U.S. DEPARTMENT OF ENERGY

Adoption of New Fuel Efficient Technologies from SuperTruck

Report to Congress
June 2016

United States Department of Energy
Washington, DC 20585

Message from the Assistant Secretary for Energy Efficiency and Renewable Energy

The U.S. Department of Energy (DOE) has prepared the enclosed report pursuant to the Explanatory Statement accompanying the Consolidated and Further Continuing Appropriations Act of 2015 (H.R. 83 - Public Law No. 113-483). Congress requested that DOE develop "a report on the industry's adoption rates of new fuel efficient technologies from the SuperTruck program into its manufacturing lines." The findings were to be reported to the Committees on Appropriations of the House of Representatives and the Senate.

The information presented in this report is derived from a variety of sources but is primarily based on discussions with the four industry-led teams participating in the DOE SuperTruck initiative about their general findings and future plans for technologies within the initiative. This information was supplemented with perspectives from technical experts within the DOE Vehicle Technologies Office and public information.

To date, the SuperTruck teams have been very successful at meeting or exceeding the goals set forth by the SuperTruck initiative with suites of technologies that have the potential for achieving market success. A number of SuperTruck technologies are already making market inroads, particularly in the areas of aerodynamics and engine/drivetrain integration. These appeal to current fleet buyers because they are cost effective and are proving to be reliable in service. Other SuperTruck technologies offer the promise of additional fuel savings within the next five or ten years when they are expected to be commercially available, particularly in the areas of more advanced aerodynamics packages and further increases in engine thermal efficiency. SuperTruck teams are having success in commercializing some technologies for fuel efficiency and noted that continued progress in reducing cost and improving reliability is needed for other technology suites to show a positive business case for customers. There are considerations beyond the technical arena, as well, having to do with market sector complexity and Federal regulations (such as the existing U.S. Environmental Protection Agency/Department of Transportation Phase 1 greenhouse gas and fuel efficiency standards and recently proposed Phase 2 standards), that will also drive the ultimate fleet adoption of some of these technologies.

Pursuant to the Congressional request, this report is being provided to the following Members of Congress:

- **The Honorable Thad Cochran**
  Chairman, Senate Committee on Appropriations

- **The Honorable Barbara Mikulski**
  Vice Chairwoman, Senate Committee on Appropriations

- **The Honorable Harold Rogers**
  Chairman, House Committee on Appropriations

- **The Honorable Nita M. Lowey**
  Ranking Member, House Committee on Appropriations

- **The Honorable Lamar Alexander**
  Chairman, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

- **The Honorable Dianne Feinstein**
  Ranking Member, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

- **The Honorable Michael K. Simpson**
  Chairman, Subcommittee on Energy and Water Development
  House Committee on Appropriations

- **The Honorable Marcy Kaptur**
  Ranking Member, Subcommittee on Energy and Water Development
  House Committee on Appropriations

If you have any questions or need additional information, please contact me or Mr. Joseph Levin, Associate Director of External Coordination, Office of the Chief Financial Officer, at (202) 586-3098.

Sincerely,

David J. Friedman

David J. Friedman
Acting Assistant Secretary
Energy Efficiency and Renewable Energy

Executive Summary

As requested by the Congress in the Explanatory Statement accompanying the Consolidated and Further Continuing Appropriations Act of 2015, the U.S. Department of Energy (DOE) prepared this report on the adoption of new fuel efficiency technologies for Class 8 heavy-duty long-haul trucks as developed under the DOE SuperTruck initiative.

The information presented in this report is derived from a variety of sources but is based primarily on discussions with the four industry-led teams participating in the DOE SuperTruck initiative about their general findings and future plans for technologies within the initiative. This information was supplemented with perspectives from technical experts within the DOE Vehicle Technologies Office and public information.

To date, the SuperTruck teams have been very successful at meeting or exceeding the goals set forth by the SuperTruck initiative with suites of technologies that have the potential for achieving market success. A number of technologies are already making market inroads, particularly in the areas of aerodynamics and engine/drivetrain integration. These appeal to current fleet buyers because they are cost effective and proving to be reliable in service. Other SuperTruck technologies offer the promise of additional fuel savings within the next five or ten years when they are expected to be commercially available, particularly in the areas of more advanced aerodynamics packages and further increases in engine thermal efficiency. SuperTruck teams are having success in commercializing some technologies for fuel efficiency and noted that continued progress in reducing cost and improving reliability is needed for other technology suites to show a positive business case for customers. There are considerations beyond the technical arena, as well, having to do with market sector complexity and Federal regulations (such as the existing U.S. Environmental Protection Agency/Department of Transportation Phase 1 greenhouse gas and fuel efficiency standards and the recently proposed Phase 2 standards), that would also drive the ultimate fleet adoption of some of these technologies.

It is important to note that a comprehensive view of manufacturer technology plans is not fully available in the public domain at this time. Commercialization timetables, market shares of particular technologies, and specific plans for future commercialization are considered business-sensitive information. Also, with two of the four SuperTruck projects still ongoing, there are technology results that have yet to reach a stage at which they can be evaluated for technical feasibility and further development or commercialization. Technologies that have reached this stage have not been commercially available long enough to achieve a significant market share that might be representative of technology potential. For this reason, DOE's ability to provide quantitative market-uptake data is limited and this report relies in large part on qualitative assessments of SuperTruck technology acceptance. DOE plans to complete further analysis of technology acceptance in the future when more data become available.

ADOPTION OF NEW FUEL EFFICIENT TECHNOLOGIES FROM SUPERTRUCK

Table of Contents

I. Introduction and Background

SuperTruck focuses on developing new fuel efficient technologies for eventual deployment on highway long-haul trucks, some of which are higher-risk technologies that original equipment manufacturers (OEMs) might not otherwise consider. SuperTruck teams have been very successful at meeting or exceeding the goals set forth by the SuperTruck initiative with suites of technologies that have the potential for being commercialized in the market. In the context of this report, "commercialized" refers to technologies that are available for sale to customers and used in revenue service.

I.A. Congressional Request

In the Explanatory Statement accompanying the Consolidated and Further Continuing Appropriations Act of 2015 (H.R. 83 - Public Law No. 113-483),[1] Congress requested that DOE provide "a report on the industry's adoption rates of new fuel efficient technologies from the SuperTruck program into its manufacturing lines." The findings were to be reported to the Committees on Appropriations of the House of Representatives and the Senate.

I.B. Notes on the Importance of Fuel Efficiency Improvements

The U.S. Department of Transportation estimates annual fuel use of Class 8 tractor/trailers to be approximately 28 billion gallons per year, or around 22 percent of total transportation energy use. This fuel is used in about 2.5 million trucks that travel about 66,000 miles per year per truck.[2] Newly purchased trucks typically accumulate higher annual mileage (about 100,000 miles per year); older trucks are re-deployed into lower mileage accumulation applications. Hence, new technologies can generally yield larger fuel use reductions because they are being applied to the highest-mileage trucks. Because this fuel use is so large (billions of gallons per year, representing almost 20 percent of on-road vehicle fuel use), even small improvements in fuel economy per truck applied to a significant percentage of the truck population can represent major petroleum and greenhouse gas (GHG) savings, as well as significant cost savings. Manufacturers and fleet purchasers can find value even in fractions of a percent improvement in fuel economy.

Although some of the fuel economy improvements discussed in this report may have small impacts on a percentage basis, the overall impact can be considerable when applied to the very large annual fuel use for the Class 8 population. As an example to illustrate this point, Volvo's trailer aerodynamics partner, Ridge Corp/FreightWing, estimates that its commercially available trailer aerodynamics package can improve fuel economy of the truck by 10 percent. Using these packages in 40 percent of the tractor/trailers on the road (as an ICCT/NACFE estimate[3] on side skirts for trailers implies could be feasible in the longer term) would result in a fuel savings across this truck fleet of 1 billion gallons per year. At a current diesel price[4] of around $2.50 per gallon, this represents a fuel cost savings to truck fleets of almost $2.5 billion per year. At an estimated cost of between $1700 and $2700[5] per trailer, the fuel savings can result in a payback of this investment in 1-2 years, depending on the ratio of trailers to tractors. This efficiency improvement reduces GHG emissions as well. Applying factors from the Argonne National Laboratory's AFLEET tool[6] to this scenario, a GHG reduction of around 15 million tonnes CO_2 equivalent per year results from the efficiency improvement.

I.C. SuperTruck Goals and Intended Results

The SuperTruck initiative began in 2009, with the goal of developing and demonstrating a 50 percent improvement in overall freight efficiency (expressed in a ton-mile per gallon metric) for a heavy-duty Class 8 tractor-trailer. Within SuperTruck, 40 percent of the total improvement in efficiency needs to come from engine technologies (which must demonstrate a 50 percent thermal efficiency engine) and the remaining 60 percent must come from vehicle system technologies.

The DOE-funded and cost-shared SuperTruck projects involve the major truck manufacturers providing Class 8 over-the-road trucks for the North American market: Daimler Trucks North America; Navistar, Inc.; and Volvo Trucks North America. Truck manufacturer PACCAR was involved in the SuperTruck initiative through a partnership with Cummins, Inc. and PACCAR's Peterbilt brand. Together, the companies in the SuperTruck initiative represent just over 99 percent of the U.S. market share for trucks, as shown in Figure 1. (Note that Mack is a Volvo Trucks brand included in Volvo's market share, and Kenworth is a PACCAR brand included in its market share.)

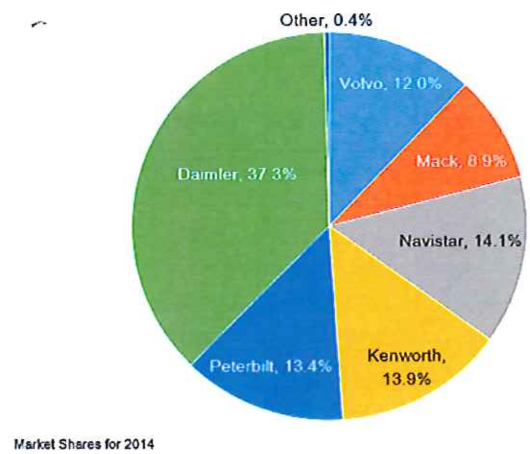

Figure 1. U.S. Truck Sales Market Share. Source: Wards Communications

The DOE SuperTruck initiative addresses technology needs that can enable the development and deployment of system efficiency technologies into the heavy truck market. The initiative is demonstrating the potential for a variety of efficiency improving technologies that can be combined to achieve very high overall vehicle efficiency. The work is addressing both near-term technology opportunities (like aerodynamics for tractors and trailers) and mid- to longer-term technology opportunities (like a systems-driven redesign of the tractor for improved efficiency). Through the work of the current SuperTruck teams, DOE will be able to demonstrate to industry stakeholders, fleets, and the general public that real-world fuel efficiency gains can be attained with technologies that are safe, reliable, durable and practical in customer drive cycles.

I.D. Current Status of SuperTruck Projects

All four of the SuperTruck teams have made excellent progress toward the performance goals set forth in the 2009 solicitation for the SuperTruck Initiative. The freight efficiency targets established for each SuperTruck project were set relative to a 2009 baseline tractor-trailer. These projects are at various stages of completion, but all are expected to be completed by the end of 2016.

- Cummins/Peterbilt have demonstrated, in an on-road 500+ mile two-day round trip highway test route including overnight hoteling, a freight efficiency improvement of 86 percent, exceeding the 50 percent target of the initiative.[7] This was achieved through integration of an advanced engine and transmission package with waste heat recovery, plus tractor and trailer aerodynamic improvements, predictive cruise control with GPS terrain management, a lithium-ion battery auxiliary power unit for idle management, low rolling resistance tires, and lightweight materials/designs. Cummins/Peterbilt have completed their project.

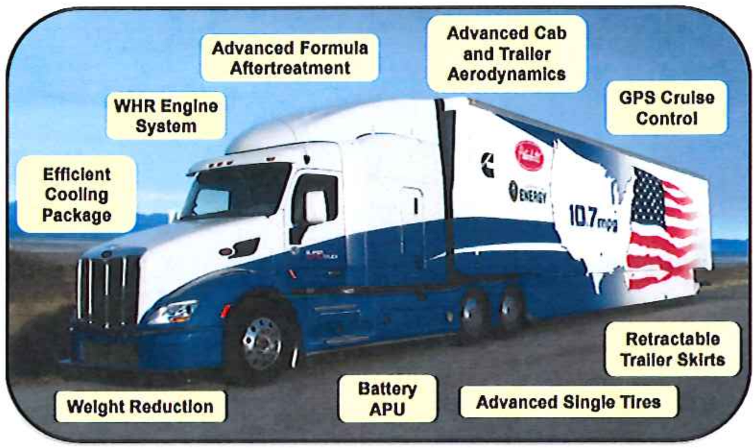

Figure 2. Cummins/Peterbilt SuperTruck (Source: Cummins 2015 DOE Vehicle Technologies Office Annual Merit Review Presentation)

- Daimler has demonstrated a freight efficiency improvement of 115 percent in on-road vehicle testing over a 5 day, 312 mile round trip. The team's technology approach includes engine downsizing, downspeeding and combustion improvements, advanced tractor and trailer aerodynamics, a parallel hybrid system (with energy storage to support idle management through electrification of accessories), predictive cruise control, and improved drivetrain lubrication packages. Daimler has also completed its project.

Figure 3. Daimler Super Truck (Source: Daimler 2015 DOE Vehicle Technologies Office Annual Merit Review Presentation)

- Volvo recently demonstrated an 88 percent freight efficiency improvement and achieved 50 percent engine efficiency. This was accomplished through aerodynamic drag reduction of greater than 40 percent, vehicle lightweighting with an ultra-light frame assembly that is 40 percent lighter than the conventional frame, kinetic energy recovery and low rolling resistance tires. Other technologies Volvo utilized to achieve the efficiency goals are intelligent cruise control with GPS terrain management, and an integrated solar roof concept. Powertrain improvements were also a critical contributor in Volvo's strategy to achieve the freight efficiency goal. They include engine downspeeding and downsizing, fuel injection and aftertreatment systems, and waste heat recovery.

- Navistar is on track to meet the freight efficiency goal and expects to complete its project work in 2016, aiming for a freight efficiency improvement of 80 percent or more.[8] It has tested its current engine package at a brake thermal efficiency (BTE) of 48.3 percent, with additional technologies yet to deploy toward the 50 percent BTE goal. Navistar has been leveraging Lawrence Livermore National Laboratory's experience in truck aerodynamics to expand its capabilities for testing and analysis, and is exploring several novel concepts for aerodynamic drag reduction (tractor cab redesigns and active ride height and pitch control for the trailer, among them). The team is also pursuing "smart" cruise control with GPS terrain management, electric heating, ventilation, and air conditioning (HVAC) systems, and weight reductions for the tractor and trailer potentially exceeding 6,500 pounds. As with the other teams, Navistar is devoting considerable attention to engine efficiency improvements, including combustion systems, air handling systems, engine accessories, and engine thermal management.

Not all technologies, whether engine or vehicle, can benefit all customers, however. Technologies must match with the duty cycle of the truck to deliver the expected fuel savings. This is reflected in the different approaches taken by the four SuperTruck teams.

II. SuperTruck Technology Uptake Assessment

II.A. Current and Near-Term SuperTruck Technologies

To assess the uptake of technology in the truck market, DOE used a variety of sources, including public technical reports and presentations by the SuperTruck teams on their projects, direct interviews with the technical experts responsible for SuperTruck achievements, and external resources such as press releases and public statements by company executives about product plans. DOE also used technical experts within the Vehicle Technologies Office to provide comments and technology insights, and drew upon DOE reports and studies (such as the SuperTruck Benefits Analysis) to supplement information gathered directly from SuperTruck teams.

To date, there has already been some level of adoption in the market for tractor and trailer aerodynamics (trailer side skirts, tractor side skirts, aero redesigns of bumpers and other components), engine downspeeding, 6x2 axles, automated manual transmissions (AMTs), predictive cruise control, and some vehicle lightweighting. These technologies have proven attractive to truck purchasers because of their generally good return on investment (ROI) and the ease with which they can be incorporated into fleet operations. Additionally, the EPA and DOT "Phase 1" fuel efficiency and GHG regulations have also been a driver in the introduction of these technologies.

Some technologies developed under the SuperTruck initiative have already reached the market in specific "packages," or combinations of technologies that are marketed as beneficial to fuel efficiency (see Case Study 1[9,10] on this page). In other cases, technologies are marketed individually (Case Study 2[11] on this page). Technologies like 6x2 axle sets, aluminum fifth wheels, and other lightweight components (like air tanks) have been explored in SuperTruck and subsequently commercialized.

COMMERCIALIZATION CASE STUDY 1

Peterbilt has made improvements to its aerodynamics packages for Class 8 tractors as a result of findings from the Cummins/Peterbilt project. The Peterbilt Model 579 EPIQ improves fuel efficiency over the conventional Model 579 by up to 14 percent, using many fuel economy enhancement features originally developed for their SuperTruck. Among the features adopted by the EPIQ truck from SuperTruck are the tractor side fairings that close gaps between the fender and front steer wheels, a front air dam to prevent air from flowing under the truck, and fairings that extend down the side of the tractor nearly to the ground, to direct airflow away from the underside of the truck. The truck also incorporates some engine downsizing and engine/transmission optimization with an AMT, concepts also explored in SuperTruck.

Technology Readiness Level (TRL) is a primary driver for the commercialization categories of SuperTruck technologies as presented in Tables 1 and 2 below. While TRLs address the progress of technology toward commercialization and help identify technologies that are nearly ready for commercial development, commercial vehicle customers pay particular attention to technology cost effectiveness as one of their key metrics for adoption. It is a generally accepted viewpoint from industry OEM and customer perspectives that technologies with a payback period of less than 18 months are more likely to be commercialized and adopted in the near-term under market driven conditions. Technologies with longer payback periods of 18-36 months may still be commercialized, but customers and OEMs may be more inclined to wait for further cost reductions or a distinct business case before widely adopting in the absence of other drivers such as regulatory requirements. Technologies with payback periods of greater than 36 months are less likely to be commercialized or adopted without further cost reduction and development in the

COMMERCIALIZATION CASE STUDY 2

Volvo announced in early 2016 that SuperTruck research "played a critical role" in designing and engineering the company's 2017 powertrain system that provides improved efficiency and performance. Volvo stated that several new features now available to customers, including a new piston design (improving fuel efficiency up to 2.5 percent), a refined turbocompounding system (improving fuel efficiency up to 6.5 percent), and common rail fuel injection systems, were derived directly from SuperTruck research.

absence of regulatory requirements. As discussed in Section II.C., payback is not the only metric considered by commercial tractor fleets – truck owners also consider technology reliability, impacts on vehicle up-time, impact of a technology on the vehicle residual value, and any impacts on maintenance costs and maintenance practices.

The SuperTruck teams have adopted strategies to meet the initiative's 50 percent freight efficiency goal with a range of technologies, some of which are cost-effective in their present state and are reaching the market. Many other technologies show great promise, but have not been proven at a sufficiently high technology readiness level to support commercial adoption.

Table 1 lists both current commercialized technologies and near-commercial technologies that manufacturers expect to deploy within the next two years. More details on these technologies are found in Section III. Technologies listed in Table 1 have either been deployed in some vehicles or are expected to be commercially available in the 2016 to 2017 timeframe ("near-term," or within the next 2 years). These technologies are at a TRL of 8 (at or near end of system development) based on public information and individual team feedback that has been aggregated for SuperTruck.

Table 1. SuperTruck Technologies – Current and Near-Term Deployment

	Commercialized technologies (current)	Near-commercial technologies (next 2 years) Technology Readiness Level 8 (End of System Development)
Engine	• Downspeeding • Intelligent torque management • Integrated engine/transmission controls	• Friction loss reduction (lubricants, materials and coatings) • Parasitic loss reduction (engine accessories) • Improved conventional combustion • Improved aftertreatment • Improved air handling (Exhaust Gas Recirculation [EGR], turbocharger) • Synthetic engine lubrication
Driveline	• Automated manual transmissions (AMTs) • Predictive transmission shifting • Optimized transmission gear ratios for downsped engines • Transmission/engine integration • 6x2 axles • Neutral shifting on downgrades • Reduced parasitic losses (lubricants and transmission design)	• Improved driveline lubricants for reduced friction
Aerodynamics	• Tractor aerodynamics (bumper designs, roof fairings, chassis fairings, tractor/trailer gap fairings) • Trailer aerodynamics (side skirts, boat tails, gap fairings)	• Trailer aerodynamics (full trailer skirts including trailer wheels, engineered trailer surfaces for reduced drag)
Weight Reduction	• Aluminum fifth wheel • Aluminum tractor and trailer wheels • Aluminum driveshaft	• Lightweight brakes

	Commercialized technologies (current)	Near-commercial technologies (next 2 years) Technology Readiness Level 8 (End of System Development)
Tire Rolling Resistance	• Single wide-base tires (tractor and trailer tandems) • Reduced rolling resistance tire compounds and designs	• Continued improvement in tire compounds and designs
Energy Management	• Predictive Global Positioning System (GPS) cruise control • Eco-driving feedback systems • Light Emitting Diode (LED) lighting • Overnight idling reduction (Auxiliary Power Unit [APU] or battery)	• Improvements to overnight idling reduction systems

II.B. Opportunities for Mid-Term to Longer-Term Deployment

Technologies introduced in this section have demonstrated potential for significant efficiency improvements as part of the SuperTruck initiative. However, they may require more than two years to be commercially viable because of: (1) technology readiness; (2) business case requiring additional development; or (3) regulatory compliance.

Technologies correlated with TRLs 6 and 7 are represented as mid-term (2 to 4 years for commercialization timeframe) opportunities; they are not yet production-ready but may become so with further development and demonstration. Technologies correlated with TRLs 4 and 5 are represented as longer-term opportunities (to be commercialized at some point in or after 2020) based on SuperTruck public information and team feedback. Technologies at this stage of readiness still require further research and development (R&D) before determining whether they are technically feasible and commercially viable. Table 2 lists these mid- to longer-term technologies in broad terms. More details on these technologies are found in Section III.

Table 2. SuperTruck Technologies - Mid- to Longer-Term Deployment

	Mid-term technologies (2-4 years from commercialization) Technology Readiness Level 6-7 (System Demonstration)	Longer-term technologies (5 or more years from commercialization) Technology Readiness Level 4-5 (Component Validation)
Engine	• High pressure fuel injection systems • Improved combustion (e.g., piston bowl designs) • Further improvements to air handling (turbocharger, EGR) • Electrified auxiliaries (water pump, cooling fan, etc.)	• Waste heat recovery • Advanced engine controls • Engine structural materials for higher peak cylinder pressures
Driveline	• Dual clutch AMTs • Gear coatings and lubricants for reduced friction	• Electrified auxiliaries • Hybridization

	Mid-term technologies (2-4 years from commercialization) Technology Readiness Level 6-7 (System Demonstration)	Longer-term technologies (5 or more years from commercialization) Technology Readiness Level 4-5 (Component Validation)
Aerodynamics	• Active aerodynamic features (grill shutters, etc.) • More extensive redesigns of tractor aerodynamic surfaces (cabs, hoods, etc.) • Tractor and trailer underbody aerodynamics • Tractor/trailer gap reduction	• Cameras to replace mirrors • Articulating/active tractor/trailer gap closures • Reconfiguration of tractor and trailer to reduce aerodynamics (e.g., engine and transmission placement, etc.)
Weight Reduction	• Lightweight suspension components • Lightweight driveline components	• Lightweight frame rails
Tire Rolling Resistance	• Automatic tire inflation systems	• Novel low rolling-resistance tire compounds
Energy Management	• Battery-based idle management systems • Cab thermal management	• Advanced predictive engine accessory and driveline controls • Wind/weather-based cruise control • Solar energy harvesting

II.C. Factors Affecting Adoption of Technology

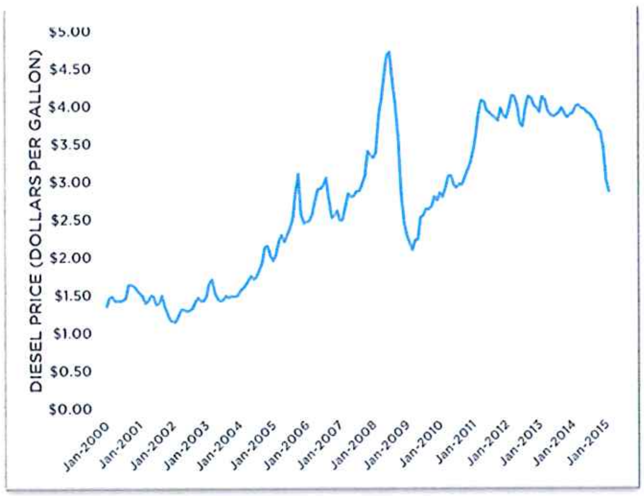

Figure 4. Diesel Fuel Price History 2000-2015 (Source: DOE Energy Information Administration)

The SuperTruck teams are developing and refining technologies with an eye toward commercialization. When and if they are commercialized, their adoption into the truck market will depend on several factors. Fleets are seeking a positive return on investment (ROI) for any incremental costs they incur in purchasing efficiency technologies, and this ROI must come largely from the fuel cost savings achieved by the technology. The cost savings are a function of fuel prices and technology effectiveness: lower fuel prices reduce the value of efficiency-driven savings while effectiveness increases the savings. Diesel fuel price volatility (as shown in Figure 4) makes it difficult to predict the market-driven adoption of new technologies that might reach the market in five or ten years. The market is complex, but changes in fuel prices are one factor that will alter ROI calculations and, ultimately, the technology adoption rate.

Fleets also pay close attention to maintenance needs. The aerodynamic aids used on the various SuperTruck prototypes reflect the teams' particular approaches to meeting the overall goals and identifying the potential for aerodynamic technologies. These aerodynamic aids present some implementation challenges, partially due to the limited clearance between items like side skirts and front air dams and the ground. Tractors in real-world service must often maneuver in tight spaces, travel in adverse weather conditions, and negotiate other obstacles such as curbs and loading docks, all of which expose aerodynamic aids to potential damage and resulting maintenance expenses. Fleet managers must factor in these potential lifetime repair expenses when they consider and specify their future fleet purchases. This is especially true of trailers, where responsibility for damage can be difficult to assess and financial reimbursement hard to manage. The Cummins-Peterbilt SuperTruck team designed its trailer with retractable trailer skirts to address these concerns: the trailer skirts can be retracted to improve ground clearance as the tractor maneuvers precarious situations.

Fleets consider other financial aspects of new technology as well. Virtually all fleets seek to minimize downtime for their equipment to ensure it is always available and ready to work as an asset for the company. For this reason, any technologies that may have (or are perceived to have) lower or uncertain reliability may be slow to reach the market in any significant quantities despite their potential for cost savings from lower fuel use. Individual fleet priorities differ, and some are likely to value reliability and usability more than fuel cost savings while others will value fuel costs savings more. Fleets may also consider the positive and negative impacts of these new technologies on the residual value of the equipment, particularly larger fleets that may only keep their trucks for two to four years before reselling them into a secondary market.

There are other economic challenges associated with market adoption for the trailer. Aerodynamics offers a significant opportunity for efficiency improvement on a tractor trailer combination, and the trailer plays a major role in that improvement. Cummins/Peterbilt SuperTruck data showed that two-thirds of the total tractor trailer aerodynamic gains are associated with the trailer, while only one-third come from the tractor. However, the trailer market is challenging, as trailers are treated as more of a commodity than tractors (there are about four trailers for every tractor, nationwide). Since there are many more trailers for every tractor, the fleet's invested cost for trailer changes could be higher than changes to a tractor for a given fuel economy improvement. The accountability for fuel savings is unclear – the tractor owner will reap the benefits of the trailer aerodynamics, but the tractor owner may or may not be the trailer owner. The trailer industry is slow to change, in general: trailer side skirts are making inroads, but other devices are being adopted at a much slower rate. Market uptake of trailer efficiency technology will require cost effective, high performance technologies such as those developed by SuperTruck. Overhauling of shipping practices to change how trailers are ordered and owned might also affect trailer uptake. Both voluntary and regulatory drivers for efficiency technologies, such as the voluntary EPA SmartWay program and the EPA/DOT Phase 2 GHG standards, will also help drive trailer technology implementation.

While Federal regulations often accelerate technology introduction, regulations can sometimes make it difficult for technologies to get a significant market share even if their ROI is good. For example, replacement of mirrors with cameras would require regulatory changes. Similar situations exist with truck platooning (regulations about vehicle following distance) or longer aerodynamic trailer tails (trailer length regulations). Many of these regulations are safety-based. This highlights the complexity of technology deployment: even highly fuel-efficient technical solutions from SuperTruck may need additional regulatory or other developments to reach their market potential.

The information in this report primarily reflects forward projections based on current assumptions about technology development, current and future market conditions (including fuel prices), and fleet motivations for vehicle purchases. Future customer needs may change based on market evolution and trends, as well as regulations. DOE made efforts to gather complete information through searches of the technical literature, review of public announcements and press releases about product plans, and direct contact with SuperTruck teams about the potential opportunities for future technology deployment by the industrial partners. Future plans for these technologies such as the timetables and specific plans for commercialization are considered business-sensitive information and not fully available in the public domain. In addition, with two of the four SuperTruck projects still ongoing, some technology results have yet to reach a stage where they could be evaluated for technical feasibility and further development or commercialization. The technologies that have reached this stage have not been commercially available long enough to achieve a significant market share that might be representative of technology potential. For these reasons, DOE has not included specific quantitative information about current and future technology uptake rates as part of this report.

III. Additional Description of Truck Efficiency Technologies (APPENDIX)

The modern Class 8 tractor-trailer is a complex and efficient mode for transporting goods, involving a large number of technologies to ensure the truck is safe, efficient, and clean. The SuperTruck initiative has spurred the development of a number of new technologies to improve existing truck designs. This section describes many of the new technologies and concepts from SuperTruck with an overview of how they work and what benefit they are intended to provide.

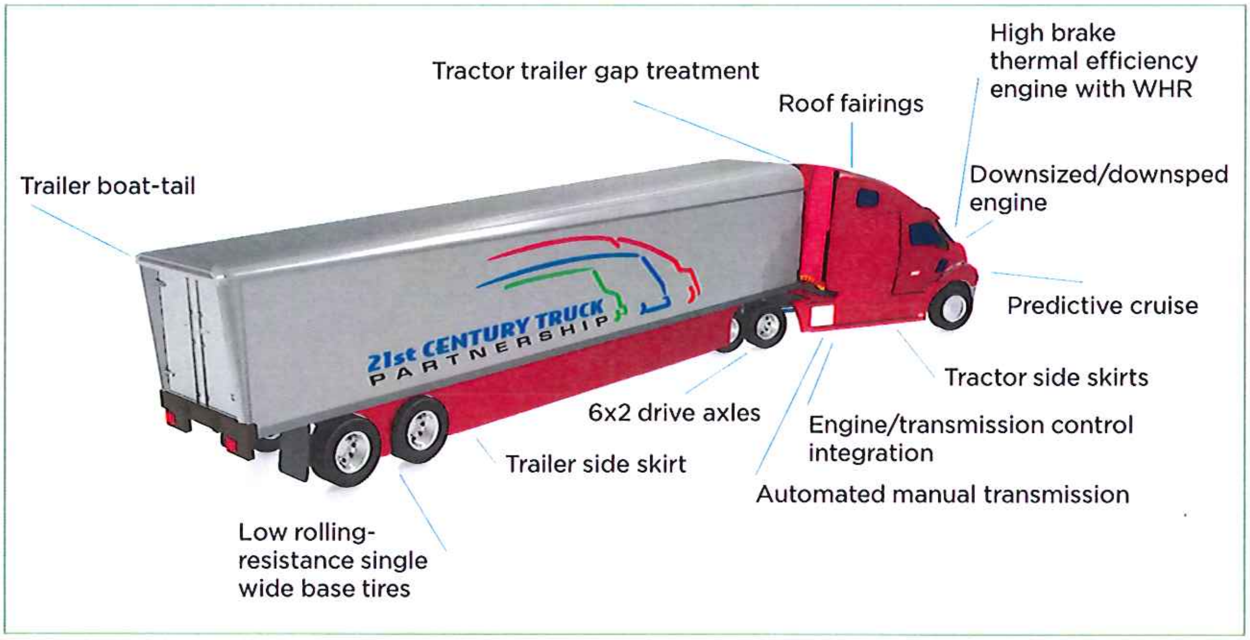

Figure 5. SuperTruck Technologies

The illustration in Figure 5 shows the technologies that are being implemented in the near-term, as described earlier in the report, and the general location of these technologies on the modern Class 8 truck. Technologies are then described below.

III.A. Engine

SuperTruck research highlighted a number of areas for improving the efficiency of the engine in converting fuel energy into motive power (that is, improving the thermal efficiency of the engine). Teams have made changes to reduce internal engine friction, improve in-cylinder combustion characteristics, and facilitate airflow into and out of the engine through turbocharging and other air handling modifications. More advanced engine efficiency technologies are also on the horizon, including waste heat recovery systems that take energy that is normally lost to the exhaust or coolant and turn that lost energy back into mechanical or electrical power for use on the truck.

III.B. Driveline

Transmissions, axles, and other components transmit the engine's power to the drive wheels, and SuperTruck teams have found opportunities for efficiency improvements here. Automated manual transmissions combine the mechanical efficiency of a clutched manual transmission with the optimized shift strategies of an automatic transmission. Manufacturers are working together as a result of SuperTruck to integrate the control systems of engines and transmissions to ensure that both are operating as a team at their highest efficiency. Transmission and axle changes allow for tractor diesel engines to be downsized and operate at lower average engine speeds (downspeeding) while maintaining driveability. Both downsizing and downspeeding offer the potential for increased efficiency. Improvements in lubrication for transmission and axle gears reduce the frictional losses in these components. New drive axle designs allow for only one of the two tractor tandem axles to drive the vehicle, eliminating the frictional losses in the second drive axle while maintaining the traction of the tandem drive axle system.

III.C. Aerodynamics

Aerodynamic improvements help reduce the drag from air resistance as the truck moves down the road. In SuperTruck, teams have added several items to the trailer to improve trailer aerodynamics. These include trailer side skirts that cover the area under the trailer and in front of the rear wheels to prevent air from being trapped under the trailer. Trailer boat tails smooth the airflow around the rear of the trailer, preventing a low pressure area from forming behind it. Fairings and gap reduction devices cover the space between the truck tractor and the trailer to prevent air from being trapped between the tractor cab and the front of the trailer.

Although the modern Class 8 tractor has been refined considerably over the past ten to twenty years to improve aerodynamics, SuperTruck teams have found areas for additional improvements. Redesigned side fairings between the front and rear wheels of the tractor help keep air from being directed underneath the tractor, while front air dams and bumper designs help direct air smoothly around the truck, rather than underneath it. Roof fairings perform a similar function on the top of the tractor, directing air over the tractor smoothly and matching the height of the tractor to the trailer. Some fairings and other treatments for addressing the tractor-trailer gap are applied to the tractor.

III.D. Weight Reduction

Truck weight reduction improves overall freight efficiency (ton-miles per gallon) either by allowing more freight to be carried on the vehicle and keep the truck within weight regulations (more tons at the same miles per gallon) or by allowing for the same cargo to be carried in a lighter truck (same tons at improved miles per gallon). Changes in the materials from which truck components are made is one way that SuperTruck teams are reducing weight (aluminum substitutions for the fifth wheel that connects the tractor and trailer, or aluminum wheel rims replacing steel ones, for example). Single wide base tires (see Tire Rolling Resistance in the next section) can also reduce weight by reducing the total number of tires and wheels.

III.E. Tire Rolling Resistance

Tire rolling resistance refers to the energy expended as tires roll on paved surfaces. This energy is expended chiefly through the flexing of tire sidewalls and the friction of the tire tread on the pavement. Tire rolling resistance can be reduced through both improvements in conventional truck tire design and materials as well as through new tire concepts such as the wide-base single tire. Manufacturers are reducing conventional tire rolling resistance by changing tire materials to add more silica (for example) and by redesigning treads for less friction. The single wide-base tire reduces rolling resistance by replacing the standard dual tire system with a single, wider tire. The net result reduces tire sidewall flexing effects (by eliminating two sidewalls) while maintaining load carrying capacity.

III.F. Energy Management

Energy management is a broad term referring to a number of efficiency technologies that improve how energy sources are used onboard the vehicle. Predictive cruise control uses GPS mapping and terrain databases to view the road ahead and adjust speed to take advantage of grades for improving fuel efficiency. Eco-feedback systems give drivers guidance on how to drive the truck for maximum efficiency through instrument panel displays. Idle management systems minimize fuel use during rest periods when the driver needs to use heating/air conditioning and other electrical loads. These systems either cycle the main engine on or off to provide these loads or use an auxiliary diesel engine, onboard batteries, or off-board electrical connection to generate the necessary power for onboard loads.

IV. Technology Readiness Level Definitions (APPENDIX)

Technology Readiness Levels (TRLs)[12]: Identify the readiness level of the technology associated with the project as well as the planned progression during the course of project execution. The following definitions apply:

1. **TRL-1.** Basic principles observed and reported: Scientific problem or phenomenon identified. Essential characteristics and behaviors of systems and architectures are identified using mathematical formulations or algorithms. The observation of basic scientific principles or phenomena has been validated through peer-reviewed research. Technology is ready to transition from scientific research to applied research.

2. **TRL-2.** Technology concept and/or application formulated: Applied research activity. Theory and scientific principles are focused on specific application areas to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.

3. **TRL-3.** Analytical and experimental critical function and/or characteristic proof of concept: Proof of concept validation has been achieved at this level. Experimental research and development is initiated with analytical and laboratory studies. System/integrated process requirements for the overall system application are well known. Demonstration of technical feasibility using immature prototype implementations are exercised with representative interface inputs to include electrical, mechanical, or controlling elements to validate predictions.

4. **TRL-4.** Component and/or process validation in laboratory environment- Alpha prototype (component) Standalone prototyping implementation and testing in laboratory environment demonstrates the concept. Integration and testing of component technology elements are sufficient to validate feasibility.

5. **TRL-5.** Component and/or process validation in relevant environment- Beta prototype (component): Thorough prototype testing of the component/process in relevant environment to the end user is performed. Basic technology elements are integrated with reasonably realistic supporting elements based on available technologies. Prototyping implementations conform to the target environment and interfaces.

6. **TRL-6.** System/process model or prototype demonstration in a relevant environment- Beta prototype (system): Prototyping implementations are partially integrated with existing systems. Engineering feasibility fully demonstrated in actual or high fidelity system applications in an environment relevant to the end user.

7. **TRL-7.** System/process prototype demonstration in an operational environment- Integrated pilot (system): System prototyping demonstration in operational environment. System is at or near full scale (pilot or engineering scale) of the operational system, with most functions available for demonstration and test. The system, component, or process is integrated with collateral and ancillary systems in a near production quality prototype.

8. **TRL-8.** Actual system/process completed and qualified through test and demonstration- Pre-commercial demonstration: End of system development. Full-scale system is fully integrated into operational environment with fully operational hardware and software systems. All functionality is tested in simulated and operational scenarios with demonstrated achievement of end-user specifications. Technology is ready to move from development to commercialization.

V. Acronyms and Abbreviations

AMT	automated manual transmission
BTE	brake thermal efficiency
DOE	U.S. Department of Energy
EGR	exhaust gas recirculation
GHG	greenhouse gas
GPS	Global Positioning System
HVAC	Heating, ventilation, air conditioning
ICCT	International Council on Clean Transportation
TRL	technology readiness level
NACFE	North American Council for Freight Efficiency
ROI	return on investment
R&D	research and development

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