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Fuel Efficient Demonstrator (FED) Bravo, Technology in Motion

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ABSTRACT

Increased fuel efficiency in military vehicles today results in two primary positive impacts to operational conditions. The first is the reduction in cost; both as a result of reduced fuel consumed and also in the costs saved due to the reduction in logistics required to transport fuel to the Warfighter in the field. The second and more important positive impact is the reduced risk of casualties to the Warfighter by reducing the frequency of fuel related logistical support required in the field.

This paper first provides an overview of the development of the Fuel Efficient Demonstrator (FED) Bravo vehicle from initial conceptual efforts through to final operational shake-out and performance testing. A review the development process from CAD modeling through to fabrication and testing will be discussed. This discussion will also focus on the unique methods and ideas used to address the particular challenges encountered in developing a demonstrator vehicle. The paper concludes with the results of this effort including a review of the objectives exceeded, met or not achieved.

INTRODUCTION

The FED Bravo project was sponsored by the Office of the Secretary of Defense (OSD) jointly executed by U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) and Primus Solutions, Inc. (World Technical Services, Inc. [WTSI] at that time). The objective of this project was to develop a technology demonstrator vehicle (not a pre-production or production vehicle).

The primary objectives included:
A) Identifying and assessing technologies that support increasing fuel efficiency and reducing fuel consumption for light tactical vehicles.
B) Developing and accessing fuel efficient tactical vehicle concepts that compare favorably and achieve the same operational capabilities of the venerable uparmored HMMWV at fully field weights.
C) Developing, fabricating, and testing a system-level demonstrator that incorporates fuel-efficient technologies.
D) Training the next generation of government engineers in fuel efficiency processes and tools.

This resulted in a fuel efficient demonstrator with HMMWV capabilities that identified and incorporated fuel efficient technologies that might become part of a conceptual "next-generation" light tactical vehicle looking forward 20 years. A secondary objective of this project was the validation of simulation models on ATC test routes via the comparison of physical vehicle performance results, allowing for improved fuel efficiency simulations in the future.

Figure 1 - FED BRAVO Vehicle at SANGB

VEHICLE DESIGN AND BUILD

Based on the "next-generation" direction for the FED Bravo effort this project was initiated with some "Out of the Box" thinking. The vehicle and powertrain architecture was defined through a "Monster Garage" concept. A consortium of Government, Automotive Industry and Academic experts collaborated to evaluate the pros and cons of different vehicle and powertrain architectures. Ultimately, a through the road diesel electric parallel hybrid vehicle configuration was defined by the consortium for this project.

This FED Bravo was to be designed and built from the ground up, not based on an existing platform. It was decided early on in the project that attempting to utilize an existing platform would minimize the potential optimization throughout vehicle. Due to the extensive componentry and large battery associated with the hybrid system, a light weight vehicle chassis was targeted to offset the weight penalty from the hybrid system. The secondary benefit to the custom light weight chassis was that it could be tuned to best suit the extensive packaging challenges that would be faced as a result of the hybrid system. The final vehicle configuration includes a through the road diesel electric parallel hybrid drivetrain, tubular chassis construction, light weight carbon fiber body panels (front and rear), unique suspension system design including geared wheel end reduction units, adjustable ride height control system, carbon ceramic anti-lock brakes, low rolling resistance tires, electrification of all vehicle accessory systems, and unique powertrain control system calibration.

Figure 2 - FED BRAVO CCS Concept

The interior and exterior design of the vehicle was a result of a collaborative effort with the College for Creative Studies (CCS) located in Detroit, Michigan. Primus sponsored a transportation design class at the college allowing the 17 participating students the opportunity to design the vehicle exterior. Primus and TARDEC engineers visited the students once a week to provide additional design parameters. The students continued to refine their designs in preparation for the presentation of their designs a. At that time, Primus, TARDEC and the CCS class professor selected the winner of the design completion. That winner of the design competition was then hired by Primus as a summer intern to complete the design of the vehicle interior.

Figure 3 - FED BRAVO Interior

In parallel, Primus and TARDEC worked collaboratively to conduct Modeling and Simulation (M&S) to verify fuel economy projections and vehicle aerodynamics as well as suspension kinematics and cooling system efficiencies. Based on the results of the M&S analysis, this data was then provided to the Primus SME subcontractors who were contracted to provide the hybrid powertrain and suspension system designs.

Primus engineers were responsible for the remainder of the vehicle design. Considerable effort was expended to develop the tubular space frame chassis and to provide packaging space for all of the vehicle system components. The design of the tubular space frame chassis resulted in extensive CAD and M&S analysis in order to solve the chassis load issues that resulted due to the size and weight of the vehicle. The hybrid powertrain added several systems requiring extensive packaging space as well as several hundred feet of associated signal wire, power cabling and cooling systems plumbing. Chassis design and packaging of the vehicle subsystem components proved to be two of the largest challenges the team overcame during this project.

The vehicle exterior design presented many special challenges, especially when it was coupled to the unique tubular space frame chassis. Primus was committed to build the vehicle exactly as it was designed by the CCS student. This decision led to very unique door hinge designs, headlamp mounting systems, exterior lighting components, under hood packaging, ballistic glass mounting, and windshield egress system mounting, just to name a few.

When the primary vehicle systems design was complete, all of the design data and component technical data specifications were compiled in a package and presented to the TARDEC team at the Critical Design Review (CDR).

The design was approved and the TARDEC Team authorized building the vehicle.

Fabrication of the extensive tubular chassis also presented a significant challenge. Several fixtures had to be designed and fabricated to accurately locate each individual tube within the space frame. The complex tubular space frame design had several of these tubes with as many as three intersections which resulted in hand fitting of the tubes. Due to the high chassis loads the space frame material specified was 4130 chrome moly tubing, this material selection resulted in special weld procedures during fabrication.

Figure 4 - FED BRAVO Tubular Space Frame and Cab

While the tubular space frame provided a positive weight savings that compensated for the additional components required for the hybrid powertrain system, it also introduced additional challenges to the project. Traditional flat surfaces to mount components did not exist in this tubular space frame design. To suit chassis loads, the space frame design resulted in a significant number of tubes with placement at compound angles. This condition resulted in very limited space to package the extensive number of system components on the vehicle, a task made even more demanding due to the complex secondary mounting brackets required to attach these components to the compound angled space frame tubing.

Once the chassis fabrication was complete, the entire powertrain package was then mocked up in the chassis. This mock up revealed that the engine, integrated starter generator (ISG) and transmission assembly could not be installed in the vehicle due to chassis tube locations. The appropriate modifications were then made to the chassis and the powertrain was installed. Lastly the front traction motor was installed along with the inverters for both the ISG and the front traction motor.

Once all of the components were mocked up and the mounting and clearances verified, the vehicle was disassembled and the chassis was sent out to be normalized and sandblasted. The chassis was then painted and placed back on the surface plate to fit the exterior body panels and doors. Fitting of the doors to the steel cab portion of the chassis proved to be a demanding effort due to the very prominent exterior body lines. Once the door fitment was complete the front and rear carbon fiber body sections and panels were attached and fitted to the cab/chassis. The overall effort applied for the fit and finish of the vehicle body was significant, brought on particularly due to the prominent body lines across the steel doors/cab and carbon fiber front and rear clips. After the panels were mounted and fitting properly, the vehicle went back in the paint booth to receive the application of the exterior body color paint.

The last step in the fabrication and build of the FED Bravo vehicle was the final assembly. The powertrain and suspension components were installed along with the brakes. Plumbing of the cooling and hydraulic systems was then started. This was a formidable challenge as the vehicle has five independent cooling systems requiring lines be run from the rear of the vehicle to the front and back again. The hydraulic system is equally complex due to the electric brake pump, antilock brake system and the electric power steering. In the end one hundred and fifty linear feet of tubing was required to be bent and properly attached to the chassis.

Figure 5 - FED BRAVO Engine Compartment

The next step was the fabrication and installation of the vehicle wiring harnesses. This also proved to be an extensive challenge, the vehicle required wiring for the three powertrain control modules, injector control module and all of the vehicle system wiring. This wiring also included the high voltage wiring for the 380VDC lithium Ion battery, high voltage distribution center, ISG and inverter, front traction motor and inverter, brake pump, 12 & 24VDC inverters, and the export power module. The final wiring consisted of well over one thousand feet of wire installed in the vehicle requiring routing, retention and abrasion protection.

As discussed previously the hybridization of the FED Bravo vehicle had a significant impact to the overall packaging and space claims for components, wiring and piping. This in turn then impacted the design and build philosophy for this project. The project started with the design process with modeling and simulation following as soon as some of the vehicle parameters were defined. In parallel to these design efforts system engineering was occurring as well, driving system specifications and component requirements. These efforts then allowed for the selection of COTS components for the vehicle systems which then needed to be integrated as a design task. This circular process is then repeated multiple times as engineering is further defined and related components located and integrated within the vehicle.

Figure 6 - FED BRAVO Rear Compartment Electronics

This circular or iterative engineering and design process is a result of a robust schedule for a demonstrator vehicle not intended for production. The emphasis was on system design and R&D into viable fuel efficient technologies for the vehicle while having the additional challenge of developing the base vehicle design concurrent with the R&D efforts. Understanding that not all of the engineering answers would be made prior to the design needing to move forward presented the need for a very close knit diverse team to execute this project. The team needed to retain its cohesion while facing an ever changing and developing vehicle design and the problems that this process would entail.

All of these factors lead to the flexible team of engineers, designers and fabricators that worked efficiently together to make rapid decisions on vehicle development considering both design and fabrication needs. As the schedule continued to move forward and the vehicle moved into fabrication the decision process within this project adapted as well. The emphasis on design for the location and integration of components shifted to focus more on fab-on-the-fly solutions to solve issues and keep the project moving forward. The team began to blend "old school" craftsmanship with modern design and engineering practices living within and up to the spirit of the "Monster Garage" philosophy. This change in direction served to balance available resources within the small team executing the project and also was required due to the assembly starting to outpace the design. The significant amount of wiring and piping within the vehicle was not able to be planned in CAD and therefore many solutions to component integration were more effectively solved on-vehicle at this stage of the project.

In parallel, a full Data Acquisition (DAQ) system was integrated into the vehicle during assembly. After the completion of vehicle assembly, system power up and debug was then started. The DAQ system was instrumental in the initial debugging and subsequent developmental testing efforts. Each vehicle system was gone through individually to ensure proper functionality. Once individual systems functionality was confirmed the engine was started and transmission placed in gear. With the engine, transmission and all other vehicle systems functional the vehicle build phase of the project is complete.

At this point the vehicle was detailed and prepared for unveiling to TARDEC leadership. The vehicle was extremely well received at the unveiling; leading to an article appearing in a local newspaper as well as in the TARDEC published Accelerate Magazine.

VEHICLE SHAKE-OUT AND TEST

The first topic to discuss in vehicle shake-out and testing is that this demonstrator project (as in most demonstrator projects) has a sample size of one for the vehicle. This presents issues with executing the project since there are multiple stakeholders that require access or use of the vehicle at the same time during the course of development. For the FED Bravo project this became readily apparent at the onset of shake-out and continued through the completion of development. On this project Primus personnel would need access to the vehicle in a running condition to test or calibrate a vehicle system such as brakes or steering, thereby preventing powertrain SME's personnel from continuing on-road powertrain development. At times this resulted in having to revert the powertrain calibration to a previous "running" version if the current developed configuration was not tuned to a reasonable running condition yet. Conversely Primus would need to "surrender" the vehicle for powertrain development and stop vehicle system development for periods of time. This push-pull dynamic for vehicle access was another example of the need for a close knit team in order to execute the project effectively.

The next stage of vehicle development was vehicle shake-out to ensure safe limited vehicle operation. Due to the complex and untested hybrid propulsion system on the vehicle it was deemed prudent to complete initial shake-out on the vehicle at a controlled, non-public road location. TARDEC provided the collaborative Primus Solutions and several subcontractor SME's hanger space and limited road access at Selfridge ANG Base. Here the Primus team worked on incremental shake-out of vehicle systems such as brakes, power steering and the adjustable pneumatic suspension while working collaboratively in parallel with the powertrain team who were completing incremental shake-out of the hybrid propulsion system. The completion of this effort resulted in a limited performance vehicle with safe and trusted operation ready for the next stages of development and testing.

Figure 7 - FED BRAVO during development at CPG

Further development of the Fuel Efficient Demonstrator (FED) Bravo vehicle was again completed collaboratively between Primus Solutions and multiple subcontractor subject matter experts. These efforts took place at the Chrysler Proving Grounds (CPG) in Chelsea, Michigan. The teams worked in parallel with the Primus powertrain subcontractor concentrating on calibration development to improve functionality and maximize fuel economy while Primus continued with the remaining subsystems and overall vehicle system development. Several test and development activities were conducted including anti-lock brake system development and testing, maximum braking distance, vehicle stability, suspension system development, maximum speed, vehicle durability, climbing 60 percent grade, park brake holding test and fuel economy. All of the testing was conducted with the vehicle ballasted to gross vehicle weight (GVW) rating of 17,000 pounds. The final step in the Primus development effort at CPG was a team audit of the vehicle performance and operation to ensure the vehicle met all of the contractual parameters before proceeding to 3rd party validation testing. Again, reaching this stage took incremental subsystem development conducted in such a way as to step toward full system performance. For example, power train development could not be allowed to outpace steering and braking system development without risking safety.

With the development effort complete the vehicle was then sent to the US Army Aberdeen Test Center (ATC) in Aberdeen, Maryland for validation testing. The testing focused on gathering fuel economy data on the Hartford Loop (paved road), Munson fuel course (secondary roads) and the Churchville course (cross country). Primus provided onsite SME support of this effort to ensure the vehicle was in operational condition at all times to secure the timely completion of the on-road validation testing. Primus SME support was also provided to help ATC approach testing this unique vehicle in a safe and non-destructive manor by providing system design and functionality expertise.

Once the on-road portion of the testing was complete, the vehicle was then installed on the Road Way Simulator (RWS) at ATC. This machine is a very high capacity chassis dynamometer with the capability to articulate the suspension system mimicking the road load profiles of the actual on-road courses. The data collected on the RWS will be used by TARDEC and compared to the actual course data for correlation purposes. Primus continued to provide SME support for vehicle diagnostics and problem solving during the RWS effort until the completion of all vehicle validation testing at ATC. The final and official results of the testing performed at ATC are still being complied at the time this paper was written.

VEHICLE DEMONSTRATION AND SUPPORT

As a demonstrator the FED Bravo vehicle was utilized for demonstration purposes several times during the course of the program. The Primus team provided logistics support for the events the vehicle was displayed at by TARDEC.

Figure 8 - FED BRAVO on display at the Pentagon

The Primus logistics support provided included vehicle transportation, vehicle preparation, detailing, vehicle load-in and setup. The FED Bravo has been featured at multiple events including the Society of Automotive Engineers (SAE) 2012 World Congress held in Detroit Michigan, the grand opening of the TARDEC Ground Systems Power and Energy Laboratory (GSPEL), Department of Energy Conference held at the Pentagon in Washington DC, AUSA Winter Symposium and Exposition in Huntsville Alabama, as well as several TARDEC events.

PERFORMANCE AND FUEL ECONOMY IMPACT

Table 1 summarizes the results of utilizing the advanced road coupled parallel 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.

The FED Bravo performance characteristics surpass all the vehicle objective parameters. Acceleration 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, M&S results indicated fuel economy would be improved by over 50%.

	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 1 FED BRAVO Performance M&S Results

The FED Bravo project had a total of 123 specific measurable vehicle characteristics or performance objectives (which included the major objectives such as acceleration and fuel economy items listed above). The remainder of the characteristics and objectives ranged from items such as heating/cooling performance and transportability to operating wiper blades and turning radius. Each of these objectives were either physically tested or judged “pass/fail-to design intent” at the conclusion of this project. The final Test and Inspection report on the FED Bravo performance and characteristics showed that 88.6% of these were “Passed” (either met or exceeded objective). This left 6.5% as “Not Tested” and 4.8% as “Failed”.

It should be noted that the “Not Tested” items were removed from the list with concurrence from TARDEC engineers in order to protect the demonstrator asset due to design constraints and/or to reduce cost and timing on the project. For instance the “emergency lane change” test was not conducted to save the time and expense of having to design and fabricate outriggers for the vehicle as well as to avoid risk of damage to the vehicle during the test (i.e. this is not a suspension demonstrator but a fuel efficiency demonstrator). This test was passed in the modeling and simulation completed on the vehicle design prior to fabrication and assembly. Roof crush (a destructive, or at least damaging test) was another example of this deviation from the test plan due to a single asset project that needed to be protected in order to ensure the primary objectives (fuel economy) could be tested.

Items that did not pass inspection were also items that were allowed to not pass with concurrence from TARDEC engineers. This included items such as turn radius (3” too large), lack of upper lift hooks (no air transport required for a demonstrator) and park brake hold on 60% grade (not an operating slope for the demonstrator). By working collaboratively with the TARDEC engineers these trade-offs allowed allocation of funding and labor to be applied to more relevant and significant vehicle performance objectives, in this case fuel efficiency.

Figure 9 - FED BRAVO at 2012 SAE World Congress

The FED Bravo vehicle was and continues to be an outstanding success for TARDEC and Primus Solutions. This success was driven by a series of factors on this project. This started with an understanding by TARDEC engineers that over-constraining the requirements for this project would inhibit its ability to succeed and that trade-off space needed to be available in order to maximize the results of this effort. TARDEC also played a key role in taking co-ownership of risk with Primus to again allow for an acceptable level of risk balanced against significant gains. A key example of this was the decision for a tubular space frame chassis, this was a high risk item that yielded great results and helped to ensure the project's success. The decision to use the space frame was presented by Primus but agreed to by TARDEC even with the higher risk associated with it.

Another factor leading to the success of this project was the team philosophy that existed within the Primus team and its subcontractor partners. All team members from designers, to fabricators, to project leads equally contributed to mitigate issues, manage risk and quickly reaching consensus in order to execute trade-offs. This team dynamic also saw team members contributing with multiple skill sets on this program, allowing for increased effective use of resources. This was a major factor that allowed the flexibility required to maximize the project outcome while meeting timing and cost constraints.

This unique mix of flexible team members working with a customer that understands the impacts due to over-constraining and can effectively manage risk against reward to achieve success within timing and cost limitations resulted in the outstanding example in systems integration and the vehicle that is FED Bravo.

REFERENCES

[1] G. Hunter, "Creating Optimized Powertrains For the Warfighter", Power and Mobility (P&M) Technical Session, Ground Vehicle Systems Engineering and Technology Symposium (GVSETS), Novi, MI, Aug. 4-6, 2015.