CONFIDENCE REPORT:

Variable Engine-Driven Accessories

ABSTRACT This report documents the confidence that North American Class 8 trucking should have in the emerging technologies related to variable engine-driven accessories. The study team engaged with the entire industry in generating the findings that are presented here. Thanks to all of those who contributed to this important work.

Trucking Efficiency is a joint effort between NACFE and Carbon War Room to double the freight efficiency of North American goods movement through the elimination of market barriers to information, demand and supply.

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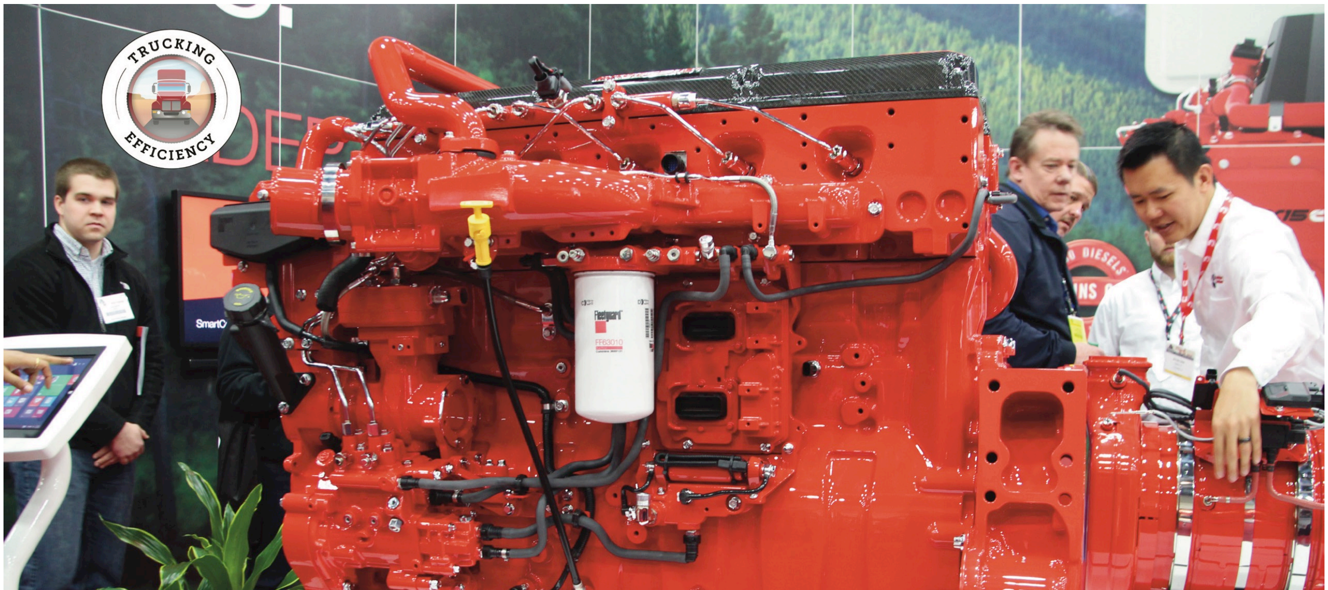


TRUCKING EFFICIENCY CONFIDENCE REPORT

VARIABLE ENGINE-DRIVEN ACCESSORIES

OVERVIEW

The fuel costs faced by the tractor-trailer industry have been swiftly and steadily rising over the past decade. In 2014 diesel fuel costs were $0.58 per mile, costing the industry as much per annum as the costs of drivers' wages and benefits combined. Despite recent fuel cost decreases, to $0.40 per mile in 2015, all indications are that fuel price volatility will continue, forcing the industry to find solutions that increase its fuel efficiency in order to stay profitable. Additionally, the U.S. EPA and NHTSA have finalized the details for the Greenhouse Gas Phase 2 (GHGp2) regulations requiring tractor, trailer, and engine OEMs to offer and produce more fuel-efficient equipment.

Fortunately, myriad technologies that can cost-effectively improve the fuel efficiency of Class 8 trucks are readily available on the market today. Unfortunately, multiple barriers have stymied industry adoption of such technologies, including a lack of data about the true performance gains these technologies offer, and a lack of confidence in the payback for investment in these technologies. To overcome those barriers and facilitate the industry's trust in and adoption of the most promising fuel efficiency technologies, the North American Council for Freight Efficiency (NACFE) partnered with Carbon War Room (CWR) to form Trucking Efficiency. The work of Trucking Efficiency has begun by producing a series of Confidence Reports, of which this report on variable engine-driven accessories is the fifteenth.

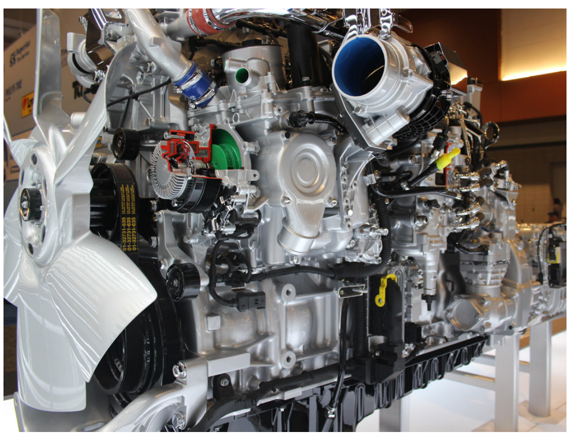
This report represents the second in a subset of reports being published on emerging technologies. Widespread innovation and technological advances are seeing the emergence of technologies and practices that could affect decisive opportunities across the transportation industry. As novel concepts, new applications, and original modes of behavior reach the market, fleets and manufacturers need information on the benefits, challenges, and risks so that everyone can profit in this evolving landscape. The first emerging technology to be covered in a Confidence Report was two-truck platooning.

The goals of this Confidence Report are: (a) to give the industry a foundational understanding of variable engine-driven accessories; (b) to understand how the Department of Energy SuperTruck teams approached variable engine-driven accessories; (c) to provide an unbiased overview of the benefits and challenges of each technology; and (d) to help fleets rationalize their future investment in variable engine-driven accessories when they become available.

Variable engine-driven accessories are evolving as potential fuel-saving strategies for long- and regional-haul fleets. Some have been available for years while others are just recently emerging. All of these devices are items that put a load on the engine, but do NOT help propel the vehicle down the road. They are therefore commonly referred to as

METHODOLOGIES

This report's conclusions were generated through desk research, conversations at a variety of trucking industry events around the country, and a series of structured interviews with fleets, technology developers, component suppliers, tractor OEMs (including the four SuperTruck team leaders), and others about the fuel savings available from variable engine-driven accessories, and the challenges and benefits of adoption. This study differs from past Confidence Report efforts in which the Trucking Efficiency team reviewed products available in the marketplace. As some engine-driven accessories are emerging technologies, only available in limited deployment, the team is using its common approach to understanding the confidence fleets should have in adopting the devices before they become available. Thus, this work does not report known benefits and consequences of adoption, but rather what the industry believes the benefits and challenges of the new technology will be.



Freightliner Detroit DD13 engine with fan and accessories

DD13 installed in a truck

parasitic loads since they are robbing power without helping to move the vehicle. Since these accessories provide essential vehicle functions, the potential efficiency gains would be accomplished through the implementation of new designs and technology to minimize the energy necessary to provide these essential functions.

FUEL ECONOMY GAINS

The fuel economy gains that can be achieved with variable engine-driven accessories for common on-highway vehicles are relatively modest. Current fuel prices make justifying the added cost for engine-driven accessories hardware that improves fuel economy difficult. However, the current and upcoming greenhouse gas regulations are likely to push at least some of these technology choices related to engine-driven accessories from optional to standard equipment on new truck orders.

UNDERSTANDING DUTY-CYCLE EFFECTS

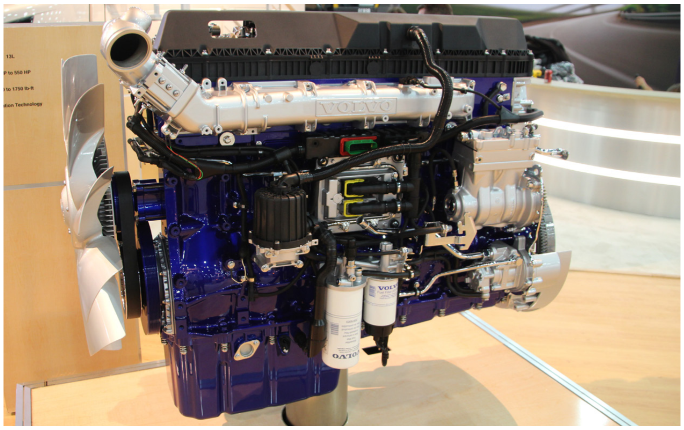
Duty cycle often has a large effect on the return on investment (ROI) of engine-driven accessories. Duty cycle is a broad term that describes how a device is used within an overall mission. Each specific vehicle has a duty cycle. For example, highway or line-haul operation, pickup and delivery, city driving, and rural driving all put different demands on the vehicle powertrain, resulting in different fuel economy, performance, and emissions.

Duty cycle for accessory systems adds yet another layer of complexity to this. Many engine-driven accessories will cycle on and off depending on a variety of different factors. So the fuel economy benefits of a new technology can vary quite a bit depending on the accessory duty-cycle factors. A specific improvement may have a big benefit for line-haul trucks and not so much for city pickup and delivery, or vice versa.

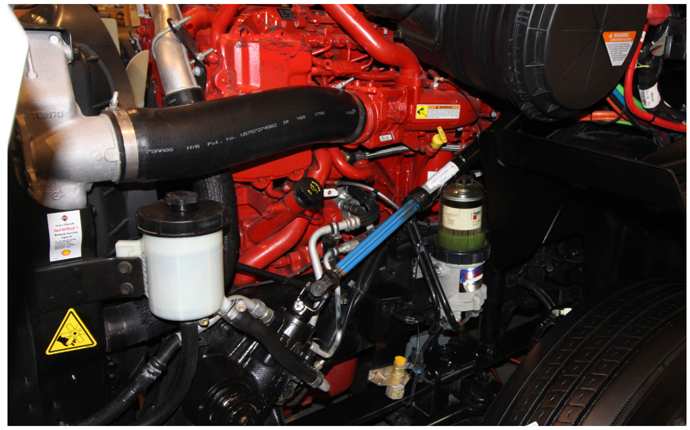
VARIABLE ENGINE-DRIVEN ACCESSORIES

The various engine-driven accessory technologies covered in the report that are either available today or in development for North American Class 8 tractors include the following:

- **Cooling system water pumps** circulate coolant through the engine and reject excess heat as the coolant passes through the radiator. New variable speed water pumps do not operate at full power all the time to reduce the load on the engine.



Volvo D13 on show stand



Cummins engine

- **Cooling fans**, located behind the radiator, draw cool air across the radiator and into the engine compartment. While many cooling fans are simple on or off devices, there are also fans that run at multiple speeds or even variable speeds to lower the engine load to only what is required at a given time.
- **Air compressors** are used to supply compressed air to the brake systems of large commercial tractor-trailers. Historically, the air compressor for the brakes turns all of the time and pumps air when necessary. New clutched air compressors eliminate the robbing of engine power when the air tanks are already at required pressure levels.
- **Power steering pumps** typically run all the time to handle worst-case needs of low-speed vehicle turning and maneuvering. New systems take into account the fact that line-haul tractors spend the vast majority of their operating hours going nearly straight down a highway when little steering effort is necessary.

"With modest fuel economy gains, payback is challenging for these systems."
– Kevin Otto, Study Manager

- **Alternators** use the engine to create electrical power both to recharge batteries as well as to power electrical loads while the engine is running. Alternators are included in this report because some operate at higher efficiencies, placing less load on the engine.
- **Air conditioning compressors** facilitate the movement of the refrigerant for the cab air conditioning system. Although only operating as required, sleeper compartments require A/C when the truck is parked. Rather than using an engine to run the compressor when the truck is parked, future A/C compressors may be electrically driven.
- **Electrically driven accessories** are not gear or belt driven by the engine as with the above accessories, but may be removed from the engine entirely IF the electrical system can support their large energy requirements.

DOE SUPERTRUCK 1 PROGRAM

From 2009 to 2015, the Department of Energy (DOE) sponsored a program with industry manufacturers to demonstrate at least a 50% improvement in freight efficiency. Each of the four teams—Cummins/Peterbilt, Daimler, Navistar, and Volvo Trucks USA—created demonstration vehicles with a variety of new technologies on them to highlight the feasibility of meeting this aggressive goal. Each SuperTruck team established its own baseline upon which to judge the improvement achieved, and all the teams were highly successful.

The NACFE study team interviewed each of the SuperTruck teams to understand their analyses and choices relative to variable engine-driven accessories. Since all of the SuperTruck teams chose vehicle technologies that would allow them to meet or exceed the program goals, their choices relative to engine-driven accessories varies as well. However, the choices do give a glimpse into the kinds of solutions that may be offered in the future. All the teams chose to implement significant improvements in aerodynamics, vehicle rolling resistance, weight reduction, downspeeding, and waste heat recovery. All of these choices meant that the horsepower required to move the vehicle down the road was reduced and the engine was turning at a slower rpm.

Therefore, due to the above vehicle system changes, each SuperTruck team made adjustments to most engine-driven accessories to take advantage of the new/revised operating modes. This led to changes in compressed air, power steering, coolant circulation, cooling fans, and alternator systems. The report discusses the new technologies that were employed.

ENABLING TECHNOLOGIES AND TRENDS

Two near-term industry trends also have an effect on the fuel economy of engine-driven accessories. Improvements being made to improve fuel economy reduce the average horsepower that it takes to propel the vehicle down the road, changing the amount of heat that needs to be rejected through the cooling system. Downspeeding slows the engine down to a lower speed during normal cruising on the highway. Both of these trends lower the fuel consumption of certain accessories and may lengthen the payback of many of the engine-driven accessory solutions.

Waste heat recovery and higher voltage are two enabling technologies that if implemented might increase the adoption of many of these variable engine-driven accessories. Waste heat recovery involves adding additional hardware to the vehicle to extract more mechanical energy from the heat generated by combustion than can be extracted from the power cylinder. Implementing a waste heat recovery system requires a redesign of the vehicle's heat exchanger systems to be most effective. Therefore, the cooling fan, water pump, and perhaps the cab air conditioning system could be affected directly.

> *"Uptime is mandatory for fleets and they have reliability concerns with variable engine-driven accessories."*
>
> – Mike Roeth, Operation Lead, Trucking Efficiency, and Executive Director, NACFE

Higher system voltage with additional electrical energy storage also offers the chance to implement improvements related to the accessories. In short, higher voltage allows the use of smaller electric motors and reduced size of wiring to get the same power output. Additional electrical storage on the vehicle (i.e., batteries) will allow the electrical system to deal with intermittent high current loads without depending on the alternator to always generate that current. It is possible that some accessories will be driven electrically when this can be done more efficiently than the current mechanical drive systems.

CONCLUSIONS AND RECOMMENDATIONS

The fuel economy gains from currently available engine-driven accessories technologies are modest, and at today's fuel prices the payback is long, leading to low levels of adoption. Many fleet owners have indicated they have significant concerns for subsystem reliability of any new technologies. However, future enabling technologies like higher vehicle system voltage, increased energy storage, and waste heat recovery will likely improve the ROI of new accessories technologies.

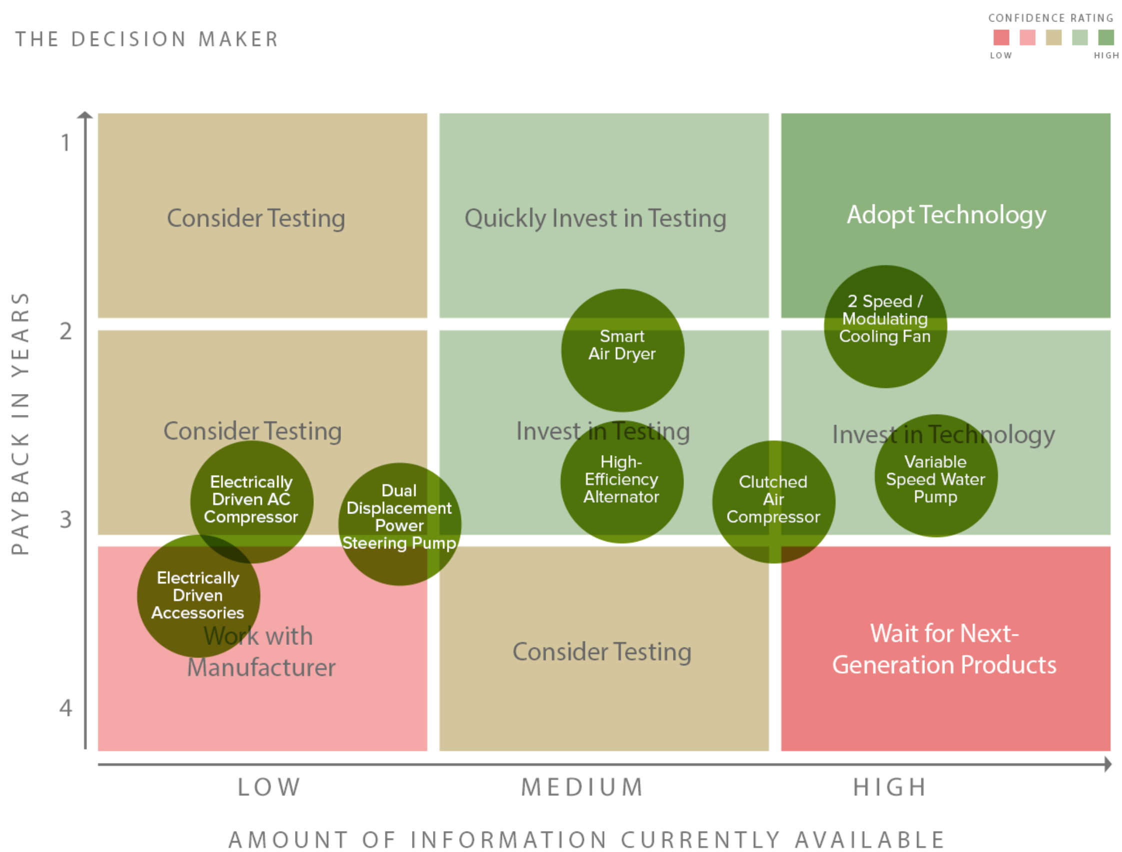
Trucking Efficiency recommends the following:

- Fleets should continue to review variable engine-driven accessory alternatives as part of their vehicle specification process. Some small improvements are likely available today that would be cost-effective for a given operation. Note that measuring the small improvements is challenging.
- Greenhouse gas regulations are likely to drive some changes to accessories that over time will increase complexity but have fuel economy benefits. It is very important to keep an eye on those improvements to ensure that fleet personnel are adequately prepared for the changes.
- Higher voltage systems will be an enabling technology for more economical changes to variable engine accessory systems to improve fuel efficiency. However, the savings enabled by improved accessories are unlikely to be a big driving force behind increasing vehicle system voltages.

CONFIDENCE RATING

For each of the Confidence Reports completed by Trucking Efficiency, the various technologies assessed therein are plotted on a matrix in terms of their expected payback in years compared to the confidence that the study team has in the available data on the performance of that technology—that is, not only how quickly fleets should enjoy a payback on their investment, but how certain Trucking Efficiency is in the assessment of that payback time. Technologies in the top right of the matrix have a short payback, usually thanks to their low upfront cost, and moreover are found to have enough performance data that fleets can be highly confident in those short payback times, usually because the technology is more mature or otherwise has a more substantial track record of results.

Many of the technologies mentioned in this report are in early design and prototyping, and not yet in deployment. Because less information is available, they are farther to the left in the confidence matrix.



Trucking Efficiency is always seeking to expand the data or case studies that we can provide to the industry. We invite you to share your own experiences with variable engine-driven accessories.

Trucking Efficiency

Trucking Efficiency is a joint effort between NACFE and Carbon War Room to double the freight efficiency of North American goods movement by eliminating barriers associated with information, demand, and supply.

Worldwide, heavy-duty freight trucks emit 1.6 gigatons of CO_2 emissions annually—5.5% of society's total greenhouse gas emissions—due to the trucking sector's dependence on petroleum-based fuels. With fuel prices still commanding nearly 40% of the cost of trucking, the adoption of efficiency technologies by all classes of trucks and fleets offers significant cost savings to the sector while reducing emissions. These technologies are relatively cheap to implement and widely available on the market today.

Trucking Efficiency provides detailed information on cost-effective efficiency technologies, including data from across a variety of fleets and best practices for adoption. This Confidence Report series from Trucking Efficiency aims to serve as a credible and independent source of information on fuel efficiency technologies and their applications.

In order to generate confidence on the performance claims of efficiency technologies, Trucking Efficiency, via these reports, gathers and centralizes the multitude of existing sources of data about the performance results of different technology options when employed in a variety of vehicle models and duty cycles, and makes all of that data openly accessible and more easily comparable. Furthermore, we assess the credibility of the available data, and provide an industry-standardized ranking of confidence in performance results, including ROI and efficiency gains.

www.truckingefficiency.org

Trucking Efficiency welcomes outside views and new partners in our efforts to help accelerate the uptake of profitable, emission-reducing trucking technologies.

Carbon War Room

Carbon War Room (CWR) was founded in 2009 as a global nonprofit by Sir Richard Branson and a group of like-minded entrepreneurs. It intervenes in markets to accelerate the adoption of business solutions that reduce carbon emissions at gigaton scale. In 2014, CWR merged with and now operates as part of Rocky Mountain Institute (RMI). RMI engages businesses, communities, institutions, and entrepreneurs to transform global energy use to create a clean, prosperous, and secure low-carbon future. RMI has offices in Basalt and Boulder, Colorado; New York City; Washington, D.C.; and Beijing.

www.carbonwarroom.com

NACFE

The North American Council for Freight Efficiency works to drive the development and adoption of efficiency-enhancing, environmentally beneficial, and cost-effective technologies, services, and methodologies in the North American freight industry by establishing and communicating credible and performance-based benefits. The Council is an effort of fleets, manufacturers, vehicle builders, and other government and non-governmental organizations coming together to improve North American goods movement.

www.nacfe.org

GET INVOLVED

Trucking Efficiency is an exciting opportunity for fleets, manufacturers, and other trucking industry stakeholders.

Learn more at www.truckingefficiency.org
Or contact: Mike Roeth at mroeth@carbonwarroom.com

TRUCKING EFFICIENCY CONFIDENCE REPORT PAGE 6

1. Introduction

This Confidence Report forms part of the continued work of Trucking Efficiency, a joint initiative from the North American Council for Freight Efficiency (NACFE) and Carbon War Room (CWR) highlighting the potential of fuel efficiency technologies and practices in over-the-road (OTR) goods movement. Prior Confidence Reports and initial findings on nearly 70 available technologies can be found at www.truckingefficiency.org.

The fuel costs faced by the tractor-trailer industry have been swiftly and steadily rising over the past decade, as shown in Figure 1. In 2014 diesel fuel costs were $0.58 per mile, costing the industry as much per annum as the costs of drivers' wages and benefits combined. Despite recent fuel cost decreases, to $0.40 per mile in 2015, all indications are that fuel price volatility will continue, forcing the industry to find solutions that increase its fuel efficiency in order to stay profitable. Additionally, the U.S. EPA and NHTSA have finalized the details for the Greenhouse Gas Phase 2 (GHGp2) regulations requiring tractor, trailer, and engine OEMs to offer and produce more fuel-efficient equipment.

Figure 1: U.S. Diesel Fuel Prices

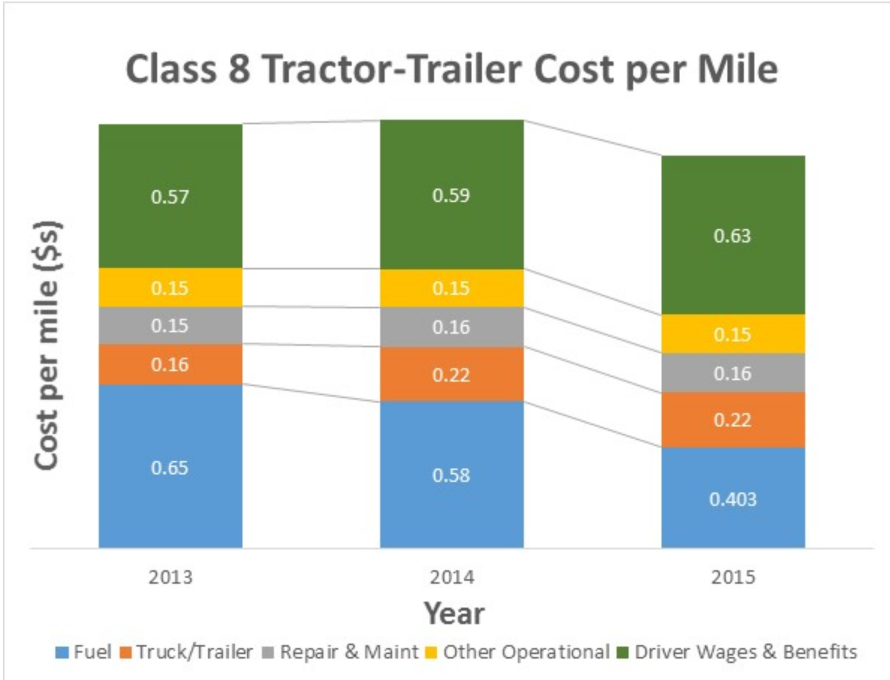


Figure 2: Trucking Operational Costs per Mile

Investment in proven technologies and practices that allow a truck or fleet to increase its fuel efficiency – meaning that it can do the same amount of business while spending less on fuel – is a hugely promising option for the industry considering this trend of fuel-price volatility.

To understand, and thereby better facilitate, the uptake of such technologies, NACFE conducts an annual review, the "Fleet Fuel Study," of the industry-wide adoption rates of about 70 fuel efficiency technologies currently available for Class 8 tractors and trailers. This work, available at http://www.truckingefficiency.org/annual-fleet-fuel-studies, has been called "the most comprehensive study of Class 8 fuel efficiency adoption ever conducted." (Truck News, 2012)

Figure 3: Fleet Study Participants

The overriding take-away from the most recent Fleet Fuel Study, completed in 2016, is that fleets are enjoying dramatic improvements in their fuel efficiency by adopting combinations of the various technologies surveyed — in 2015, the 17 fleets improved their fleet-wide fuel economy by 3%. The study found that the trucks put into service in 2015 were 16% better than the ones being replaced. The fleet-wide fuel economy improved to 7.06 mpg, while the U.S. average, for the approximately 1.7 million tractors in over-the-road goods movement, is 5.83 mpg. This finding was drawn from research into the use of fuel efficiency products and practices by 17 of the largest, most data-driven fleets (Figure 3). Those fleets represent both regional and long-haul tractors and trailers, in both dry goods and refrigerated cargo movement, and boast a combined inventory of 62,000 tractors and 217,000 trailers. The 2016 study reviewed 13 years of adoption decisions by these fleets, and described their specific experience with the nearly 70 technologies. The fleets shared the percentage of their new purchases of tractors and trailers that included any of the technologies. They also shared 13 years' worth of annual fuel economy data for the trucks in their fleet. With these two pieces of information, which will be updated every year, NACFE can generate insights into the following aspects of the industry:

- Adoption curves for each of the technologies indicate which technologies have the steepest adoption rates, which are being adopted steadily but slowly, and which are not being purchased at all. These curves also show how uniformly (or not) fleets are acting in their adoption patterns.
- Identification among the various fleets of the innovators, early-majority, late-majority, and even laggards, in new technology adoption.
- Comparison of technology adoption rates to overall fuel efficiency.

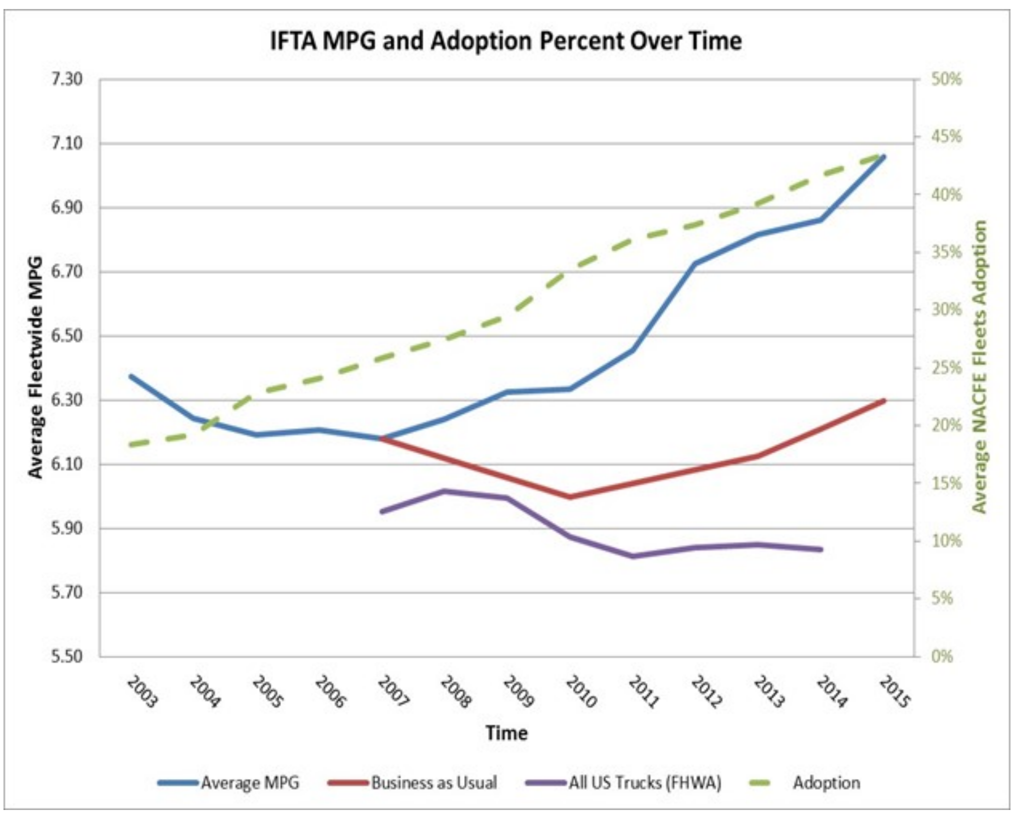


Figure 4: MPG per Truck – Blue line represents fleets surveyed by the Fleet Fuel Study

1.1. Trucking Efficiency's Confidence Reports

NACFE's Fleet Fuel Studies provide useful insights into adoption trends in the industry, as well as into the specific practices of different major fleets. NACFE hopes that this information alone could spur additional investment, particularly by fleets that may be lagging the overall industry when it comes to certain widely-adopted technologies. However, while conducting the studies, it became clear that some technologies are still only adopted by the most progressive or innovative fleets in spite of their strong potential for achieving cost-effective gains in fuel efficiency. To facilitate the wider industry's trust in and adoption of such technologies, NACFE and CWR formed Trucking Efficiency and began this series of reports, called "Confidence Reports," which take an in-depth look at those most-promising but least-adopted technologies one-by-one.

Confidence Reports provide a concise introduction to a promising category of fuel efficiency technologies, covering key details of their applications, benefits, and variables. The reports are produced via a data mining process that combs public information and collects otherwise-private information (which is shared with Trucking Efficiency for the purpose of the reports), in order to centralize an unparalleled range of testing data and case studies on a given technology set.

Variable engine accessories represent various such technologies, many of which are not yet available, but are emerging as fuel-saving strategy for long- and regional-haul fleets.

The goals of this Confidence Report are: (a) to give the industry a foundational understanding of variable engine accessories; (b) to understand how the Department of Energy SuperTruck teams approached variable engine accessories; (c) to provide an unbiased overview of the benefits and challenges of each technology; and (d) to help fleets rationalize their investment in variable engine accessories.

This NACFE Confidence Report on variable engine accessories is one in a series of NACFE-focused reports on configuring vehicles and operations to improve their fuel efficiency. Visit www.truckingefficiency.org to view this and other completed reports on tire pressure systems, 6x2 axles, idle reduction, electronically controlled transmissions, electronic engine parameters, low rolling resistance tires, lightweighting, downspeeding, preventive maintenance, trailer and tractor aerodynamic devices, low-viscosity lubricants, two-truck platooning and efficiency testing methods.

1.2. About this Report

This NACFE confidence report discusses and explores the role that variable engine accessories play in the overall fuel efficiency picture of current and future on-highway trucks. Through this study, we have identified several accessories that present opportunities for gains in efficiency although all are not currently implemented in most on-highway vehicles today. These accessories provide essential vehicle functions, so the potential efficiency gains would be accomplished through the implementation of new designs and technology to minimize the energy necessary to provide these essential functions.

Some confidence report readers such as college students, environmental specialists or others who are new to the industry may not have a strong technical background, so some brief explanation of the devices described in this report may be warranted. All of these devices are items that put a load on the engine, but do NOT help propel the vehicle down the road. They are therefore commonly referred to as 'parasitic loads' since they are 'robbing' power without helping to move the vehicle. This report includes:

- **Alternator:** This component uses the engine to create electrical power both to recharge batteries as well as powering electrical loads while the engine is running. Alternators are included in this report because some operate at higher efficiencies so as to place less load on the engine.
- **Water Pump:** This device circulates the coolant through the entire loop of cooling the engine and rejecting extra heat as the coolant passes through the radiator. New variable speed water pumps do not operate at full power all this time to reduce the load on the engine.
- **Cooling Fan:** The fan behind the radiator draws cool air across the radiator and into the engine compartment. While many cooling fans are simple on or off devices, there are also now fans that run at multiple speeds or even variable speeds to lower the engine load to only what is required at a given time.
- **Air Compressor:** Large commercial tractor-trailers have air brake systems, so they require compressed air. Historically the air compressor for the brakes turns all of the time and pumps air when necessary. New clutched air compressors eliminate robbing engine power when the air tanks are already at required pressure levels.
- **Air Dryer:** The air dryer removes moisture from the compressed air for the brakes. New 'smart' air dryers assist in optimizing when to run the air compressor and purge the moisture from air dryer system.
- **Power Steering Pump:** Power steering pumps typically run all the time to handle worst case needs of low speed vehicle turning and maneuvering. New systems take into account the fact that line haul tractors spend the vast majority of their operating hours going nearly straight down a highway when little steering effort is necessary.
- **Air Conditioning Compressor:** The AC compressor aides the movement of the refrigerant for the cab air conditioning system. Although it only operates as required, sleeper compartments require AC when the truck is parked. Rather than using an engine to run the compressor when the truck is parked future AC compressors may be electrically driven.
- **Electrically Driven Accessories:** While the above accessories are either gear or belt driven by the engine, future components may be removed from the engine entirely IF the electrical system can support their large energy requirements.

Far more detailed explanations of all of these devices are included in the body of the report.

The energy available in the fuel to power a typical Class 8 tractor produces positive work or output to the powertrain and waste in the form of heat and exhaust, an example of which is shown in Figure 5.

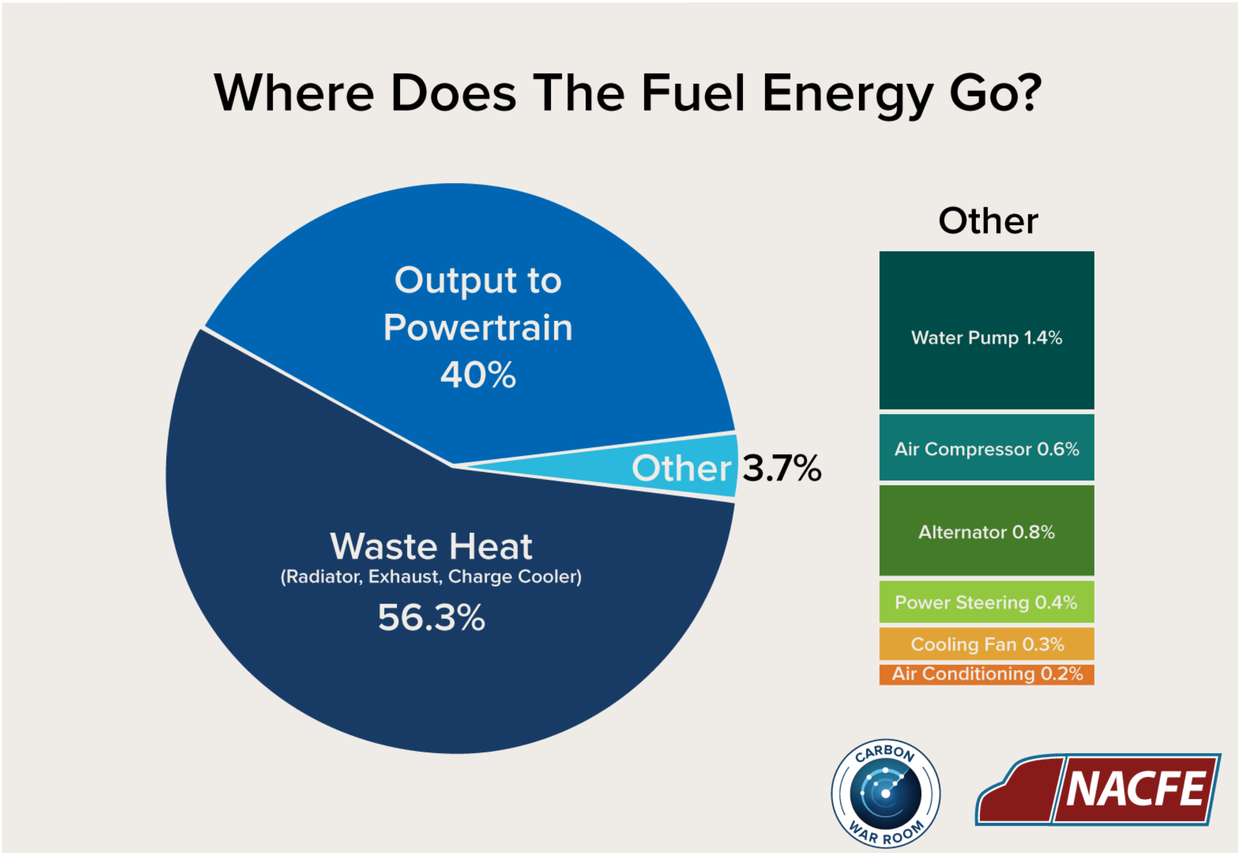


Figure 5: Average Fuel Consumption of Accessories

The accessories evaluated along with a typical estimated effect on fuel economy are listed below. These numbers can vary greatly depending on the duty cycle of the vehicle in question, so the numbers below in Figure 6 are estimates for a typical line-haul application. The contribution of these items goes up significantly in pickup and delivery and other applications.

Accessory System	Typical Range of % Fuel Consumed to Provide Function
Water Pump	1.1 – 1.8 %
Air Compressor	0.25 – 0.8
Cooling Fan	0.2 – 0.4
Power Steering Pump	0.3 – 0.6
Alternator	0.5 – 1.0
Air Conditioning Compressor	0.1 – 0.2
Not Considered: Oil Pump, Fuel Pump	

Figure 6: Typical Fuel Consumption Ranges for Accessories

Therefore, these accessories consume about 3-5% of the total fuel consumed by the engine in a typical line-haul application. In many other duty cycles like pickup and delivery, the percent of fuel used by the accessories is likely somewhat higher.

The opportunities for improving efficiency of the systems are many and involved. Most require the introduction of additional hardware and complexity to take advantage of the opportunity to save fuel. An example of this is the recent introduction by two engine makers of variable speed electronically controlled water pumps as part of their newest engine specifications.

Each of these accessory and potential opportunities are for improving the efficiency of the system. Many improvements will require the implementation of additional technologies on the vehicle to realize the potential savings. In some extreme cases, a larger change in vehicle systems would be required before the savings could be realized. For example, it could be most efficient to provide an electrically driven power steering system for trucks in the future to avoid continuous operation of the power steering pump. However, the vehicle would need a much higher voltage alternator and electrical storage system (think hybrid electric) to provide this functionality economically.

It should be noted that some of the fuel savings being discussed in this Confidence Report could be realized by significantly reducing the time that the vehicle engine spends idling for long periods of time. Details of this subject have been adequately treated in the Idle Reduction Confidence Report that was issued in 2014, so this is considered out of scope for this Confidence Report.

As can be seen from the discussion thus far, the fuel savings offered by any one of the new technologies related to engine accessories is likely to be modest. However, it is important to keep in mind that, like any new fuel savings opportunity, payback for the investment depends heavily on the price of diesel fuel. What may not be attractive with $2/gallon fuel may be very attractive when the price jumps to $4/gallon or more. As everyone knows, it is very hard to predict what diesel fuel prices will average throughout the life of the vehicle.

2. Duty Cycle Explained and its effect on Engine Accessories

Part of any discussion on heavy duty truck fuel economy, especially one that involves engine-driven accessories, is understanding a concept known as 'duty cycle'. Duty cycle is a broad term that is used to describe how a device is used within an overall mission.

First, we might describe the duty cycle of the vehicle. This is often described as either highway or line-haul operation, pickup and delivery, city driving, rural, etc. Each of these use profiles will put different demands on the vehicle powertrain and therefore result in different fuel economy, performance and emissions. For example, vehicle emission cycles are designed to simulate a variety of these different conditions in a short test cycle to aid manufacturers in development and testing. In Figure 7 below, the World Harmonized Vehicle Cycle (WHVC) shows the way a vehicle is operated to evaluate emissions output. As you can see, it emulates a portion of urban, rural and highway conditions.

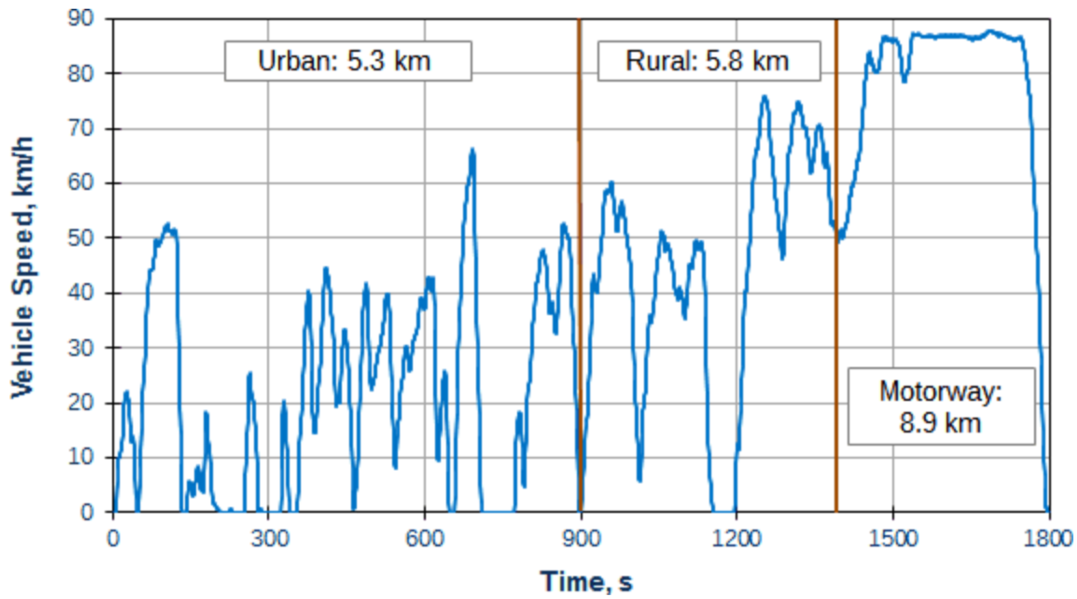


Figure 7: World Harmonized Vehicle Emissions Cycle

Of course, there are other key factors like load, temperature, terrain, winds, etc. that also figure in to that equation when the vehicle is operated in the real world. If you take this cycle and focus on the engine's operation, it will have a profile of how much time it spends in various segments of its operating envelope. The engine manufacturer will look at this data, as is shown in the example below, and through analysis determine the best way to optimize the performance, emissions and fuel economy of the engine for a profile of operation.

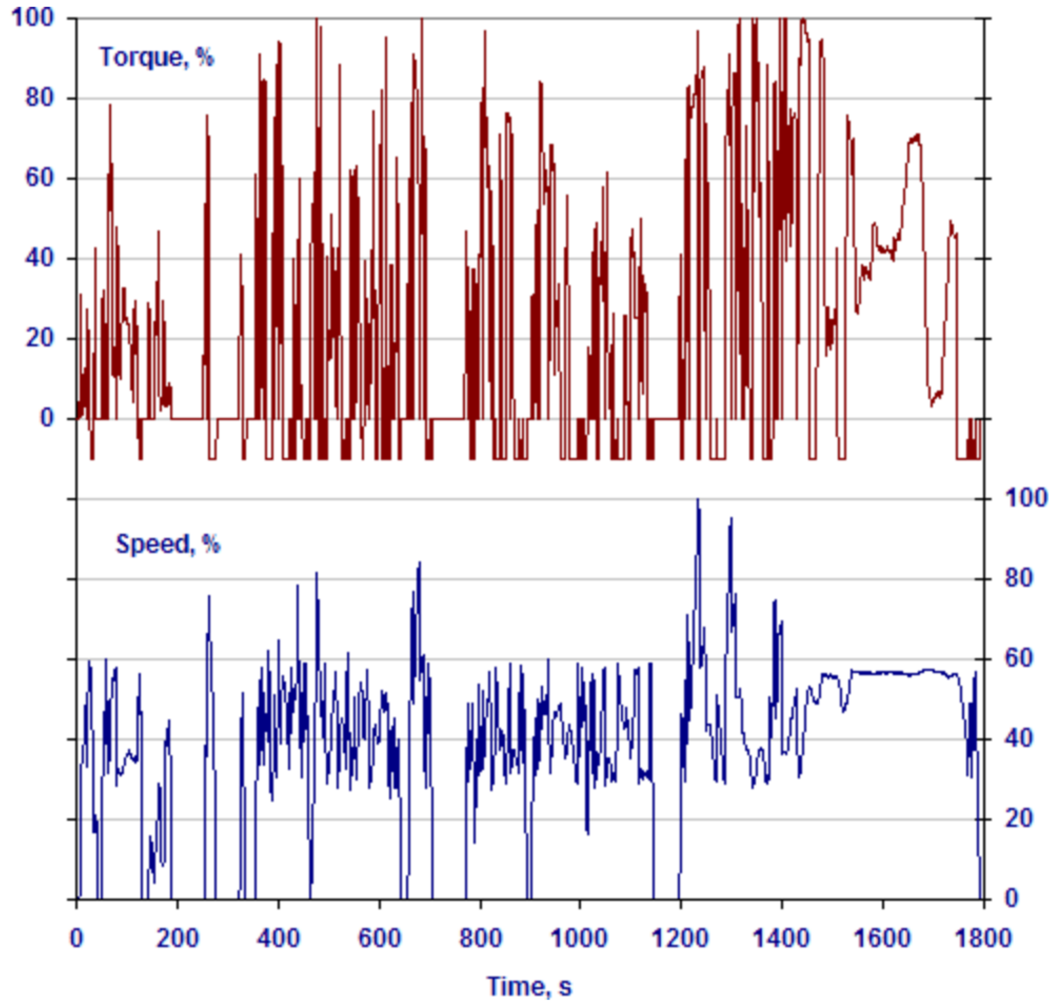


Figure 8: World Harmonized Transient Test Cell Cycle

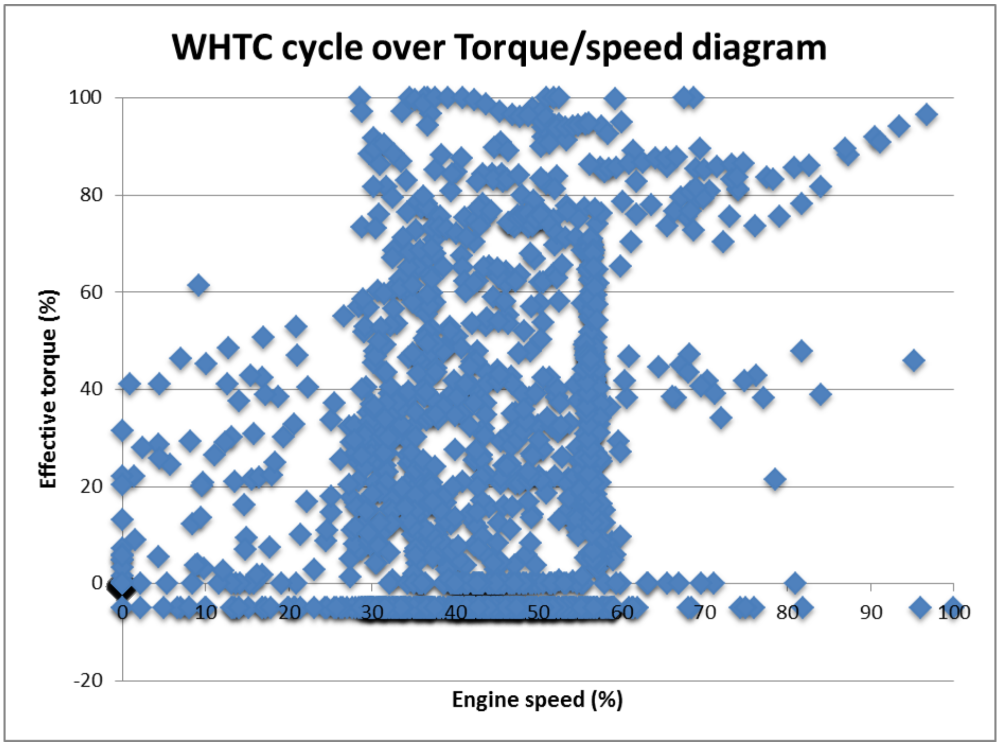


Figure 9: World Harmonized Test Cycle – Engine Speed vs. Torque

The cycle shown above represents an engine dynamometer version of the vehicle cycle shown in Figure 8 called the World Harmonized Transient Cycle. This cycle is used to evaluate engine emissions and performance across the modes of operation listed, but the key data is portrayed as torque and engine speed vs. time. Another view of this same cycle is shown below in Figure 9, where the engine data is plotted in engine speed vs. torque. These data can then be used to optimize the engine for its various operating points.

Vehicle and engine manufacturers typically use a small number of key routes or profiles that represent the way that their products are operated in the real world to evaluate performance and fuel economy. In this way, it becomes easier to compare the effects of various changes to the system on an 'apples to apples' basis.

Duty cycle for accessory systems adds yet another layer of complexity to this. Let's use the air compressor system as an example to discuss accessory component duty cycle. The amount of compressed air a vehicle consumes depends heavily on the number of brake actuations and the number of air dryer purge cycles that the vehicle experiences during a given duty cycle. Of course, leaks can also add to this air consumption profile. Therefore, a city driving cycle with many stops and starts will consume much more air than an on-highway route that is mostly interstate highway and has relatively few brake actuations.

The air compressor is an on-off device – that is, it is either pumping up the air tanks or it is not. So, duty cycle for an air compressor describes what percentage of time the compressor is activated during the overall vehicle drive cycle that is being measured. The amount of fuel consumed by a traditional air compressor can then be correlated to the amount of on and off time and the horsepower it takes to drive that device in each respective mode.

The other accessory devices can be evaluated in a similar manner. It is important to keep in mind that the fuel economy benefits of new technology can vary quite a bit depending on duty cycle factors. A specific improvement may have a big benefit for line haul trucks and not so much for city pickup and delivery. It is also possible for the effects to be quite the opposite. Let's pursue the previously mentioned air compressor above as an example.

If the engine comes with a clutched air compressor, this may be a bigger benefit to the line haul vehicle because the engine avoids driving the air compressor in the 'unloaded' mode for a very large percentage of the engine operation since typical air compressor duty cycles for a line haul truck are in the 10 - 15% range. The clutch mechanism offers no savings if the air compressor is pumping. In city driving, the air compressor duty cycle might be 40% or higher, so the savings for the clutch mechanism would be much less. Of course, there are other ways to make the air compressor more efficient besides using a clutch, so this discussion would also need to cover other technology improvements.

3. Learning from the DOE SuperTruck I Program

From 2009 to 2015, the Department of Energy sponsored a program with industry manufacturers to demonstrate at least a 50% improvement in freight efficiency. The project leads were Daimler, Cummins/Peterbilt, Volvo Trucks USA and Navistar (See Figure 10). Each of the four teams created demonstration vehicles with a variety of new technologies on them to highlight the feasibility of meeting this aggressive goal.

Figure 10: SuperTruck Photos

As part of researching this subject, The NACFE study team interviewed each of the SuperTruck teams to understand their analysis and choices relative to variable engine accessories. The team would like to express its sincere appreciation for the resource committed by these companies for this work.

The table below (Figure 11) is a summary of the choices related to accessories made by each of the SuperTruck teams. Input from these teams is included in the detailed descriptions of the various variable engine accessory technologies later in this report. It is important to note that most of the fuel economy and freight efficiency gains were achieved through improvements in aerodynamics, weight reduction, rolling resistance reduction and powertrain improvements. The following link is a DOE report on the success of the SuperTruck program:

https://energy.gov/sites/prod/files/2016/06/f33/EERE_SuperTruck_FS_R121%20FINAL.pdf

Note that all four teams chose to implement a form of waste heat recovery as part of their technology choices. A discussion of waste heat recovery is shared later in this Confidence Report, but it is instructive to note that the fuel economy gains for this technology are far higher than those available through improvements in accessory systems alone.

		Cummins Peterbilt	Freightliner	Volvo	Navistar
Core SuperTruck Systems	Waste Heat Recovery	Refrigerant working fluid, mechanically coupled to powertrain Captures heat from EGR/Exhaust	Drives electric generator	Mechanically coupled to powertrain Captures heat from EGR/Exhaust. Ethanol based working fluid.	Ethanol based working fluid Exhaust post aftertreatment only Drives electric generator
	Hybrid	No	Yes - Downsize from 15L to 11L engine 120 kw motor, 360V, 2.4 kw-hr LiIon battery pack	Downsize engine - 13L to 11L Dual alternator system captures kinetic energy and stores in battery - not used for propulsion 15 KwH LiIon battery pack for hoteling	Tried but abandoned Implemented 48V motor/generator
Accessories	Alternator	Traditional system - upsized to 240 A 12.1 kW-hr LiIon battery pack for hoteling	Electric starter/alternator - motorcycle sized 12V battery	Dual 24V alternator system Predictive energy management Super cap for starting	48V 15 kw motor/generator 48V Li Ion battery pack Start/Stop Trailer has Solar Panels WHR drives 48V generator for power/storage
	Cooling Fan	Little need: WHR Reconfiguration of the heat exchanger arrangement at the front of the vehicle	Variable speed - hydraulic drive w/PS pump system	Variable speed viscous drive cooling fan system - very seldom used	3 speed direct drive Supplemental electric fans in front of cooling package - 48V Electronic controlled thermostat Higher Top Tank Temperature
	Power Steering Pump	Traditional system	Accusteer closed center steering gear+ 1L accumulator	Pump resized to work with downspeeded/downsized engine package - dual displacement Conventional system	Closed Center steering - Electro-mechanical w/ accumulator Electronic flow metering
	Water Pump	Reduced capacity due to WHR system configuration	Variable speed - viscous drive current production	Improved cooling circuit with fully variable speed pump	Variable speed - viscous drive
	Brake Air Compressor	Traditional system	Clutched, intelligent, electronically controlled	Clutched, intelligent, electronically controlled	Clutched, intelligent, electronically controlled
	AC Compressor(s)				
	Cab	Traditional Engine Driven	Electric compressor plus electric fan on condenser	24V Electric HVAC performs all functions - moving and hotel.	48V electric - single unit for both functions Switchable cab/sleeper delivery 8 hr hotel load capable w/battery pack
	Sleeper	Electrified (Battery HVAC) - 12.2 KwH battery pack - 10 hour hotel capability	Sleeper HVAC driven by hybrid battery - only abt 1.5 hours hotel capability	Sleeper HVAC provided by battery pack - 14 hrs capable	See above
		Cummins Peterbilt	Freightliner	Volvo	Navistar

Figure 11: SuperTruck Team Choices on Accessories

4. Industry Trends Related to Engine Accessories

There are several near-term industry trends related to fuel economy/freight efficiency that influence the subject of variable engine-driven accessories.

The first of these is the large number of products being implemented to lower aerodynamic drag. To the extent that these key improvements reduce the average horsepower that it takes to propel the vehicle down the road, better aero aids will ultimately change the amount of heat that needs to be rejected through the cooling system.

- Therefore, the effort of the water pump, cooling fan and radiator to manage coolant temperatures generally gets easier, if the components in the system remain as they are (e.g. radiator frontal area, fan size, drive ratio, shrouding, etc.). Thinking that these factors will stay the same long term is probably a poor assumption, but for the time being, generally lower average fuel consumption probably will drive lower fan engagement times.
- In addition, this could also mean that the value of a variable speed water pump might go up slightly.
- On the other hand, the demands for electrical service, compressed air, power steering, air conditioning, etc. are unlikely to change. Therefore, their percent of the overall fuel consumed will go up compared to the total amount of fuel used, even though those functions will not likely consume more energy.

The second major trend related to improving fuel economy is downspeeding. In short, downspeeding slows the engine down to a lower speed, or RPM, during normal cruising on the highway. For many of these accessories, the amount of horsepower it takes to drive them is closely related to engine speed.

- Therefore, slower speeds mean less horsepower consumed by the devices. These include the cooling fan, power steering pump, water pump, the air compressor when unloaded and the friction of the alternator drive mechanism.
- The improvement in the fuel consumption of accessories due to downspeeding is likely to be too small to measure, but there is a very minor benefit.

In summary, these trends lower the fuel consumption of these accessories and therefore may lengthen the payback of many of these variable engine accessory solutions.

5. Increasing Vehicle System Voltage

There has been some recent discussions and studies completed related to the vehicle system voltage that relate to the subject of variable engine-driven accessories. Of course, the standard system voltage for vehicles in the United States is 12V. However, in most of the rest of the world, commercial vehicles are designed to operate with 24V systems. In addition, new technologies that require (or at least could greatly benefit from) a higher system voltage are emerging. These new technologies include new higher pressure fuel systems, electrically assisted steering, electrical APUs, more sophisticated engine management devices to improve fuel economy, etc. Basically, any place where high consumption of electrical power is required can benefit from a higher system operating voltage assuming the components and controls are designed to work with that new voltage. The reason is simple – higher voltage means lower current required to reach the same power levels. Higher voltage allows for smaller wiring and smaller, more efficient electrical actuators and motors.

Of course, the higher system voltage also raises many questions relative to connector specification, technician procedures, tools, and perhaps most of all, compatibility with other lower voltage systems and components (e.g. trailers). One other key factor in transitioning to a higher system voltage is that the need for electrical energy storage on the vehicle would go up. Therefore, this would likely increase the number of batteries required increasing the space needed and weight for those systems. These subjects are discussed in much more detail in the TMC Future Truck Information Report – 2015-3; Exploring the Potential for 48-Volt Commercial Vehicle Electrical Systems.

For the purposes of this Confidence Report, a new higher system voltage would be an enabling technology for several accessory systems. These could include electrically driven or assisted power steering pumps, electrically driven air conditioning compressors, different strategies relative to alternators, and perhaps even electrically driven cooling pumps. Powering accessories electrically allows for only using those accessories when necessary as opposed to driving them all the time via the engine gear train or a drive belt. Of course, driving these accessories electrically would necessitate adding battery capacity to the vehicle which would add both weight and wiring complexity.

One thing to keep in mind relative to powering engine-driven accessories electrically is that the gains from driving them electrically must be much higher than the energy used in the mechanical drive mechanism. Typically, driving a pump or compressor directly through a gear or drive belt is 95% plus efficient from an energy standpoint. To drive an alternator converting mechanical energy to electrical energy and then using the electrical energy to drive a motor would be less than 50% efficient. Therefore, the savings must be large with an electrically driven system vs. a mechanically driven one for it to make sense from an overall energy consumption standpoint.

When it comes to hydraulic systems like the power steering pump, a similar situation applies. In the case of a power steering pump, it is pumping all the time but at relatively low power consumption levels except when steering effort is demanded. To drive the power steering pump intermittently (i.e. either electrically or using a clutch) to shut the pump off for periods of time to avoid that power consumption requires the implementation of a pressure accumulator to store energy for when it is needed by the steering gear. It also requires a significant redesign of the power steering gear system hydraulics. To make this practical from a fuel consumption standpoint, the savings from driving the pump intermittently would have to be higher than the added cost in components, weight and complexity that accompany a system of this type.

6. Findings

After discussions with component and engine manufacturers, tractor builders and end user fleets, the study team arrived at the following key conclusions.

6.1. Fuel Economy Gains Are Modest

The fuel economy gains that can be achieved with variable engine-driven accessories for common on-highway vehicles are relatively modest.

- Compared to the fuel economy gains of improved aerodynamics, weight reduction, rolling resistance, vehicle powertrain integration, downspeeding, 'smart' terrain based cruise control, and minimizing extended idle times, the opportunities in the engine-driven accessories area are generally smaller.

Current fuel prices make justifying added cost for engine-driven accessories hardware that improves fuel economy difficult.

There are some technologies available today that should be evaluated for the fleet's next purchase to see if they offer an attractive return on investment (ROI) and are available on the equipment specification that is chosen:

- 2 speed/ modulating cooling fans
- Clutched air compressors
- Smart air dryer
- Cab heaters and battery operated sleeper HVAC for hoteling needs
- Variable speed water pumps

The current and upcoming Greenhouse Gas regulations are likely to push at least some of the technology choices related to engine-driven accessories from optional to standard equipment on new truck orders.

6.2. Concerns for Subsystem Reliability.

In numerous discussions with fleet leaders, they have always strongly emphasized the point that any change in technology to improve fuel economy must be economically justified. Therefore, the added initial cost plus any projected maintenance costs associated with that new technology and any other monetized benefits and consequences, should have an acceptable Return on Investment (ROI). In addition, the changes must not come with high potential reliability risks. Vehicle downtime is just not acceptable in today's freight supply chain.

It is no secret that several technology changes of the past 15 years have added significantly to the cost of maintaining fleet vehicles. Fleet managers are, in general, risk averse when it comes to these types of improvements. However, if the technology change proposed is relatively large (e.g. waste heat recovery), then fleet managers would like the chance to test this technology in small quantities beforehand to gain experience before rolling it out to their entire fleet.

High levels of downtime were experienced throughout the last decade during the implementation of 2002 and 2007 emissions regulations. The industry must deliver high levels of uptime through manufacturer and field validation.

6.3. Payback is Insufficient to Entice High Levels of Adoption

Driving accessories through means other than mechanically could offer benefits, but come with a higher cost. It is important to note that mechanically driving accessories via either a belt or gear drive is highly efficient from an energy standpoint. For an alternate means of driving the accessories to be cost effective (e.g. electrical or hydraulic), the savings must be quite high to overcome the losses associated with storing the energy in some way and then using it later when it is needed.

Here's an example:

- Generating electrical energy from mechanical energy through the alternator is only about 60% efficient. Storing that energy in a battery is approximately 85% efficient. Using the electrical energy to drive a motor is perhaps 80% efficient at best. Therefore, to deliver 5 kW to the power steering pump motor or other accessory, you would have to generate about 12 kW at the alternator to start the process.
- However, to generate the same 5 kW by driving the pump mechanically would only require 5.5 kW at the drive pulley.
- So, unless there is more than a 50% gain in efficiency of the overall system, the electrical drive does not make sense from a fuel economy standpoint. Of course, you would also need to consider that the electrical system adds a great deal of hardware and complexity to the system. Unless this hardware was already on the vehicle for another reason, the costs would likely outweigh the benefits.
- It is important to note that this might actually be possible through the use of a more sophisticated power steering system, but this would add additional weight and complexity to the hydraulics by adding a different valve system and a reservoir to store power steering fluid under pressure for use when needed.

There are many new technologies that will be available in the future that will be worth a look when the development process is completed. These will be outlined in the individual sections for each of the engine-driven accessories.

6.4. Future Enabling Technologies Would Likely Improve ROI

A couple of technologies on the horizon have the potential to drive significant changes to the engine-driven accessories picture:

- Waste heat recovery
- Higher system voltages and additional electrical storage for the vehicle.

Waste heat recovery is a system that may be associated with meeting the more stringent GHG regulations that will become effective over the next decade or so. This technology involves adding additional hardware to the vehicle to extract more mechanical energy from the heat generated by combustion than can be extracted from the power cylinder. It is technically feasible, and has been demonstrated by the various SuperTruck teams, to get additional power from the exhaust energy in the EGR cooler and the exhaust after it exits the aftertreatment system. Implementing a waste heat recovery system most likely requires a complete redesign of the vehicle's heat exchanger systems to be most effective. Therefore, the cooling fan, water pump and perhaps the cab air conditioning system could be affected directly.

Higher system voltage with additional storage offers the chance to implement additional improvements related to the accessories. In short, higher voltage allows the use of smaller electric motors and reduced size of wiring to get the same power output. Additional electrical storage on the vehicle (i.e batteries) will allow the electrical system to deal with intermittent high current loads without depending on the alternator to always generate that current. It is possible that some accessories will be driven electrically when this can be done more efficiently than the current mechanical drive systems. Candidates for this technology would include:

- Higher voltage alternators and starters
- Air conditioning compressors
- Power steering systems
- Cooling fans (supplemental to existing belt driven fans)
- Air compressors

In this area, there are generally three alternatives that have been discussed:

- Convert North American vehicles to 24V
- Convert North American vehicles to 48V
- Convert vehicles to diesel – electric hybrid vehicles with system voltage at 300V plus

This subject has been explored extensively in the TMC Information Report 2015-3 - Exploring the Potential for 48-Volt Commercial Vehicle Electrical Systems. You can access this report at the following link:
http://www.trucking.org/ATA%20Docs/About/Organization/TMC/Documents/Position%20Papers/Future%20Truck%20Information%20Reports/TMC_IR_2015_3.pdf

7. Greenhouse Gas 2 Regulations

In August 2016, the US EPA and NHTSA released new requirements for commercial truck fuel economy that will need to be met in the future, known as Greenhous Gas Phase 2 (GHGp2). These new regulations will require engine, truck and trailer manufacturers to develop and implement technologies that will significantly reduce the overall amount of fuel consumed in the US. Of course, this reduction in fuel consumption will correspondingly reduce the amount of CO2 that is released into the atmosphere because of burning that fuel.

The regulations have specific requirements that aim to reduce the overall fuel consumption of heavy-duty combination vehicles by 25% or more by 2027. The regulation is quite complex, but there are separate requirements that must be met by engine manufacturers, truck manufacturers and trailer manufacturers. Each manufacturer will need to implement a combination of technology changes to comply with the requirements. For an idea of the complexity, the regulation itself cover 1,690 pages and there are an additional 3000+ pages of documentation to clarify and explain details of reasoning and justification.

EPA determines compliance to the GHGp2 requirements by asking the manufacturers to input relevant information into a computer simulation model called the Greenhouse Gas Emissions Model – GEM for short. The model calculates a score for each vehicle combination and the vehicle manufacturer must meet certain standards for their total production output – similar in concept to the CAFE requirements that automobile manufacturers must meet.

7.1. GHGp2 Regulations and Engine Accessories

The engine-driven accessories outlined in this Confidence Report are addressed in the GHGp2 regulations in either the sections related to the engines or the combination tractors. Coolant pumps and the air compressor (if it is not pumping air) are addressed in the engine part of the regulation as they are traditionally driven by the engine as part of the engine certification testing. The remainder of the accessories studied in this report are typically added on after engine certification testing and therefore fall into the combination tractor vehicle requirements.

Improvements in the coolant pump and air compressor drive systems will be taken into account as the engine manufacturers test their engines and verify compliance with the GHGp2 regulations. This input goes directly into the GEM models that are used to determine the 'score' of the overall combination vehicle. Some improvements like variable speed water pumps and clutched air compressors are already on the market.

The remainder of the accessories are a more complicated story. The GEM model does not consider the variety of possible fuel economy improvements that can be made in each of the accessory areas. As a result, if a vehicle manufacturer wants to claim fuel savings for a new system (e.g. an improved power steering pump) then the manufacturer must apply for an 'off cycle credit' or supply a significant amount of test data supporting the improvement. Given that improvements on the individual accessory systems are relatively modest, vehicle manufacturers are likely to focus on other technologies that have a larger impact and require less documentation for approval.

Therefore, it is likely that improvements that will be seen in the accessories area in the shortest amount of time will be ones that are highly cost effective from a payback standpoint and do not carry a significant reliability risk. Examples of this might include high efficiency alternators and improvements in air compressor/air dryer management that reduce the power consumption of the air system. Other improvements in each of the accessory systems that are already available or might be available soon are noted in the individual accessory topics in Section 9.

8. Availability of Variable Engine-Driven Accessories

There are a number of these technologies available today. Of course, for these to be attractive to the fleet, they must provide an acceptable payback for the duty cycles the fleet normally runs. The study team after discussions with the manufacturers have developed Figure 12 for the current availability of these technologies at the various truck builders.

	Peterbilt	Kenworth	Volvo	Mack	International	Freightliner	Western Star
Clutched Air Compressor	N/A	N/A	Optional on D11 & D13	Optional on D11 & D13	Optional on N13	N/A	N/A
Smart Air Dryer/Air Compressor	N/A	N/A	Optional	Optional	N/A	N/A	N/A
Variable Speed Water Pump	N/A	N/A	N/A	N/A	N/A	Standard on DD13 and DD15	Standard on DD13 and DD16
Two Speed Water Pump	Standard on MX	Standard on MX	Standard on D11 & D13	Standard on D11 & D13	N/A	N/A	N/A
Standard Efficiency Alternator	Standard	Standard	Standard	Standard	Standard	Standard	Standard
High Efficiency Alternator	N/A	N/A	Optional	Optional	Optional	Optional	Optional
2 speed cooling fan	Optional	Optional	Optional	Optional	Optional	Optional	Optional
Modulating cooling fan	Optional on MX	Optional on MX	Optional	Optional	N/A	N/A	N/A
Dual Displacement power steering pump	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Figure 12: OEM Availability Matrix

9. Engine-Driven Accessories Details

This section details the various engine-driven accessory technologies either available today or in development for North American Class 8 tractors. Each section will describe the technology and its function as well as its benefits and consequences.

9.1. Cooling System / Water Pumps

In its simplest form, the vehicle cooling system consists of an engine-driven water pump that moves coolant through a series of passages to keep the engine components cool from the extreme heat that is generated through combustion. This heat is then rejected to the atmosphere through the vehicle radiator/cooling fan system. Coolant temperature is generally maintained within a reasonable range by a mechanical thermostat that controls water flow through the system. Allowing components to exceed their temperature limits will result in either shorter life or, in some cases, immediate failure.

Conveniently, this warm coolant also provides heat to the vehicle passenger compartment to keep the occupants comfortable when the temperatures are cool outside. As engines and emission systems have become more complex over the years, it has become necessary to add a number of additional devices to the cooling system to maintain emissions (e.g. EGR coolers).

The diagram (Figure 13) below shows the flow through a typical cooling system (not shown – EGR cooler):

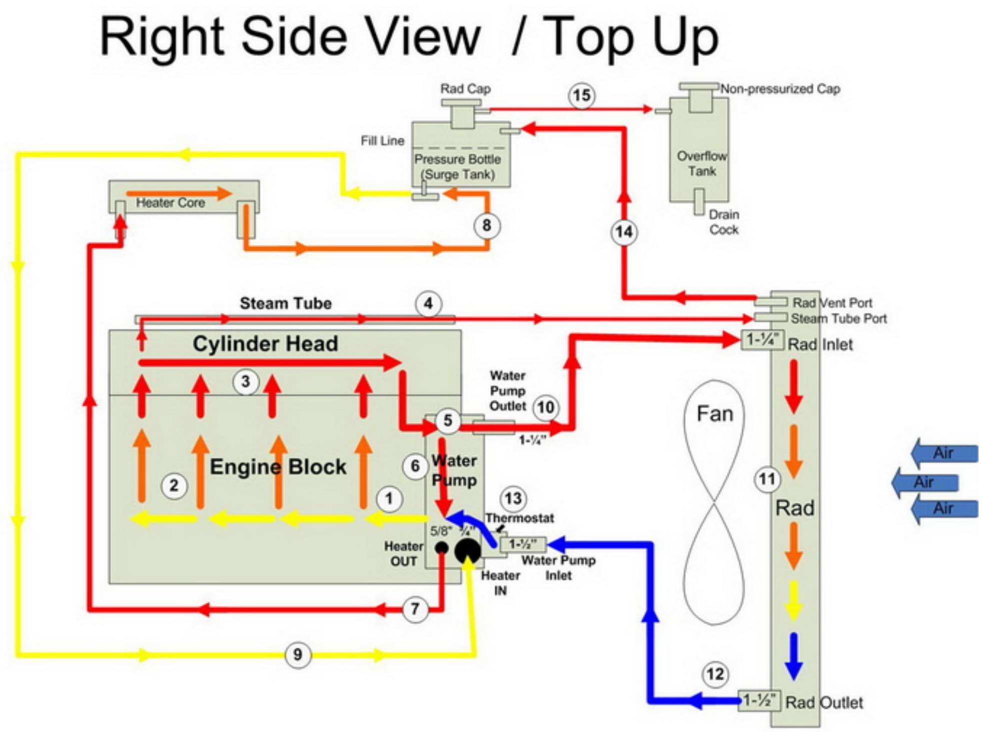


Figure 13: Vehicle Cooling System Schematic

Water pumps come in all shapes and sizes, but all have the same fundamental job – to pump coolant through the engine components and radiator system. Illustrations of the variety are attached below. (See Figures 14 and 15)

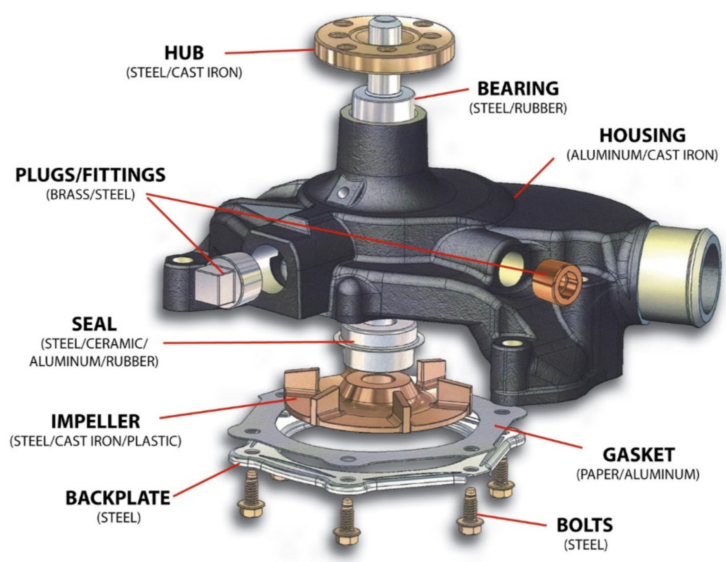


Figure 14: Water Pump

Figure 15: Example Water Pumps

The water pump and water flow rate are sized to manage the heat rejection from the various sources at the limits of engine operation and ambient conditions. Sources of heat rejection include:

- Rejected heat from combustion from the power cylinder and cylinder head to the coolant
- Rejected exhaust heat from EGR cooler to the coolant
- Rejected heat from the oil to the coolant
- Other devices that require temperature management – DEF tanks, aftertreatment injectors, etc.
- Most heat is then rejected through the radiator to the atmosphere and the cooling fan is used when necessary. Occasionally some of that heat is also used to warm the cabin of the vehicle.

Components are sized to handle the worst conditions expected to be encountered by the vehicle. Those worst conditions usually include a combination of the following:

- Engine running at maximum power and near torque peak speed
- Engine running very high EGR rates to manage NOx/in cylinder peak temperatures
- Oil temperature running near its limit
- Ambient temperature at very high limits (think 100 F or above)
- Vehicle speed is very low so the ram air effect on the radiator is minimized - for instance while climbing a steep grade.
- Air density is low (high altitude)

At all other times, the water pump/cooling system is oversized for the application. Therefore, in theory, the water pump could run at lower speeds when the demands for heat rejection are less. Traditionally, water pumps have been belt or gear driven and run at a fixed ratio to engine speed, so speed variation was not possible with traditional designs. The water pump normally consumes about 1.1 to 1.8% of total fuel consumed by the engine. Reduced water pump speed will result in lower coolant flow rates and pressures through the system, but if controlled properly, sufficient flow velocity would be available to maintain adequate heat rejection efficiency. The slower speed will result in less horsepower needed to drive the water pump and therefore slightly improved fuel economy.

The typical power consumption of a water pump is shown below. (See Figure 16) Therefore, in normal operation, a water pump on a heavy-duty engine requires between 3 and 6 horsepower depending on engine speed. If hardware and controls are in place, about one-third of this power requirement could be avoided and still maintain proper cooling of all the engine components. From a fuel economy standpoint, this would be in the range of .3 to .7% - a number that would be difficult to measure in back-to-back fuel economy tests.

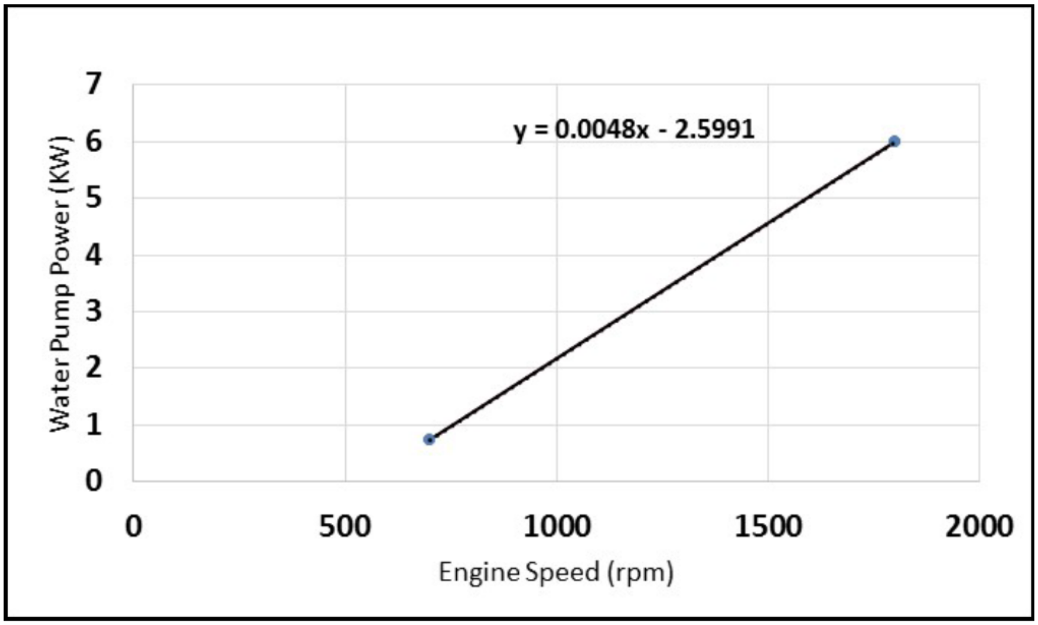
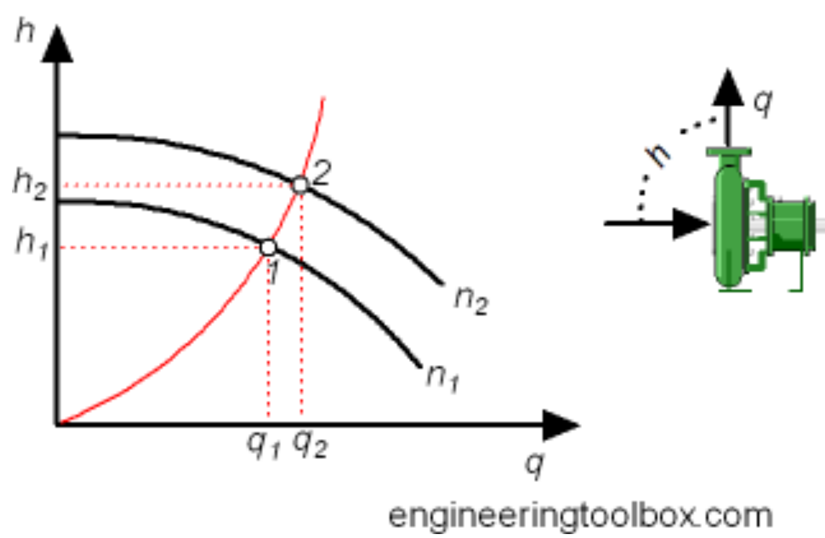


Figure 16: Water Pump Power vs. Engine Speed



h=pressure, n=speed, q=flow, red line = system curve of flow vs. pressure

Figure 17: Water pump flow and pressure vs. pump speed

The above chart (Figure 17) shows the effect of running the water pump at a slower speed – both flow and pressure are reduced in a predictable relationship. Therefore, if pump speed can be managed through controls without compromising the cooling necessary, the overall horsepower requirement of driving the water pump can be reduced accordingly.

Three engine manufacturers have recently introduced variable speed water pumps to their product line. The manufacturers are not quoting fuel economy savings from these devices at this point. However, these components are part of their array of changes to meet the GHGp2 requirements. Though we have no confirmation, it is probably safe to say that the other manufacturers will be following suit in the near future.

From a confidence standpoint, when these variable speed water pumps are introduced by engine manufacturers, they will exhibit very good reliability and will produce the results anticipated. Engine manufacturers are unlikely to take much risk on a component that is so critical to the reliability and durability of their products. However, the increased cost of the variable speed water pump and its controls will likely increase maintenance costs when a failure occurs. The payback for this feature from a fuel consumption standpoint has been estimated to be about 2.5 years assuming $2.50/gal fuel, but we have no pricing information for this option at this point.

Benefits	Challenges
• Reduced power/fuel consumption for most cooling situations	• Increased cost • Slight increase in weight and packaging size • Additional maintenance items

9.2. Air Compressors

Today all Class 8 vehicles and most Class 6-7 vehicles have an engine-driven air compressor that provides pressurized air for use by the brake system as well as other devices on the truck. Figure 18 below shows a schematic diagram of the overall air supply system for the vehicle. The compressors are usually directly mounted to the engine and are gear driven. There are both single and twin cylinder compressors available depending on the engine and OEM's designs and air demand requirements.

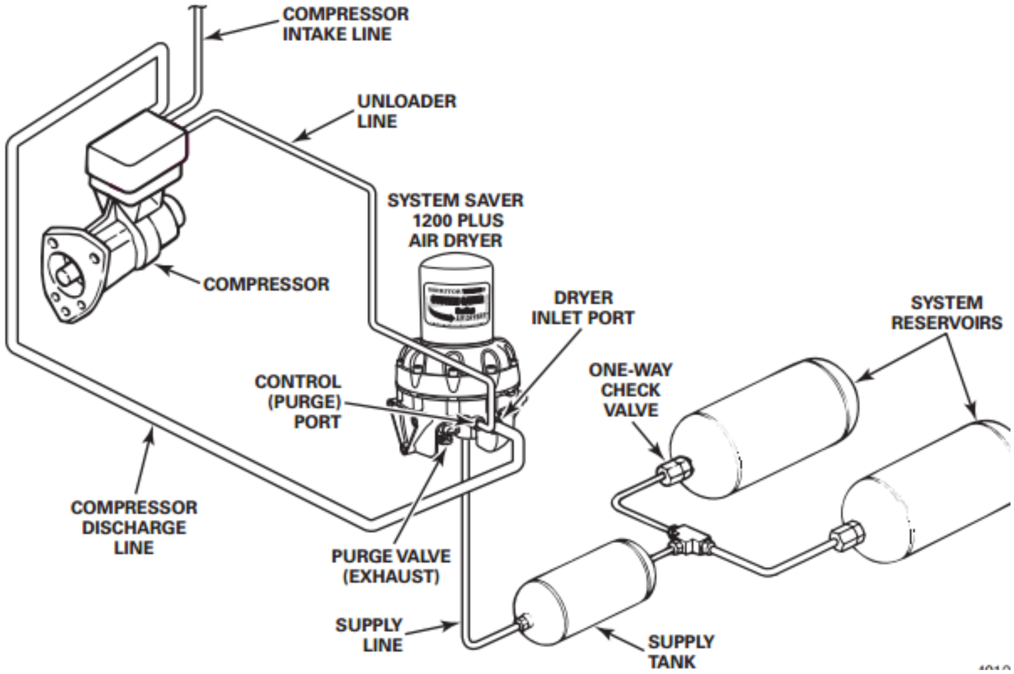


Figure 18: Compressed Air System Schematic

The air pressure is monitored and controlled typically by a governor valve which maintains the pressure between two set limits. The upper pressure is normally termed the ‘cut-out’ pressure and the lower pressure limit is called the “cut-in” pressure. They are typically set at 130 psi for cut-out and 110 psi for cut-in. The ratio of time at cut-out to cut-in is called the duty cycle and this can vary between 10-30% depending on the type of operation and the amount of air the system consumes.

When the compressor is charging the air system (on-load), the amount of power consumed is a function of air system pressure and the engine rpm. This typically equates to 2 - 3 Kw (2.5 to 4 hp) at 1200 rpm. When the air system has reached the desired “cut-out” pressure the air governor provides a signal to the compressor, which allows the air compressor to pump against low pressure, however because the compressor is still rotating there are frictional losses which have a parasitic power consumption of 0.3-0.7 Kw (0.4 to 0.9 hp) at 1200 rpm.

While the design of air compressors has remained fundamentally the same for many years, with the advancement in computer aid design and flow simulation together with new materials, big improvements are taking place to make the compressors breathe more efficiently and therefore consume less power during both on- and off-load phases.

9.2.1. New Developments – Clutched Air Compressors

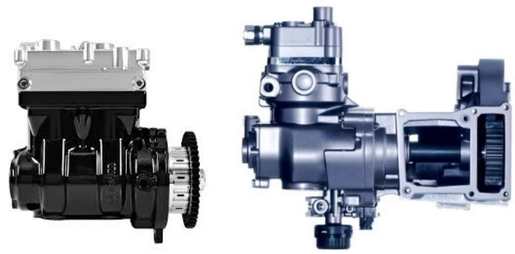


Figure 19: Examples of Clutched Air Compressors

There are now several OEMs introducing or offering clutched air compressors (See Figure 19 above). These designs typically have a multi-plate clutch arrangement mounted on the input drive to the compressor. When the air system pressure reaches its "cut-out" pressure, in addition to a signal to the compressor cylinder-head, there is also a signal sent to the clutch, which essentially disengages the compressor from the gear drive and therefore minimizes power consumption when the compressor is not pumping. When the system air pressure drops the clutch is re-engaged and the compressor starts to deliver air again. Payback period for this option is estimated at about 3 years with $2.50/gal fuel.

Benefits	Challenges
• Reduced power consumption when not pumping • Less compressor wear • Lower oil-carry over	• Increased cost • Slight increase in weight and packaging size • Additional maintenance item

9.2.2. New Developments – Smart Air Dryer

Figure 20: Examples of Smart Air Dryer Systems

As mentioned earlier, the majority of air systems are controlled by a governor valve, which essentially is a mechanical valve which switches between two preset pressures. There is no consideration given to what driving mode the engine is in or when is the most efficient time is to draw power from the engine to drive the compressor.

With a smart air dryer (Figure 20) the air pressure in the reservoirs are monitored by a pressure sensor, and in addition the vehicle CAN bus is also monitored to determine what driving state the engine/vehicle is in. The system determines when the vehicle/engine is in an over-run or coasting phase and operates the compressor most efficiently during these phases.

The electronics used to control the air dryer are more typically installed in another vehicle electronic control module such as a chassis controller or ABS electronic unit. However it can also be integrated in the air dryer which is typically the approach being taken in Europe.

Because there is more information available on the air system operation, it can also be used for prognostics for either vehicle on-board or off-board diagnostics. This provides for optimum use of the air dryer and compressor as well as notice of servicing or maintenance requirements. Payback for this option is estimated to be between 2 and 2.5 years at $2.50/gal fuel.

Benefits	Challenges
• Reduced power consumption by better timing of on / off-load phases • Air system prognostics. • Ability to determine air cartridge replacement cycles based on consumed air. • Better air compressor utilization	• Currently not available through all truck OEMs as of March 2017 • Modest cost increase • Slight increase in weight and packaging size • Additional system complexity

9.2.3. Future Developments and Trends

The current design of gear driven air compressors continues to evolve with lower weight, better air delivery, optimized cooling and reductions in power consumption, these new designs will be introduced in to the market over the next five years.

There is a general trend to higher displacement single cylinder compressors which have the advantage of providing the same output as today's twin cylinder compressors but in a lighter and more compact package with lower power consumption.

Clutched air compressors are been introduced at some vehicle OEMs , however at this point there is not widespread adoption. In general, they are better suited to lower duty cycle operations, such as line-haul. In some cases, they are being introduced as part of a fuel-efficiency package.

The major compressor suppliers have developed electrically driven compressors, at this point they are being considered for specific dedicated applications such as hybrid or fully electric vehicles which have a need for an electrically driven air compressor and higher voltage and power levels to drive it. In the near term it is not foreseen that electrically driven compressors will be adopted for widespread use.

There is clearly a trend to a wider adoption of smart air dryers, in most cases this is linked to both the air dryer and compressor. While there is a small fuel efficiency improvement (0.1-0.3%) they are also being adopted to provide improved system prognostics.

9.3. Cooling System / Cooling Fans

In its simplest form, the vehicle cooling system consists of an engine-driven water pump that moves coolant through a series of passages to keep the engine components cool from the extreme heat that is generated through combustion. This heat is then rejected to the atmosphere through the vehicle radiator/cooling fan system. Coolant temperature is generally maintained within a reasonable range by a mechanical thermostat that controls water flow through the system. Allowing components to exceed their temperature limits will result in either shorter life or, in some cases, immediate failure.

The diagram below (Figure 21) shows the water flow through a typical cooling system (not shown – EGR cooler):

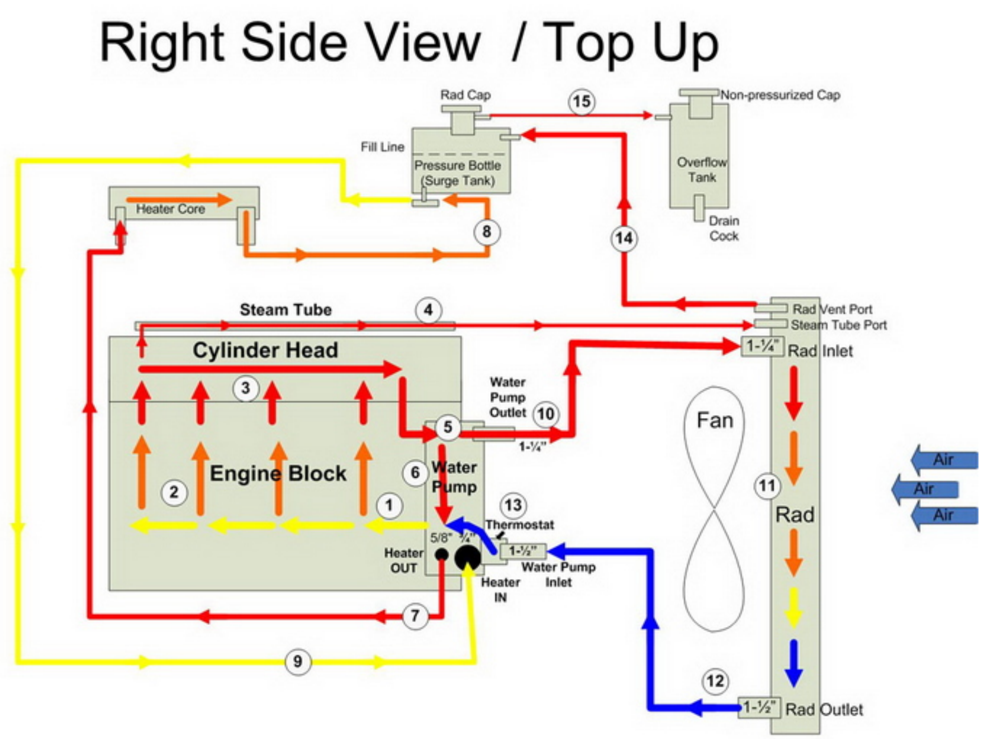


Figure 21: Cooling System Schematic

Another thing that is not shown in the diagram above is that there are normally two other heat exchangers in front of the radiator. The first is the condenser for the vehicle cabin air conditioning system that uses a refrigerant to carry heat from the truck cab and reject it to the atmosphere. The second is the charge air cooler that removes heat from the combustion air for the engine that is being delivered from the turbocharger to the engine power cylinders. Charge air coolers are necessary to improve the engine power density – that is minimize the number of liters of engine displacement necessary to create horsepower.

The heat exchanger system at the front of the vehicle mostly depends on ram air as the vehicle moves down the highway to facilitate the heat rejection necessary from these three heat exchangers. However, on occasion, the needed heat rejection must be augmented by the use of the cooling fan to force more air across the heat exchangers.

The selection of the heat exchanger configuration is made by both understanding the heat rejection requirements of each of the critical systems and the allowable packaging requirements by the OEM chassis (frontal area, mounting, thickness/depth, fan diameter, fan speed and efficiency, etc.). The addition of cooled Exhaust Gas Recirculation systems to engines starting in 2002 substantially increased the heat rejection requirements of engine cooling systems. This, combined with shrinking of the vehicle's frontal area to improve vehicle aerodynamics, has created more challenges for the vehicle cooling package over time. This has caused an increase in cooling fan horsepower when engaged and also a proliferation of fan shroud configurations.

The diagram (Figure 22) below depicts the horsepower of a typical fan on a heavy-duty engine cooling system. You will note that when the fan is fully engaged, it can take up to about 10% or more of the total output of the engine. The end result is the fuel consumption goes up substantially any time the fan is engaged. Almost all vehicles today have fan control systems that only engage the fan when needed and allow it to idle or spin freely at very low friction so little power is consumed when it is not needed. Fortunately, a line-haul application only needs to use the cooling fan from 2 to 5% of the time when evaluated on a year around basis. So, using these two numbers, the fuel consumption due used by a standard on-off cooling fan is approximately 0.3% of the total fuel consumed.

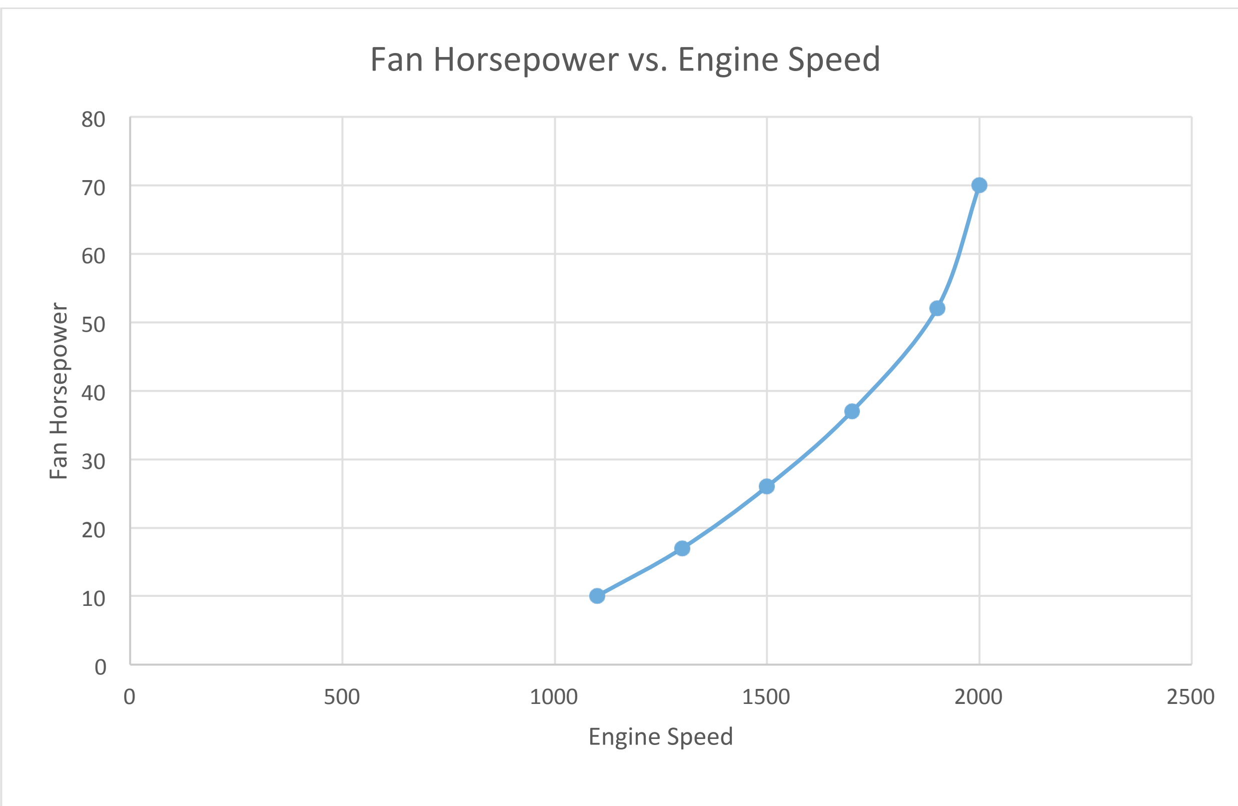


Figure 22: Fan Horsepower vs. Engine Speed

It should be noted that some duty cycles like pickup and delivery or vocational operations and those with very high engine idling time can consume substantially more fuel due to cooling fan operation. It should also be noted that the fan on time numbers can vary substantially based upon other duty cycle factors, ambient temperatures, altitude, etc.

The fan control systems are designed to trigger fan operation only when it is necessary. They include using engine coolant temperature, charge air temperature, and air conditioning refrigerant pressure to trigger fan operation.

There are a number of options available in the marketplace that help reduce the fuel consumption due to the cooling fan. They include 2 speed/modulating fan drives and fully modulating fan drives. Depending on application, savings for a 2 speed/modulating cooling fan would be perhaps one third of the fuel burned due to fan operation. It is estimated that payback for adding a 2 speed/modulating cooling fan is a 1 to 2 year based on $2.50/gal fuel.

2 speed/modulating cooling fan:

Benefits	Challenges
• Reduced power consumption compared to single speed fan • Less fan clutch and belt wear	• Increased cost • Increased fan control system complexity • Slight increase in weight and packaging size • Fully modulating fans not available from all truck OEMs as of March 2017

A second alternative exists in the cooling fan area. Some fully modulating fans are available to further reduce the fuel consumption during fan on operation. The control system for these fans can vary the speed from 0 to full on and only adds enough fan speed to meet the cooling requirements of the vehicle as it needs it. Further fuel savings are possible using this arrangement, but they are typically used in applications that require a much higher percentage of fan on time (extra heavy loads, severe ambient conditions, lots of stop and go operation, etc.) than a normal line-haul application. Payback would be expected to be about the same as above, but only if the application drives the need for the more sophisticated fan drive and control. These fully modulating fans have the same benefits and challenges as the 2 speed/modulating cooling fans.

9.4. Power Steering System

Virtually all heavy-duty trucks have power steering systems to assist with the turning of the vehicle when necessary. The power steering system consists of a hydraulic engine-driven power steering pump, a steering gear, control valves to route the hydraulic fluid depending on the direction of the turn, a small fluid reservoir, and hydraulic hoses to route fluid to the appropriate components. In addition, a fluid cooler is sometimes required to keep the hydraulic fluid in the proper temperature range. See graphics below (Figures 23 and 24) that illustrate the various system components.

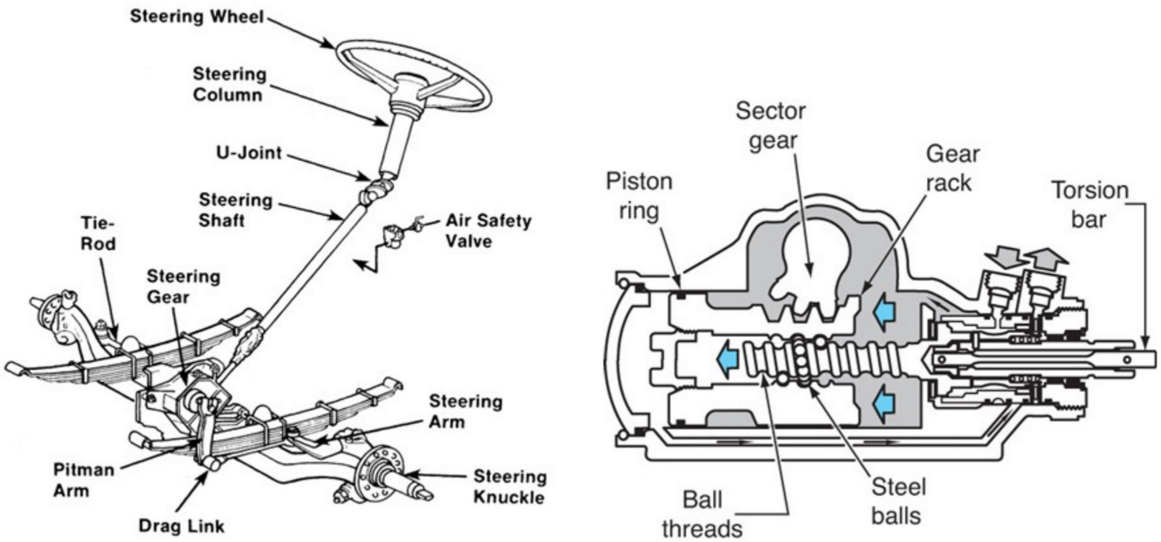


Figure 23: Power Steering System Schematic

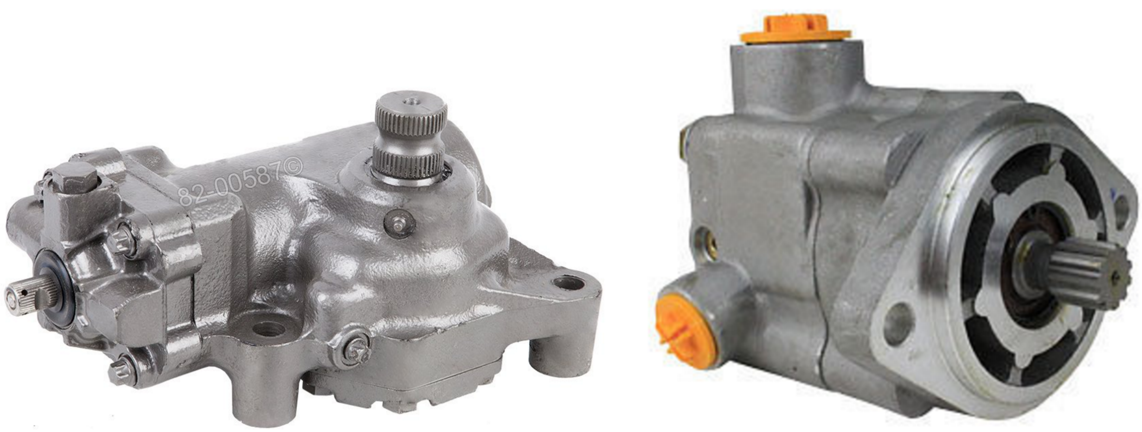


Figure 24: Typical Power Steering Pump and Steering Gear

The power steering pump is turning and generating pressure/flow any time the engine is running. The components are sized such that adequate pressure and flow is available for low speed maneuvering of the vehicle (e.g. parking lot situations). In all other conditions the components are oversized for the function they need to perform. Turning the power steering pump and maintaining pressure to be available at all times consumes energy that is mostly not used for performing the work of guiding the vehicle.

There are many ways to save some of this energy, but they require additional hardware in order to take advantage of the opportunity. One way to do this that is now just coming to the marketplace is to use a dual displacement power steering pump. The chart below (Figure 25) shows the torque requirement and pump speed of a fixed displacement vs. a dual displacement power steering pump. The dual displacement power steering pump works by using the full displacement available when the engine is at a low speed. Once the engine/pump speed is sufficient, the dual displacement power steering pump automatically switches to the pump with smaller displacement that takes less horsepower to turn. Therefore, when the vehicle is going down the highway, the power steering pump is consuming significantly less power than a conventional pump. Note that the claimed fuel savings are in the 30% range. This amounts to about .1 to .15% improvement in overall vehicle fuel economy. Payback of this system is estimated to be quite long at $2.50/gal fuel.

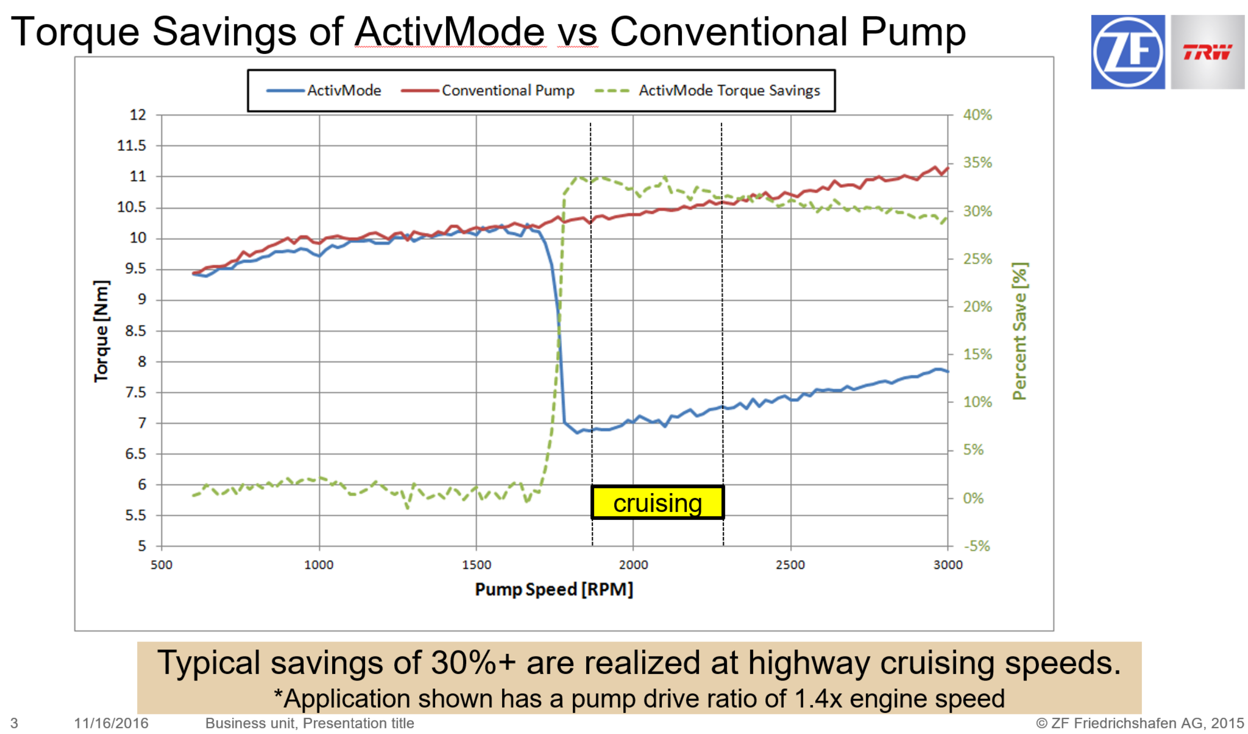


Figure 25: Dual Displacement Power Steering Pump Power Curves

Benefits	Challenges
• Fuel Savings • System consumes less power for highway driving	• Not available from any truck OEMs as of March 2017 • Increased cost • Increased steering system complexity • Potential added maintenance cost and concerns related to reliability

There have been additional ideas discussed relative to steering improvements, but none are yet on the market. For example, if the power steering pump is driven electrically, then it would run only when necessary. However, a system such as this would require the addition of a pressurized reservoir of sufficient volume to steer the vehicle while the power steering pump is brought up to speed and pressure after a demand is sensed. Analysis indicates that powering such a pump using 12 V would require more current than typical electrical systems can provide. Therefore, implementing a system as described would require significant additional modifications to make it feasible. In this case, the incremental savings would not seem to justify the investment necessary to implement such a system.

In a hybrid vehicle, the increased voltage would be available from the high voltage battery pack. Also, implementing electrically driven power steering would be necessary if the vehicle had the capability to turn off the ending at a traffic stop or could run any part of the duty cycle without the engine running. None of these options are broadly available in the marketplace at this time, but may be in the near future.

Of course, given the criticality of the steering function in the vehicle, any modifications must have the highest reliability. Clearly, extensive testing to modifications of the steering system must be performed before any such modifications are implemented.

9.5. Alternators

The alternator generates all the electrical energy stored and consumed on the vehicle. One thing you may not know about the alternator is that is not a particularly efficient way to generate this power. Typical overall efficiency of the power generation process is on the order of 20% compared to the energy input to generate it. The following is an illustration of this concept. (See Figure 26)

Alternator Efficiency of Converting Mechanical to Electrical Energy

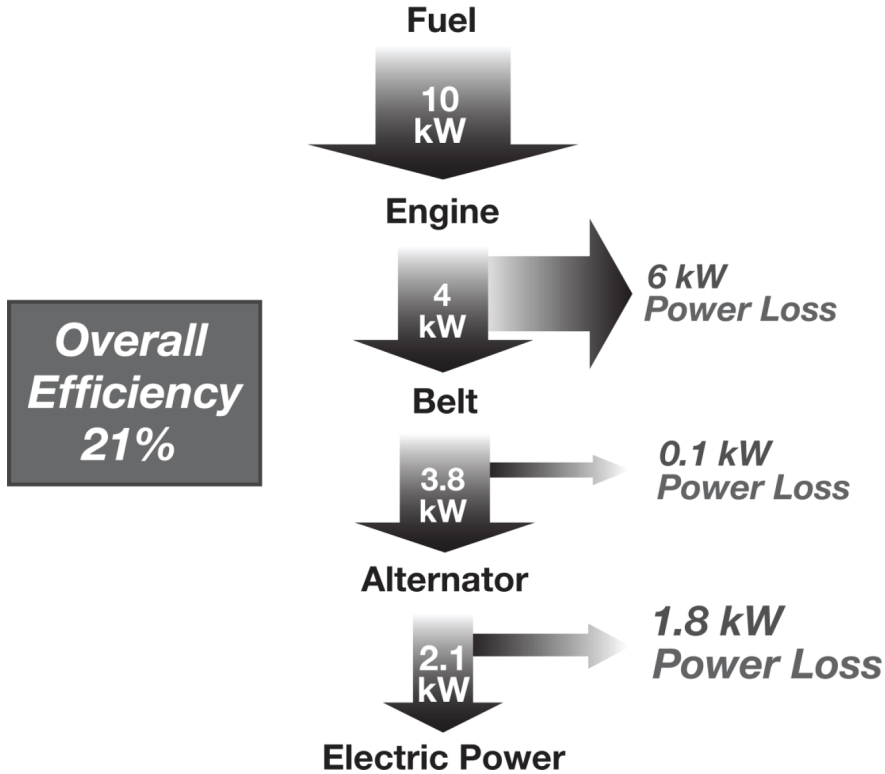


Figure 26: Alternator Energy Conversion Efficiency

The efficiency is somewhat lower when the electrical energy is stored in the battery and then used later. Taking all factors into account, it costs about $0.35/kWh to generate electrical power on the vehicle at a fuel price of $2.50/gallon. By comparison, the average residential electrical rate in the US is about $0.12/kWh.

Alternators are offered to the market in basically two efficiency ranges. The standard alternators generally have a maximum efficiency rating somewhere in the 55-60% range and the high efficiency models are generally in the 68-75% range. These efficiency gains are mostly due to using conductors that allow greater fill of the windings in the alternator. Using these numbers, a fleet could expect to see a very slight improvement in average total fuel consumed by the vehicle of about 0.1% using the high efficiency alternator.

Depending on the application, choosing a high efficiency alternator can save from $350 – $550 in fuel costs over 500K miles (over-the-road tractor w/$2.50/gal fuel). However, these savings will change based on vehicle duty cycle and application. Obviously, the savings change with fuel price as well. The payback of implementing higher efficiency alternators is estimated to be around 2 years.

Benefits	Challenges
• Slightly Improved Fuel Economy	• Increased cost

	• Not available from all truck OEMs as of March 2017

9.5.1. New Technology to Improve Alternator Efficiency

The design and implementation of today's standard alternators is a good compromise between component cost and efficiency. Small additional gains in efficiency could be made with improved technology, but the cost penalty would be very high and overwhelm the gain from reduced fuel consumption.

However, there are a couple of trends that would allow improved efficiency in electrical power generation.

- The first of these is moving to a higher system voltage. Higher voltage systems would allow the design of more efficient voltage rectification and regulation systems. Of course, changing vehicle system voltage to a higher level would bring with it a number of other changes that would have to be implemented in the design of the vehicle, including adding additional batteries, wiring, inverters/voltage converters, etc.
- The second trend is a hybrid technology implemented in the vehicle system. Most experts agree that hybrid technology only makes sense in the near term in commercial vehicles where there is a high incidence of stop-and-go driving. The gains in fuel economy that can be realized for the standard line-haul application are modest and don't offset the increase in cost, weight and complexity that come with a hybrid vehicle arrangement. However, if hybrid technology is implemented, then the entire system of electrical generation and propulsion has to be significantly redesigned.

9.6. Air Conditioning Compressors

The modern air conditioning system for vehicles includes a belt driven, clutched compressor that takes power from the engine to drive a refrigerant through a closed cycle system of heat exchangers and valves. The heat exchanger and refrigerant system are designed to remove heat from the passenger compartment of the vehicle and reject that heat through the air conditioning condenser coil that is located in front of the radiator. Below is a schematic of the components and refrigerant flow through the system (See Figure 27).

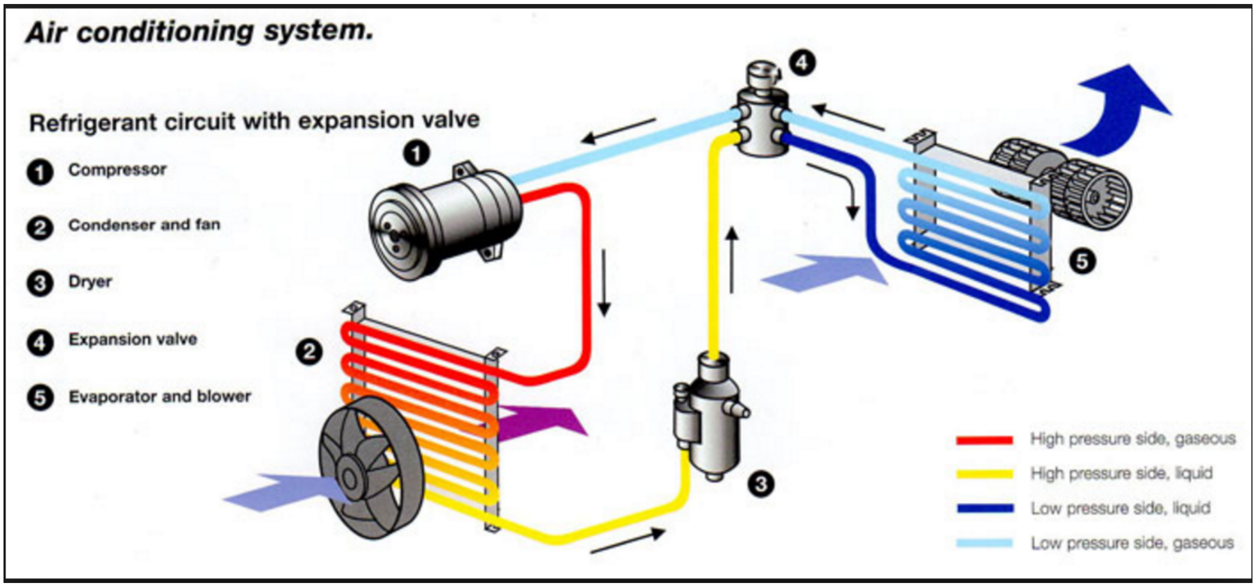


Figure 27: Air Conditioning System Schematic

How much energy does the A/C system use? Generally, a very modest 0.1 to 0.2% of total fuel used. However, this can vary significantly depending on the outside temperature and humidity conditions and the duty cycle of the vehicle. Of course, this fuel consumption is higher during the summer months and lower during the winter months. Keep in mind that the air conditioning system is used during the winter months to improve the function of the windshield defrosting function. Even the paint color of the cab and the amount of cab insulation can affect the amount of fuel used to maintain comfortable temperatures. The air conditioning system components are chosen based on the volume of the passenger/sleeper compartment to meet reasonable cooldown time requirements when the cab temperature is high.

A major source of fuel consumption with the air conditioner is running the engine while the vehicle is stopped for rest stops, breaks, etc. The typical engine will use between .5 and 1 gallon of fuel per hour if left running at idle. Higher engine speeds will consume more fuel.

The typical truck cab air conditioning system can cool both the driver's compartment as well as the sleeper compartment. However, the latter function is sometimes handled by an auxiliary power unit (APU) so that engine idling can be avoided. Some APU systems are powered by a small diesel engine while others are powered by batteries to provide the sleeper cooling function and other hotel functions. Details of these APU systems have been discussed in the Idle Reduction Confidence Report.

NACFE is not aware of any higher efficiency air conditioning systems that are available in the marketplace at this time. Therefore, in order to save fuel on when the air conditioner is in use, the selection of lighter paint colors, improved cab insulation and avoiding unnecessary engine idling are the best paths to minimizing fuel consumption relating to the air conditioning function. The amount of fuel used to perform this function is a relatively small portion of total fuel used. The only electrically driven air conditioning compressors on the market now are ones used for battery APUs and ones that are installed on hybrid electric transit buses. None are available or projected for the standard on highway vehicle right now.

Electrically Driven Cab Air Conditioning Compressor

Benefits	Challenges
• Possible fuel savings if vehicle is equipped with higher voltage and capacity electrical system	• Not available from OEMs except for specialty vehicles (e.g. hybrid transit bus) • Increased complexity of electrical system • Higher voltage and higher output electrical system required • Potential increased cost and reliability concerns

10. Enabling Technologies for Variable Engine Accessories

As described early, waste heat recovery and higher voltage are two enabling technologies that if implemented might increase the adoption of many of these variable engine-driven accessories. The following details recent advancements in waste heat recovery.

10.1. Waste Heat Recovery

Waste heat recovery is a term that is used to describe methods used to extract more work from the heat that is generated from the combustion of fuel in the power cylinder. In today's engines, a little more than 40% of the heat generated in the combustion process is converted to mechanical energy to propel the vehicle down the road. However, there are a number of places where the rest of the heat generated goes unused – most of that heat is eventually rejected to the atmosphere. If there were a means to capture this heat energy and turn it into energy to power the vehicle, then the overall fuel economy of the vehicle would be improved.

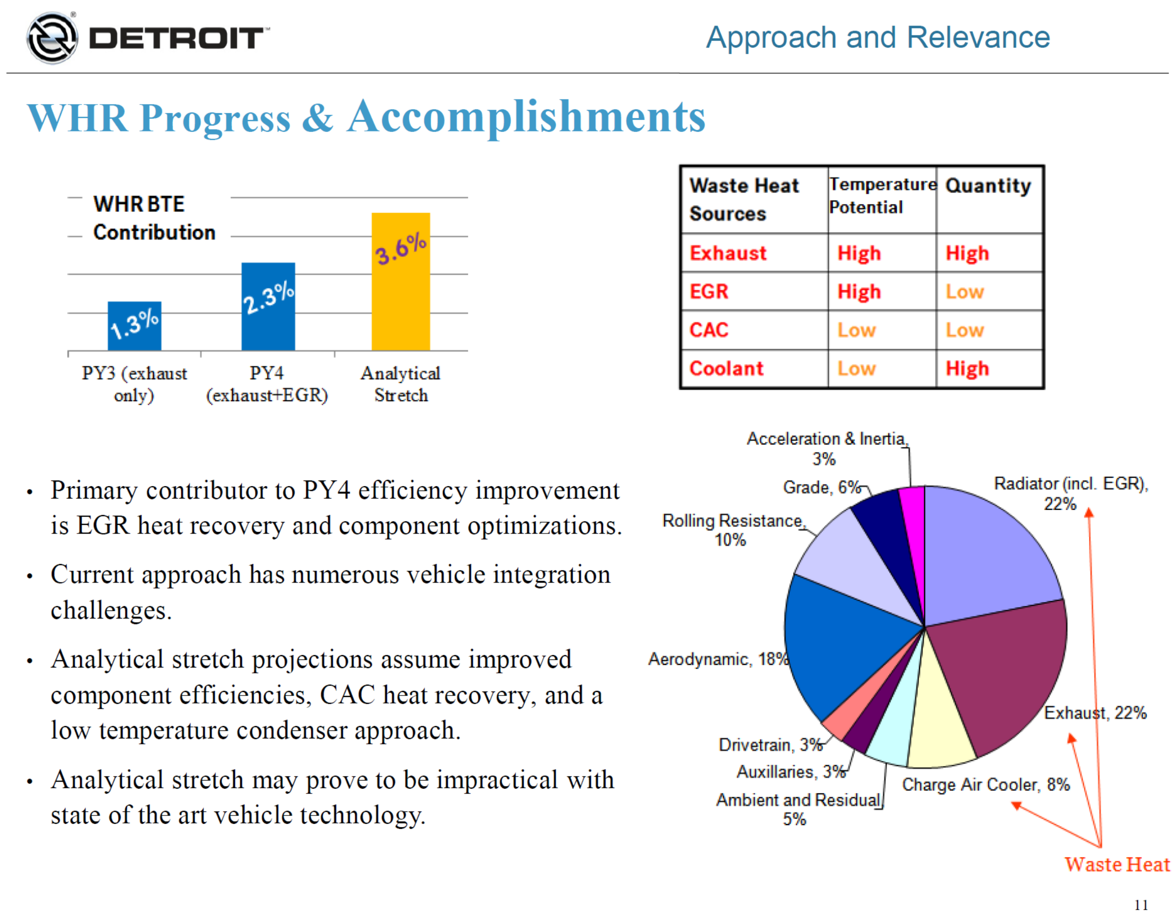


Figure 28: One SuperTruck Team's Evaluation of WHR Energy Available

There are three places in particular where capturing this heat energy might be feasible: the exhaust gas that goes out the stack, the radiator and the charge air cooler (See Figure 28 above). The SuperTruck programs that were run jointly by the DOE and various vehicle and engine manufacturers have demonstrated what these type of systems might look like in the future.

Each of the SuperTruck groups has devised different solutions that demonstrate how this capability might be brought to the marketplace as a piece of technology to satisfy the GHGp2 requirements. In short, each of the teams implemented a closed cycle heat exchanger/turbine system to take heat from the hot components (EGR or exhaust or both). This heat evaporates a working fluid that can be used to expand through a turbine to extract work from the gas. The working fluid is then run through a condenser to return it to its original state. In this sense, it works rather like a steam turbine system in an electric power plant. The turbine work can then be used to either generate electrical power to be used by the vehicle or to deliver the power mechanically to the vehicle powertrain.

The key to this technology going forward will be the cost/benefit analysis since additional equipment is required, adding to the vehicle's cost, weight, packaging size, maintenance, etc. Much hardware would have to be added to the vehicle to facilitate the gain in fuel economy. There would have to be a reasonable payback period and ROI for this technology to make sense. Clearly, this solution would get more attractive as the price of diesel fuel goes up from its current levels.

How, would waste heat recovery affect the engine-driven accessories? It really affects them in a number of ways. First, if the fuel economy of the vehicle is getting better, that means that less heat overall needs to be rejected to the atmosphere. In addition, the distribution of that heat rejection could change significantly based on the way the new engine system with waste heat recovery is configured.

- For example, if the heat that was coming from the EGR gas is no longer going into the engine coolant, then the radiator system can be smaller. However, another heat exchanger must be added to accommodate the condenser function of the waste hear recovery system. These changes will inevitably affect the cooling fan system. This will likely result in a major reconfiguration of the heat exchanger and fan system at the front of the engine.
- A pump must be added to manage the flow of the working fluid around the waste heat recovery system, so an additional drive mechanism will be necessary (either electric or mechanical).
- A drive mechanism must be able to either generate electrical power (think another alternator) or the power must be returned mechanically to the engine powertrain in some manner.
- If the power is stored electrically, then additional battery capacity may be necessary on the vehicle to facilitate the power storage. Also, there would need to be a way to feed that energy back into the power train through some kind of motor/generator arrangement.
- If additional battery capacity is added (and if the battery operates at higher voltages), that could enable other changes to engine-driven accessories to make those systems more efficient.
- If the power generated is delivered to the powertrain mechanically, then there must be either a gear drive or belt drive system connected somewhere in the powertrain. It would be expected that there would be some kind of gearbox and/or fluid coupling to match the speed of the turbine expander to that of the powertrain that it is driving. In addition, a clutch would likely be added to disconnect the system when insufficient power is available from waste heat.

The following are some block diagrams (Figures 29 to 31) of potential waste heat recovery systems:

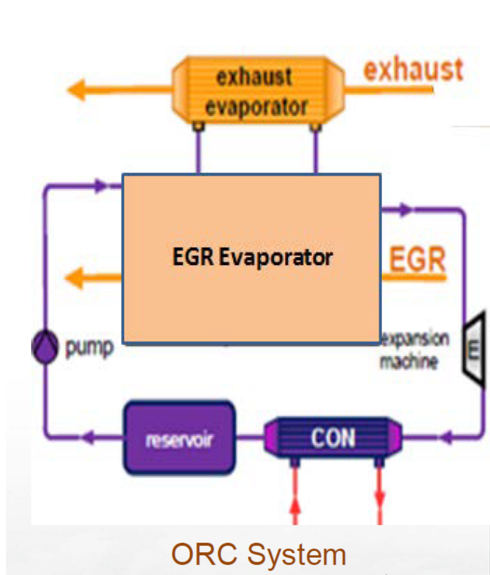


Figure 29: Example WHR System Schematic

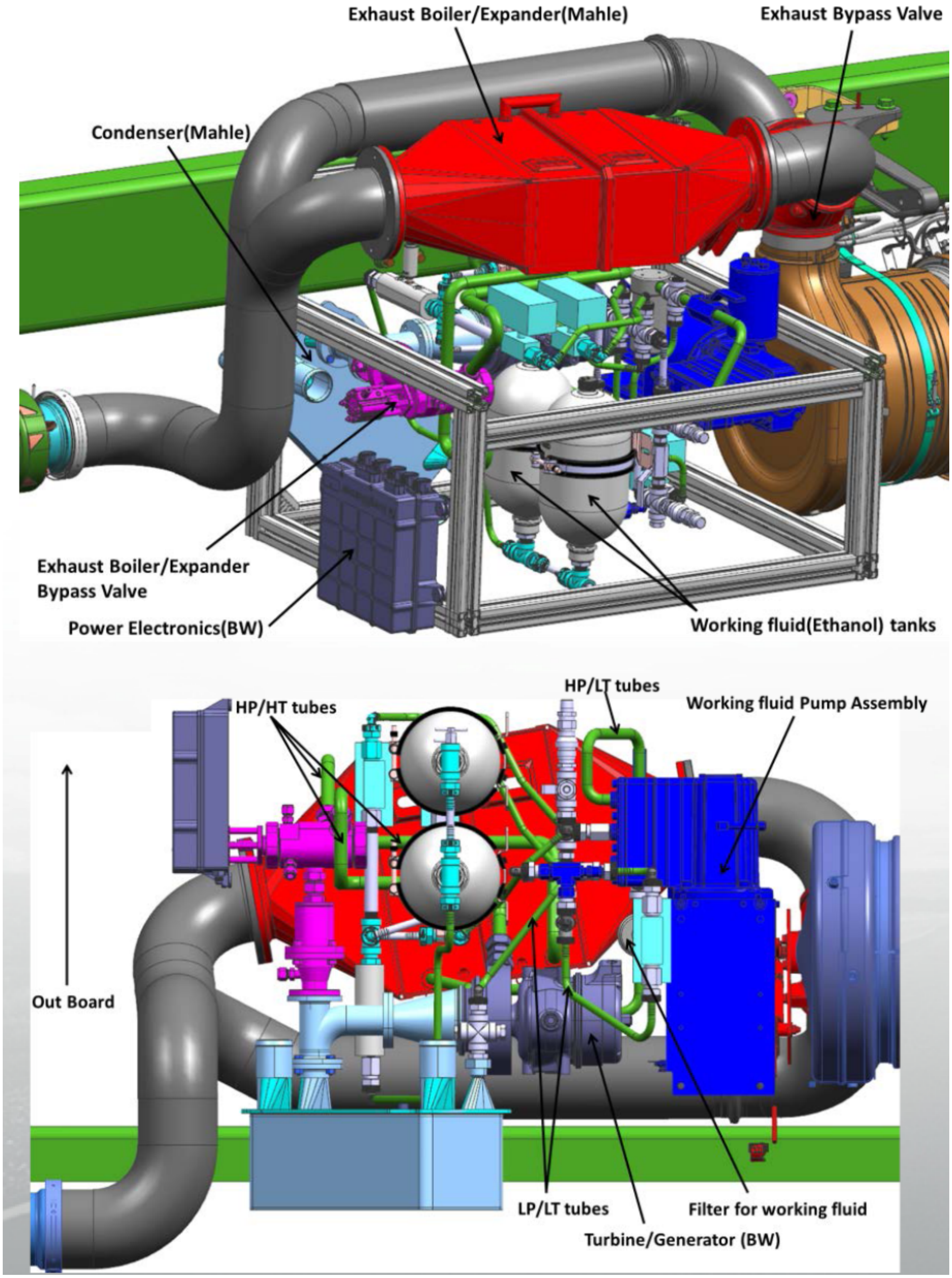


Figure 30: Illustration of WHR System Hardware – 2 views

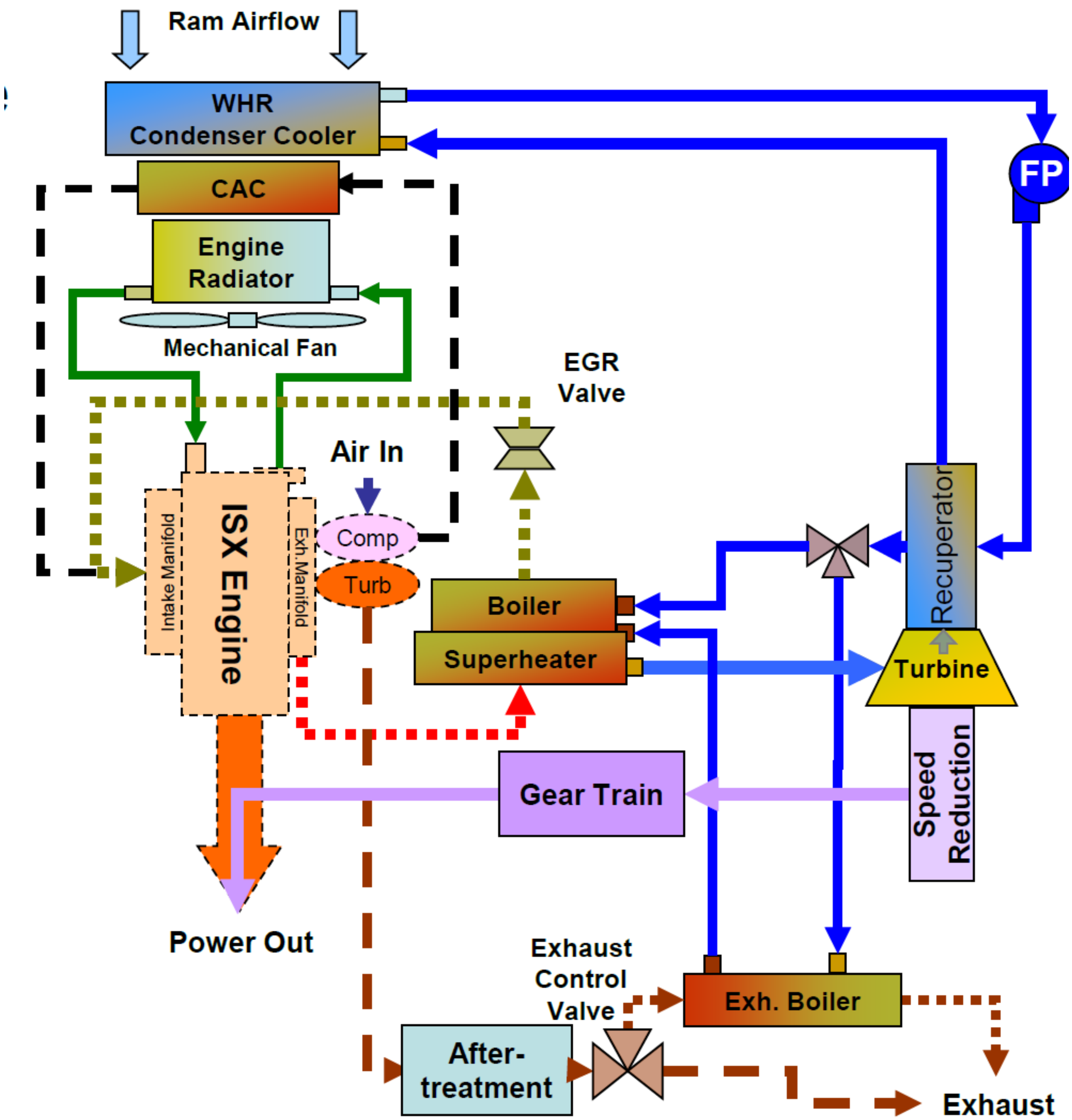


Figure 31: WHR System Flow Illustration

11. Insights from Interviews

In conducting the research for this Confidence Report the study team spoke with technology developers, component suppliers, tractor OEMs, fleets and others about the fuel savings available from variable engine accessories, and the challenges and benefits of adoption.

For this Confidence Report, we interviewed a small number of key fleet managers to get their views on the subject of engine-driven accessories and how they approach the choices of what to use and not use in this category for their particular equipment and duty cycles. The fleets represented a broad range of vehicle types and applications in the heavy-duty space including long-haul logistics providers, private fleets, one fleet using specialized trailers and delivery equipment. Each fleet was asked to self-describe with respect to their acceptance of freight efficiency technologies. Half of the participants considered themselves innovators or early adopters. (See Figure 32)

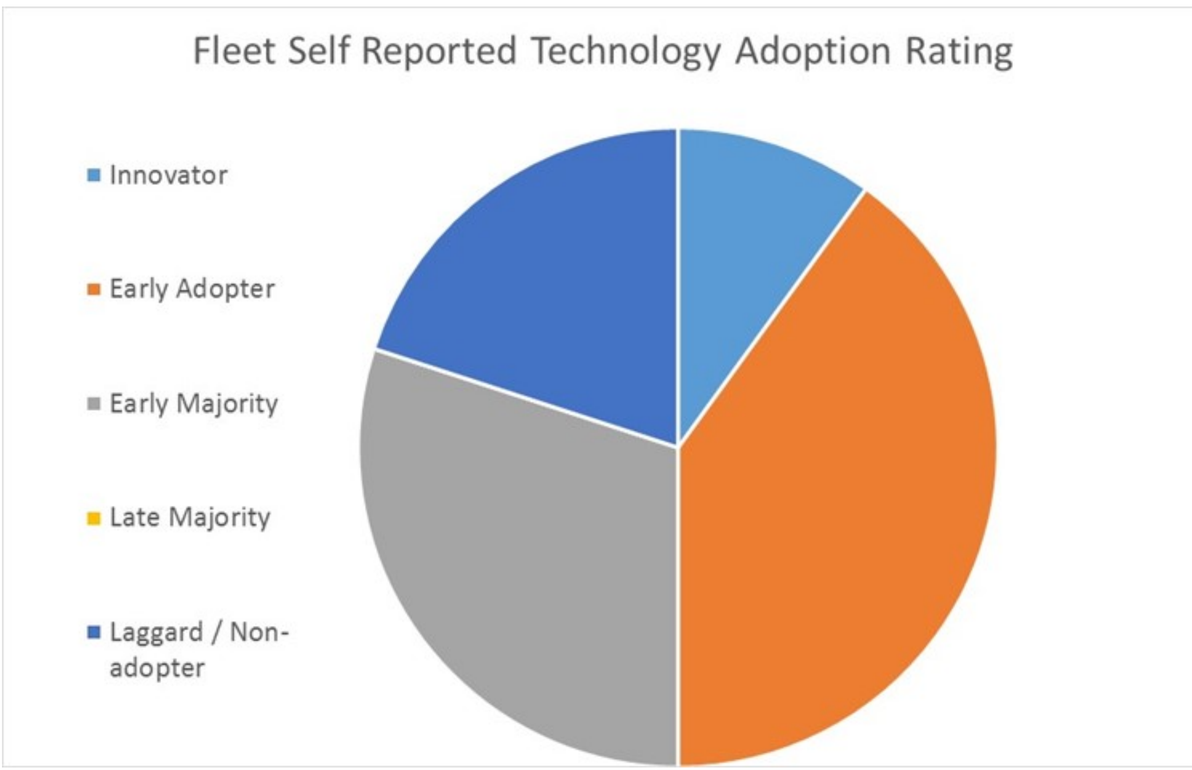


Figure 32: Fleet Interview Feedback

Each fleet manager had a good idea of the choices currently available in the marketplace related to engine-driven accessories. They also accurately understood that the fuel economy improvements that are possible in this area are modest compared to many other technologies that are now available. Given this, none of the managers has done an extensive experimentation with engine-driven accessory technology. Of course, all recognize the current price of fuel extends the payback for investment in new fuel saving technologies.

In general, the managers agreed on the following points:

- Any technology they try needs to meet their company's ROI guidelines before it would be considered for a broad implementation across their fleets.
- Most managers are willing to try new technologies in small samples to gain understanding on the steps necessary for a broad implementation at the fleet level.
- All managers emphasized the need for reliability and durability of the improvements. The lessons from issues with prior implementations of new technology on their vehicles are still fresh in their minds.
- If a new fuel saving technology is forced by regulations, most managers wanted at least a year to evaluate small samples to get familiar with the technology and implement plans in their operations to deal with the new equipment they would be purchasing.

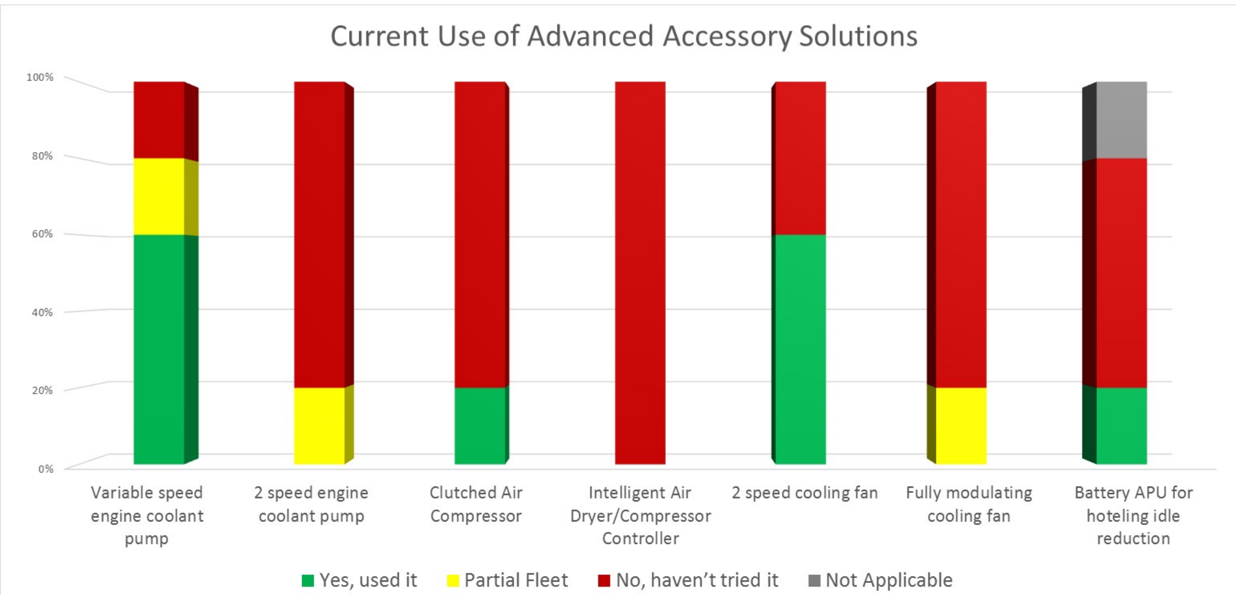


Figure 33: Fleet Interview Feedback on current use of Technologies

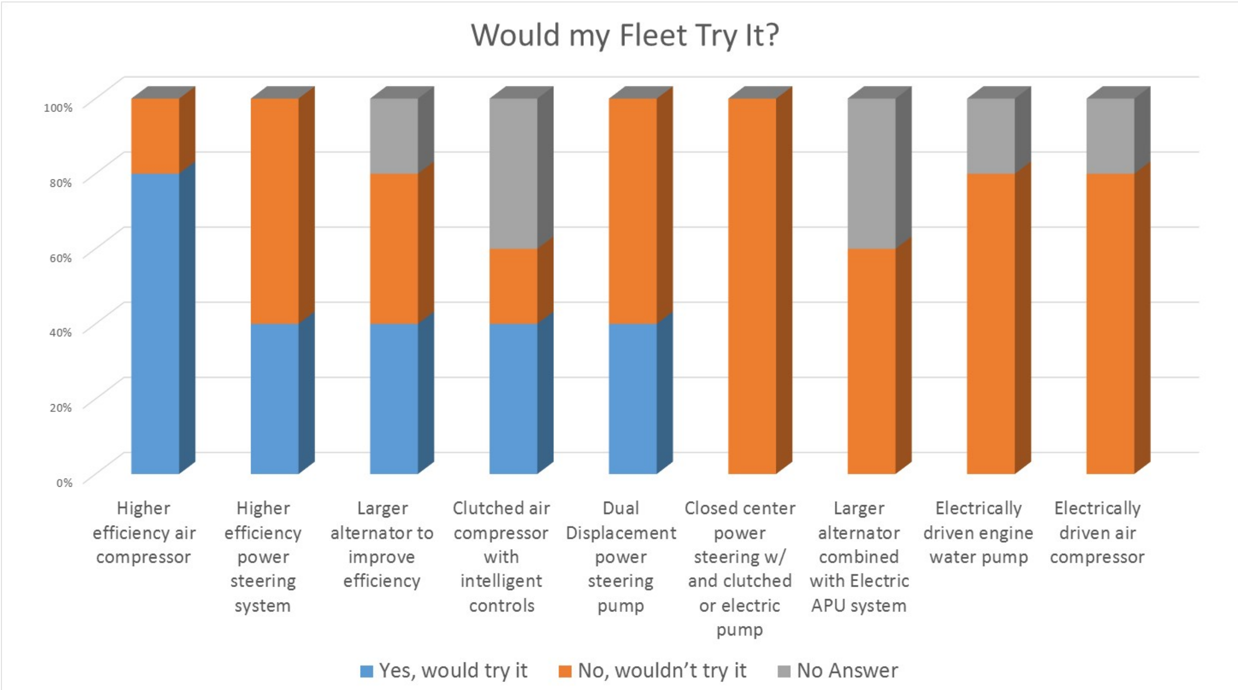


Figure 34: Fleet Interview Feedback on Willingness to try Technologies

Figures 33 and 34 above summarize the feedback received from the fleet managers interviewed related to engine-driven accessories technologies.

All the managers were familiar with the broad outlines of the recently released Greenhouse Gas Phase 2 regulations. However, most are taking a 'wait and see what unfolds' approach to understanding what they mean to their particular fleets. Interestingly they viewed many of these major technologies that are being discussed (like waste heat recovery) as likely 10 years away from implementation.

There was less agreement among the fleet managers on the possibility of a vehicle system voltage change from 12V to either 24V or 48V. Some saw this as something that would come in the future, but were unclear when a transition might start to happen. Others felt that there was no real need to change to a higher voltage. Most felt that if a voltage change were made, that it should be done in only one step rather than going from 12V to 24V and then from 24V to 48V. Of course, higher voltage levels become an enabling technology for some of the more advanced fuel saving ideas related to accessories.

Quotes from Fleet Maintenance Leaders

- On Reliability, "The past few years have given us a lot of new challenges to manage due to the introduction of less than reliable new technology – like aftertreatment systems or electric APUs. When it comes to accessories technology improvements, the new equipment must be proven reliable before I'll be willing to implement in my fleet across the board."
- On payback, "Any optional new technology that we implement must meet return on investment guidelines before it will be considered as part of a large purchase. Given that the fuel economy savings from new accessories are generally small, this makes measuring the potential

improvement from anything new very difficult for us. This means it's a harder sell to our management to make the investment."

- Concerning adding weight, "For this fleet, choices on new technologies are driven not only by the savings and ROI, but also on how it fits with our operation. Our fleet is extremely weight sensitive, so anything that adds even small amounts of weight gets a big magnifying glass before a big order is placed."
- On a large change such as higher voltage, "I've heard a good deal of discussion about the potential change from 12V to something higher – like 24V or 48V. I would say two things about this. First, making the change in two steps makes no sense to me. Second, I don't yet see a connection to fuel economy or operational improvements to justify making that kind of leap yet. The industry is going to have to provide a better story for the change in real terms before I'm getting on board."
- Concerning a big change with waste heat recovery, "I see the introduction of waste heat recovery systems as a huge change to the engine and vehicle. If this change is going to be forced by GHGp2 regulations, I want a chance to see and test it well ahead of time to understand the technology and prepare my fleet for it."
- Concerning urgency for GHGp2, "It seems to me that the Greenhouse Gas Phase 2 regulations are too far out for us to worry too much about right now. I'm going to wait for more info to come out on this before I get to excited about it."

12. Conclusions

- Fuel economy gains from currently available accessories technologies are modest.
    - The payback for these devices is extended based on today's fuel prices.
    - Duty cycle of each accessory in the individual fleet operation is critical to the ROI calculation.
- Strong fleet feedback has indicated they have significant concerns for subsystem reliability of any new technologies.
- Payback of many new technologies to save fuel in accessories is currently insufficient to entice high levels of adoption.
- Future enabling technologies like higher vehicle system voltage, increased energy storage and waste heat recovery will likely improve the ROI of new accessories technologies.

13. Recommendations

- Fleets should continue to review variable engine accessory alternatives as part of their vehicle specification process. Some small improvements are likely available today that would be cost effective for a given operation. Note that measuring the small improvements is challenging.
- Greenhouse gas regulations are likely to drive some changes to accessories over time that will increase complexity but have fuel economy benefits. It is very important to keep an eye on those improvements to assure that fleet personnel are adequately prepared for the changes.

- Higher voltage systems will be an enabling technology for more economical changes to variable engine accessory systems to improve fuel efficiency. However, the savings enabled by improved accessories are unlikely to be a big driving force behind increasing vehicle system voltages.
- NACFE will continue to monitor developments in this area and update the information, conclusions and recommendations in this report.

14. Confidence Rating

For each of the Confidence Reports completed by Trucking Efficiency, the various technologies assessed therein are plotted on a matrix (Figure 35) in terms of their expected payback in years compared to the confidence that the study team has in the available data on the performance of that technology – that is, not only how quickly fleets should enjoy a payback on their investment, but how certain Trucking Efficiency is in the assessment of that payback time. Technologies in the top right of the matrix have a short payback, usually thanks to their low upfront cost, and moreover are found to have enough performance data that fleets can be highly confident in those short payback times, usually because the technology is more mature or otherwise has a more substantial track record of results.

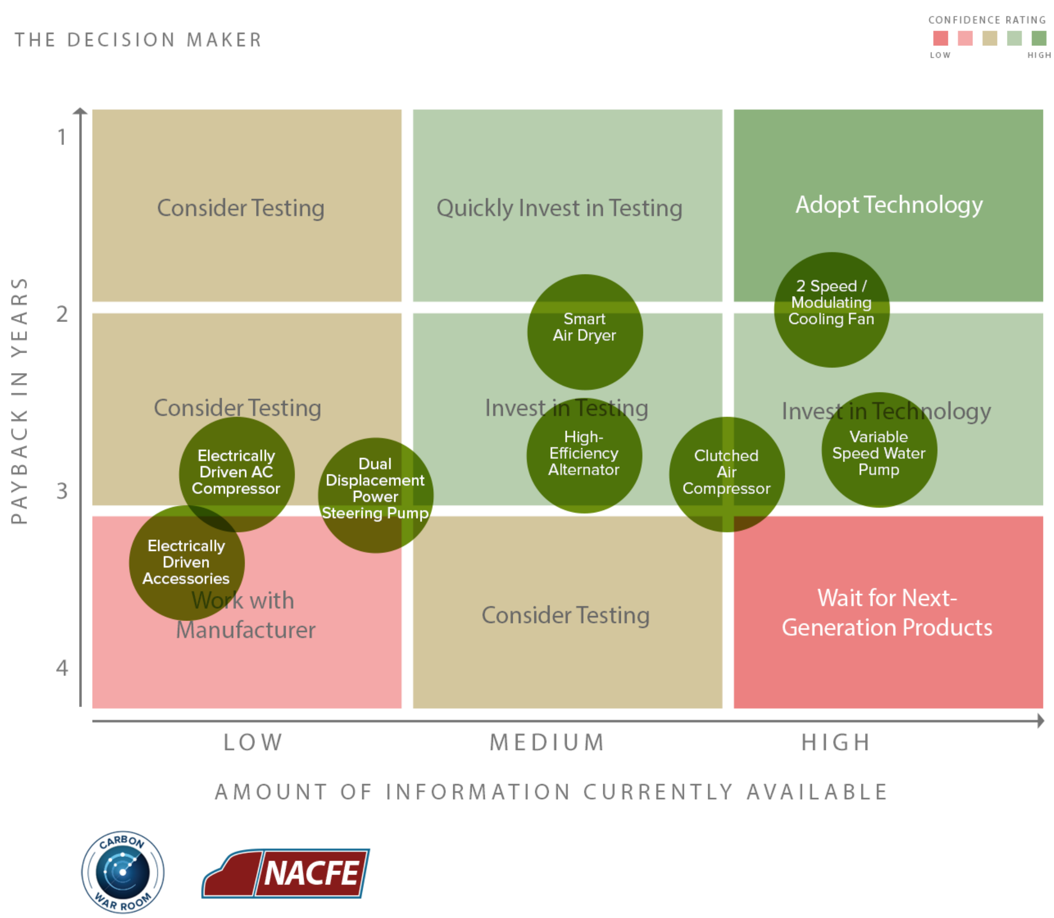


Figure 35: Confidence Matrix

15. Appendix A - References

Figure 1: U.S. Diesel Fuel Prices	Mihelic, R., "Heavy Truck Aerodynamics Beyond 2025," presentation at SAE 2015 COMVEC Session 15CVA2000 Aero Keynote, Oct. 2015, raw data from DOE.	Contact Author for copy
Figure 2: Trucking Operational Costs per Mile	Roeth, M., North American Council for Freight Efficiency (NACFE) graph from data from American Transportation Research Institute (ATRI), "An Analysis of the Operational Costs of Trucking: 2015 Update," Sep. 2015,	http://atri-online.org/wpcontent/ uploads/2015/09/ATRI-Operational-Costs-of-Trucking-2015-FINAL-09-2015.pdf
Figure 3: Fleet Study Participants	Roeth, M., North American Council for Freight Efficiency (NACFE), "2015 Annual Fleet Fuel Study," May, 2016,	http://nacfe.org/wpcontent/ uploads/2015/05/NACFE-2015-Annual-Fleet-Fuel-Study-Report-050115.pdf
Figure 4: MPG per Truck – Blue line represents fleets surveyed by the Fleet Fuel Study	Figure 4: MPG per Truck – Blue line represents fleets surveyed by the Fleet Fuel Study	http://nacfe.org/wpcontent/ uploads/2015/05/NACFE-2015-Annual-Fleet-Fuel-Study-Report-050115.pdf
Figure 5: Average Fuel Consumption of Accessories	Chart created from multiple sources by the AuthorC	Contact Author for copy and details
Figure 6: Typical Fuel Consumption Ranges for Accessories	Table created from multiple sources by the AuthorTab	Contact Author for copy and details
Figure 7: World Harmonized Vehicle Emissions Cycle	World Harmonized Vehicle Cycle	https://www.dieselnet.com/standards/cycles/whvc.php
Figure 8: World Harmonized Transient Test Cell Cycle	World Harmonized Transient Cycle	https://www.dieselnet.com/standards/cycles/whtc.php
Figure 9: World Harmoized Test Cycle – Engine Speed vs. Torque	WHTC cycle - Torque/Speed diagram	http://www.car-engineer.com/wp-content/uploads/2012/12/WHTC.png?46ac1a
Figure 10: SuperTruck Photos	NACFE files	
Figure 11: SuperTruck Team Choices on Accessories	Table from SuperTruck Team interviews created by Author	Contact Author for Copy
Figure 12: OEM Availability Matrix	OEM Availability Table created by author from interviews, desk research, and communications	Contact Author for Copy
Figure 13: Vehicle Cooling System	Image – flow diagram cooling system operation	https://encrypted-tbn1.gstatic.com/images?q=tbn:ANd9GcT

Schematic		g0pKnE95_5Lxk25GxXKQLMliXOx0kbFd1aronqVsAA77Kb7fq
Figures 14-15	Water Pump Images	http://publications.lib.chalmers.se/records/fulltext/241984/241984.pdf - Figure 2.1 http://www.vanderhaags.com/display.php?width=300&id=978027 https://swampsdiesel.com/wp-content/uploads/7l-07-11-cummins-water-pump.jpg https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRAVY-v4yDHt-JPFb6lspbjB4jMqdGpomGiJ0QXMgZ2yu38z_R7FQ
Figure 16: Water Pump Power vs. Engine Speed	Center for Alternative Fuels, Engines & Emissions West Virginia University Heavy-Duty Vehicle Diesel Engine Efficiency Evaluation and Energy Audit October 2014 Final Report Arvind Thiruvengadam, Ph.D. – Principal Investigator	http://www.theicct.org/sites/default/files/publications/HDV_engine-efficiency-eval_WVU-rpt_oct2014.pdf
Figure 17: Water pump flow and pressure vs. pump speed	Water pump flow vs. pressure chart	http://www.engineeringtoolbox.com/affinity-laws-d_408.html
Figure 18: Compressed Air System Schematic	Compressed Air System Diagrams - Maintenance Manual 34 System Saver Series Single Cartridge Air Dryers - System Saver Series	http://www.meritorwabco.com/MeritorWABCO_document/mm34.pdf Page 10/52 Figure 1.6
Figure 19: Examples of Clutched Air Compressors	Air Compressor Images	http://www.wabco-auto.com/products/category-type/air-compressors/ http://www.knorr-bremsecvs.com/en/products_1/compressors/compressors.jsp?q=clutch%20compressor
Figure 20: Examples of Smart Air Dryer Systems	Smart Air Dryer Images	http://www.meritorwabco.com/MeritorWABCO_document/SP-1239.pdf http://www.knorr-bremsecvs.com/en/products_1/airtreatment/airtreatment.jsp
Figure 21: Cooling System Schematic	Image – flow diagram cooling system operation	https://encrypted-tbn1.gstatic.com/images?q=tbn:ANd9GcTg0pKnE95_5Lxk25GxXKQLMliXOx0kbFd1aronqVsAA77Kb7fq
Figure 22: Fan	Chart created by Author using data listed in 'Cummins	Cummins Secrets of Better Fuel Economy

Horsepower vs. Engine Speed	Secrets of Better Fuel Economy' brochure	https://cumminsengines.com/uploads/docs/cummins_secrets_of_better_fuel_economy.pdf
Figure 23: Power Steering System Schematic	Images of Power Steering System	http://slideplayer.com/slide/4312792/ Slides 4 and 50
Figure 24: Typical Power Steering Pump and Steering Gear	Power Steering Gear and Power Steering Pump Images	http://www.buyautoparts.com/autoparts/Freightliner/Power_Steering_Gear_Box.html https://www.google.com/search?q=heavy+duty+power+steering+pump&espv=2&biw=1192&bih=780&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjCweeRv73RAhUE0oMKHbg7AmkQ_AUIBygC#tbm=isch&q=freightliner+cascadia+power+steering+pump
Figure 25: Dual Displacement Power Steering Pump Power Curves	Chart of Torque Savings of ZF TRW ActiveMode vs. Conventional Power Steering Pump	ActiveMode Presentation for NACFE 5July2016.pdf Website: http://www.zf.com/corporate/en_de/products/product_range/commercial_vehicles/trucks_css_activemode_steering_pump.shtml#tabs1-0
Figure 26: Alternator Energy Conversion Efficiency	Improving Alternator Efficiency Measurably Reduces Fuel Costs - BY MIKE BRADFIELD, MSME - Remy, Inc. – Figure 1	http://www.delcoremy.com/documents/high-efficiency-white-paper.aspx
Figure 27: Air Conditioning System Schematic	Air Conditioning System Diagram	http://www.autoairconparts.co.uk/wp/wp-content/uploads/2016/03/Car-Air-Conditioning-System.jpg
Figure 28: One SuperTruck Team's Evaluation of WHR Energy Available	SuperTruck Program: Engine Project Review Recovery Act – Class 8 Truck Freight Efficiency Improvement Project PI: Sandeep Singh (Engine) Detroit Diesel Corporation June 12, 2015 -Slide 11	https://energy.gov/sites/prod/files/2015/06/f23/ace058_singh_2015_o.pdf
Figure 29: Example WHR System Schematic	SuperTruck – Development and Demonstration of a Fuel-Efficient Class 8 Tractor & Trailer Vehicle DOE Contract: DE-EE0003303 Project Officer: Ralph Nine Navistar Principal Investigator: Russ Zukouski DOE MERIT REVIEW 12 June, 2015 – Slide 15	https://energy.gov/sites/prod/files/2015/07/f24/vss064_zukouski_2015_o.pdf
Figure 30: Illustration of WHR System Hardware – 2 views	SuperTruck – Development and Demonstration of a Fuel-Efficient Class 8 Tractor & Trailer Vehicle DOE Contract: DE-EE0003303 Project Officer: Ralph Nine Navistar Principal Investigator: Russ Zukouski DOE MERIT REVIEW 12 June, 2015 – Slide 17	https://energy.gov/sites/prod/files/2016/06/f33/vs064_zukouski_2016_o_web.pdf
Figure 31: WHR System Flow Illustration	David Koeberlein-Principal Investigator Cummins Inc. Cummins SuperTruck Program	https://energy.gov/sites/prod/files/2015/06/f23/ace057_koeberlein_2015_o.pdf

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Figure 32: Fleet Interview Feedback	Graphic created by Author based on Interview Feedback	Contact Author for Copy
Figure 33: Fleet Interview Feedback on current use of Technologies	Graphic created by Author based on Interview Feedback	Contact Author for Copy
Figure 34: Fleet Interview Feedback on Willingness to try Technologies	Graphic created by Author based on Interview Feedback	Contact Author for Copy
Figure 35: Confidence Matrix	NACFE Original Graphic for this report	
General Text References	SuperTruck Annual Reports to DOE – Navistar	https://energy.gov/sites/prod/files/2016/06/f32/ace059_zukouski_2016_o_web.pdf https://energy.gov/sites/prod/files/2016/06/f33/vs064_zukouski_2016_o_web.pdf https://energy.gov/sites/prod/files/2015/06/f23/ace059_zukouski_2015_o.pdf https://energy.gov/sites/prod/files/2015/07/f24/vss064_zukouski_2015_o.pdf
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