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Assessing the Commercialization Status of the U.S. Department of Energy "SuperTruck" Technologies and their Applicability in Tactical Wheeled Vehicles

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ABSTRACT

The U.S. Department of Energy established the SuperTruck program in 2009 with the goal of developing and demonstrating technologies that can vastly improve the efficiency of Class 8 over-the-road trucks. Several teams participated in the program and developed prototypes that demonstrated more than double the fuel economy of conventional trucks. As part of the High-Efficiency Truck Users Forum program CALSTART investigated the approaches taken by the different teams and analyzed the military applicability of the technologies that were employed.

INTRODUCTION

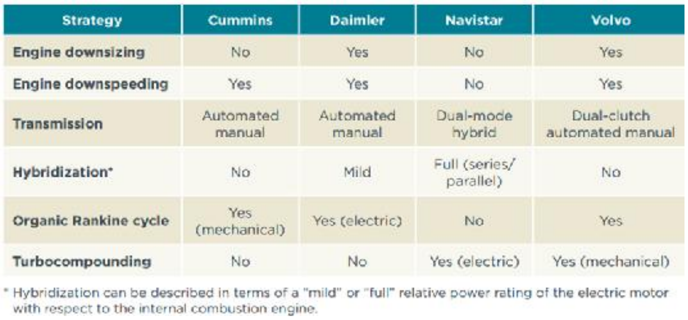
In this project CALSTART and High-Efficiency Truck Users Forum (HTUF) stakeholders assessed the commercialization status of U.S. Department of Energy SuperTruck technologies and their military relevance to certain U.S. Army Tactical Wheeled Vehicle (TWV) classes which share similar specifications to the commercial Class 8 truck. However, important differences such as drastically increased idling (military trucks idle at or above 50 percent of their engine-on time) and the JP8 single-fuel policy required of all military vehicles, ultimately limit the full-scale adoption of all SuperTruck technologies. An exception to this single-fuel policy applies to tactical trucks based in the U.S., which unlike their combat-ready overseas counterparts can occasionally be outfitted for diesel fuel. Key transition technologies were noted that reflect crossover areas between military and SuperTruck applications.

SUPERTRUCK PROGRAM APPROACH

In 2009 the U.S. Department of Energy coordinated with four teams to develop advanced-generation, highly-efficient prototype Class 8 trucks under the SuperTruck program. This public-private partnership had three main goals:

- Achieve a 50 percent freight efficiency improvement,
- Demonstrate 50 percent brake thermal efficiency (BTE),
- Design a pathway to 55 percent BTE.

The Class 8 truck sector was selected due to its disproportionately higher fuel use than other commercial vehicles. In 2011 only one quarter of registered medium and heavy-duty commercial trucks were Class 8, but these same vehicles consumed two-thirds of overall fuel use (see Transportation Energy Data Book, Edition 32). SuperTruck teams were given the freedom to investigate and deploy any technology they wanted, only constrained in their focus by the three objectives listed above. Ultimately, teams approached the project by combining a variety of prototype and pre-production technologies on a final demonstration vehicle as shown below.



Strategy	Cummins	Daimler	Navistar	Volvo
Engine downsizing	No	Yes	No	Yes
Engine downspeeding	Yes	Yes	No	Yes
Transmission	Automated manual	Automated manual	Dual-mode hybrid	Dual-clutch automated manual
Hybridization*	No	Mild	Full (series/ parallel)	No
Organic Rankine cycle	Yes (mechanical)	Yes (electric)	No	Yes
Turbocompounding	No	No	Yes (electric)	Yes (mechanical)

* Hybridization can be described in terms of a "mild" or "full" relative power rating of the electric motor with respect to the internal combustion engine.

Figure 1: Key differences between SuperTruck teams

Daimler and Volvo both used engine downsizing and down-speeding technologies with automated manual transmissions. Daimler included mild hybridization in their powertrain strategy, while Navistar investigated full hybridization. The Navistar design was ultimately foregone as no prototype was completed for this project. All teams with prototypes incorporated Waste Heat Recovery (WHR) systems based on the Organic Rankine Cycle; the Volvo team also employed a mechanical turbo-compounding system, increasing power output and BTE.

CUMMINS/PETERBILT TEAM APPROACH

The Cummins/Peterbilt team completed their demonstration vehicle in April 2014, achieving 51 percent BTE and an 86 percent freight efficiency improvement, detailed in the chart below.

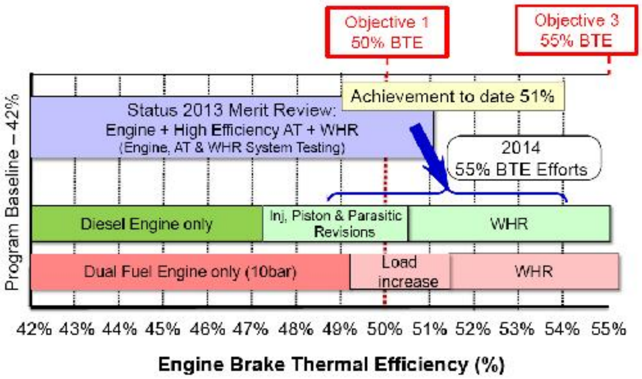


Figure 2: Cummins/Peterbilt technical progress and improvements

The prototype BTE achievement of 51 percent is identified above and was accomplished through engine advancements, high-efficiency after-treatment and a prototype WHR system. The pathway to 55 percent BTE is also noted through advanced WHR efforts, injector piston and parasitic revisions in the engine. Various tractor and trailer aerodynamic enhancements also increased fuel economy to an average of 10.7 miles per gallon (MPG) in multiple tests nationwide. Freight efficiency was improved by 86 percent through a variety of tractor and trailer optimization techniques; focusing on aerodynamics, engine and transmission advances, and vehicle weight reductions.

DAIMLER TRUCK NORTH AMERICA APPROACH

Daimler completed their prototype vehicle in March 2015. The team already demonstrated over 50 percent BTE and modeled a pathway to a 50 percent freight efficiency improvement in early tests, shown in Figure 3. Aerodynamics, powertrain and drivetrain development for the tractor, light-weighting, energy management, parasitic losses, and engine efficiency measures lead to a Freight Efficiency Improvement above 50 percent.

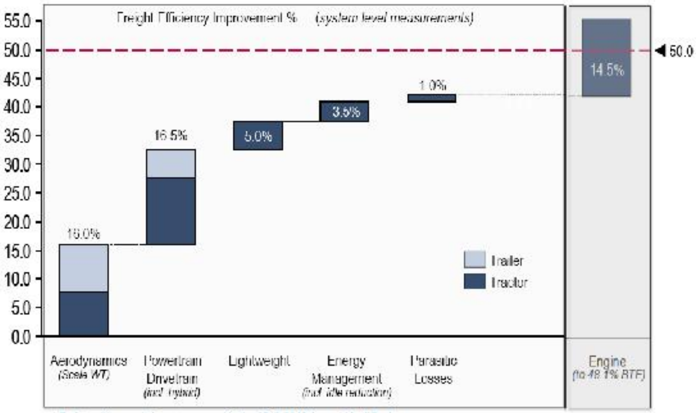


Figure 3: Daimler Trucks North America Freight Efficiency Status (Source: Daimler trucks North America)

The team downsized the engine from 14.8L to 10.7L, reduced EGR, increased compression ratios, and optimized the turbocharger, piston bowl shape, and variable speed water pump. Low viscosity oil and higher oil film temperatures along with a high-efficiency lower restriction after-treatment were also focus areas.

The final prototype from this team achieved 12.2 miles per gallon and freight efficiency improvement of 115%, far surpassing the program goal of 50%. The advanced aerodynamics led to a unique vehicle appearance.

Figure 4: Freightliner (DTNA) SuperTruck unveiling in Spring 2015 (photo courtesy of Stephanie Babcock)

The final prototype includes a combination of commercially-available technologies and other concepts that will not be available commercially until the early 2020s.

VOLVO GROUP AAPROACH

Volvo is the third and final team on track to complete a prototype, due in June 2016. Thus far the team has demonstrated 43 percent freight efficiency improvement over baseline and 48 percent BTE on a test vehicle through advanced powertrain integration and optimization. The BTE improvement strategy shown below highlights the eight different advancement areas Volvo is focusing on to improve their baseline powertrain.

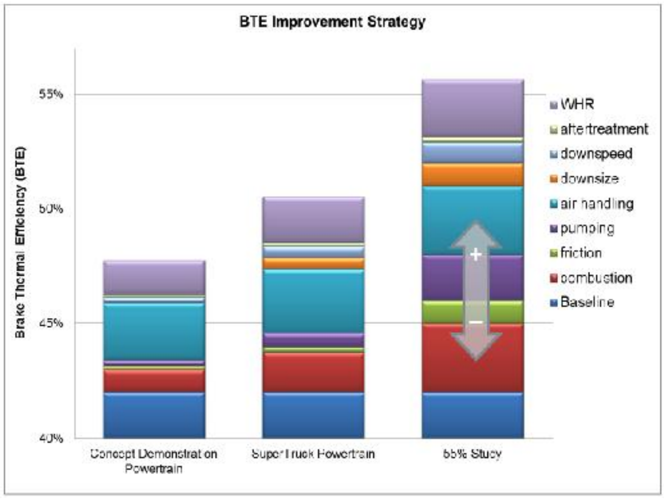


Figure 5: Volvo technology focus areas (Source: International Council of Clean Transportation)

TECHNOLOGIES OVERVIEW

There were eight overarching technology focus areas in the SuperTruck program, each contributing to the BTE or Freight Efficiency improvement requirement detailed in the project goals. The matrix analysis that follows this overview identifies the relevance of these technologies to the military heavy-duty line-haul Tactical Wheeled Vehicle (TWV). The first focus area is Engine Efficiency, which included detailed improvements to the combustion cycle and new control systems for enhanced fuel efficiency, depicted below.

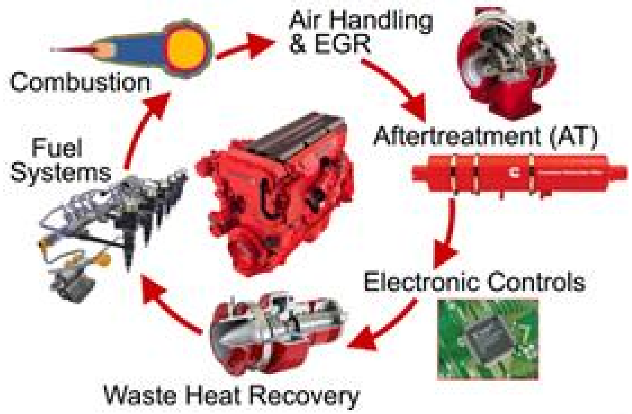


Figure 6: Integration of Cummins component technologies (Source: Cummins/Peterbilt)

This two-pronged approach addressed both short-term and long-term concerns in the trucking industry; increased fuel economy and adjustment for varying drive-cycles, respectively. One of the teams ensured that engine controls were calibrated to function with a dramatically downsized engine while another team focused on integrating the WHR and after-treatment systems. While some of these improvements and system roll-outs are currently in field validation and aiming for near-term commercial deployment, many of the more complex systems will not be commercially available before 2020. Regardless, these engine efficiency strategies have broad applicability to the TWV and military vehicles in general, as they decrease fuel consumption while increasing vehicle automation.

Improving aerodynamics on the Class 8 truck involves reducing aerodynamic drag while balancing the additional weight of tractor and trailer enhancements. The effectiveness of these additions is highly dependent on vehicle speed. Every technique and component used on SuperTruck demo vehicles is commercially available today; these include tractor fairings, chassis skirts, wheel covers, and other enhanced aero packages, including the rear-view cameras shown below.

Figure 8: Advanced rear-view truck cameras (Source: Navistar)

The difficulty with incorporating these technologies on the TWV lies in the varying tractor that is often pulled by military vehicles, which is distinctly different than the standard box trailer modeled and demonstrated in the SuperTruck program. However, the tactical trucks based in the U.S. might qualify for some of these technologies, unlike the combat-ready vehicles overseas which often require body armoring and cladding.

A handful of light-weight components were categorized together as **Weight Reduction** techniques, which are helpful to offset addition of advanced batteries, WHR, and other equipment. Specific advances in manufacturing for major vehicle systems also fall under this category. Tandem, or 6x2 axles and wide-base single tires are currently commercially available and can be responsible for major weight savings on Class 8 trucks.

Figure 9: Commercially-available tandem axles (Source: Meritor)

The above tandem axle shows a disconnected front and rear axle in the tractor; the unpowered rear axle merely trails behind the front, significantly reducing weight. On a different track, one team manufactured a fully-aluminum tractor chassis, saving nearly 4000 pounds while maintaining structural rigidity. This full-system light-weighting technique is extremely applicable to the TWV, helping to offset the constant weight additions for body armoring and cladding.

The main reasons why **Electrified Auxiliaries** were investigated and developed for the SuperTruck program were overall system efficiency gains and pathways to idle reduction mechanisms. Electrifying certain engine components, such as oil, water, and power steering pumps as well as air conditioning compressors and cooling fans allows these truck subsystems to run from a power source independent of the engine. A frame-mounted auxiliary power unit (APU) is shown in Figure 10.

Figure 10: Commercially-available battery APU system (Source: Kohler)

This scheme, along with integration of APU and battery-assisted HVAC systems is necessary for idle reduction in Class 8 trucks. The idle reduction capability is extremely relevant for the TWV and other military vehicle platforms as it is an enabler for engine-off activities and other fuel-reduction strategies. Additionally, this electrification is required for the military's program of advanced vehicle automation.

Some advanced components were prototyped for the SuperTruck program or are currently available as pre-production units and are expected to transition to widespread commercial availability in the short-term.

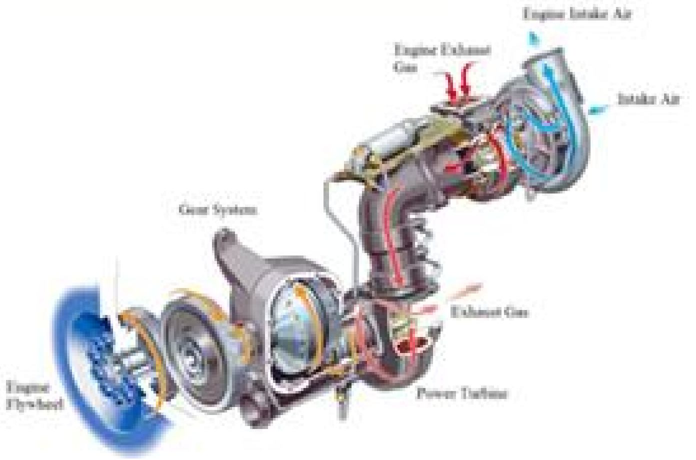


Figure 11: Mechanical turbo-compounding diagram (Source: KTH Royal Institute of Technology)

One of the major benefits of the SuperTruck program was its requirement to develop advanced technologies and actually deploy them on a vehicle. All teams focused significant efforts on **Waste Heat Recovery** (WHR) systems as a means to increase BTE. Prototype systems captured heat from the engine and used it to move a working fluid through the organic rankine cycle, ultimately producing mechanical or electrical power. Deployment of thermoelectric generators was not part of any SuperTruck team but should be of interest to the US Army.

Though finalizing WHR designs will require lighter and cheaper components for integration, this technology represents the long-term future of Class 8 efficiency strategies. Other pre-production techniques include electrical and mechanical turbo-compounding, which use a difference in pressure to generate mechanical work or electricity. All WHR prototype technologies along with electrical turbo-compounding systems (including controllers) are appropriate for TWV and broad-scale military vehicle deployment due to their packaging capability within other engine efficiency strategies.

There are only a few **Hybridization** technologies which retain relevance to the SuperTruck teams and the TWV. Designs must be able to support multiple electrical loads without substantial weight increase. Battery-assisted idle reduction, as discussed previously, involves maintaining power to key subsystems while the engine is turned off during periods of extended idling. This reduces fuel consumption and enables engine-off activities on heavy duty vehicles. Mild hybrid electric powertrains provide fuel economy benefits with minimal increased onboard componentry, allowing for efficiency gains that may have been offset by weight increases associated with the advanced generation powertrain. These systems are currently in prototype form and will most likely be commercially available only in three to five years.

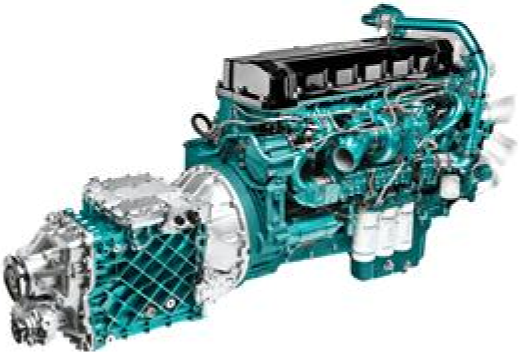


Figure 12: Volvo dual clutch automated-manual transmission integrated with downsized engine (Source: Volvo Group)

Reduction in Driveline Losses is closely tied to engine optimization technologies and strategies; in fact the advanced automated manual transmission favored by the SuperTruck teams is imperative in enabling the multitude of engine enhancements. Down-speeding and engine downsizing are only possible due to optimized integration with automated manual transmissions (AMT); effectively creating an advanced driveline that reduces fuel consumption. The automated manual transmission is commercially available today and when paired with the engine optimization strategies described previously is very attractive for deployment on the TWV. These advanced AMT systems reduce opportunity for operator error while retaining overall robustness and performance, key tenets of military strategy on future heavy duty vehicles.

TECHNOLOGY INSERTION MATRIX

CALSTART and its HTUF stakeholders performed an analysis of the technologies chosen by the SuperTruck and matched them to the requirements and specifications of similar tactical-wheeled vehicles currently in use in the U.S. Army. In particular the 915- and 916-class line-haul tractors may provide the best and earliest opportunities to adopt SuperTruck technologies to military applications. The following matrix listed each of the major SuperTruck technologies, assessed the compatibility to military applications and then added in commercial availability estimates:

Technology Pathway by Source	Relevance to Heavy-Duty Line-Haul TWV?		Current Technology Status	Commercial Availability (CALSTART estimation)
	Yes	No		
Engine Efficiency*				*Of interest to U.S.-based tactical vehicles
Engine design and combustion processes	X		Field Validation	2014-2017
Engine friction and parasitics	X		Field Validation	2014-2017
Predictive Engine Controls	X		Prototype	2017-2020
Downsized Engine	X		Prototype	2014-2017
Engine Downspeeding	X		Production	2014
Improved Aerodynamics*				*Of interest to U.S.-based tactical vehicles
Roof Fairings/Vortex Generators	X		Production	2014
Cab extender fairings	X		Production	2014
Chassis skirts/side tank fairings	X		Production	2014
Wheel covers	X		Production	2014
Fly-swatter mudflaps	X		Production	2014
Weight Reduction				
Chassis light-weighting	X		Prototype	2017-2020
Component light-weighting	X		Pre-Production	2014-2017
Tandem (6x2) axle	X		Production	2014
Wide-base single tires	X		Production	2014
Electrified Auxiliaries**				**Required for military program of advanced vehicle automation
Oil pump, water pump, power steering pump	X		Prototype	2014-2017
A/C compressor, cooling fans, air system	X		Prototype	2014-2017
Auxiliary Power Unit	X		Production	2014
Battery-HVAC	X		Production	2014

Technology Pathway by Source	Relevance to Heavy-Duty Line-Haul TWV?		Current Technology Status	Commercial Availability (CALSTART estimation)
	Yes	No		
Waste Heat Recovery				
Organic rankine cycle	X		Prototype	2020-2025
Thermoelectric generator	X		Prototype	2020-2025
Electrical turbo-compounding	X		Pre-Production	2014-2017
Mechanical turbo-compounding	X		Production	2014
Electrically-assisted turbocharger	X		Prototype	2014-2017
Hybridization				
Electrically-Assisted Idle Shutdown	X		Prototype	2017-2020
Micro/Mild Hybrid Electric Vehicle	X		Prototype	2017-2020
Hybrid Electric Vehicle (parallel, series, and dual-mode)		X	Production	2014
Range-Extended Series Hybrid		X	Field Validation	2017-2020
Driveline Losses				
Automated Manual Transmission	X		Production	2014
Automatic Transmission	X		Production	2014

GLOSSARY OF ADVANCED TECHNOLOGIES

Automated Manual Transmission: Automatic clutch actuation enables increased fuel economy over standard automatic transmissions.

Automatic Transmission: Torque converter decouples engine and transmission, enabling gear shifts.

Auxiliary Power Unit: A battery or diesel-powered APU can run vehicle electronics in place of the engine, reducing idle fuel consumption and enabling start-stop technologies.

Battery Heating Ventilation and Air Conditioning (HVAC): Battery-powered HVAC systems are generally more efficient than conventional systems and can run off their own battery pack or the vehicle batteries; they are an enabler to start-stop technologies as well.

Cab Extender/Roof Fairings and Vortex Generators: Fixtures on the tractor lessen the gap with the trailer, simulating one long object, reducing air flow between bodies and associated aerodynamic losses.

Chassis Light-Weighting: All-aluminum tractor chassis is 40 to 45% lighter than baseline and require manufacturing process advancements for prototype.

Chassis Skirts and Side Tank Fairings: Fixtures on the tractor and trailer frames lessen the gap between frame and road, reducing air flow beneath the vehicle and associated aerodynamic losses.

Component Light-Weighting: Light weight brake rotors and calipers, plastic fuel tanks, single propeller shafts, cast aluminum alloy wheels, aluminum axle hubs, composite front axle leaf springs, aluminum clutch housings, and aluminum cab frames all contribute to the overall light-weighting scheme.

Downsized Engine: Reduced engine displacement, combined with other enhancements maintains power production while increasing fuel economy.

Electrically-assisted Idle Shutdown: Automatic engine shut-off procedure supports electrical loads from APU or vehicle battery power.

Electrically-assisted Turbocharger: A small motor on the turbo shaft generates power or helps to spin the turbo.

Electrified Auxiliaries: Oil, water, and power steering pumps, A/C compressor, cooling fans, and the air system are electrified to run independently of engine power.

Electrical Turbo-Compounding: A turbine recovers energy from the exhaust system which is then used to generate electrical power.

Engine Design and Combustion Processes: Focuses are on increased peak combustion pressure, optimum valve timing, higher injection pressure, compression ratio increases, optimized piston bowl shape, calibration for fuel efficiency, turbo optimization, and reduced EGR rates.

Engine Down-speeding: Reduced RPM level at which peak torque is developed allows for decreased engine speed, reduced frictional losses, and lower fuel consumption.

Engine Friction and Parasitics: Reductions are achieved through integration of low friction pistons, rings, coatings, cylinder materials and configurations, as well as thermal barrier coatings on key components.

Fly-Swatter Mud Flaps: Grid-like holes in standard mud flaps allow air to pass through and reduce wind resistance at high speeds.

Hybrid Electric Vehicle (parallel, series, and dual-mode): Parallel hybrids create mechanical power (from the engine) or electrical power (from an electric motor). Series hybrids have combustion engines that drive an electric generator which in turn powers electric traction motors. Dual-mode hybrids choose in which mode (parallel or series) to operate based on fuel efficiency at a given speed.

Mechanical Turbo-Compounding: A turbine recovers energy from the exhaust system which is then used to generate mechanical power.

Micro/Mild Hybrid Electric Vehicle: Micro HEV can shut down engine when idling. Mild HEV can shut down engine when coasting, braking, or idling.

Organic Rankine Cycle: Thermodynamic cycle that recovers heat from engine exhaust and other heat exchangers by using a working fluid that absorbs waste heat and is then expanded in a downstream turbine, producing additional useful power and lowering overall emissions.

Predictive Engine Controls: Algorithms that incorporate GPS and road mapping data to predict and control future response of the engine.

Range-Extended Series Hybrid: These series hybrids are designed to run primarily on battery power, but have a fuel generator to recharge the battery when driving for extended distances.

Tandem (6x2) Axle: Removed drive axle from rear tractor wheels creates un-powered trailing axle, substantially decreasing componentry and weight.

Thermoelectric Generator: Current is generated across a high-temperature, low-temperature gradient and (usually) fed to an energy storage device for later use.

Wheel Covers: Reduce drag from air flowing over wheels.

Wide-Base Single Tires: Replaced dual-tire configuration by a wide-base single tire decreases overall surface friction.

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