared; this is the cause of the sharpest decline in the fuel economy vs. time for the series hybrid-electric.

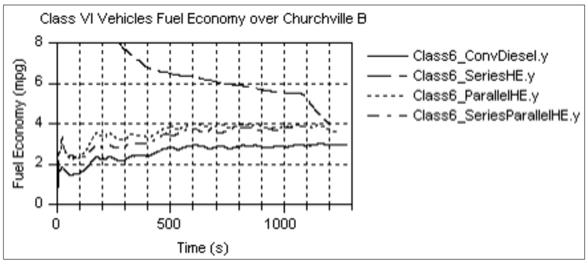

Figure18: Fuel Economy Results for FMTV 1078 on Churchville B by Power System

The preliminary results for all the vehicles run over Churchville-B are shown in Table 2 (The final numbers will depend on the final selections made for actual power system components and power system management algorithms). The results showed a clear improvement in fuel economy for most of the hybrid-electric vehicles over their respective conventional diesel baseline vehicle. This was most significant for the Class III vehicles with a Parallel hybrid-electric slightly edging out the Series hybrid-electric at about 9 mpg (or 3.8 km/l). The series and series-parallel hybrid-electrics had the best fuel economy of 3.9 mpg (or 1.7 km/l) for the class VI vehicle. The three hybrid-electrics had fairly comparable fuel economies between 2.9 and 3.1 mpg (or 1.2 and 1.3 km/l) for the class VII vehicle. There was little notable difference for the Class VIII vehicles.

Table2: Fuel Economy (mpg) for Vehicles on Churchville-B- *values pending final trade selections

Vehicle Class	Conv. Diesel (mpg)	Series HE (mpg)	Parallel HE (mpg)	Series-Parallel HE (mpg)
Class III	6.2	8.9	9.0	6.9
Class VI	3.0	3.9	3.5	3.9
Class VII	2.6	3.1	2.9	3.0
Class VIII	1.1	1.2	1.1	1.1

The results for all the vehicles run over Munson are shown in Table 3. These results show much less relative variability in each power system's fuel economy. The Class III vehicles performed best at 18.5 mpg (or 7.9 km/l) for the Parallel hybrid-electric. The Class VI vehicles had much less variability with the Parallel hybrid-electric at 10.3 mpg (or 4.4 km/l), only slightly above the conventional diesel. The Class VII performed best with the series-parallel hybrid-electric power system at 7.5 mpg. (or 3.2 km/l) There was little notable difference for the Class VIII vehicles.

Table3: Fuel Economy (in mpg) for Vehicles on Munson- *values pending final trade selections

Vehicle Class	Conv. Diesel (mpg)	Series HE (mpg)	Parallel HE (mpg)	Series-Parallel HE (mpg)
Class III	15.7	17.6	18.5	16.8
Class VI	10.1	9.5	10.3	9.6
Class VII	6.7	6.6	7.2	7.5
Class VIII	3.5	3.5	3.5	3.6

4 Conclusions

The vehicle models were successfully developed for Class III, VI, VII, and VIII tactical wheeled vehicles each with four types of power systems. The vehicle model was validated to the FMTV 1083 A1 (Class VII) vehicle, and the vehicles with hybrid-electric power systems were defined with power systems that provide matching performance with their respective baseline conventional diesel-powered vehicle.

The results indicated the hybrid-electric power systems provided substantial gains in fuel economy for tactical wheeled vehicles over the conventional diesel powered versions for most conditions. This is most evident for the Class III and Class VI hybrid vehicles when run over a hilly Churchville-B terrain which enable the hybrid power systems to regenerate more energy during downhill braking. The Class VII hybrid vehicles saw a significant gain on the Churchville-B terrain as well, but the difference was minimal for the Class VIII vehicle.

The Class III vehicle also showed a marked improvement in fuel economy when run over the mostly flat Munson course, though with less relative gains than in the Churchville-B course. However, the Class VI, VII, and VIII vehicle essentially provided only small gains in fuel economy in some simulations over that of the conventional diesel. The parallel hybrid-electric vehicle provided the most consistent gains over the conventional diesel when run over Munson.

These results are only preliminary and further study will be conducted before the conclusions are finalized. Improvements such as more refined rule-based or fuzzy logic controls can be made to the power system management algorithms of the hybrid-electric power architectures that might improve the vehicle's fuel efficiency. In addition, more types and sizes of engines and motors should be modeled and included in these models to expand the simulation options for each type of power system. Furthermore, additional operating conditions should be explored such as extended periods of silent watch or idling and other types of situations commonly encountered. The final conclusions will be provided in a future report.

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