2010 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
POWER AND ENERGY MINI-SYMPOSIUM
AUGUST 17-19 DEARBORN, MICHIGAN

How Hybrids Fit in Today's Fight: Hybridization of Military Vehicles for Silent Operation and Improved Efficiency

Thomas Deweerdt
AVL Powertrain Engineering, Inc
Plymouth, MI

Gene Liao, PhD
World Technical Services Inc.
Sterling Heights, MI

ABSTRACT

This paper will discuss via case study both military and civilian hybrid vehicle development focusing on the processes required from the selection of the hybrid propulsion system architecture, component down-selection using advanced modeling and simulation tools, body/chassis development and integration, design verification testing using an advanced dynamometer test facility, and final full vehicle validation on the test track. The paper will incorporate results from the FED (Fuel Efficiency Demonstrator) program where AVL is responsible in collaboration with World Technical Services Inc., for delivering a fully developed hybrid propulsion system integrated into the demonstrator vehicle.

INTRODUCTION

Ground Vehicle Systems have seen a tremendous transformation in the demands placed upon supporting today's military unit of action (MUA). The usage, serviceability and maintainability needs have pushed existing vehicles to the limits of their original specifications. These demands coupled with the additional requirements focused on delivering a more responsive, versatile and deployable unit of action have resulted in the need to rethink today's ground vehicle systems.

Hybridization has the capability to enable a number of new mission profile functions such as export power, silent watch and silent mobility, as well as a number of strategic initiatives including improved sustainability, reduced mean time between failure (MTBF) and improved MUA fuel efficiency. The steady growth in commercial sector vehicle hybridization coupled with the significant government investment in infrastructure development for advanced energy storage technologies now provides a solid foundation for the military to consider hybridization as an integral part of the next generation of military ground vehicle systems.

The remaining sections of this paper will describe in general terms the processes by which military and civilian hybrid demonstrator vehicle development is approached at AVL Powertrain with example results derived from both.

Sources of Hybrid Efficiency and Emissions Reduction

Whenever a power system transfers energy from one form to another- such as a hybrid's conversion of mechanical energy into electricity and then back again – the system will experience a decrease in energy efficiency. Hybrid electric vehicles offset those losses in a number of ways which, when combined, produce a significant net gain in efficiency and related emissions reductions. These aspects of the HEV system are able to save so much energy that the vehicle as a whole overcomes these initial conversion losses. There are four primary sources of efficiency and emissions reduction found in hybrids:

Smaller Engine Size

Most traditional "direct drive" engines are sized to provide enough power for relatively infrequent, fast accelerations. In the more frequent cruising mode, these engines are much larger than they need to be. By adding and electric motor to deliver partial or complete power during accelerations, an HEV can be equipped with a smaller, more efficient combustion engine while providing acceleration performance equal to its conventional counterpart.

Regenerative Braking

Regenerative braking recovers energy normally lost as heat during braking, and stores it in the batteries for later use by the electric motor. Therefore, the engine-powered generator is used to produce electric energy only when regenerative braking does not provide a full battery stat of charge (SOC).

Power on Demand

HEV's can temporarily shut off the combustion engine during idle or coasting modes, when the electric motor alone can provide sufficient power to keep the vehicle's systems running without burning petroleum fuel. This mode of operation is particularly appealing for military applications requiring silent mode operation.

Constant Engine Speeds and Power Output

In a hybrid application, the diesel engine controls algorithm can be designed to operate more consistently at its optimum engine speed, power output, and operating temperature to increase fuel efficiency and reduce emissions.

Case Study: Military Hybrid Propulsion System Development

Background

As part of the Federal Strategic Sourcing Initiative (FSSI) team, World Technical Services, Inc (WTSI) has contracted AVL Powertrain Engineering, Inc (PEI) to assist in an electric hybrid concept study supporting the Fuel Efficient Ground Vehicle Demonstrator (FED) project of the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC). Based on these results, AVL has been requested to implement the chosen hybrid propulsion system architecture in the form of a full-scale demonstrator based on the M1114 High Mobility Multipurpose Wheeled Vehicle. The following sections outline AVL's product development methodology to ensure product requirements and program deliverables are met.

Requirements Definition

In order for the hybrid propulsion system development process to begin, a well defined set of component and subsystem requirements must be identified. This includes both static and dynamic performance specifications, significant component properties, vehicle dynamic requirements, environmental requirements, torque management methodology and drive cycle characterization. In some instances predefined requirements are unknown and require additional research and modeling to determine an optimal design solution that best fits program constraints. Capturing these critical component and system level attributes lay the foundation for successful execution of forthcoming hybrid vehicle development activities.

Modeling and Simulation

Traditional approaches such as paper based processes with linear workflows increase the possibility that design bugs will be detected late in the development process, leading to higher costs. Such a process is not amenable to implementing an HEV design that requires nonlinear workflows.

Model based design seeks to resolve and improve upon many of the weaknesses associated with these processes. The key idea is that the development process centers on a system. Requirements capture the system boundary constraints. This system model is an executable specification that is elaborated throughout the design using simulation as a key verification and validation step. This executable specification forms the sole “truth” source for all the teams to check designs against requirements via simulation. When software and hardware implementation requirements are included, such as fixed-point or timing behavior, code can be automatically generated for embedded deployment.

For purposes of this case study, the following baseline conventional powertrain architecture was modeled using AVL Cruise simulation tools as depicted in figures 1 and 2 respectively.

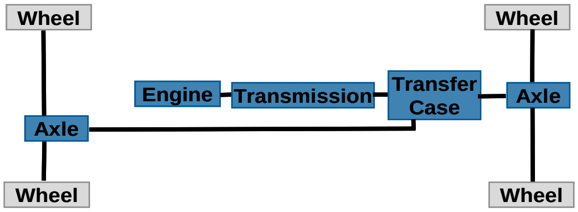

Figure 1: Conventional Powertrain Architecture

This is a key element towards establishing a base point from which all other proposed hybrid architectures will be measured against.

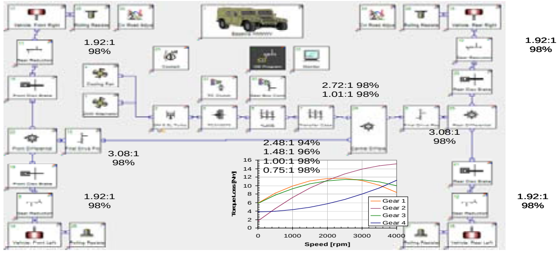

Figure 2: Conventional AVL Cruise Model

Hybrid Propulsion System Architecture

Once the baseline powertrain model has been established, various hybrid architectures are defined, modeled and compared to it. The end goal is to maximize fuel efficiency while meeting required performance criteria. The various hybrid propulsion systems investigated in this case study are depicted in figures 3 through 5.

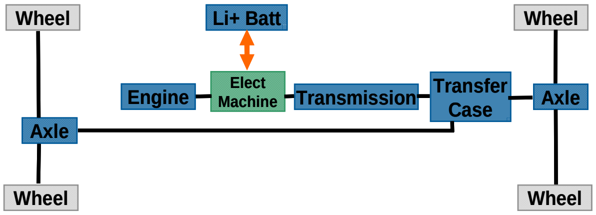

Figure 3: Parallel ISG Mechanically Coupled 4X4

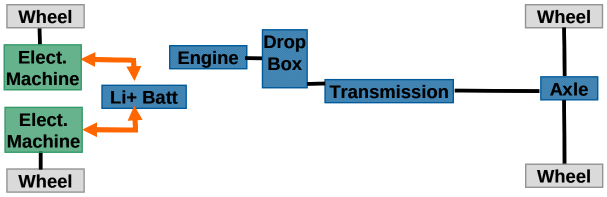

Figure 4: Through the Road (TTR) w/Front E-drive

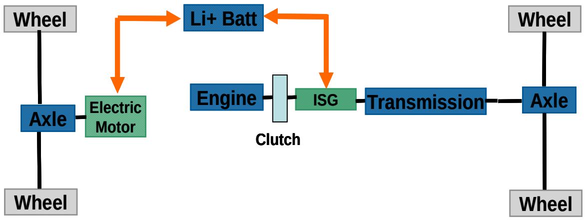

Figure 5: TTR Front E-drive w/ ISG

The architecture depicted in figure 5 is selected based on attainment of stringent performance requirements and simulation data that maximizes fuel efficiency for the given program constraints.

Component Down Select

In general, the operating range and efficiency of typical DC electric motors is characterized in figure 6.

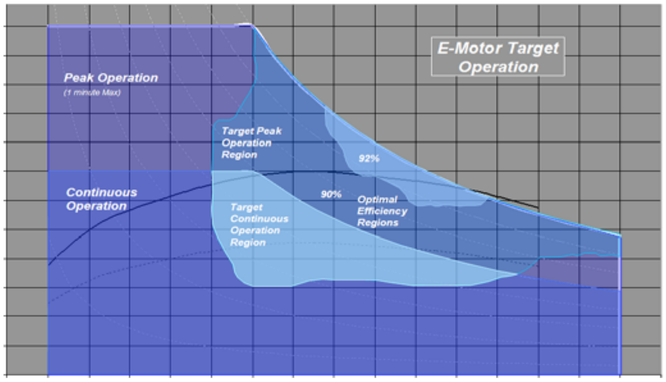

Figure 6: Generic Motor Operating Range and Efficiency

As such, the e-motor(s) sized for this application compliments the internal combustion engine (ICE) speed/torque efficiency relationship as seen in figure 7.

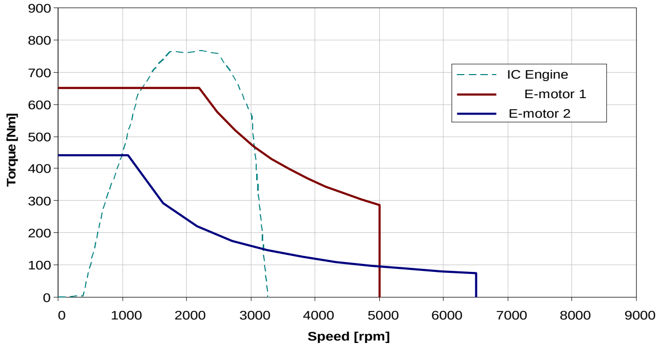

Figure 7: E-motor/ICE Speed/Torque Relationship

For initial analysis and component selection purposes, a Matlab script is used to estimate the recoverable energy for pertinent drive cycles of interest. This tool and its corresponding output seen in figure 8 allows quick iteration to identify potential improvements through hybridization without the need to optimize a control strategy for each component.

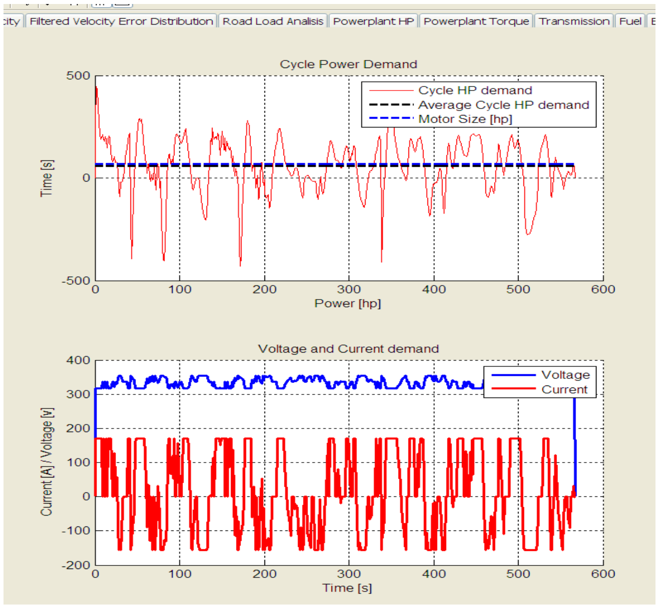

Figure 8: Drive Cycle Energy Assessment

Inputs to the calculation include:

- Engine full load data and efficiency map
- E-motor full load data and efficiency map
- Battery size and I^2R limit
- Transmission ratios
- Vehicle mass, coefficient of drag, and rolling resistance

Other major propulsion system components are down selected in a similar fashion using simulation tools as a guide towards final selection. Other pertinent factors such as cost, functional limitations, weight, and packaging considerations are captured in a weighted matrix that scores all considered options to facilitate optimal component selection.

In order to characterize functional component limitations vehicle level dynamic performance specifications must be considered. This case study includes a 60% grade requirement as well as an 18” step requirement. The following calculations relating to figure 9 and 10 identify the wheel torque requirements to achieve these initiatives. Since propulsion torque can be obtained via ISG, front e-motor, ICE, or any combination, COTS component selection will be limited to this performance criteria and the controls methodology that will induce loads on these components.

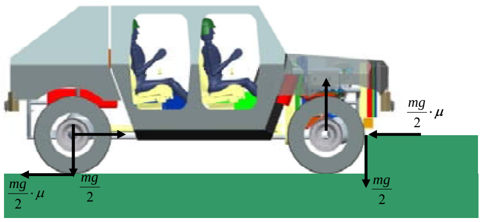

Figure 9: 18" step Climb Requirement

Tire static radius = R

Static rolling resistance = R_{stat}

$$R_{stat} = \mu\ (m(g)/2) \tag{1}$$

Required wheel torque = T_{wheel}

$$T_{wheel} = (R_{stat} + m(g)/2)\ R \tag{2}$$

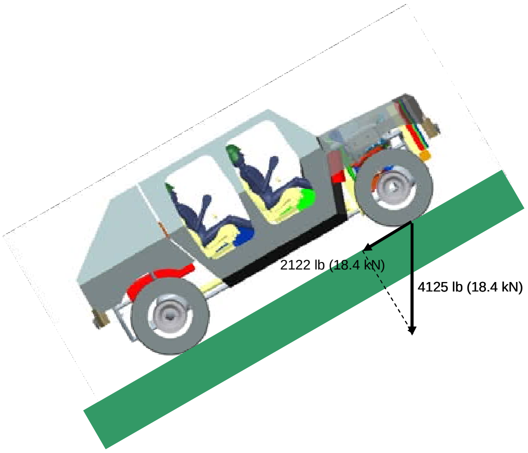

Figure 10: 60% Grade Requirement

Tire static radius = R

Static rolling resistance = R_{stat}

$$R_{stat} = (\mu\ (m(g)/2))\ (\cos(\text{atan}(\sigma))) \tag{3}$$

Grade resistance = R_{grade}

$$R_{grade} = (m(g)/2)\ (\sin(\text{atan}(\sigma))) \tag{4}$$

Required wheel torque = T_{wheel}

$$T_{wheel} = ((R_{stat} + R_{grade})/4)\ R \tag{5}$$

State Matrix/Energy Flow Analysis

Boundary Conditions/State Matrix

In general, the propulsion system boundary conditions seen in figure 11 consist of three major subsystems; 1) ICE/ISG rear drive propulsion, 2) e-drive front propulsion, and 3) high voltage battery/inverter/controls. I/O requirements for each subsystem are identified before state definition and control algorithms can be developed.

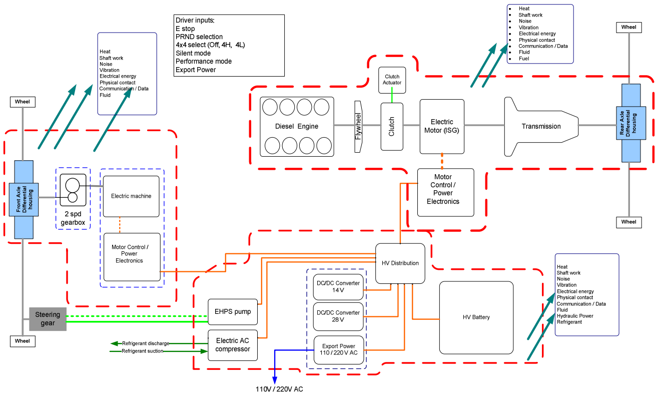

Figure 11: Propulsion System Boundary Conditions

State definition and systems level DFMEA can be done in concert with each other where each mode of operation and subsequent potential failure mode can be identified and addressed early on in the design phase. At a high level, these states include but are not limited to the following: 1) normal system start-up, 2) system operation to include forward/reverse drives, 4X2, 4X4 mode, silent operation, limp home, and performance operation. 3) normal Vs emergency shut down, etc., etc. Since maintaining battery state of charge (SOC) is directly proportional to the amount of power being generated from the ISG, ultimately impacting fuel economy, simulation modeling is used extensively to optimize the energy management strategy in order to minimize fuel consumption.

Energy flow analysis

In order to better conceptualize system energy flow, it is useful to create an energy flow diagram for each identified state as shown in figure 12.

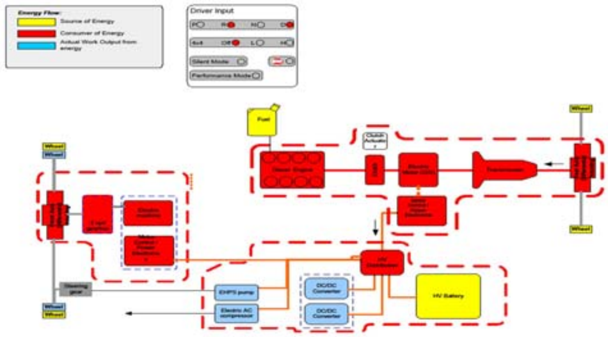

Figure 12: Propulsion System State Energy flow

This visual communication will help facilitate system and component level DFMEA analysis and will be used as initial mode specific simulation input from which the final controls methodology will be derived from.

Controller Development

Overview

For this case study and others requiring ICE and e-motor propulsion system optimization, AVL will develop A hybrid controller using AVL/Cruise in cycle run simulations. In this case, the cycle run simulations are used to model performance on predefined military drive cycles.

From a driver/vehicle input perspective, the controller receives the following data:

- Driver brake pedal signal
- Driver accelerator pedal signal
- Wheel angular velocity
- Battery state of charge
- Transmission current gear selection

The hybrid controller is responsible for providing the following outputs:

- The state of the combustion engine on/off switch
- The state of the clutch as engaged or disengaged
- Transmission desired gear selection
- Load signal to the combustion engine
- Load signal to the electric motor
- Load signal to the brakes

Algorithm Development

Given the current vehicle velocity, the maximum and minimum torque at the wheel among all potential gear selections and load signals is computed. The driver demand is interpreted from the pedal signals with respect to the aforementioned values, such that: 100% accelerator pedal correlates to a driver demand for maximizing wheel torque. In this case, demanded torque is a positive value. 100% brake pedal correlates to a driver demand for minimizing wheel torque. In this case, demanded torque is a negative value. For intermediate pedal positions interpolation is used to determine the wheel torque demanded by the driver.

Given a certain wheel torque demanded by the driver, the controller subsequently determines which gear selections are capable of providing the demanded torque. In the event that the wheel torque demanded by the driver could be provided by more than one gear, then the controller will select the gear which requires a minimum of fuel energy and electrical motor energy. The possibility of providing a fraction of the demand by the electric machine and the remaining portion by the combustion engine is considered.

In order to provide state of charge management, the energy comparison assigns a weighting factor to electrical energy based upon the state of charge. Thus, at a low state of charge generating power is favored, but at a high state of charge usage of the motor is favored. In order to eliminate the potential for high frequency gear shifting, another weighting factor is applied to slightly favor the currently selected gear. This prevents rapid switching between gears in the case where energy usage is very nearly equal between two gears at certain vehicle velocities.

In the case where the vehicle regenerative braking is used, the clutch between the ICE and ISG is activated and the motor is switched off. This allows more braking energy to be captured by the electric generator, rather than lost due to motoring of the engine. The controller is designed to abide by various user specified or component specific limitations. These include maximum torque and power permitted by the electric machine, as well as, the I^2T limit to prevent excessive heat generation in the battery.

Exception handling is implemented to advance the timing of up shifting when the driver has a high accelerator pedal demand. This is necessary because the shifting event requires a certain time interval to complete. If the controller were to wait to begin up-shifting until the time when gear N+1 provides greater torque than gear N, the problem arises that the shifting time will take so long as to result in the engine entering an over speed condition where very little power and torque is available.

Figure 13 shows a typical example of a hybrid controller in operation.

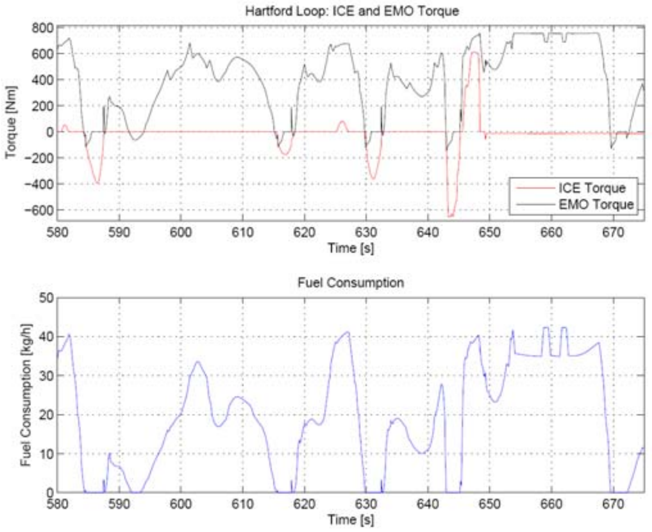

Figure 13: Example Hybrid Controller Operation

Power demand is usually satisfied by the combustion engine (black line) without e-motor assistance. At high driver demand, the electric motor will assist (red line). After the I^{2}T limit is reached, the electric motor no longer assists. When the driver desires to slow the vehicle, the generator recovers energy. When the driver demand to slow the vehicle increases about a certain threshold, the clutch is disengaged and the engine is shut off.

Thermal Considerations

Thermal control is critical to achieve the desired performance, life, and safety of energy storage system in vehicle application. Thermal management of full hybrid vehicle includes high voltage battery pack, power electronics, and electric machines.

Battery performance, life, and cost directly affect the performance, life, and cost of the HEVs. Battery temperature influences the availability of discharge power, energy, and charge acceptance during energy recovery from regenerative braking. These affect vehicle drive-ability and fuel economy. Temperature also affects the life of the battery. Therefore, ideally, batteries should operate within a temperature range that is optimum for performance and life. The desired operating temperature range is different for different battery types. Usually, the optimum temperature range for the battery operation (desired by the battery manufacturer) is much narrower than the specified operating range for the vehicle (identified by the vehicle manufacturer). For example, the best operating temperature of lithium-ion battery is from -10°C to 50°C. An effective thermal management system is critical to maintain the health and life span of the battery

The goal of a thermal management system is to deliver a battery pack at an optimum average temperature (dictated by life and performance trade-off) with even temperature distribution as identified by the battery manufacturer. However, the pack thermal management system has to meet the requirements of the vehicle - it must be compact, lightweight, low cost, easily packaged, and compatible with location in the vehicle. A thermal management system may use air for heat/cooling/ventilation, liquid for cooling/heating, insulation, thermal storage such as phase change materials, or a combination of these methods. The thermal management system may be passive (i.e., only the ambient environment is used) or active (i.e., a built-in source provides heating and/or cooling at cold or hot temperatures). The thermal management control strategy is done through the battery electronic control unit.

Power electronics play an important role in the success of HEVs. Typical power electronic circuits used in hybrid HEV include rectifiers, inverters, and DC/DC converters. Conventional circuit topologies, such as buck converters, voltage source inverters and bidirectional boost converters are challenged by system cost, efficiency, controllability, thermal management, voltage and current capability, and packaging issues.

At power levels of 100kW, even with efficiency of 96 to 98%, the power losses of each power electronic unit are 2 to 4kW. With two or three electric motors and associated power electronics circuits, as well as a high power bidirectional DC/DC converter, the heat generated in the hybrid system could be significant. Significant advancements in the thermal management of both the power electronics and motors for the HEV propulsion system must be achieved to meet the automotive industry's goals of reduced weight, volume and cost.

The main areas of concern in the thermal management of power electronics are:

- Operating temperature of IGBTs (which should be less than 125°C)
- Contact resistance between various layers of a power module
- Low thermal conductivity thermal paste
- Heat flux limitations (ideally, faster IGBTs would have to reject heat at a rate of 250 W/cm^2)
- Limitations on the inlet cooling fluid temperature (it is desirable to use the engine coolant at 105°C)
- Cost of the cooling system; weight and volume.

Vehicle Body Integration

The design of vehicle body takes the accounts of military vehicle requirements, weight, passengers protection, weight, packaging, aerodynamics, and styling. The styling of vehicle body was created by College for Creative Studies (CCS). FED program engaged a team of Transportation Design students at the CCS to help develop the interior and exterior features. Approximately 15 CCS Transportation Design juniors are spending the winter semester researching requirements for military vehicles and designing FED concepts.

Lightweight materials have a strong correlation to any attributes directly related to mass including the following FED requirements: fuel economy, vehicle weight (VCW, GVW), gradeability, speed on grade, acceleration, lane change, and range. The materials key attributes include density, stiffness (modulus of elasticity), strength (yield/ultimate tensile), and corrosion. Vehicle body considered for the use of advanced high strength steels for weight reduction include: body structures, exterior panels (fenders, hood, etc), interior panels (floor, tunnel, etc), cargo bed, brackets, and chassis structures. The different metal thickness are applied to vehicle surface armor areas including underbody vehicle, underbody wheel, sides/doors/front/rear opaque, roof opaque, and transparent armors.

Further weight reduction is considered using composite materials in hood and cargo compartment. Plastics and fiber-reinforced composites are being applied throughout automotive subsystems to reduce weight (20-50% weight reduction) and parts numbers. Carbon fiber components are being used as body parts on production automobiles. The benefits include low weight, high strength, break resistance, corrosion resistant, and vibration resistant. Various molding/forming processes are used to produce composite components.

Chassis Integration

The chassis integration involves suspension and steering sub-systems. The suspension sub-system affects ride, handling, ride height adjustment, obstacle negotiation, load leveling, cargo loading, transportability, and fuel economy. The key attributes include: weight, package, damping, spring rate, power used (mild terrain), power used (rough terrain), regenerative capability, adjustable ride height, and complexity. Continuously variable damping suspension using Magneto-rheological (MR) fluid was selected. The MR fluid is ideal for semi-active dampers. Under a low power magnetic field, these fluids change from a liquid to a semi-solid (and back) in microseconds. Some MR damping systems have a sub-10 millisecond response times. This, in conjunction with proven military damping hardware provides a system with superior durability across the range of extreme conditions experienced by modern military vehicles. The benefits include 1) improvement in vehicle ride and handling, 2) reduction of shock loads transmitted into vehicle body and suspension components, and 3) reducing required suspension travel which improves component life cycles and enable reduction in component sizes and mass.

The steering sub-system has a strong correlation to the following FED requirements: handling, turning circle, and fuel economy. The key attributes include: weight, package, power used (low duty cycle), power used (high duty cycle), steering feel, steering handling and complexity. Conventional hydraulic powered steering system with electrically powered pump (instead of engine driven), or Electric Hydraulic Power Steering (EHPS) was selected. It can operate with steering gear/center link or rack and pinion layout and support hybrid vehicle configurations by allowing power steering system to function, when engine is switched off. Assist level of EHPS can be varied according to vehicle loading and driving conditions (parking, urban driving, highway cruising). Additionally, steering feel can be fine tuned via software programmed parameters.

Design Validation and Testing

Methodology

The design validation and test objectives for the hybrid propulsion system are focused on the characterization of the stabilized and dynamic control system response. With the intended coupling of the diesel engine to the electric motor, many potential control system interactions may arise. These control issues can be exacerbated by the existing engine controller's inability to handle rapid load changes. Given the large power potential available from the electric motor, proper diesel engine hardware and controls characterization is key to avoiding any operation which could cause instability in the base vehicle powertrain. The systems level testing planned will not fully isolate the engine's controller response, but will rather characterize the response of the powertrain, which will include the transmission, shaft, and motor inertias as utilized in the vehicle.

In order to facilitate this methodology, testing is carried out in multiple phases. Phase 1 testing establishes baseline conventional powertrain operation. Phase 2 testing will characterize the rear electric drive system independent of the IC engine in order to isolate engine inertia. Introduction of these components include the electric drive system, battery system, and all associated wiring, fusing, connectors, and junction box. Consistent with our example case study, a third phase of testing will introduce electric front axle propulsion.

Once the characterization and performance requirements for each individual propulsion subsystem is tested and validated, complete hybrid controls integration can begin. This initial hybrid controller software is derived from previous modeling and simulations performed earlier in the design stage. After test and validation of the base hybrid system is complete, it can easily be optimized to ensure propulsion system operating targets are being met. Final validation and optimization will occur on vehicle at a local proving ground.

Conclusion

Hybrid propulsion system development for military and commercial applications is becoming increasingly complex with added power requirements and minimal precious opportunity to capture regenerative energy. The integral use of mechanical, electrical, and software methodologies makes system integration more challenging and the design process significantly more complex than for conventional vehicles. Design teams need an organized design approach to address these system complexities and to ensure reliability and performance objectives are met. Additionally, HEV development requires collaboration and optimization across multiple engineering domains. Model based design allows for the reuse of design information across all teams and through various stages of development. This approach – modeling and simulating the system behavior prior to building the actual hardware – leads to the added benefits of lower costs, increased time savings, and customer satisfaction.

REFERENCES

[1] B. Cho et Al., "Hybrid Vehicle Technologies: Trends, Challenges and the Future", International Conference on Automotive Technologies, Istanbul, 2008

[2] H. Husted, "Comparative Study of the Production Applications of Hybrid Electric Powertrains", SAE Technical Paper, 2003-01-2307

[3] B. Mahapatra, "Model-Based Design for Hybrid Electric Vehicle Systems", Advantage Business Media, 2010