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THE U.S. SUPERTRUCK PROGRAM

EXPEDITING THE DEVELOPMENT OF ADVANCED HEAVY-DUTY VEHICLE EFFICIENCY TECHNOLOGIES

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EXECUTIVE SUMMARY

Heavy-duty vehicles constitute the largest or second largest source of transport-sector carbon emissions in every major economy around the world. The fuel use of these vehicles, and hence their carbon emissions, can be reduced by new developments in technology and changes in policy. In the United States, heavy-duty engine and vehicle efficiency standards pertaining to 2020 and later trucks, tractors, trailers, and buses are to be developed in the 2014–2015 time frame. These standards need to take into account the availability of advances in technology, as well as how regulatory test procedures promote given technologies.

The U.S. Department of Energy (DOE) SuperTruck program is a cost-shared, public-private partnership that promotes precompetitive research and development (R&D) to improve the freight-hauling efficiency of heavy-duty Class 8 long-haul tractor-trailer trucks. The $284 million program aims to help accelerate the development of advanced efficiency technologies that are not currently available in the market. It leverages public and private industry efforts to develop, demonstrate, and showcase technologies that can greatly increase the efficiency of this class of trucks, which moves the most freight, consumes the most fuel, and has the highest carbon dioxide emissions of the heavy-duty fleet. Relative to approximate 2010 baseline technology, the program seeks a 50% increase in overall tractor-trailer freight efficiency and a 20% increase in engine efficiency [i.e., achieving 50% brake thermal efficiency (BTE) relative to an approximate 42% baseline] by 2015.

Four industry teams were competitively selected for the program. This report investigates, compares, and assesses the implications of the four teams' ongoing work. Descriptions of the technical specifications, the engineering results, and the technology choices of the various teams are based on public data from DOE analysis, industry reports on the projects, and communication with members of the teams.

The assessment finds that the teams have each achieved substantial progress toward the project objectives. In particular, three of the four teams have approximately achieved the tractor-trailer fleet target of a 50% freight efficiency increase. These SuperTruck program findings imply a dramatic increase in on-road freight efficiency; the program's results, for example, are equivalent to increasing tractor-trailer fuel economy from approximately 6 to 7 miles per gallon to approximately 9.5 to 10.5 miles per gallon for a loaded tractor-trailer. Examining the teams' engine progress through mid-2013 reveals that all the teams have achieved 48% BTE, and one team has exceeded the 50% BTE target. All the teams have identified technical pathways to achieve the 50% BTE target.

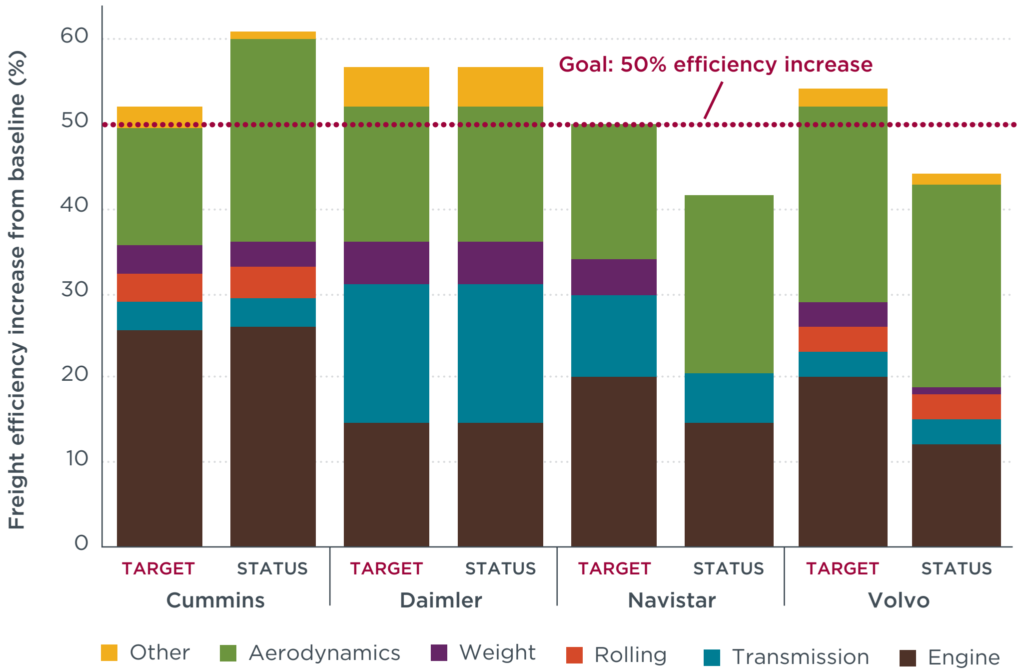

Figure 1. Comparison of U.S. SuperTruck targets and 2013 status for tractor-trailer freight efficiency in miles/ton-gal. *Each team was given the flexibility to select its own baseline vehicle and duty cycle to measure freight efficiency. Therefore, the efficiency improvements shown are not directly comparable.*

This analysis makes clear that substantial effort and investment from the public and private sectors are contributing to long-term economic efficiency and environmental goals. The SuperTruck program is an example of long-term R&D policy that involves the private sector in R&D activities to accelerate technology development. It promotes R&D investments that individual companies are unable or unwilling to undertake alone, and it encourages integrated full-vehicle collaboration among technology providers that would otherwise not occur. The program leverages public investment in applied research and enables the knowledge gained in the laboratory to be turned into useful technological innovations in the vehicle fleet. The technologies investigated can also help inform policymakers' future efficiency goals, for example, in tractor-trailer regulations for 2020 and beyond.

The implications of such a comprehensive program for advanced efficiency technology could be quite profound. The heavy-duty vehicle industry is global; many of the technologies demonstrated in this U.S.-based program can be customized for other markets that are striving for more efficient commercial freight transport. To maximize the value of the program, we recommend that industry and DOE representatives publish rich and detailed information to quantify the SuperTruck technologies' impacts. This will aid policymakers' deliberations to set future policy that will promote the use of the most cost-effective of these advanced efficiency technologies, accelerating their deployment in the marketplace.

INTRODUCTION

The global heavy-duty vehicle fleet is nearly exclusively fueled by petroleum-based fuel. Heavy-duty vehicles are the first or second largest (along with automobiles) transport-sector carbon emitter in every major economy around the world. Although there are barriers to the deployment of efficiency technologies, technology and policy developments could reduce heavy-duty vehicle fuel use and carbon emissions. For example, research and development (R&D) programs are advancing new technical solutions, emerging voluntary fleet-based actions are accelerating the adoption of off-the-shelf technologies, and efficiency standards are requiring incremental efficiency improvements for trucks and buses.

In the United States, none of the current heavy-duty vehicle efficiency policies approach the technology-forcing nature of existing 2025 light-duty vehicle efficiency regulations. A second phase[1] of U.S. heavy-duty engine and vehicle efficiency standards is to be developed in the 2014–2015 time frame and will pertain to 2020 and later trucks, tractors, trailers, and buses. Among the more prominent issues in the development of these standards are technology availability, how the regulatory test procedures promote given technologies, and how stringent the standards should be. Therefore, a fundamental question is how much of the in-development technology work—for example, from industry and government R&D programs—will be used in the rulemaking.

The U.S. Department of Energy (DOE) SuperTruck program is one of the most prominent and ambitious R&D programs in the world for heavy-duty vehicle efficiency. The SuperTruck program is a project sponsored by DOE and cost-shared by four competitively selected teams led by major engine and truck manufacturers. The program leverages public and private industry funds to help spur the development of new efficiency technologies, foster a friendly competition among manufacturers and suppliers,[2] showcase state-of-the-art vehicle technologies, and allow detailed engineering data collection and public reporting on those efforts. DOE's Office of Energy Efficiency and Renewable Energy administers the project. From a public funding perspective, the project is supported by funds from the American Recovery and Reinvestment Act and congressional appropriations provided to DOE. Including the cost-sharing from industry, the total program cost is estimated at approximately $284 million across the four teams (Gravel, 2013).

The goal of the SuperTruck program is to develop and demonstrate a wide range of state-of-the-art, commercially feasible efficiency technologies for Class 8 long-haul tractor-trailers.[3] According to U.S. Energy Information Administration data, tractor-trailers represent approximately 2% of the total on-road vehicle population in the United States but amount to 6% of the total vehicle miles traveled, and in 2013 they consumed about 20% of the fuel used for transport (EIA, 2013). The four projects are focusing on measures to improve the overall efficiency of long-haul Class 8 trucks to be demonstrated at the full-vehicle system level. The technologies developed under the SuperTruck program are considered high-risk investments, and without the program

1 First-ever greenhouse gas (GHG) and fuel efficiency standards were developed jointly by the U.S. Environmental Protection Agency (EPA) and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA). This first phase of regulations covers new engines and vehicles with model years 2014 to 2018 (EPA and NHTSA, 2011).

2 The program facilitates development of precompetitive technical knowledge through investments in R&D.

3 Vehicles in Class 8 have a gross vehicle weight rating (GVWR) at or above 33,000 lb.

they would not be expected to begin entering the market over the next decade. This report summarizes the strategies followed and the results obtained by the SuperTruck teams, thereby providing a synthesis of relevant technical data for the ongoing deliberations on U.S. heavy-duty vehicle efficiency policy as well as potential heavy-duty vehicle efficiency programs in other markets.

SUPERTRUCK PROGRAM OBJECTIVES

The R&D efforts of the program should lead to the achievement of the following three objectives (NRC, 2012):

1. Vehicle freight efficiency: Develop and demonstrate a 50% improvement in overall freight efficiency of a heavy-duty Class 8 tractor-trailer measured in ton-miles/gal[4] relative to a 2009 "best-in-class" commercially available truck baseline. This objective includes demonstration via full-vehicle testing over a test cycle representative of a typical long-haul Class 8 truck.[5]
2. Engine efficiency: Develop an engine that achieves 50% brake thermal efficiency (BTE) under highway cruise conditions. This objective includes demonstration via engine dynamometer testing under a load representative of driving on a level road at 65 mph. From an approximate baseline of 42% BTE, an increase to 50% BTE (i.e., 8 BTE percentage points) represents a 20% increase in engine efficiency and a 20% increase in overall vehicle freight efficiency.[6]
3. Engine efficiency: Show a technical pathway to achieve 55% engine BTE. This objective would identify and evaluate potential approaches and an engine technology roadmap to achieve 55% BTE via modeling and analysis.

Additional requirements for the development projects are to incorporate compliance with prevailing U.S. Environmental Protection Agency (EPA) emissions standards,[7] as well as all the vehicle safety and regulatory requirements that apply for commercial tractor-trailers. As the ultimate purpose of the program is to develop advanced technologies that can be transitioned into the marketplace, a validation of cost-effectiveness and commercialization potential is a high-priority deliverable for later project phases.

BASELINE CONFIGURATIONS

The freight efficiency improvement objective is measured with respect to a "best-in-class" 2009 model year baseline truck. Each team had the flexibility to specify its own baseline vehicle configuration. Specific details about the selected baseline vehicles are not publicly available. However, Table 1 shows the average characteristics, along with their standard deviations, for the four baseline truck configurations as reported in a program benefit analysis study (TA Engineering, 2012). The teams also had flexibility in the definition of the duty cycle to estimate fuel economy and freight efficiency. Each team defined its own duty cycle based on available data and knowledge of its clients' driving

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4 Equivalent to 33% reduction in load-specific fuel consumption (gallons per 1,000 ton-miles).

5 The test cycle should include a minimum of 75% of the distance traveled under highway conditions with a vehicle weight of 65,000 lb. Test cycles are not the same for all the teams.

6 Equivalent to 16.7% reduction in load-specific fuel consumption (gallons per 1,000 ton-miles).

7 Particulate matter (PM) emissions standard of 0.01 g/bhp-hr (grams per brake horsepower–hour), nitrogen oxides (NO_X) emissions standard of 0.2 g/bhp-hr, and nonmethane hydrocarbons (NMHC) emissions standard of 0.14 g/bhp-hr for model year 2010 and newer heavy-duty diesel engines measured over the transient Federal Test Procedure (FTP) cycle and the multimodal steady-state Supplemental Emissions Test (SET) cycle. The certification process also includes not-to-exceed in-use testing requirements with limits of 1.5 × FTP standards (Federal Register, 2001).

patterns.[8] These flexibilities make it difficult to draw direct and precise quantitative comparisons among the results obtained by the different teams. Because of the differing freight efficiency and BTE baselines, and because the vehicles are tested over different duty cycles, even if all the teams achieve the 50% improvement objective, the final demonstration vehicles are not expected to achieve the same absolute values of freight efficiency. In this sense, the figures discussed in this report for the different SuperTruck teams are a starting point for more detailed analysis that could be conducted as richer technical data are made available (e.g., specific baseline data for the four projects).

Table 1. Baseline truck average characteristics (TA Engineering, 2012).

Baseline truck characteristic	Average	Std. dev.
Engine displacement (liters)	13.8	1.3
Engine peak horsepower	470	14
Engine peak BTE (%)*	43.1	2.0
Vehicle curb weight (lb)	32,493	892
Vehicle payload (lb)	32,508	892
Aerodynamic drag coefficient†	0.58	0.03
Frontal area (ft2)†	113.4	1.7
Rolling resistance coefficient (kg/ton)†	5.7	1.1
Fuel economy (mpg)‡	5.54	0.50
Freight efficiency (ton-mpg)‡	90.0	7.4

*Some parasitic loads differ by participant. †Not all the teams provided values.
‡Efficiencies were estimated over duty cycles that differ among teams.

We also make several additional notes and caveats. It is not the objective of this report to compare the teams' results on an absolute basis, but rather to make the most quantitative comparisons possible about their different strategies and to assess the expected fuel consumption reductions from individual technologies.

It is also necessary to keep in mind that some of the technologies discussed in this report are only applicable to long-haul driving conditions (i.e., sustained high speeds at high load with little to no stop-and-go driving). Some of the technologies discussed here are not directly applicable to vehicles designed for urban driving patterns that mainly involve stop-and-go driving. For example, using aerodynamic devices at low speed may actually decrease a vehicle's fuel efficiency because the vehicle would be carrying the extra weight of the devices while undergoing minimal aerodynamic load.

8 The resulting drive cycles consist of mostly highway cruise with average speeds between 55 and 65 mph and road grades up to ±7%, representative of U.S. roads (TA Engineering, 2012).

SUPERTRUCK TARGETS AND STATUS OF PROJECTS

The four projects selected for awards under the SuperTruck program are led by Cummins Inc., Daimler Trucks North America LLC, Navistar Inc., and Volvo Technology of America Inc. These industry teams are leading vehicle and engine manufacturers in the North American market, and together they account for more than 75%[9] of the Class 8 market in the United States. The teams are composed of a number of partners, including engine, truck, and trailer manufacturers as well as suppliers, fleet owners, universities, and national laboratories (see the Appendix for a list of team members and their roles). This diverse group of manufacturers, suppliers, and technology developers are working on different technologies to address particular energy loss mechanisms. Figure 2 illustrates a hypothetical energy audit for a complete vehicle showing the different energy loss mechanisms. The proportion of the fuel energy that gets converted into indicated work is a direct measure of the engine's fuel conversion efficiency. Factors that affect an engine's fuel conversion efficiency include irreversibilities in the combustion process, the amount of energy leaving the engine cylinder as heat, and the energy remaining in the exhaust at the end of the expansion process. These indicated efficiency losses represent fuel energy that was not converted into work during the combustion process. Moreover, not all of the energy that is converted into work makes it to the final engine shaft output. Some of the energy is used in overcoming engine friction, some is used to pump air into the engine and exhaust gases out of the engine, and some is used to power engine auxiliaries (e.g., water pump, oil pump, fuel pump) and accessories (e.g., cooling fan, alternator, power steering fluid pump, compressor for cabin air conditioning). The BTE value, expressed as a percentage, is the ratio between the useful work at the engine shaft output and the fuel energy input. Finally, the work that makes it to the drive axle(s) (after driveline losses are accounted for) is used to overcome vehicle road loads of inertia, aerodynamic drag, road grade, and rolling resistance.

9 Class 8 U.S. market share in 2012 was 31% Freightliner (Daimler), 16% International (Navistar), 14% Kenworth, 14% Peterbilt (Cummins team), 10% Volvo, and 8% Mack (subsidiary of Volvo). Cummins (market share of 37%) provides engines to the entire group of vehicle OEMs. Source: Polk US HD database.

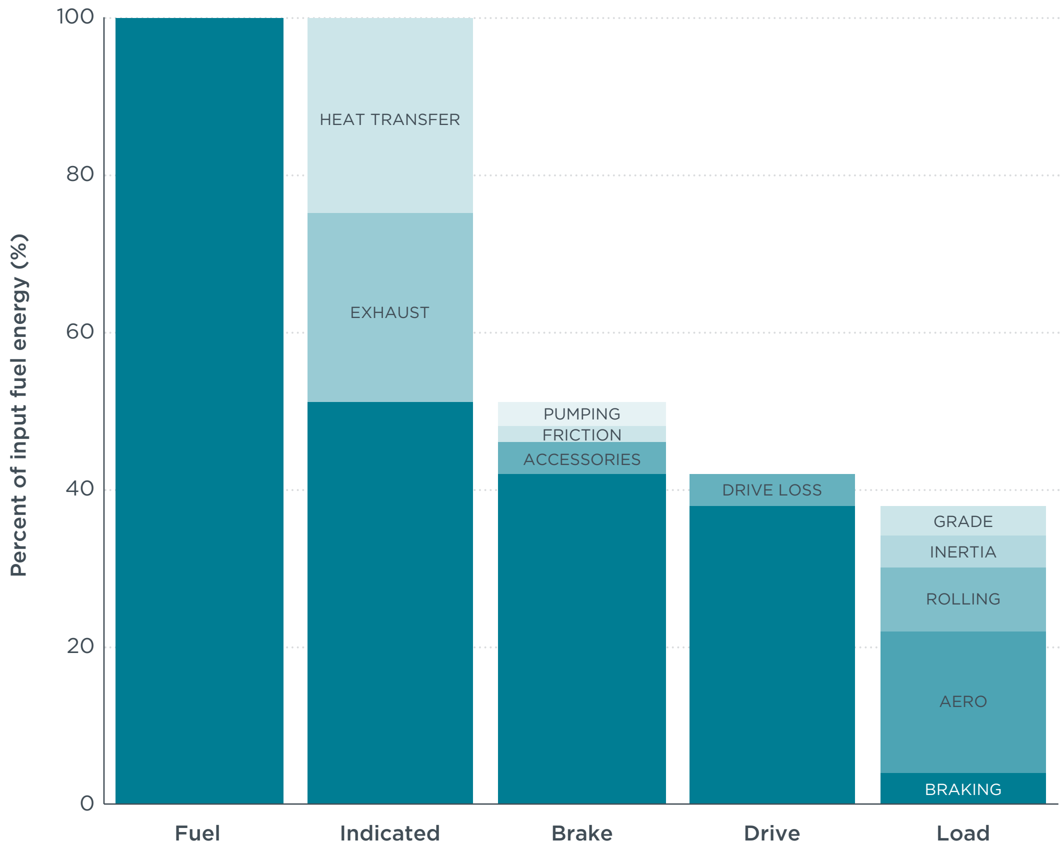

Figure 2. Energy loss mechanisms within a vehicle energy audit.

Each technology improves efficiency in a different way. In general, engine technologies help attain higher efficiency through combustion optimization (i.e., maximizing work extraction from the combustion process) and minimization of thermal and parasitic losses, transmission technologies attain higher efficiency by maximizing the time that the engine operates near maximum efficiency points, and vehicle technologies attain higher efficiency through reducing the road loads and therefore the power demand. Isolating the contribution from each of these technologies is difficult because some technologies may influence more than one loss mechanism at the same time. Positive and negative synergies would occur, and complete vehicle integration is critical for a true impact on vehicle efficiency.

The technical approaches and selected technologies are different for each SuperTruck team, providing four unique paths and multiple solutions toward the same objectives. Suppliers and technology developers are tackling each loss mechanism in differing ways, which adds an important innovation element to the program. Table 2 summarizes several key differences among the programs. The Cummins team prioritized engine efficiency with an advanced organic Rankine cycle waste heat recovery (WHR) system. The team is also developing an aerodynamic Peterbilt tractor-trailer combination with various load reduction technologies. Daimler's team aimed for a balanced approach focusing on hybridization, engine downsizing/downspeeding, WHR, and improved aerodynamics. Navistar's team prioritized aerodynamics and hybridization with additional focus on combustion efficiency and turbocompounding. The Volvo team joined the SuperTruck program in June 2011, a year later than the other teams. The team focused on engine downsizing/downspeeding, tractor-trailer aerodynamics, WHR, and turbocompounding.

Major technology areas that are being pursued similarly among the teams include tractor and trailer redesigns to improve aerodynamics and reduce weight. Also, all the approaches include wide-based, low–rolling resistance tires and 6×2 axle configurations. Another similarity among the teams is the work toward integrated solutions that at the same time reduce the loads and keep the engine operating at high efficiency. The following sections provide detailed descriptions of each team's pathways and progress to date.

Table 2. Key differences between SuperTruck teams.

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.

ENGINE BRAKE THERMAL EFFICIENCY OBJECTIVE

Figure 3 shows the different pathways to achieve 50% engine BTE, assuming a common baseline of 42% BTE. It also shows the current status of the programs as of mid-2013. Each family of improvements presented may represent many subsets of technologies. This figure emphasizes the diversity of approaches that the teams are taking. As mentioned above, direct quantitative comparisons among the different programs cannot be done on an absolute basis because the teams started with different baseline vehicles and are measuring their results over different duty cycles.

As shown in Figure 3, all the teams have achieved engine BTEs higher than 48%, and one team exceeded the 50% target. All the teams have identified technical pathways to achieve the 50% target for engines. The Cummins work indicates an approximate 22% engine efficiency increase (i.e., an increase in BTE from 42% to 51%), whereas the Daimler, Navistar, and Volvo teams demonstrated 14 to 15% engine efficiency increases, as based on progress through mid-2013.

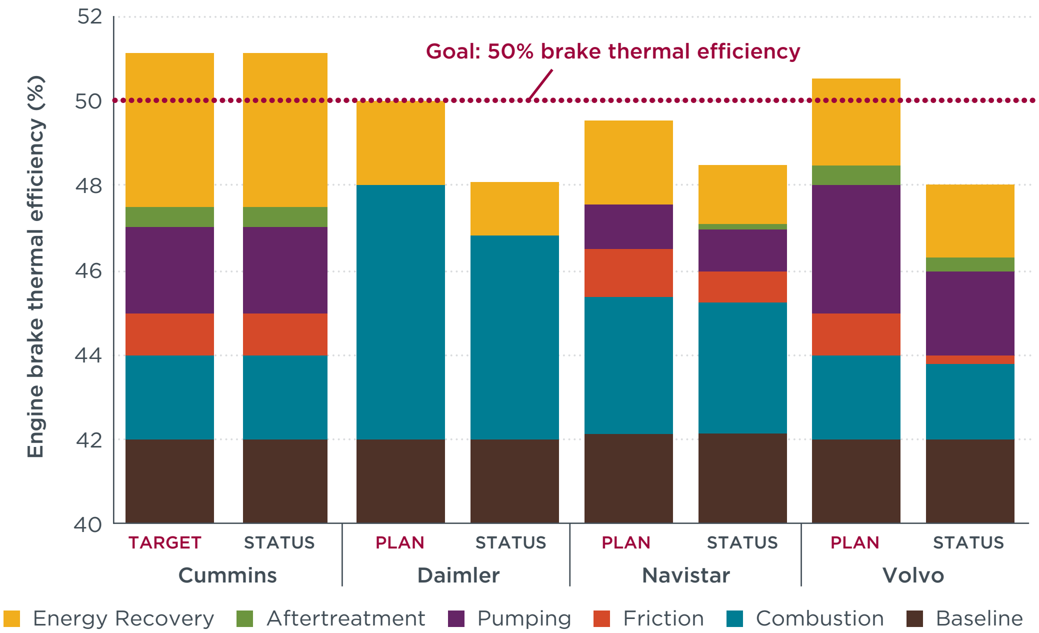

Figure 3. SuperTruck teams' 50% engine BTE targets and 2013 status.
For Daimler, the combustion bin includes pumping, friction, aftertreatment, and combustion improvements. For Volvo, the pumping bin includes BTE gains from turbocompounding, so the energy recovery bin only includes WHR.

One confounding factor is that there is continuing progress with each team, hence the results shown only represent a "snapshot" of the achievements as of mid-2013. Any comparison made cannot take into account the differing timelines, priorities, and rate of reporting of the different teams, including work completed since mid-2013. The following sections provide additional details on each program. When stating the potential benefits of engine technologies, assuming a baseline BTE of 42%, a 1% *absolute* improvement means that the new BTE is 43%. On the other hand, a 1% *relative* improvement means that the new BTE is 42.42%. To avoid confusion, we use a plus sign for absolute improvement (e.g., +1%) to remind the reader of the arithmetic nature of those percentage points.

Cummins Engine Efficiency Approach

The engine efficiency target was exceeded with a demonstrated 51.1% BTE.[10] This was accomplished through improvements in engine design, gas flow optimization, reduction in parasitic losses, improved aftertreatment, and WHR system. Cummins' research and development efforts are based on its 15-liter ISX engine.

Engine design improvements include increased compression ratio, optimized piston bowl shape, optimized injector specification, and calibrations. These engine design changes account for approximately +2% BTE absolute improvement. Gas flow optimization improvements included lower differential pressure in the exhaust gas recirculation (EGR) loop and increased turbocharger efficiency. These gas flow optimization improvements account for approximately +2% BTE absolute improvement.

10 Peak BTE measured over a single point representative of driving at 65 mph in level road, not over transient (i.e., FTP) or multimode steady-state (i.e., SET) cycles.

A 30% reduction in engine friction[11] with respect to the ISX 2009 model year engine was achieved by use of a reduced-friction shaft seal, a variable-flow lubrication pump, reduced-power coolant and fuel pumps, and reduced-friction gear train and power cylinder kit. These improvements in mechanical efficiency produce benefits across the entire engine speed/load map, with the greatest improvements in the lower load portions of the map. These friction reduction improvements account for approximately +1% BTE absolute improvement.

Figure 4 shows Cummins' WHR system, which is based on an organic Rankine cycle using a low–global warming potential refrigerant as working fluid. The system recovers heat from the EGR cooler as well as the exhaust stream (the heat exchanger is located downstream of the aftertreatment system) and converts that heat to power, which is mechanically coupled to the engine output. The engine demonstration also sought gains from low-temperature coolant and lubricant heat rejection via a parallel loop. The system includes a recuperator that transfers post-turbine energy back into the working fluid loop prior to the condenser. This recuperator reduces condenser heat rejection requirements and improves overall system efficiency. The WHR system accounts for approximately +3.6% absolute improvement in BTE. The system features a cooling module that is capable of rejecting WHR condenser heat at power levels greater than the highway cruise point without cooling fan assist. One potential drawback of the system is the added weight (although it has been reduced to about 300 lb); the system has not yet been shown to be cost-effective for commercialization.

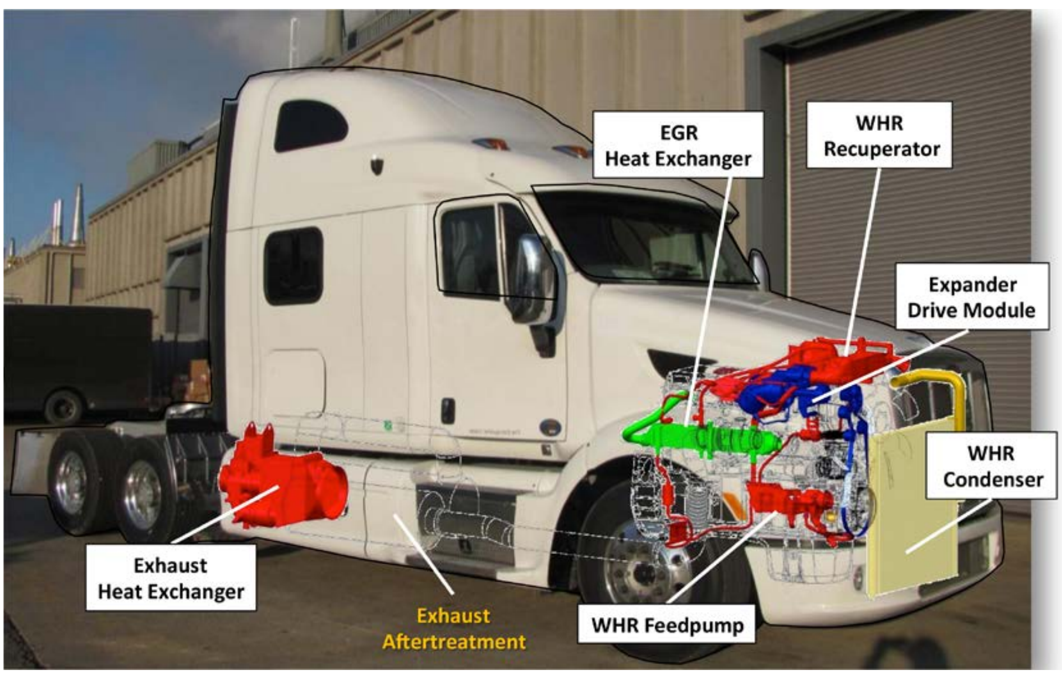

Figure 4. Cummins waste heat recovery (WHR) system (Stanton, 2013).

11 Reduction of friction mean effective pressure (FMEP).

As a result of the trade-off between engine efficiency and NO_x emissions behavior, engine-out NO_x emissions of 4.3 g/bhp-hr[12] were reported. While improving engine efficiency, the NO_x increase also aids passive soot regeneration and reduces the frequency of diesel particulate filter (DPF) active regeneration events. Therefore, to comply with current emissions regulations, improvements in the efficiency of the NO_x aftertreatment system were necessary. These improvements include an optimized NO_x sensor, closed-loop control, integration with the WHR heat exchanger, and a new selective catalytic reduction (SCR) catalyst formulation. These improvements resulted in a tailpipe NO_x emission level of 0.08 g/bhp-hr. These aftertreatment system improvements enable absolute BTE gains of approximately +0.5%.

The pathway to achieving 55% engine BTE includes further improvements in closed-cycle thermal efficiency (i.e., combustion), open-cycle thermal efficiency (i.e., pumping), mechanical efficiency (i.e., friction), and further improvements of the WHR system. Research is being conducted to scope potential fuels and combustion alternatives. The team is investigating a wide array of alternatives including diesel premixed charge compression ignition (PCCI), diesel low-temperature combustion, dual-fuel homogeneous charge compression ignition (HCCI), and single alternative fuel compression ignition HCCI. The main focus is to shorten the duration of combustion (more premixed combustion) and to increase the effective expansion ratio of the combustion products. Other plans to enhance engine efficiency include air-handling system matching, combustion uniformity studies, WHR integration, and variable valve actuation (VVA). These analytical roadmaps will be updated with component-testing data.

Daimler Engine Efficiency Approach

Daimler's baseline engine was a Detroit Diesel DD15. The team has demonstrated a 48.1% engine BTE with a downsized 11-liter engine that also operates at a lower speed while cruising at highway speeds. Figure 5 illustrates this approach. The engine operational point at cruise speed moves from point 1 to point 2 as a result of reduced vehicle load (enhanced aerodynamics, lower tire rolling resistance, and other factors allow power demand reductions of about 50 hp in the figure). An automated manual transmission is used to enable a 300-RPM drop in engine speed at the same power demand level, moving the operational point from 2 to 3. The last step is downsizing the engine (point 4 is relative to the green lug curve; point 3 is relative to the red lug curve) to make the engine operate closer to peak torque where the lowest brake-specific fuel consumption (and highest BTE) region is located.

The compression ratio and peak combustion pressure have been increased, and the engine piston bowl shape has been redesigned. The combustion system has been optimized for thermal efficiency (reducing EGR rates), which results in lightly controlled engine-out NO_x emissions (3 to 5 times those of the baseline 15-liter engine). This puts some constraints on the aftertreatment system because it has to be resized and the backpressure reduced to achieve high engine efficiency. The turbocharger has been resized to account for the lower mass flow rates due to downspeeding of the engine, and for the lower EGR rates.

12 Measured over the SET cycle. Typical engine-out NO_x emissions for EPA 2010 compliant engines are about 3.0 g/bhp-hr.

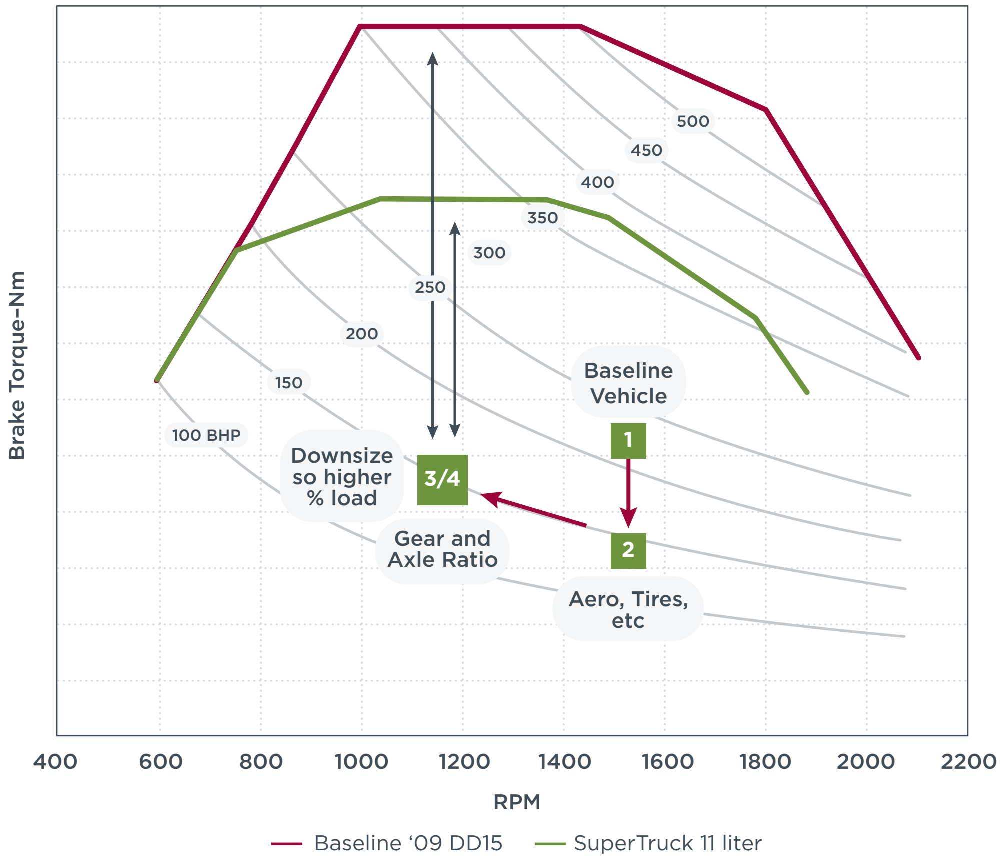

Figure 5. Daimler's downspeeding/downsizing approach (Sisken, 2013).

Parasitic load reductions have been implemented in the water pump and cylinder kit. Research continues at Massachusetts Institute of Technology (MIT) to further reduce the parasitic loads via altered cooling to the mid-stroke area of the liner, oil circuit and pump optimization, and a new lubricant formulation.

A novel predictive engine controller is being developed that enables the engine to stay at its best possible fuel economy operational point when transitioning between different speeds and loads. This controller uses a neural network model trained with an extensive mapping of engine operation to optimize fuel efficiency (up to 5% relative improvement in brake-specific fuel consumption from baseline) and to reduce calibration complexity.

An organic Rankine cycle WHR system has demonstrated +1.3% BTE absolute improvement using ethanol as the working fluid. The system recovers heat from the exhaust stream and uses an electrical generator to provide power to an electric hybrid drive system or to charge a high-voltage battery. Additional heat recovery from the radiator and charge air cooler is expected to achieve an additional +0.7% BTE absolute improvement (for a total +2.0%). Additional combustion system optimization, reduction in parasitic loads, and a reduced-backpressure turbocharger are expected to provide +1.2% BTE absolute improvement to achieve the 50% BTE objective.

Daimler's plan to achieve 55% BTE includes obtaining +4.5% BTE absolute improvement from refinement of calibrations, parasitic load reduction for the air compressor and power steering, and possibly turbocompounding. The WHR system is expected to be refined to obtain +2.5% BTE absolute improvement.

Navistar Engine Efficiency Approach

The Navistar SuperTruck team temporarily suspended its activities in October 2012 to focus on production launches and will resume in April 2014. The team had already demonstrated 48.2% engine BTE. Navistar's baseline engine was a 13-liter MaxxForce with 42.15% BTE. The combustion system was enhanced (+3% BTE absolute improvement) using a higher compression ratio, higher peak cylinder pressure (220 bar), and a common-rail injection system operating at 2,900 bar. A further +1% BTE absolute improvement was obtained from improved air handling (with VVA) and a two-stage turbocharger. Engine friction reduction was accomplished with electrified variable-speed oil and water pumps for an absolute improvement of +1% BTE. Electrical turbo-compounding (in which a turbine/generator feeds electric power to an electric motor coupled to the engine output shaft) provided +1.5% BTE absolute improvement.

Because of the complexity, weight, and long expected payback period of an organic Rankine cycle WHR system, the team decided not to include it to achieve the 50% BTE objective. Instead, power cylinder friction reduction components will be implemented, as well as a next-generation turbocompounding system and reoptimized combustion. Navistar is the only team that has presented information regarding technology cost (Table 3). Its final program projections show an average expected payback period of less than 1 year for the aforementioned set of engine technologies. No information regarding hybrid system expected payback time was given, however. Note that the final projections show a 17.4% relative improvement, representing a 49.5% BTE. The projections do not add up to the final objective of 50% BTE.

Table 3. Navistar projections toward 50% BTE and expected payback time (De Ojeda, 2013).

Technology	BTE improvement (%)	Payback (years)
Combustion	7.7	0.5
Air system	2.2	1.2
Friction accessories	2.7	0.5
Turbocompounding	4.8	1.6
Overall	17.4	0.9

Navistar's 55% BTE approach is based on the reactivity controlled compression ignition (RCCI) concept being developed by Argonne National Laboratory. This work focuses on low-temperature-combustion fuel reactivity testing performed with alcohol/gasoline and diesel mixtures. The best BTE obtained so far has been 45.1% (from combustion only, and targeting 47% BTE) with better-controlled engine-out PM and NO_x emissions. Navistar's aftertreatment approach targets engine-out emissions lower than 1 g/bhp-hr NO_x and 0.02 g/bhp-hr PM and allows the use of a moderate SCR efficiency of about 80%. The current target is to obtain BTE above 47% at NO_x levels below 0.15 g/bhp-hr. The additional efficiency pathway to achieving 55% BTE demonstration includes further improvements in engine friction, turbocompounding, VVA, and possibly an organic Rankine cycle WHR system.

Volvo Engine Efficiency Approach

Volvo uses a powertrain "right-sizing" approach in which a downsized, downsped engine is used to operate in a region of high thermal efficiency in the engine map. Figure 6 shows Volvo's approach. In the figure, point 1 represents typical road load conditions for the baseline vehicle. Vehicle-level improvements such as aerodynamics and low–rolling resistance tires decrease the load requirements, moving the engine operation to point 2. Engine downspeeding to point 3 is accomplished by changing the gear ratios of the transmission/drive axle. Finally, the engine is downsized to operate at point 4 near the peak efficiency region of the downsized engine map.

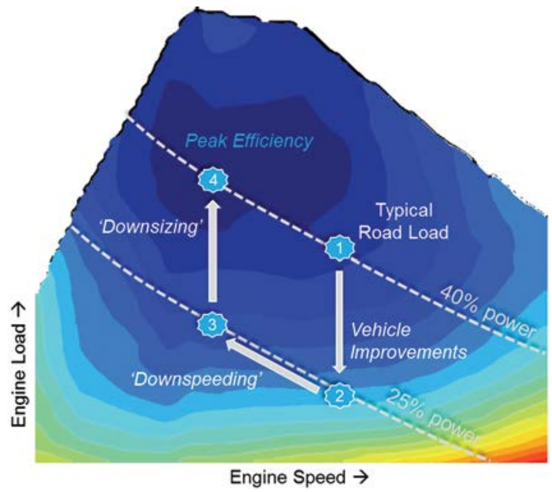

Figure 6. Engine "right-sizing" concept (Amar, 2013).

The 11-liter engine includes other technologies such as a reduced-friction power cylinder unit, a high-pressure fuel injection system, an improved combustion chamber, an improved aftertreatment system, and improved oil and cooling circuits. In contrast to the other teams, Volvo is planning to implement both turbocompounding and WHR technologies. The WHR system features a closed-loop controller and provides stable dynamic control over aggressive highway driving. Initial tests have exceeded expectations, with the WHR being enabled 77% of the time including warmup for a transient highway drive cycle. So far, the team has demonstrated a 48% BTE measured in a test cell as an integrated powertrain system 1.5 years ahead of schedule. Chassis installation for on-road evaluation is ongoing, and the expected fuel economy improvement is around 10% (Gibble & Amar, 2013). In Figure 3, the turbocompounding benefits are included in the "pumping" bin, so the "energy recovery" bin only includes WHR. Both the turbocompounding and the organic Rankine cycle WHR systems are mechanically connected to the engine output shaft.

Volvo's work toward 55% BTE has focused on scoping innovative engine configurations and combustion modes. The complete strategy is being refined on the basis of results of parallel investigations in the first phase of the project. Pennsylvania State University is researching advanced combustion with multiple fuels. Initial engine tests achieved 51% BTE with mixed-mode PCCI combustion with 20% energy substitution by dimethyl ether (DME) and 30% energy substitution by propane. Next steps include full engine simulations of proposed regimes and fuels and continued research engine testing to verify concepts.

VEHICLE FREIGHT EFFICIENCY OBJECTIVE

Figure 7 shows the different pathways to achieving 50% improvement in freight efficiency from the corresponding "best-in-class" 2009 baseline trucks. It also shows the current status of the programs as of mid-2013.[13] The figure could mistakenly imply that the efficiency gains from engine, transmission, and load reduction technologies are independent of each other. The technologies shown are complexly interrelated, and positive or negative synergies may be expected when applying two or more engine, transmission, and load reduction technologies at the same time. For example, load reduction technologies and transmission technologies may shift the engine operational points to lower or higher BTE regions; also, two or more technologies could be affecting the same loss mechanism showing diminishing returns. However, for ease of understanding, the authors wanted to provide incremental (i.e., linearly additive) improvements. Another confounding factor is that there is continuing progress with each team, and the results shown represent only a "snapshot" of the achievements as of mid-2013. Any comparison made cannot take into account the differing timelines, priorities, and rate of reporting of the different teams. The following sections provide additional details on the different teams' approaches.

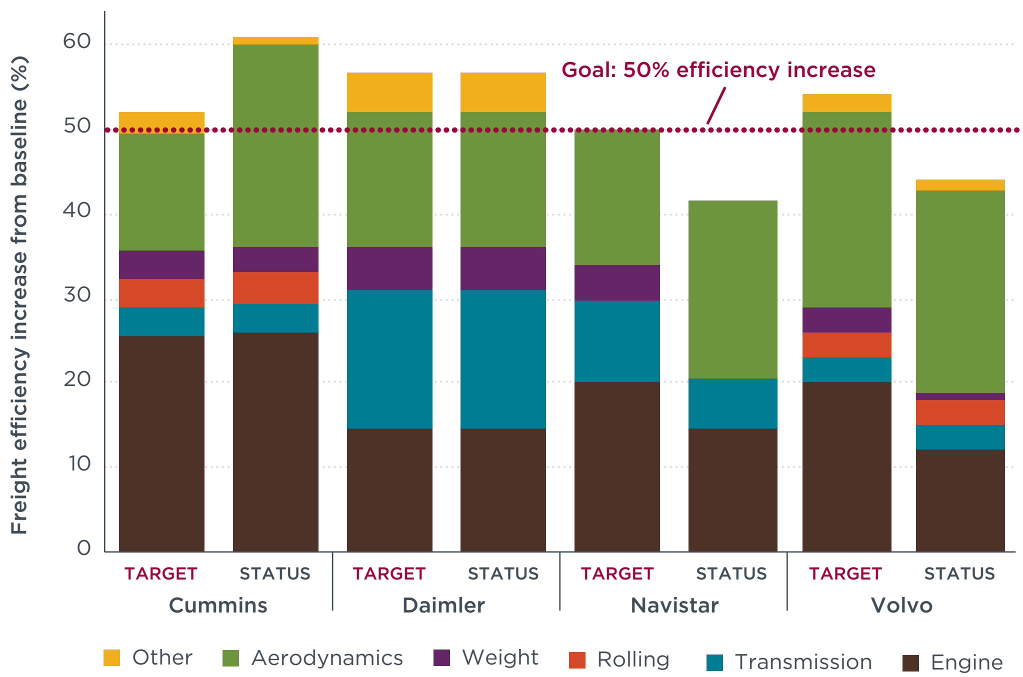

Figure 7. SuperTruck teams' freight efficiency targets and 2013 status. *Each team was given the flexibility to select its own baseline and duty cycle to measure freight efficiency. Therefore, the efficiency improvements shown are not directly comparable. The Daimler transmission bin includes drivetrain losses and rolling resistance. The Volvo transmission bin only includes drivetrain losses.*

13 The Navistar SuperTruck team temporarily suspended its activities in October 2012 to focus on production launches and will resume in April 2014.

Cummins Vehicle Freight Efficiency Approach

Cummins' team achieved the vehicle freight efficiency objective, demonstrating a 61% improvement in freight efficiency over a realistic drive cycle. A Peterbilt Model 587 tractor was tested at 65,000 lb gross vehicle weight (GVW) (32,705 lb payload) and reported fuel economy values in the range of 9.3 to 10.2 mpg. Cummins is not following the hybrid pathway. A vehicle energy analysis conducted over 27 drive cycles for Class 8 vehicles showed that the contribution of inertia and braking energy was in the range of 0% to 2%. On the basis of these numbers, hybridization was not considered a priority. Electrification of components was not considered because of the multiplicative effect of the different energy conversion efficiencies involved (fuel to mechanical in the engine, mechanical to electric in a generator, and electric to mechanical in the component to be electrified). The Cummins team is achieving the objectives with a combination of advanced tractor-trailer aerodynamic improvements, high-efficiency advanced transmission, truck and trailer weight reduction, low–rolling resistance tires, a driver display with fuel economy tools, and route management systems.

Aerodynamic improvements of tractor and trailer provide 24.9% freight efficiency improvement without a major cab redesign (Koeberlein & Damon, 2013). It is worth mentioning that this target alone is of the same order of magnitude as the engine improvements (at about 26%). For reference, a current SmartWay-certified[14] trailer would provide about 14% drag coefficient reduction and about 7% freight efficiency improvement. The only caveat of the aerodynamic package is that it brings more than 2,000 lb of added weight to the vehicle. This would represent additional load to the vehicle at lower speeds and/or when climbing hills, where the aerodynamic advantage is low or nonexistent.

Weight reduction provides about 3% freight efficiency improvement. Figure 8 shows how the added weight of aerodynamic devices and idle management system (negative values imply weight gain and hence losses in freight efficiency) is compensated by weight reduction of the truck and the trailer.

14 SmartWay-verified aerodynamic technologies include advanced trailer gap reducers, trailer skirts, trailer end fairings, and trailer boat tails.

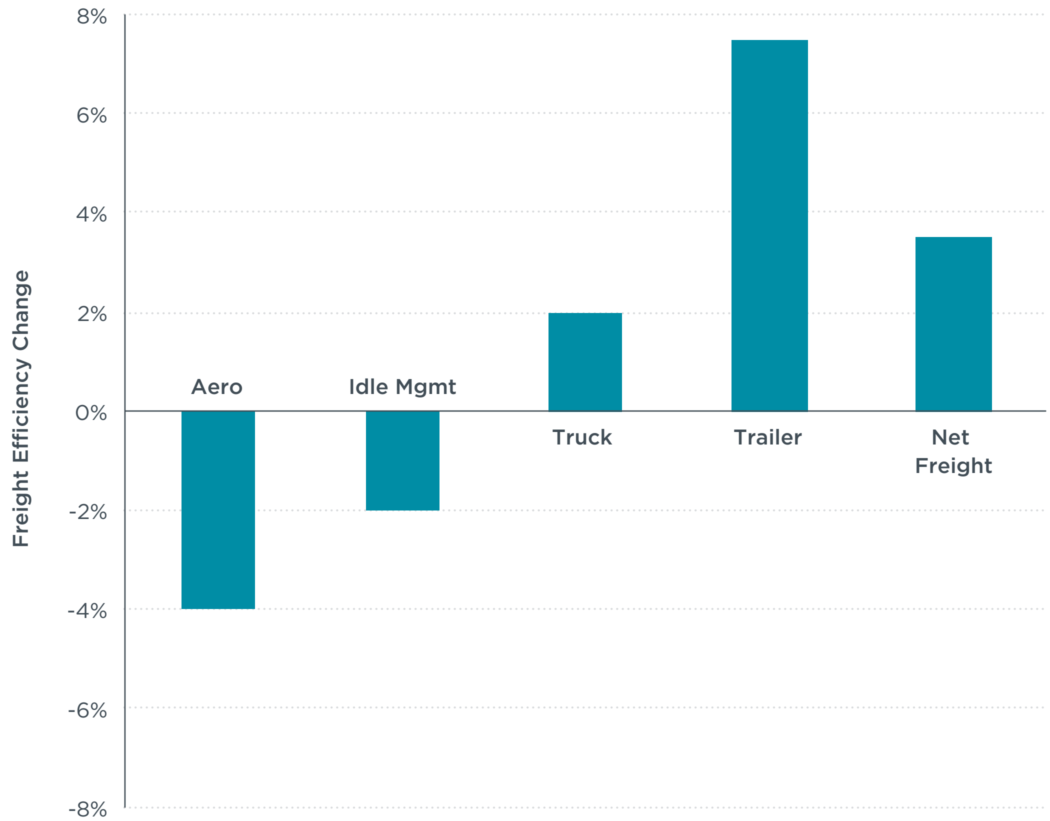

Figure 8. Freight efficiency improvement through weight reduction (Koeberlein, 2013).

An advanced automated manual transmission will be fully integrated with the 15-liter engine, enabling engine speed reductions of about 200 RPM at vehicle cruise speed. Lower engine speeds reduce parasitic losses at full power and provide approximately 3.5% freight efficiency improvement. Low–rolling resistance tires provide about 3.5% freight efficiency improvement, and the use of driver tools and route management systems is expected to provide an additional 2.5% in freight efficiency.

Cummins has presented an additional objective to achieve 68% freight efficiency improvement over a defined 24-hour duty cycle that includes an extended idling period. This is not an explicit DOE goal but a Cummins goal. A 76% improvement in overall freight efficiency over a 24-hour duty cycle is to be achieved via further optimization and the use of an idle management system.

In early 2013, a 950-mile driver acceptance event was held in Texas with US Xpress drivers and commercial freight. The campaign provided critical and valuable feedback from end users in terms of functional evaluation of aerodynamic devices in trailers (loading/unloading) and general drivability of the vehicle. The demonstration truck has generated interest among customers that has led to an effort to get it into production as quickly as possible. Commercial feasibility requirements remain an obstacle to mass production. For example, additional work is needed to make the WHR system cost-effective. Because of the expected difficulties in mass production and commercialization of a fuel cell auxiliary power unit, the team is looking for suitable alternatives for idle management, such as lithium-ion battery systems.

Daimler Vehicle Freight Efficiency Approach

A 2009 Freightliner Cascadia raised-roof sleeper cab was selected as Daimler's baseline. An important challenge for the team has been the integration of multiple new components and subsystems into the final vehicle, resolving any trade-off between their functionality and efficiency. Figure 9 shows the eight cross-functional SuperTruck work streams that are being integrated. By mid-2013, the team was using computer-aided simulation tools to develop designs and had yet to build a complete prototype vehicle. The roadmap to achieve 50% freight efficiency includes tractor and trailer aerodynamics, hybrid powertrain, cooling system integration (between engine, WHR, and hybrid systems), low–rolling resistance tires, predictive technologies, eco-driver feedback, electric air conditioning, and a fuel cell auxiliary power unit.

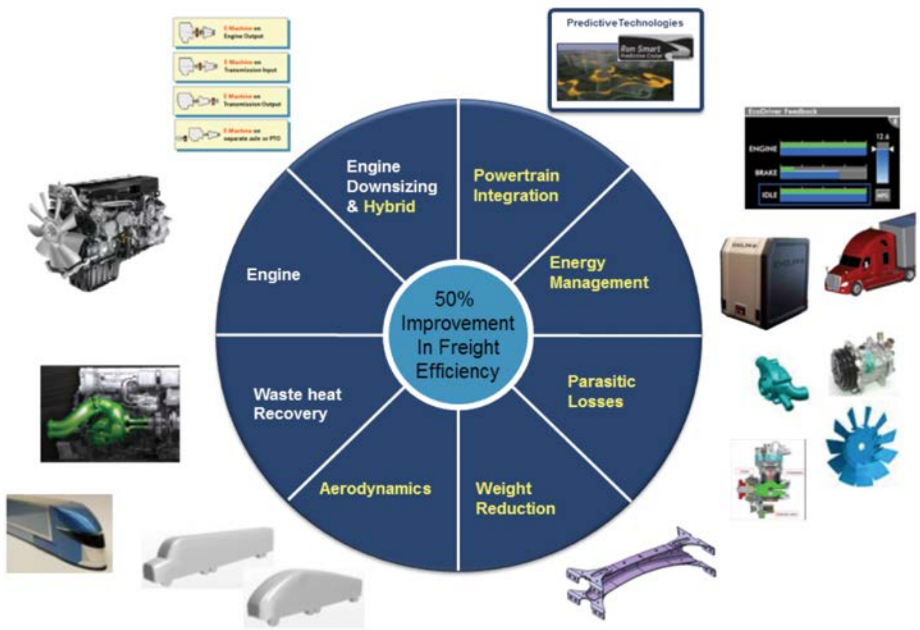

Figure 9. Daimler cross-functional areas (Sisken, 2013).

So far, a 56.5% improvement in freight efficiency has been measured on an individual system level. Increasing the engine efficiency from 42% BTE to 48.1% BTE provides a 14.5% improvement in freight efficiency. An additional 16% improvement comes from tractor and trailer aerodynamics, with about half of the reduction coming from the trailer (Rotz & Ziegler, 2013). Powertrain and drivetrain technologies provide a 16.5% improvement. This category includes optimization of the hybrid system, transmission, axles, wheel ends, wheels, and low–rolling resistance tires for both tractor and trailer. The hybrid system uses a parallel architecture in which the system electric motor is located between the engine and transmission and can provide up to 60 kW of propulsion power. The system stores regenerative braking energy in a 3-kWh battery and operates at 360 V. An automated manual transmission enables downspeeding of the engine. Lightweighting of the vehicle provides a further 5% improvement. Other improvements include 3.5% from energy management (including idle reduction) and 1% from reduction in parasitic losses. Next steps include complete vehicle integration of the different subsystems and complete buildup of a SuperTruck demonstrator vehicle.

Navistar Vehicle Freight Efficiency Approach

Navistar's team focused its vehicle efficiency efforts on hybridization and tractor-trailer aerodynamics. The ArvinMeritor hybrid powertrain shown in Figure 10 features dual-mode series/parallel architecture without clutches. The vehicle will run in series mode (i.e., electric only) at speeds below 50 mph and will switch to parallel operation at higher speeds. The system features a high-power (350 kW, 750 V) liquid-cooled lithium-ion battery with 28-kWh capacity. This dual-mode system allows the diesel engine to operate constantly at operational points close to the peak thermal efficiency either when charging the battery or when powering the drive axles trough a two-speed overdrive transmission. The system was designed to reduce size and weight and is similar in size and weight to a conventional manual transmission with a clutch. The system would also enable electrified accessories such as the power steering fluid pump, air compressor, and air conditioning compressor. This lightweight hybrid powertrain would provide about 6% freight efficiency improvement.[15]

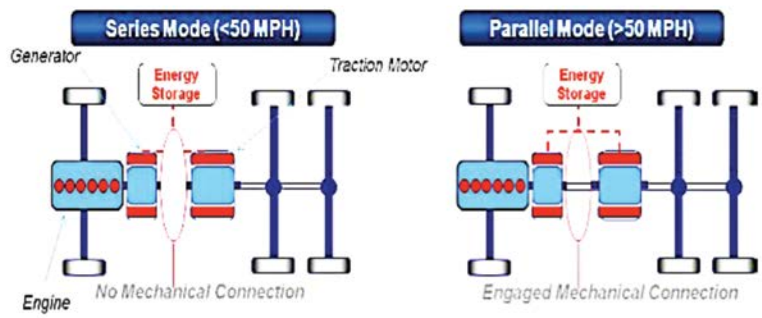

Figure 10. Navistar series/parallel hybrid system (Oehlerking, 2013).

Several aerodynamic scale models have been developed and evaluated in the wind tunnel. A 42% reduction in aerodynamic drag (which translates to roughly 21% improvement in freight efficiency for the concept vehicle) is expected with changes to both the truck and the trailer. For the truck, a rear-engine concept is under study that would allow moving the driver and windscreen forward, enabling an enhanced aerodynamic body shape. Lawrence Livermore Laboratory is developing an aerodynamic trailer concept. Figure 11 shows Navistar's aerodynamic enhancements in different areas of the tractor and the trailer.

Besides hybridization and aerodynamics, a predictive cruise control system was also developed. This system uses map altitude data and GPS positioning to predict upcoming hills and valleys. The system is said to produce 3 to 10% fuel economy improvement (De Ojeda, 2013).

The team has built and tested a first vehicle prototype that features the hybrid system. A second vehicle that includes other technologies such as turbocompounding, active fifth wheel, active ride height, 6×2 rear axle, disc brakes, and aerodynamic trailer is already assembled but has not yet been tested. The team plans to build a third, final SuperTruck vehicle demonstrator at the end of the project.

15 The Navistar test cycle for validation includes 75% highway-type route and 25% urban-type route. The potential savings of the hybrid system would increase to about 10% if a higher percentage of urban-type driving were used. Simulations showed 15 to 25% freight efficiency improvement over transient cycles.

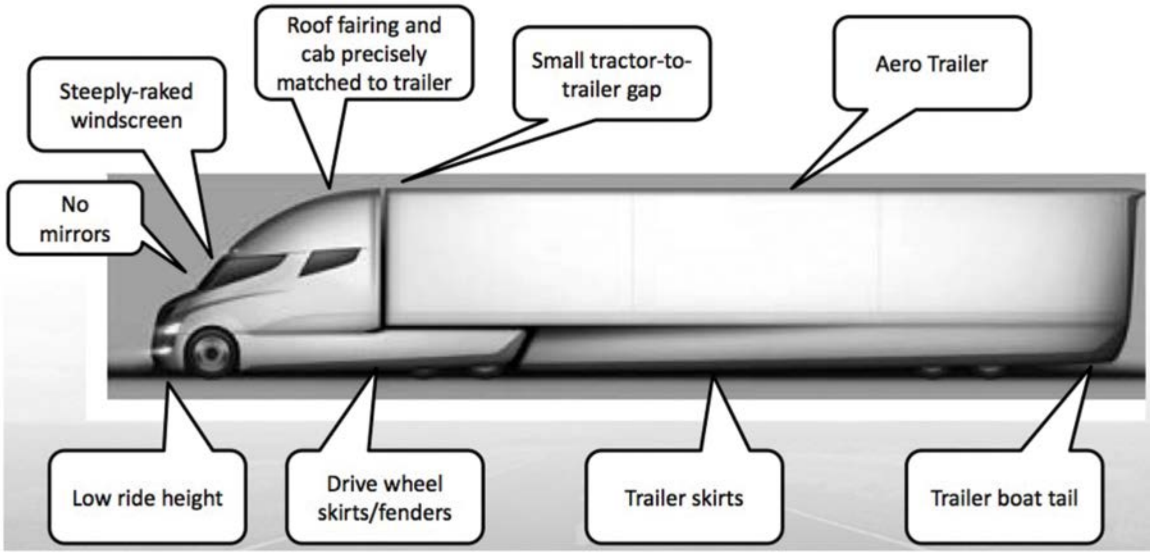

Figure 11. Navistar aerodynamic concept (Oehlerking, 2013).

Volvo Vehicle Freight Efficiency Approach

Volvo's approach to achieving the 50% improvement in freight efficiency relies on full vehicle integration. Simulations are used to predict the effect of component improvements on complete vehicle efficiency and to identify and evaluate the most promising technologies. These simulations revealed that aerodynamic and rolling resistance improvements can lead to a requirement for extra braking effort to manage vehicle speeds during hill descents. Predictive vehicle controls and torque management tools may be able to address this issue. After long-haul duty cycle analysis, the Volvo team decided not to include a full hybrid system because of weight and cost considerations. However, the team is evaluating different energy recovery systems (that may or may not include some form of micro-hybridization) to take advantage of the extra braking energy available.

Complete vehicle geometry (tractor and trailer) is being optimized through computational fluid dynamics simulations to balance powertrain cooling and aerodynamic requirements. Figure 12 shows Volvo's aerodynamic concept. Aerodynamic drag reduction of 20% provided a 10% freight efficiency improvement validated through on-road testing. The target drag reduction is set at 40% (about 16% freight efficiency improvement). Use of low–rolling resistance tires aims for up to 20% reduced load relative to the baseline, providing up to about 5% improvement in freight efficiency.

Figure 12. Volvo aerodynamic concept (Amar, 2013).

The team plans to use a dual-clutch transmission that will cause less torque interruption and fewer transient effects during shifting. This transmission would enable fuel efficiency savings from engine downspeeding, because the engine would be able to maintain torque by sustaining turbocharger boost without disengaging the driveline, allowing cruising at lower engine speeds. Also under investigation is a "smart" 6×2 axle configuration that reduces parasitic loads and weight by reducing the number of moving parts and meshing gears.

The team is working on various designs to reduce the weight of the truck in order to compensate for the added weight of new technologies such as aerodynamic devices, a WHR system, and turbocompounding. A new frame concept, lightweight suspension, aluminum wheels, composite roof materials, a downsized engine, and the 6×2 axle are expected to provide equivalent weight savings.

A 25% reduction in auxiliary loads is projected. Among these, a new LED lighting system provides estimated fuel savings of more than 100 gallons of fuel per year per truck.[16] Integrated energy management and predictive controls are also expected to increase vehicle efficiency. Installation of the concept powertrain into the concept vehicle is ongoing, and the next step is to conduct over-the-road tests to validate complete vehicle performance.

16 Assuming 120,000 miles traveled per year and fuel efficiency of 6 mpg, 100 gallons per year represents 0.5% of total fuel consumption.

DISCUSSION

R&D POLICY

Substantial effort and investment by both the public and private sectors are required to achieve long-term economic efficiency and environmental goals.

Private-sector R&D investments usually target short-term research that requires relatively high rates of return (e.g., increased sales or market share) over relatively short periods. The risks involved when investing in long-term technologies (that may or may not achieve commercial success) hinder private investment in technology development. In this regard, the private sector alone is not expected to deliver the changes required.

Public-sector goals such as energy security, economic efficiency, and protection of the environment require long-term R&D strategies that set priorities and policy direction. The government's role is usually greater in the initial phases of basic and applied R&D than in the next phases of precompetitive demonstrations and commercialization. The SuperTruck program with its cost-sharing format engages both the public and private sectors through sharing the risk of long-term R&D, stimulates private initiatives, and facilitates the process of technology development and demonstration.

Another desirable characteristic of the program is its "systems-level" approach, which benefits the commercial vehicle sector in a broad fashion. A large number of manufacturers and suppliers are involved at various levels and collaboratively develop technologies in diverse areas such as engines, transmissions, controls, aerodynamic devices, tires, integrated trailer design, lightweight materials, aftertreatment devices, and idle reduction devices.

PROGRAM BARRIERS

The different SuperTruck program teams have identified some issues and barriers to overcome when developing their programs.[17]

Weight and Packaging

Fuel-saving technologies such as aerodynamic fairings and WHR systems may add substantial weight to the vehicle, affecting the ton-miles per gallon metric. In order to avoid altering the payload capabilities of the vehicles, an important challenge is to reduce overall vehicle weight to accommodate these technologies without nullifying their benefits. Some of the teams mentioned that their final demonstration vehicles are expected to save some weight but not a substantial amount. Another related issue is the need for appropriate packaging (i.e., without affecting design constraints or vehicle aerodynamics) of additional components such as heat exchangers of WHR systems or hybrid battery packs.

System Integration

The complex interdependences between different systems create challenges (and, arguably, opportunities) in terms of appropriate integration of the systems into the vehicle. Modeling and simulation play a key role and have been used to conduct theoretical analysis and validate concepts before building prototypes. As an example of a

17 ICCT conducted interviews with three of the four SuperTruck teams.

key integration issue, when optimizing an engine for fuel economy, there is a trade-off with NO_x emissions. This creates the need for SCR systems with higher conversion efficiency.[18] At the same time, aftertreatment systems require fuel-efficient thermal management because better engine efficiencies could lower exhaust temperatures.[19] This inherent trade-off between efficiency and engine-out NO_x requires a balancing act in order to achieve emissions compliance while maximizing overall efficiency and cost-effectiveness.[20]

Another important integration issue is the fact that a vehicle designer cannot ignore the shape of the trailer when designing a truck for better aerodynamics. A nonaerodynamic trailer could hurt the overall efficiency of the vehicle even with an optimized aerodynamic tractor. Complete tractor-trailer integration is the key path to achieving vehicle efficiency.

Some other integration issues are:

- Effects of WHR and turbocompounding on exhaust (and aftertreatment catalyst) temperature and cooling demands.
- Effects of increased engine efficiency and reduced vehicle load on exhaust gas temperatures and energy availability for WHR and turbocompounding.
- Thermal and fluid dynamics trade-offs between cooling devices and aerodynamics (e.g., WHR systems require added heat rejection, but cooling equipment is expected to be placed in a smaller engine compartment to help reduce vehicle aerodynamic drag).
- Integrated control of key transient parameters of the engine, auxiliaries, hybrid systems, advanced transmissions, WHR systems, and aftertreatment devices.

End User Acceptance

Some possible end user experience issues when adding the technologies so far discussed may include:

- Vibration and noise issues in the powertrain due to engine downspeeding.
- Safety and reliability issues when using “engine braking” with a downsized and downsped engine.
- Safety concerns due to use of ethanol as working fluid for WHR systems.
- Operational difficulties from aerodynamic improvements. Mechanical inspection of tires and drivetrain could be made more difficult by the presence of trailer skirts; loading and unloading operations could be impeded by boat tails at the trailer door. Truck maneuverability also could be affected if the tractor-trailer gap is reduced.
- Driver acceptance of advanced transmissions and powertrains.

18 Diesel exhaust fluid (aqueous urea solution; DEF) used in SCR systems represents an additional operational cost. DEF consumption ranges from about 2 to 5% of diesel fuel use. Current DEF cost per gallon ranges from about 70 to 90% of diesel fuel cost per gallon.

19 There are already high in-use NO_x emissions associated with SCR system operation at low load and cold weather (Lowell & Kamakaté, 2012).

20 Peak engine thermal efficiency is usually reported at a steady-state condition that is favorable for the aftertreatment system. Emissions compliance is measured over engine testing (transient FTP and multimode steady-state engine test SET) and in-use not-to-exceed (NTE) vehicle testing. These tests are expected to account for transient behavior and regions of lower exhaust temperatures.

Cost-effectiveness and Commercialization

Although the objectives of the program include development of commercially available technologies, information about cost is lacking. Only one of the teams reported an expected technology payback time. Commercialization of fuel-efficient technologies might be an issue if the technology is not yet mature or if the cost is too high. Not all the technologies developed during this program are expected to be commercially viable in the short term. Some of the technologies are in the prototype stage or need developments in other areas to enable their feasibility (e.g., improvements in electric storage technologies could enable the electrification of components and the use of hybrid systems). Technologies in an early stage of development are not yet proven to be sufficiently reliable for wide-scale use in the variety of environments and applications that the vehicle may find over a million-mile-plus lifetime. However, the program outcomes may prove quite useful in determining which technologies are more promising and should be prioritized. A recent program benefit analysis report (TA Engineering, 2012) concluded that under favorable technology cost and fuel price assumptions, market penetration estimates of SuperTruck configurations (including different technologies) are significant and range from 19% to 59% in 2020 and 36% to 73% in 2050.[21] SuperTruck technologies are projected to reduce fuel consumption and greenhouse gas emissions by 30% and to save 6 billion barrels of oil by 2050, according to a conservative scenario. Programs such as SmartWay can help to accelerate the transition of the most promising technologies into the market.

Most of the teams agreed that the most cost-effective technologies are those related to aerodynamics—in particular, trailer aerodynamics. Other technologies that are "off-the-shelf" and can provide immediate savings are the 6×2 tandem axles and low–rolling resistance tires (along with automatic inflation systems). It is important to focus on the type of application because cost-effectiveness calculations would depend on the expected duty cycle and the vehicle miles traveled per year. Some of the technologies developed by the program are only applicable to line-haul applications and may prove not to be feasible for other types of vehicle vocations. The best truck specification is the one for the specific duty cycle that the truck will see over its life.

21 Two technology platforms (a hybrid and a nonhybrid platform), two vehicle incremental cost cases (high and low), and two oil price cases (high and low) were studied. The ranges cover the lowest and highest market potential cases studied.

CONCLUSIONS

DOE's SuperTruck program represents a great example of an R&D program that will help to ensure the emergence of key technologies that will be critical to achieve energy, environmental, and economic goals. The SuperTruck teams have made sizable R&D investments that, absent the program, they would be unable or unwilling to undertake alone. The $284 million program leverages public and private industry efforts to develop, demonstrate, and showcase technologies that can greatly increase the efficiency of long-haul tractor-trailers.

Our assessment finds that the teams have each achieved substantial progress toward the project objectives. In particular, three of the four teams have approximately achieved the tractor-trailer fleet target of a 50% efficiency increase. These SuperTruck program findings imply a dramatic increase in on-road efficiency; the program's results, for example, are equivalent to increasing tractor-trailer fuel economy from approximately 6 to 7 mpg to approximately 9 to 10.5 mpg for a loaded tractor-trailer operating at highway cruise speeds.

Along with the SuperTruck teams' success toward their full-vehicle goals, there was similar success toward the engine-specific goals. Examining the teams' engine progress reveals that all teams have achieved engine BTEs higher than 48%, and one team exceeded the 50% engine efficiency target. All the teams have identified technical pathways to achieve the 50% engine BTE target. As based on progress through mid-2013, the Cummins work indicates an approximate 22% engine efficiency increase, whereas the Daimler, Navistar, and Volvo teams demonstrated 14 to 15% engine efficiency increases relative to the approximate 42% baseline.

The implications of such a comprehensive program for advanced efficiency technology could be quite profound. The heavy-duty vehicle industry is highly global. As a result, many of the technologies demonstrated in this U.S.-based program are highly applicable and can be customized for other markets that are striving for more efficient commercial freight transport. The global manufacturers and suppliers for the SuperTruck program are advancing the state of the art in engines, transmissions, controls, aerodynamic devices, tires, integrated trailer design, lightweight materials, aftertreatment devices, and idle reduction devices. The roll-out of these technologies is currently limited, but the public-private program paves the way for these technologies to more quickly enter the fleet.

We recommend that the industry and DOE representatives continue to publish increasingly rich and detailed information to quantify the SuperTruck technologies' impacts. Data transparency and richness is important to ensure that the public investment in SuperTruck translates to technology deployment and real-world reductions in fuel use. This data exchange is especially important and timely, given that U.S. agencies are deliberating the next phase of efficiency regulations in 2014–2015 for the new heavy-duty vehicles for 2020 and beyond. Direct data exchange among individual SuperTruck technology providers (e.g., engine, transmission, aerodynamic devices, tire manufacturers) and regulatory agencies would further ensure that the results are connected to emerging policy. In particular, the regulatory agencies are facing questions about regulatory structure for engines, the inclusion of trailers, and technology availability. The results from SuperTruck can help to inform these questions. Rich information will also be important for sharing and showcasing the program's developments to markets around the world.

Further investigation is warranted on several other practical and market factors regarding the viability of the advanced efficiency technologies in the market. The benefits from the R&D investments can only be realized when the technologies enter the market and achieve commercial success. Therefore, examining the potential for various SuperTruck technologies to become cost-effective and commercially viable for the heavy-duty vehicle fleet at higher volumes will be critical. Understanding various systems integration, weight and packaging, and end user acceptance issues will also be critical. These are all important issues. Nonetheless, the first steps in demonstrating the technology solutions that can deliver dramatically increased tractor-trailer efficiency are well under way.

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APPENDIX

Table A1. Cummins Team

Team member	Role
Cummins Inc.	Project lead
Peterbilt Motors Co.	Vehicle integration, aerodynamics
Utility Trailer Manufacturing Co.	Lightweight trailer
Cummins Turbo Technologies	Turbomachinery
Cummins Fuel Systems	Fuel system
Cummins Emissions Solutions Inc.	Aftertreatment
Eaton Corp.	Advanced transmission
Delphi Corp.	Solid oxide fuel cell idle management
Bendix Commercial Vehicle Systems LLC	Brake system and drive axle control
Alcoa Inc.	Wheels
Bridgestone and Goodyear	Low-rolling resistance tires
Modine Manufacturing Co.	Vehicle cooling module, WHR
VanDyne SuperTurbo Inc.	Turbocompounding/supercharging
Dana Corp.	Lightweight drivetrain
Bergstrom Inc.	HVAC
Logena Automotive LLC	Network interface
Oak Ridge National Laboratory	Fast-response engine
Purdue University	Low-temperature combustion, VVA
U.S. Xpress Enterprises Inc.	End user review, commercial viability

Table A2. Daimler Team

Team member	Role
Daimler Trucks North America LLC	Project lead
Detroit Diesel Corp.	Engine system
Oak Ridge National Laboratory	WHR generator and controls
Massachusetts Institute of Technology	Parasitic reduction
Atkinson LLC	Engine controls
Robert Bosch LLC	Engine systems
Mahle Industries Inc.	Engine systems
Corning Inc.	Aftertreatment
Johnson Matthey Inc.	Aftertreatment
Eberspächer	Aftertreatment
Mitsubishi Fuso Truck and Bus Corp.	Hybrid
Mercedes-Benz Technology North America LLC	Hybrid
ITK Engineering AG	Hybrid
Behr America Inc.	Aero/cooling
CD-adapco Group	Aero/cooling
Auto Research Center, LLC	Aero/cooling
Modine Manufacturing Co.	Aero/cooling
Detroit Transmission	Powertrain/parasitics
Bendix Commercial Vehicle Systems LLC	Powertrain/parasitics
Consolidated Metco Inc.	Powertrain/parasitics
Accuride Corp.	Powertrain/parasitics
Michelin North America Inc.	Powertrain/parasitics
Schneider National Inc.	Fleet
Walmart Stores Inc.	Fleet
National Renewable Energy Laboratory	Energy management
Oregon State University	Energy management/lightweighting
Delphi Corp.	Energy management
Telogis Inc.	Energy management
Toray Industries Inc.	Lightweighting
Strick Corp.	Lightweighting (trailer)
Inmagusa SA de CV	Lightweighting (rails)

Table A3. Navistar Team

Team member	Role
Navistar Inc.	Project lead
Alcoa Inc.	Lightweighting
Advanced Transit Dynamics Inc.	Trailer aerodynamic devices
Behr America Inc.	Cooling systems
ArvinMeritor Inc.	Hybrid powertrain
Michelin	Low-rolling resistance tires
Wabash National Corp.	Trailer technologies
Argonne National Laboratory	Dual-fuel engine/hybrid system
Lawrence Livermore National Laboratory	Aerodynamic testing
Robert Bosch LLC	High-pressure common rail system
Federal Mogul Corp.	Friction reduction

Table A4. Volvo Team

Team member	Role
Volvo Group North America Inc.	Development and integration of advanced powertrain and vehicle technologies
Volvo Technology of America Inc.	Project lead
Freight Wing Inc.	Trailer aerodynamic add-on devices
Grote Industries LLC	Advanced lighting systems
Pennsylvania State University	55% BTE simulation and testing
University of California, Los Angeles	WHR control simulation

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