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CREATING OPTIMIZED POWERTRAINS FOR THE WARFIGHTER

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ABSTRACT

The diverse range of military vehicles and operational conditions share a number of powertrain objectives including high fuel efficiency and fuel adaptability to lessen the logistical impact of conflict; low heat rejection to minimize the cooling system losses, vulnerability and powertrain package space; tractive power delivery to provide superior mobility for the vehicle; and light weight to allow for more armor to be used and/or payload to be carried.

This paper first provides an overview of the operational powertrain requirements of military vehicles. A review the processes used to integrate powertrain components into an optimized system specifically developed for modern combat vehicle applications is then provided, including an example of how the process was employed to develop an advanced powertrain for a tactical vehicle demonstrator based on military optimized off-the-shelf components. The paper concludes with a summary of some further military specific engine and transmission technologies trends to be considered as part of an optimized mobility solution for heavy combat vehicles.

INTRODUCTION

The American Warfighter deserves the absolute best possible technology in all aspects of their duties. Combat vehicles used by our soldiers provide mobility, protection, platforms for command and control, weapons delivery, tactical support and recovery. As the operational requirements for these functions increase, more demands are placed on the vehicle powertrain. Future combat vehicle powertrains must deliver core abilities needed to increase vehicle mobility and provide the additional electrical power needed for increased vehicle system electrical demands and export power when stationary. These capabilities must be delivered in a package that minimizes the powertrain system space claim and mass, allowing for more armor to be used for the protection of our soldiers while providing mobility.

Increasing vehicle content, armor, communication and electric power needs are increasing vehicle weight and reducing mobility. Integrating the latest level technologies including Integrated Starter Generator systems (ISG) and advanced Lithium Ion batteries for energy storage, with modern engine and transmission design, will increase the vehicle capability and reliability, reducing risks to the Warfighter. The powertrain must be designed to ensure that the integration of each of the powertrain systems results in a powertrain that meets or exceeds the needs of the Warfighter.

SHARED OBJECTIVES – SWaP-C

The Warfighter relies on a wide range of mobility capabilities in the defense of the US, including combat and tactical vehicles. Wheeled, tracked, and amphibious platforms are employed in operational theaters as diverse as shoreline, heavily forested, desert and urban scenarios. These vehicles must all be capable of reliably operating in a range of ambient conditions from arctic to extreme heat.

Figure 1 - Example Range of Military Vehicles

Many generic delineators are used to describe military tactical and combat vehicles, including Wheeled, Tracked, Support, Light, etc. Examples of vehicles for some of the categories are shown in Figure 1. These examples cover a wide, but not exhaustive, range of military vehicles each having a range of missions. Even with such vehicle diversity, from a powertrain perspective there are a set of common objectives of:

- Reduced powertrain size or space claim within the vehicle,
- Reduced weight to facilitate increasing vehicle payload and protective armor.
- Increased power, allowing for higher acceleration, sustained top speed, gradeability and payload (or armor), and
- Reduced cost related to fielding and operations.

Collectively these Size, Weight, Power and Cost objectives are commonly referred to as 'SWaP-C' criteria.

For many military vehicles a fifth criteria, cooling or heat rejected to the vehicle from the powertrain system is a specific parameter to be accounted for and reduced. Reducing the cooling system and powertrain bay heat loads in turn reduces heat exchanger space claim, the parasitic fan power requirements and system weight and improves vehicle fuel economy, thus supporting the SWaP-C objectives.

Other shared criteria for powertrains supporting SWaP-C objectives include compatibility with the fuels such as Jet A, JP-8, JP-5, and high sulfur diesel fuel available in military operation theaters, commonality with other Mil-Spec fluids, supportability, maintainability and staff training.

SWaP-C POWERTRAIN INTEGRATION

Current combat vehicles are powered using either 4-stroke diesel engines or gas turbine engines, often coupled with basic automatic transmissions using torque converters. Onboard 28VDC electrical requirements are provide for by engine driven generators. Although these powertrains are functional in combat applications, many are based on designs that have their roots in the 1960s. These products suffer from poor duty cycle fuel consumption resulting in added risks to support troops, added complexity for battle field logistics and increased operational costs. Functionally, the needs of the warfighter, and therefore the requirements for the vehicles, have continued to evolve. Ageing architectures are less able to support the broad demands imposed by a wide range of expected mission profiles while still meeting fuel economy, vehicle performance, and powertrain package requirements while providing the target export power and other objectives.

The age and diversity of combat powertrain components complicates the repair depot parts inventory and availability logistics, as well as the service training required to support the range of significantly different powertrains and control systems in the field. By developing a powertrain system that uses a common control architecture, a significant level of commonality in the major systems and that is scalable or based on high volume production components (engine, transmission and electrical generation architecture), the burden of the logistics and inventory would be reduced, component costs would be lower and the supporting infrastructure, such as training and servicing, could be simplified.

Future military powertrain architectures must meet the need for higher on-board electric power for auxiliaries, weapons system, communication and surveillance, possible supplemental propulsion, and export power. Additionally, these architectures should take maximum advantage of the advanced control capabilities available and applied to the powertrain components.

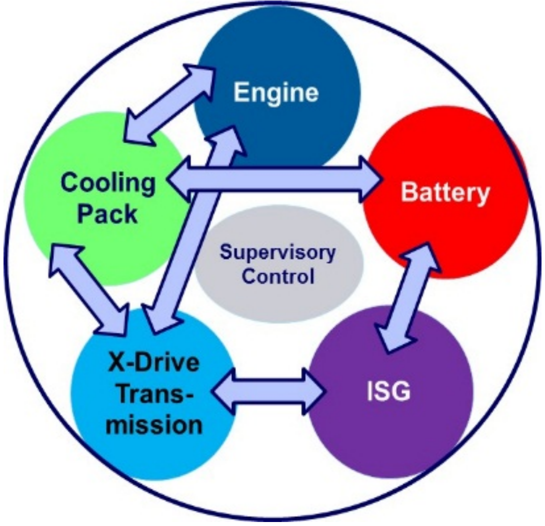

Figure 2 - Major Components and Interactions of a Modern Military Powertrain

In order to achieve the powertrain functional requirements, each of the separate systems must be capable of performing synergistically with the other elements of the powertrain. Coordinated controls are crucial in this aspect, and the powertrain integration effort includes all elements of the supervisory controls development. As shown in Figure 2**,** the supervisory control is at the center if the future powertrain and is responsible for ensuring the components perform as an optimized system.

Five key engineering areas of effort are involved in the integration of a powertrain, as outlined below. An example of how these efforts were applied to deliver the powertrain for an advanced tactical vehicle demonstrator will be described later in this paper.

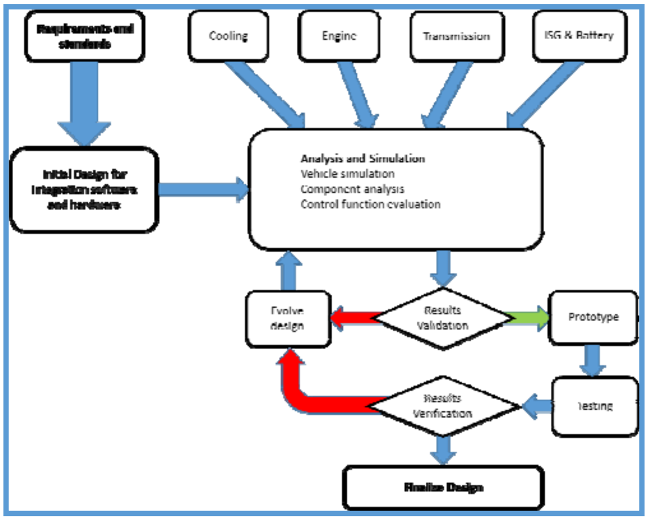

Figure 3 - Overview of Powertrain Integration Process

System Level Requirements (SLR) Development

These efforts are focused on the translation of vehicle level requirements into the initial powertrain system and sub-system level attributes required to deliver the SLR set for the vehicle powertrain. The initial work includes development of a vehicle model representing a target application for the powertrain using a vehicle performance model such as AVL-CRUISE^{TM}. From these modeling efforts the translation or 'cascade' of the system level requirements into usable sub-system level objectives and goals, and communication of these data to the engine, transmission, cooling pack, ISG and battery teams is performed.

Maintenance efforts throughout the development program include refinement of the SLR based on changing objectives for the target vehicle, development results and progress from each of the component suppliers, with the focus on realizing and implementing synergies that are possible from optimizing the interfaces and behavior characteristics of the sub-systems.

Software Development and Integration

Control software efforts are focused on the development of software architecture and functionality for the system supervisory control and coordination of sub-system controls for the powertrain components (engine, transmission, cooling pack and electrification). A high level control system architecture definition for the interfaces between the supervisory control module and the engine, transmission and electrical control functions is developed to provide a coordinated powertrain system that delivers optimized performance. Characteristics of the system components are used to develop plant models for the components and integrated system. These models form the basis for a rigorous control software development process, utilizing quality control and documentation practices. This process results in a robust software architecture and control capability.

Hardware Design and Integration

Hardware efforts are focused on powertrain layout design or architecture, selection of components, interface analysis, procurement of specific system level components, and integration of all powertrain components into a representative vehicle or hull mock-up to provide a powertrain validation platform. An initial 3D computer aided design (CAD) model of the integrated powertrain is developed to visualize the powertrain architecture and refine the layout concepts to take advantage of package space, functionality and serviceability. From this architecture, detailed preliminary 2D drawings, required for procurement of integration/mounting components are developed. As the system components are refined, the integrated system design and detailed drawing are also refined.

This system architecture and component characteristics are then used to develop and maintain a dynamic system model to assist in the analysis led development of the powertrain. This approach allows the mechanical interfaces between components to be evaluated and refined as the engine, transmission, cooling pack, battery pack, and ISG are developed by the respective suppliers. The results of these analyses are used to refine the system 3D designs and detailed 2D drawings for robustness and implementation of improvements realized from the concurrent development of the powertrain sub-system. Integration components reflecting the final iteration of the designs for the vehicle packaging requirements, powertrain components and mounting are then procured for build and test.

The engine, transmission, cooling pack, ISG and battery pack provided by their respective suppliers are the interfaced and integrated into the vehicle or mock-up hull for validation testing.

Validation of the Integrated Powertrain

The validation effort is focused on providing the planning, data, and information needed to validate the powertrain system level interface requirements, performance, package power density, heat rejection and system level durability objectives are met by coordinating the efforts of the engine, transmission, electrification and cooling systems to provide an optimized powertrain package. This effort includes execution and implementation of system level FMEAs, development and execution of reliability and durability plans, control system validation planning and execution, and performance validation test planning all leading to the execution of performance and durability validation testing. Analyses of the validation test data are then performed to assess results and to provide feedback for future development efforts.

Coordination

Throughout these efforts, the key responsibility of the powertrain integration team is to provide the communication framework and path amongst the suppliers of the engine, transmission, electrification components, cooling pack and the vehicle platform to ensure the success of the powertrain development effort. It is crucial to facilitate this communication and coordination through the implementation of regular coordination meetings, status reviews, monthly reports, periodic System Functional Reviews, the Preliminary Design Review, the Critical Design Review, the Technology Readiness Review, and updates to the Risk Management plan, system documentation, and system validation testing support. The objective of the coordination effort is to set the team direction, track and document the progress of the powertrain development efforts, identify and resolve areas of conflict, and take maximum advantage of the opportunities for simultaneous system optimization possible in the powertrain.

INTEGRATION METHODOLOGY EXAMPLE

The following sections summarize an example of how the engineering approaches described above were used to develop an advanced powertrain for a military vehicle. The example covers the application of high volume commercial off the shelf components, adapted to military requirements, combined to create an advanced driveline architecture applied to a light tactical vehicle (GVW ~7700kg).

Military Optimized Off-The-Shelf Powertrain

Figure 4 - FED BRAVO Vehicle

This Military Optimized Off-The-Shelf example summarizes a program to design, build, and validate a road coupled parallel diesel-electric hybrid propulsion system used to propel the FED BRAVO demonstration vehicle.

This program emphasized a rapid development cycle and utilization of technologies available from commercial off-the-shelf (COTS) components to minimize total costs and time to demonstration, stressing the need for upfront design and planning. The boundaries and constraints of the program's technical objectives pushed the component decision stage to occur early in the program, requiring a deep knowledge of potential synergies and the ability to quickly react to changes. A thorough methodology for execution of development, validation and integration of the hybrid system was crucial to achieve a robust and cost effective solution.

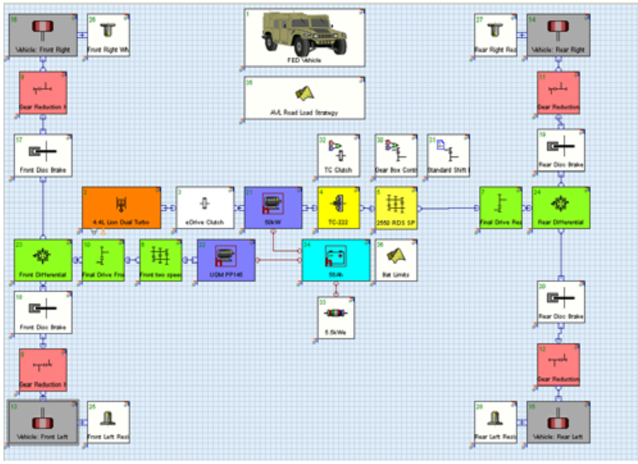

Figure 5 – AVL-CRUISE Model of the FED BRAVO

Figure 5 depicts the AVL-CRUISE model developed to simulate the vehicle and evaluate the impacts of various powertrain architectures to achieve the vehicle level performance and fuel economy goals. The AVL-CRUISE model provided simulation of longitudinal vehicle dynamics and all powertrain components, including the internal combustion engine (ICE), engine disconnect clutch, Integrated Starter Generator (ISG), the transmission, differential, final drives at the rear axle; front motor (FMOT), 2-speed manual transmission, differential, final drives at the front axle; and battery, wheel end reduction units (WERU) and tires.

This model was used to define the powertrain architecture selected, and to define the engine, transmission, and electrical drive component functional requirements needed to support this architecture and performance criteria.

As shown in Figures 5 and 6 there are three propulsion sources in the FED vehicle model: Internal Combustion Engine (ICE), an Integrated Starter Generator (ISG) and the front motor (FMOT). The ICE and ISG arrangement constitutes a parallel hybrid system whereas the inclusion of the FMOT adds a unique Through-The-Road (TTR) hybrid functionality for the front axle tractive effort. The main task of the energy management and control design was to utilize all three propulsion sources in the most fuel efficient manner while ensuring vehicle performance criteria are achieved.

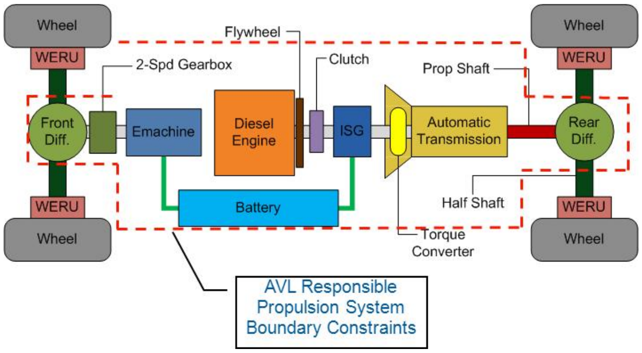

Figure 6 - FED BRAVO Powertrain Architecture

A model based approach was used for the control algorithm development. The controller model developed consists of signal conditioning and powertrain management functions including driver demand calculation, torque management, safety limit monitoring and fault tolerance, component/local and system/global efficiency calculations, power split based on energy management and real-time optimization. The energy management scheme includes road load based power split and optimization methodology developed by AVL. This represents part of continual effort to use AVL's state of the art integrated simulation and development tools such as AVL-CRUISE, AVL-DRIVE^{TM} and AVL HYBRID DESIGN toolkit to design energy efficient vehicles. The main objective of these tools is to help the designer strike the right balance between fuel economy, performance, emissions and drive quality. The main goal of the algorithm development for the FED Bravo was to improve fuel economy by optimizing the overall hybrid system efficiency while maintaining vehicle drivability and performance.

Three main modes of powertrain operation are 1) Engine only, 2) EV (ISG and FMOT) only and 3) Hybrid. Emphasis was placed on attaining smooth transitions between these different modes under varying driving conditions.

Engine Selection

Modern heavy-duty on-highway diesel engines have evolved based on the combination of regulatory demands for lower emissions and commercial pressures to improve fuel efficiency, life cycle costs, and various performance criteria. To take advantage of the capabilities these state of the art commercial off-the-shelf (COTS) diesel engines offer, defense system providers seek solutions that adapt these products to military applications. Goals for this adaptation include maintaining or improving the high thermal efficiency of these engines, reducing the amount of heat rejection relative to the baseline COTS product, meeting applicable emissions expectations for defense uses, and improving service part availability. These defense applications also require compatibility with the fuels such as Jet A, JP-8, JP-5, and high sulfur diesel fuel available in military operation theaters. Such fuels can have markedly different properties than the ultra-low sulfur diesel (ULSD) fuel COTS engines are developed to utilize. These differences in fuel properties must be considered in the hardware and calibration adaptation to defense applications. Once these considerations have been successfully addressed, the adapted COTS diesel engines can then be considered for application in defense related ground vehicle and power system applications.

Based on the modeling efforts, the set of ICE functional requirements were determined. These included objective torque peak and power levels of 500ft-lbf and 250Hp, respectively. Table 1 lists the engines and ratings available at the time the program was performed.

Engine	A	B	C	D
Displacment	3.0	4.4	6.5	6.7
Configuration	V6	V8	V8	V8
Rated Power (Hp) @ RPM	275 @4000	275 @3000	205 @3200	300 @2800
Torque Peak (ft-lb) @ RPM	440 @2000	516 @2200	440 @1800	660 @1600
FIE	HPCR	HPCR	PLN	HPCR
~ Weight (lbm)	470	620	850	990

Table 1 - Available Engines

The diesel engine selected for use in this program was a 4.4L diesel engine used currently in Land Rover SUV applications, manufactured by Ford (engine 'B' in Table 1).

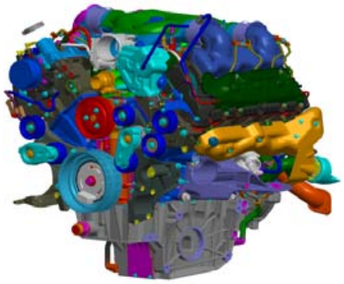

Figure 7 - 4.4L V8 FED BRAVO Engine

This is a four stroke, dual sequentially turbocharged engine that features Bosch high pressure common rail injection. The production engine produces a maximum of 330 Hp but was detuned to 275 Hp for this application. The engine produces 516 lb_f-ft of torque at a power density of 63 hp/L

The engine was optimized for tactical military application by removing the EGR system, adjusting the turbomachinery to compensate for operation without EGR, calibration to achieve the desired target full load torque curve while attaining USEPA 1998 emissions criteria, and operation with JP-8 fuel. No exhaust aftertreatment was applied nor required. Figure 8 shows a peak Brake Thermal Efficiency (BTE) of 42% was attained for the FED BRAVO application whilst satisfying the emission goals.

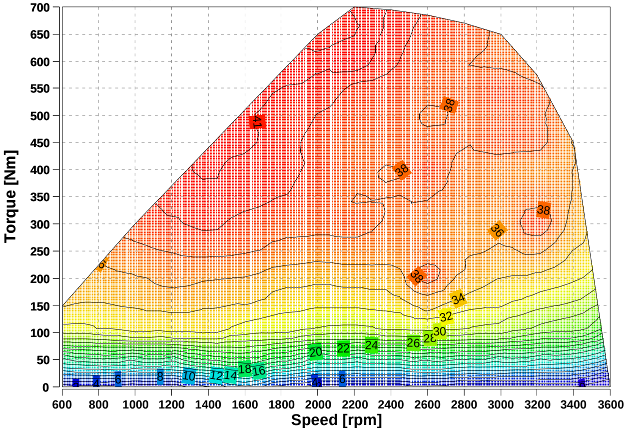

Figure 8 - Brake Efficiency of FED BRAVO Engine

Similar adaptation of commercial off the shelf (COTS) engines to military use is covered in reference [1]. .

Transmission

The transmission utilized for the FED BRAVO vehicle is an Allison 2550 SP six speed heavy duty transmission.

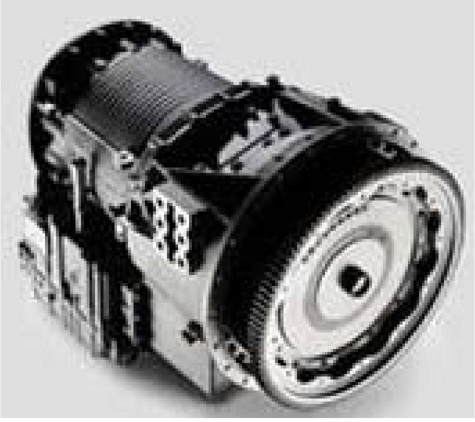

Figure 9 - Allison 2550SP

After a transmission down-select process was performed, this transmission was found to be the COTS option that best satisfied the cost, timeline packaging, speed and torque range needs and the program requirement for use of an automatic transmission. No modifications were performed to this unit for the FED BRAVO application.

Type	Auto with TC and lock-up
Forward Speeds	6
Reverse Speeds	1
Dry weight	330
Control	Electronic
PTO	Y
Max input torque	660*

*With Torque Management Algorithm

Table 2- Transmission Characteristics

Integrated Starter Generator (ISG)

The Integrated Starter Generator consists of a 50kW enclosed electric machine with four primary functions. The functions include:

- Convert electrical energy into usable mechanical shaft work
- Recover mechanical shaft work into usable electrical energy
- Provide a mechanical connection between rotating components of the internal combustion engine system to the transmission system and transfer diesel engine torque though the shaft
- Provide a rigid structural connection between the housings of the internal combustion engine system to the transmission system

A 50kW UQM permanent magnet synchronous machine was identified as the preferred ISG technology. The ISG was located between the diesel engine and transmission. The ISG is controlled by a separate controller / inverter assembly connected to a direct current high voltage system.

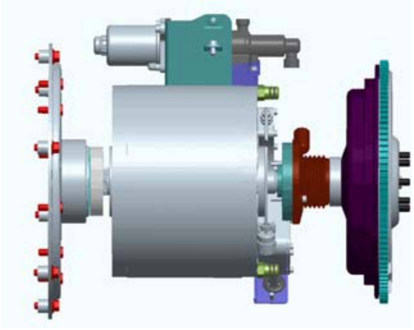

Figure 10 - ISG Location Between Engine and Transmision (Component View)

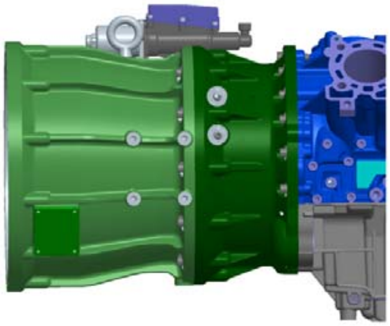

Figure 11 - ISG Housing

The clutch between the engine and the ISG is actuated by an automated hydraulic piston controlled by the Hybrid Control Unit (HCU) via CAN. The clutch allows the engine to be disconnected from the transmission during EV modes and is utilized for engine start/stop and transitional events.

Rear Differential

The requirement for a reverse rotation output from the differential needed for the wheel end reduction units (WERU) severely limited the choices available for off the shelf differentials. Additional requirements for remote locking differential, independent housing, ground clearance and high torque capacity meant that only the Xtrac 522 differential would be able to meet these requirements. Options using a traditional axle were investigated but were found to need a large ring and pinion to meet slip torque requirements which would not allow the ground clearance requirements to be attained.

Figure 12 - Xtrac 522 Rear Differential

Front Propulsion System

The Front Axle E-Drive selected consists of a two speed selectable gear case with differential carrier and an electric machine providing the input power. The electric machine was selected was a UQM PowerPhase145. This electric machine is approximately 280mm in diameter and 280mm in length with a single splined output shaft. The differential used is an Eaton Posi Limited Slip p/n 19689-010.

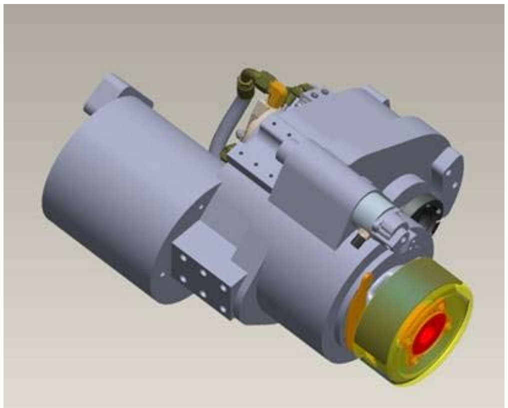

Figure 13 - Front Motor Drive Unit

The Front Axle E-Drive gear case provides two gear ratio combinations and a mechanism to change between the two gear states. The high gear setting is utilized for the majority (over 95%) of the total vehicle operation. The low gear is required to provide the necessary torque multiplication to traverse major climbing events such as a vertical 18 inch rigid step. The gear case includes a gear change mechanism with electric actuation and position feedback.

The Front Axle E-Drive is chassis mounted and attached to the front drive axles with flexible constant velocity joints. The Front Axle E-Drive weighs less than 140 kg (including e machine, fluids, and mounts)

Battery

With an approximate gross vehicle weight of 7712 kg and a top speed requirement of 112 km/h, a battery with high energy capacity was required in order to meet the performance and fuel economy requirements for the project. Additional requirements for the battery for EV mode and export power generation required a battery from A123

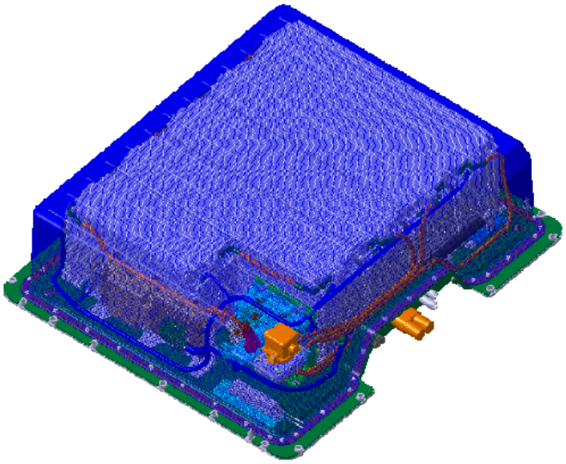

Figure 14 - Battery Pack

with a capacity of 22.8 kWh. The battery is a lithium ion design with 357 prismatic cells, each with a capacity of 20.0 A-h and a nominal cell voltage of 3.3 volts at 80% state of charge (SOC) resulting in a total nominal voltage of 393V. The total weight of the pack is 288kg with dimensions of 1046 mm x 918 mm x 296 mm which includes the battery management system (BMS), interlocks and connectors which are all contained within the battery sub-system enclosure. The BMS controls all aspects of battery usage and monitoring and temperature monitoring functionality is continuously monitored for best battery usage and performance. Communication is standard J1939 CAN and information is to be communicated over the vehicle high speed CAN network.

The battery does require a thermal management system. This system operates to keep the battery in the ideal operating temperature range of 10-35ºC and avoid reaching the maximum operating temperature of 60ºC. Full performance is available up to 40ºC while reduced performance above 40ºC is controlled in the hybrid control system.

Cooling Pack

Two cooling systems were developed and utilized in the FED BRAVO demonstration vehicle. The first cooling system, shown in Figure 15, is configured to provide both low temperature and high temperature cooling capability for the engine and transmission. The low temperature portion of this system provides for charge air cooling and fuel cooling. This system operates at 6psi pressure and utilizes a dedicated coolant pump and heat exchanger. The high temperature portion of this system operates at 15psi and provides for engine cooling (engine head, block and lube oil), cab heat, and primary cooling of the transmission fluid. The transmission fluid also utilized a secondary air to fluid heat exchanger. Both the coolant to air heat exchangers from the high temperature and the low temperature cooling loops share a common, controlled fan.

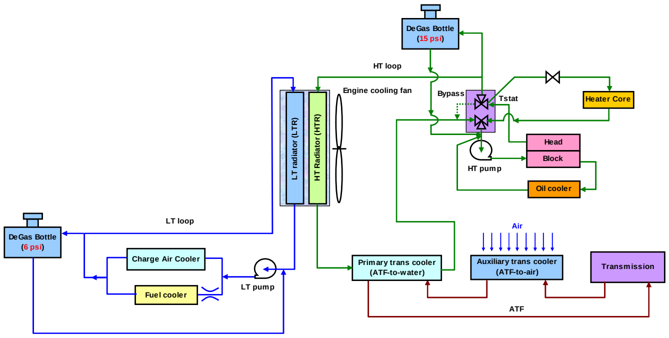

Figure 14 - Engine and Transmission Cooling System

Cooling of the electrical components of the powertrain and provisions for cab air-conditioning were provided by the dedicated cooling loop shown in Figure 16. This loop employs a dedicated coolant pump and heat exchanger to provide cooling for the two DC-DC convertors, the two power inverters, the ISG, the FMOT and the DC-AC inverter used to provide export power. This loop also provides cooling for the battery pack, supplemented by cooling from a vehicle AC system cooled chiller to assist in keeping the battery pack within its optimal temperature range.

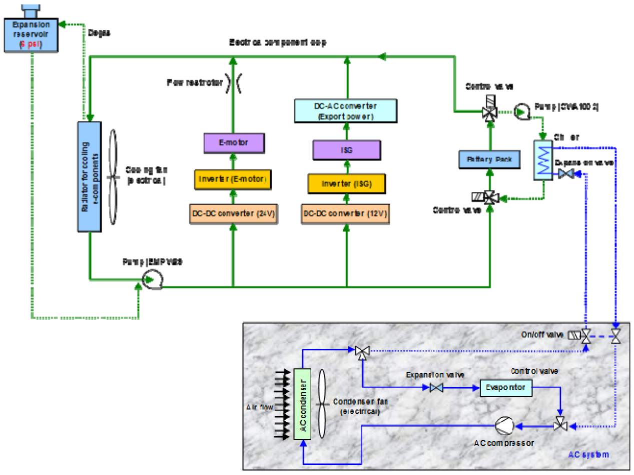

Figure 15 - Electrical and Cab AC Cooling System

Control System Development

The ICE and ISG constitute a parallel hybrid system whereas the inclusion of the FMOT adds Through-The-Road (TTR) hybrid functionality. The main task of the energy management and control design is to utilize all three propulsion sources in the most fuel efficient manner while ensuring minimal performance characteristics.

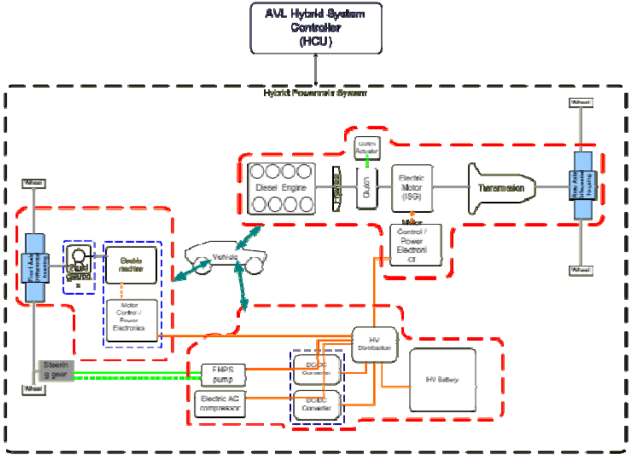

Figure 17 - FED BRAVO Hybrid System Layout

A model based approach was used for the control algorithm development and refinement. The controller model developed consists of signal conditioning and powertrain management functions including driver demand calculation, torque management, safety limit monitoring and fault tolerance, component/local and system/global efficiency calculations, power split based on energy management and real-time optimization.

To provide safety, performance and manage energy availability the vehicle level powertrain management system determines whether (or not) to allow engine only, EV only or hybrid modes to occur, to allow 4x4 propulsion, and to implement performance mode to enable 'flight mode'. Figure 18 depicts the major functions of the powertrain manager algorithm.

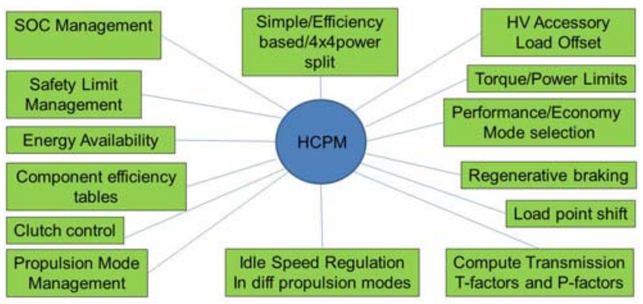

Figure 18 - Powertrain Manager Functions

More details of the control system and powertrain tractive effort management are given in [2] and [3].

Powertrain System Validation

Prior to installation of the powertrain components into the FED BRAVO demonstration vehicle, the system was tested in an AVL powertrain dyno cell. This testing allowed for component by component validation, system validation and test cell based calibration work to be performed in a time and cost efficient manner.

The first phase of test focused on the engine, torque converter and transmission. This allowed for mapping of the base conventional powertrain efficiencies, baseline fuel economy evaluation and transmission shift strategy development to be performed without the potential 'masking' of the other components.

Phase 2 testing (engine de-coupled from powertrain) allowed for a similar level of testing, evaluation and calibration to be performed on the electric drivetrain components. The ISG was characterized as both motor and generator in this phase.

Phase 3 involved dyno testing of the complete powertrain, allowing power split and overall system interactions to be developed and tuned, including drive cycle fuel economy and transient response, system calibration and evaluation.

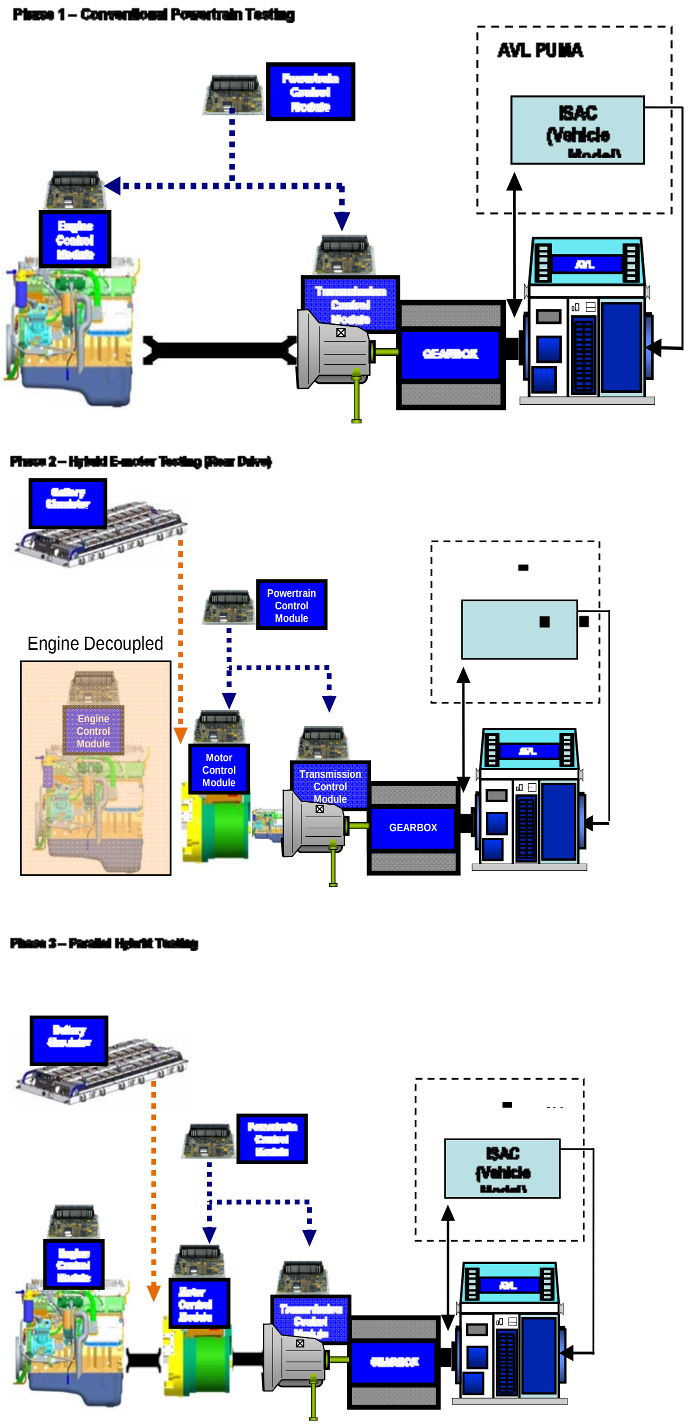

Figure 19 - Three Phase of Powertrain Dyno Testing

After completion of the powertrain dyno testing the system was installed in the demonstration vehicle (Figure 20).

Figure 20 - FED BRAVO Engine Compartment

Vehicle Performance and Fuel Economy Impact

Table 3 summarizes the results of utilizing the advanced through the road hybrid system developed for the FED BRAVO vehicle, compared to a sub-set of the program threshold and objective targets and the current HMMWV levels.

	Targets		Baseline HMMWV	Hybrid FED Vehicle
	Threshold	Objective	6.5L Turbo	4.4L Dual Turbo
Mass lbm			15400	17000
Accelerate 0-30 mph s	11.8	9.4	9.8	7.3 / 5.9 (Eng Only/Hyb)
Accelerate 0-50 mph s	37.5	26.1	32.6	20.8/ 14.0 (Eng Only/Hyb)
Velocity on 0% grade mph	60	70	66	85.2
Velocity on 5% grade mph	35	45	37	64/70 (Eng Only/Hyb)
Launch vehicle on 60% grade	Pass	Pass	Pass	Pass
Primary Roads Paved mpg			5.6	12.5
Trails mpg			3.8	7.3
Secondary Roads mpg			7.2	11.2

Table 3 FED BRAVO Results

The FED BRAVO performance characteristics surpass all the vehicle objective parameters. Acceleration, enabled by efficient use of the electric drive system, is significantly improved, as is the performance on grade compared to the benchmark vehicle.

The vehicle fuel economy was characterized using three independent duty cycles: Primary Road (Paved), Secondary Roads (low grades), and Trails (Off-Road, Steep Grades). In all three duty cycles fuel economy was improved by over 40%.

This example illustrated the improvement achieved using Off-The-Shelf components in an effective and efficient manner to create a high performance hybrid powertrain for a tactical military vehicle. The next section studies the potential of using engine and transmission technologies developed specifically for military use for heavy, tracked combat vehicles.

HEAVY COMBAT VEHICLE POWERTRAIN

Figure 16 - Example Advanced Heavy Combat Vehicle

Information security requirements in place for heavy combat vehicles and their powertrain components limit the information that can be shared in this discussion, but some general comments can be made and directions inferred based on publically available information.

Figure 22 depicts the AVL CRUISE vehicle model developed to define and evaluate powertrain component capabilities against vehicle performance goals. This model accounts for (among other parameters) Objective Functions

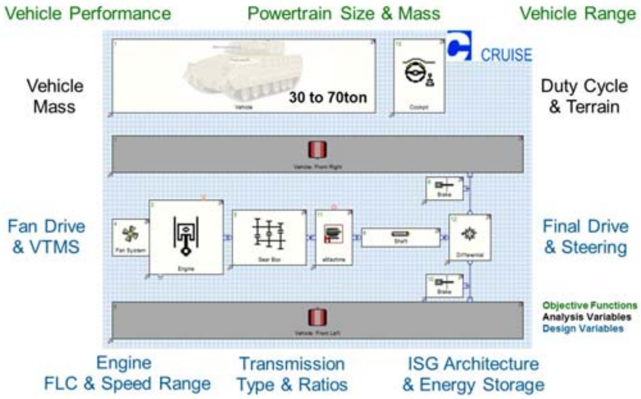

Figure 17 - AVL CRUISE Tracked Vehicle Model

of vehicle performance (including launch, grade-ability, and maximum sustained speed), vehicle fuel economy or range, and the powertrain size and mass, as it affects vehicle space claim and total weight.

The Design Variables evaluated or selected to improve the Objective Functions include

- Engine Characteristics such as full load curve (including peak power and torque rise) and operating speed range, power available at tactical idle to drive export electrical power, and the feasible fuel efficiency characteristics of the engine selected.
- Transmission Characteristics such as transmission type (automatic or automated), number of speed ratios, torque converter characteristics (if applicable), and overall mechanical efficiency capability.
- Power Electrical System Characteristics including ISG capacity and architecture (i.e.in-line with engine v. transmission driven), battery capability, and power management strategy.
- Cooling Pack Characteristics such as fan drive arrangement, fan type and efficiency impacts, cooling pack capacity and restriction, and engine compartment thermal management strategies, and
- Final Drive / Steering System Characteristics such as mechanical v. hydrostatic steering, turning rate, final drive ratio, and track system characteristics.

Recognizing that vehicle characteristics (notably weight due to increased payload or armor), duty cycles and terrain characteristics are not constants, the model must be executed over a range of these (and other unlisted) variables to provide a robust solution for the future combat vehicle powertrain.

Engine Trends for Advanced Powertrains

Current combat vehicles are powered using either 4-stroke diesel engines or gas turbine engines. Although these powertrains are functional in combat applications, many are based on designs that have their roots in the 1960s. Poor fuel consumption, especially incurred by the turbines at tactical idle speed can cause logistical issue with fuel supply and range, prompting the adaptation of alternative technologies. In some cases the production of replacement power plants has ceased, and the low demanded volume for others has driven mismatches with supply and demand for new engines or replacement components.

Significant interest has been focused recently on the development of a new, dedicated power plant for combat vehicle applications. One of the goals for this Advanced Combat Engine (ACE) effort would be to provide a scalable, modular architecture allowing significant engine component/parts commonality between engine variants that cover a broad range of power requirements for various vehicle needs. Doing so would significantly reduce the supply logistics burden and commonize much of the service and maintenance practices and training. This would result in in lower acquisition and fielding costs and improve component availability and vehicle ready time.

TARDEC has publically expressed interest in the use of Opposed Piston 2-Stroke (OP2S) engine technology to power future compact vehicle platforms. Owing to the aforementioned security concerns, specific requirements for the ACE program will not be discussed, but some of the advantages of OP2S technology for combat engines can be illustrated using a current production engine manufactured by Kharkiv Morozov Machine Building Design Bureau KMMBDB (aka 'Kharkov') in Ukraine.

One of the crucial criteria for combat vehicle is the powertrain space claim. Figure 23 depicts the 6 cylinder version of this engine. Current power ratings of ~1400Hp are claimed to be attained within this package space of slightly less than $1m^3$.

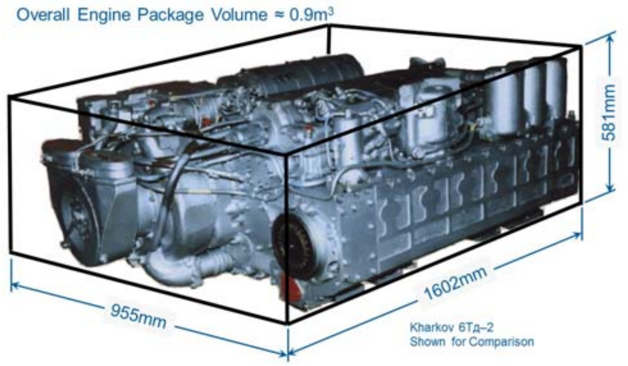

Figure 23 - Kharkov 6TD-2 Package Dimensions

To cover a range of applications, Kharkov has 'scaled' the engine by providing various power capacities through changing cylinder count. A 6 cylinder, 5 cylinder and 3 cylinder version of the engine are available, all based on the same bore and stroke, cylinder kit (piston, liner, connecting rod and injectors) with changes to the air handling system, crank and block (to facilitate the cylinder count). This allows for a range of claimed peak powers from 600Hp (3 cylinder), 1050Hp (5 cylinder), to 1400Hp (6 cylinder) to be provided with significant component commonality. The impact of cylinder count (and implied power rating) on engine length and weight is shown in Figure 24. Note that the engine width and height remain constant for the range of cylinder counts.

One of the other significant factors piquing interest in OP2S application to combat vehicles is the ability to deliver low heat rejection at high specific power levels. Figure 25 compares the 'typical' trend in heat rejection from the engine per unit of shaft power delivered (kW of heat rejected per kW shaft power produced) from conventional 4-stroke diesel, compared to data available for the Kharkov OP2S engines.

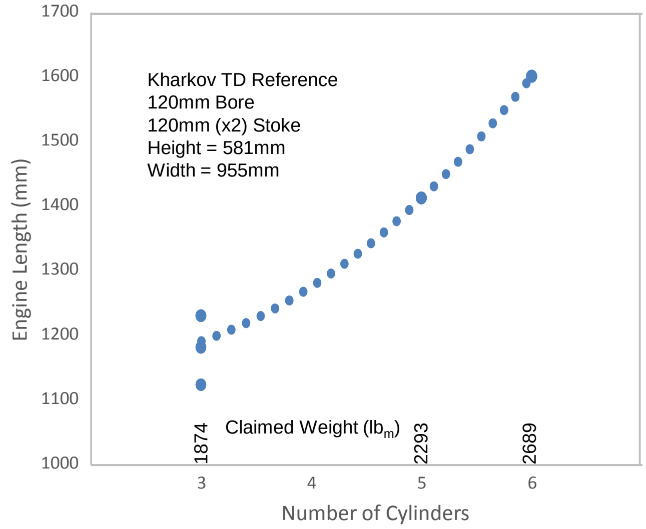

Figure 24 - Impact of Cylinder Count on Engine Length - Kharkov OP2s

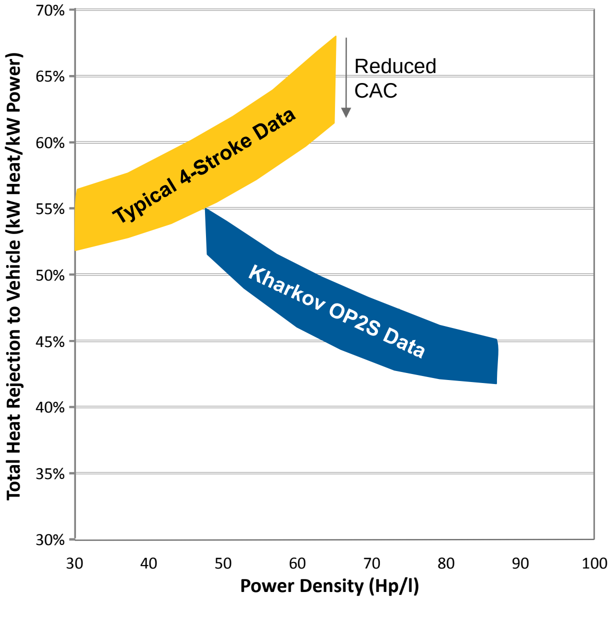

Figure 25 - Heat Rejection v. Specific Power Trends

For 4-stroke engines, the ratio of heat rejected to shaft power tends to increase as power density (Hp per liter of engine displacement) is increased. This increase can be mitigated somewhat by reducing the level of charge air cooling (resulting in increased intake manifold temperatures) to reduce the heat rejection to the vehicle. Data found for the Kharkov OP2S engines show that even at high power densities, the amount of heat rejected to the vehicle remains very low relative to that of a 4-stroke engine. (Author's Note: The trend to reduce heat rejection as power density is increased with the Kharkov TD series may reflect other technologies being implemented during design refinement to increase power).

Transmission Trends for Advanced Powertrain

There is interest in pursuing a potentially significant fuel consumption advantage from the use of transmissions having a much higher number of gear ratios (i.e. 24 to 32 transmission gear ratios) than are used with today's currently fielded torque converter equipped cross-drive automatic transmissions (typically 4 to 5 gear ratios). Current transmissions utilize the torque multiplication capabilities of the torque converter slip to provide the required acceleration, launch and grade characteristics needed of a heavy tracked vehicle in adverse conditions. This capability comes at the cost of reduced overall powertrain efficiency when the torque converter is in 'slip', affecting not only vehicle fuel economy but total heat load to the vehicle. By using high number of gear ratio mechanical auto-shift transmissions, the launch characteristics can be provided by using extremely low transmission gearing (and minimal clutch slip). The smaller steps between gear ratios also allow engine operation to be maintained closer to the engine peak power point during acceleration to improve vehicle performance and closer to the engine peak efficiency point during steady vehicle speed operation to improve overall vehicle efficiency and range.

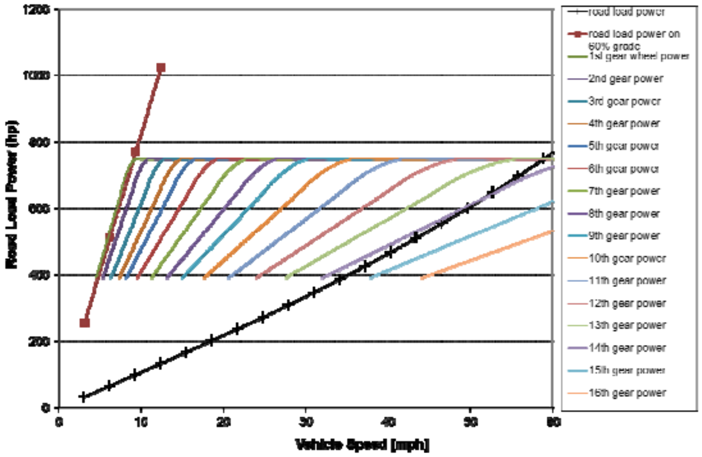

Figure 18 - Increased Speed Ratio Transmission Characteristics

RECOMMENDATIONS

Future efficient military powertrains can utilize the emerging technologies from both 'Off-The-Shelf' components developed for the commercial vehicle market adapted to military use and those being specifically developed for and applicable to the needs of military vehicles. In either case, the development process of creating detailed system level and component level functional requirements, using an analysis based approach to determine optimum control system and hardware architecture, developing and implementing a detailed validation plan, and most importantly maintaining an understanding and communication path among the powertrain component supply base are crucial for the success of a modern efficient powertrain for the Warfighter. This process allows the best overall most robust system combinations to be identified and refined in a time and cost efficient manner. The key is to find the optimum combination of all the components – engine, transmission, electrical and cooling system – to deliver synergistic results.

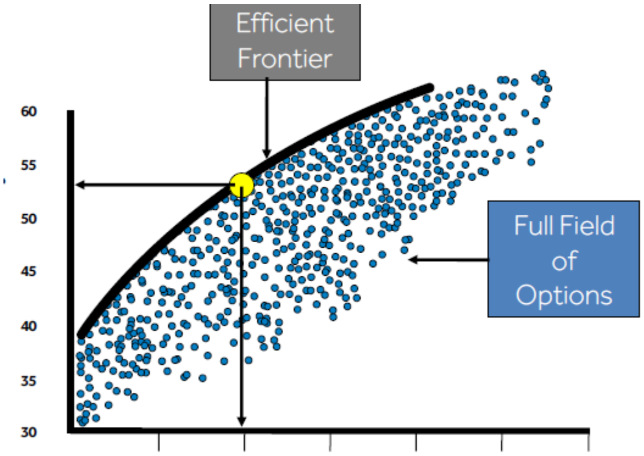

Figure 27 - Finding the Robust Combination

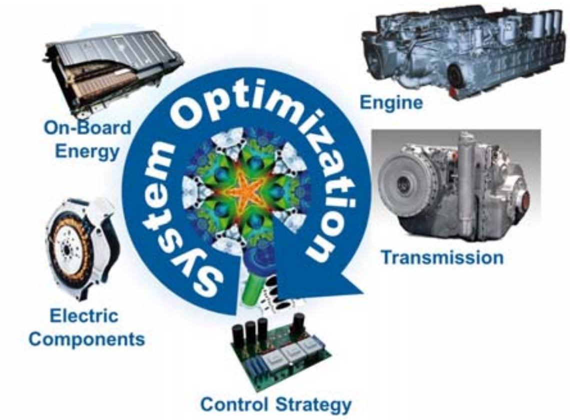

Figure 28 - Optimizing the Modern Powertrain System

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