California Environmental Protection Agency

AIR RESOURCES BOARD

DRAFT
TECHNOLOGY ASSESSMENT:

ENGINE/POWERPLANT AND DRIVETRAIN OPTIMIZATION AND VEHICLE EFFICIENCY

June 2015

State of California
AIR RESOURCES BOARD

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EXECUTIVE SUMMARY

Heavy-duty on-road trucks provide a variety of essential functions that are critical to California's economy. Ranging in size from the smaller heavy-duty pick-ups and vans (class 2b) through the large eighteen wheeled tractor-trailers (class 8), their vocations are diverse ranging from long haul (over-the-road) freight movement, local freight delivery, to construction and worksite support. Most heavy-duty trucks use conventional fuels (i.e., diesel and gasoline), with diesel fuel being the primary fuel for the heavier trucks.

Presented below is an overview which briefly describes the technologies that are evaluated in this assessment, the potential for further fuel consumption improvement, existing demonstration programs, and proposed next steps. For simplicity, the discussion is presented in question-and-answer format. It should be noted that this summary provides only a brief discussion on these topics. The reader is directed to subsequent chapters in the main body of the report for more detailed information.

1. Why is making heavy-duty trucks more efficient so important?

Although heavy-duty trucks represent only four percent of the vehicles on the road, they account for about 20 percent of carbon dioxide (CO2) emissions from the transportation sector and consume about 20 percent of on-road fuel. As a result, the U.S. Environmental Protection Agency (U.S. EPA) and the Air Resources Board (ARB) continue to focus attention on strategies to reduce the fuel consumption and resulting greenhouse gas (GHG) emissions from these vehicles.

In California in 2006, the Legislature passed and the Governor signed the Global Warming Solutions Act of 2006, also known as, Assembly Bill (AB) 32. In AB 32, the Legislature declared global warming poses a serious threat to the economic well-being, public health, natural resources, and the environment of California. AB 32 created a comprehensive, multi-year program to reduce GHG emissions to 1990 levels by the year 2020. Key to reaching this goal is reducing the fuel consumption of motor vehicles, such as heavy-duty trucks, that rely on petroleum based fuels. Less petroleum-based fuel consumed results in less CO2 emissions.

In 2007, the ARB approved a list of nine discrete early action measures that included the Tractor-Trailer GHG regulation. The Tractor-Trailer GHG Regulation was approved by ARB in 2008, and became effective January 1, 2010. The regulation reduces the fuel consumption of long-haul tractor-trailers by improving their aerodynamic performance and reducing their rolling resistance.

In addition to the mandates of AB 32, both former-Governor Schwarzenegger and current-Governor Brown have established more aggressive long-term GHG reduction goals. Governor Schwarzenegger by Executive Order S-03-05 has directed that GHG emission levels be reduced to 80 percent below 1990 levels by 2050. In his 2015 inauguration address, Governor Brown proposed the goal of reducing today's petroleum use in cars and trucks by up to 50 percent by 2030. And more recently, Governor Brown has introduced by Executive Order B-30-15 an intermediate goal of reducing GHG emission levels by 40 percent below 1990 levels by 2030.

As well as providing GHG reductions to contribute to meeting the goals above, making heavy-duty trucks more efficient will help enable the use of advanced technologies such as hybrid systems and battery-powered and fuel cell vehicles. More efficient trucks require less power to operate and hence help reduce the range and power concerns associated with some advanced technologies. Such advanced technologies will be necessary to help California reduce criteria pollutant emissions, such as oxides of nitrogen (NOx), enough to achieve health-based national ambient air quality standards.

2. How does this report relate to the Phase 1 and Phase 2 heavy-duty truck GHG standards?

At the national level in 2011, U.S. EPA and U.S. Department of Transportation's (U.S. DOT) National Highway Traffic Safety Administration (NHTSA) jointly adopted GHG emission standards and fuel economy standards for medium- and heavy-duty engines and vehicles. Informally known as the "Phase 1" GHG regulations, these regulations established national GHG emission standards for heavy-duty on-road trucks. These regulations phase in between 2014 and 2019. In 2013, the ARB approved for adoption California regulations identical to the federal Phase 1 regulations. This provided California with the ability to certify engines and vehicles to the new standards, as well as enforce them.

ARB is working closely with U.S. EPA and NHTSA as they develop "Phase 2" GHG regulations which will establish post-2018 GHG emission standards based on the implementation of new and advanced cost-effective control technologies. U.S. EPA and NHTSA are expected to propose Phase 2 GHG standards in spring 2015. This report evaluates the fuel consumption reduction potential of various technologies that can be installed on heavy-duty trucks to improve fuel efficiency. These are the same technologies that are being evaluated by U.S. EPA and NHTSA as part of the Phase 2 regulatory development process.

3. How does this report relate to the need for further NOx emissions?

While significant progress has been made in reducing emissions from heavy-duty engines and vehicles, California still faces significant ambient ozone challenges in the South Coast Air Basin and San Joaquin Valley. U.S. EPA has classified both areas as extreme nonattainment areas for the 2008 8-hour ozone standard. Nearly 34.6 million people in the state, 91 percent of the population, live in an area of nonattainment for the 8-hour ozone federal standard (2008). Current programs will reduce NOx and particulate matter less than 2.5 microns (PM2.5) emissions over 50 percent by 2030. However, meeting federal ozone and PM2.5 standards in the South Coast and San Joaquin Valley regions will require significant further reductions over the next 15 years. This includes meeting the federal 80 parts per billion (ppb) 8-hour ozone standard by

2023, the 75 ppb 8-hour ozone standard by 2031, and the 12 micrograms per cubic meter PM 2.5 standard by 2025. Further near-term emissions reductions are essential in meeting these air quality standards.

In the past, many NOx reduction technologies (such as exhaust gas recirculation and changes to ignition timing) have resulted in increased fuel consumption and reduced fuel efficiency. However, the introduction of selective catalytic reduction (SCR) technology in 2010 allowed for optimization of high fuel efficiency while achieving low tailpipe NOx emissions (and reduced GHG emissions). There are many other technologies that provide for optimization of both, and will require a balanced approach in which systems integration is important and engine operation and control strategies must optimize both for performance and emissions. For example, technologies that result in the retention of exhaust heat energy during periods of low-load/low-speed operation (e.g., stop-start), or provide efficiency gains during periods of high temperature combustion (e.g., cylinder deactivation) have the greatest potential for improving fuel economy without increasing NOx emissions. Additional discussion of NOx control technologies for heavy-duty engines (both diesel and natural gas) will be developed as part of three separate upcoming technology assessment documents, 1) Lower NOx Heavy-Duty Diesel Engines, 2) Heavy-Duty Hybrid Vehicles, and 3) Low Emission Natural Gas and Other Alternative Heavy-Duty Fuel Engines, expected to be released later this year.

4. What are engine/powerplant and drivetrain optimization technologies?

Engine/powerplant and drivetrain optimization technologies (referred to collectively as engine technologies in the remainder of this report) consist of new and modified heavy-duty truck engine and transmission technologies that would result in improved fuel consumption and subsequent reduction in GHG emissions. Examples include waste heat recovery systems, stop-start systems, higher efficiency aftertreatment, air handling improvements, and combustion and fuel injection optimization. The majority of engine technologies evaluated are applicable to diesel engines. Table ES-1 is the complete list of engine technologies evaluated.

Table ES-1: Engine Technologies Evaluated

• Advanced Transmissions and Engine Downspeeding
• Waste Heat Recovery
• Engine Downsizing
• Stop-Start
• Automatic Neutral Idle
• Combustion and Fuel Injection Optimization
• Higher-Efficiency Aftertreatment
• Reduced Friction
• Auxiliary Load reduction
• Air Handling Improvements
• Cylinder Deactivation
• Stoichiometric Gasoline Direct Injection
• Lean-Burn Gasoline Direct Injection
• Camless engines
• Opposed Piston Engines
• Free Piston engines
• Advanced Combustion Cycles

5. What are vehicle efficiency technologies?

Vehicle efficiency technologies consist of modifications to current heavy-duty trucks (excluding the engine technologies discussed above) that would result in improved fuel consumption and reduction in GHG emissions. Examples include improved aerodynamics, using lightweight materials, improving axle efficiency, and connected vehicle technologies (i.e., predictive cruise control). Table ES-2 is the complete list of vehicle efficiency technologies evaluated.

Table ES-2: Vehicle Efficiency Technologies Evaluated

• Aerodynamics
• Lightweighting
• Low-Rolling Resistance Tires
• Automatic Tire Inflation
• Vehicle Speed Limiters
• Axle Efficiency Improvements
• Idle Reduction
• Improved Air Conditioning
• Connected Vehicles

6. What information was gathered to develop this report?

Staff conducted an extensive literature search of the technologies listed in Tables ES-1 and ES-2. The core questions staff sought to answer for each technology included:

- How does the technology work?
- What, if any, implementation issues or challenges exist?
- What is the potential fuel consumption reduction (FCR) of the technology?
- What is the technology-readiness level of the technology?
- To which vehicle category does the technology apply?

Sources of information included an extensive list of published reports, research papers, and documented conversations with technology experts. Primary sources of information included:

- A 2010 study on technologies and approaches to reduce fuel consumption of medium and heavy-duty trucks (NAS, 2010);
- A 2009 study to assess the fuel consumption technologies for medium- and heavy-duty vehicles (TIAX, 2009); and
- The Regulatory Impact Analysis conducted by U.S. EPA and NHTSA in support of their Phase 1 rulemaking (U.S. EPA, 2011c).

Staff recognizes that both U.S. EPA and NHTSA have sponsored new research in support of the Phase 2 rulemaking that will be released publically with their Notice of Proposed Rulemaking (NPRM) in the spring of 2015. Once this information is made publically available, ARB will use it to reevaluate the FCRs of the technologies presented in this report.

7. What is the potential for reducing fuel consumption in these vehicles by using these technologies?

The potential reductions in fuel consumption are significant. These benefits for the suites of key engine and vehicle technologies identified in this report are summarized in Table ES-3. Table ES-3 shows the potential additional fuel consumption improvement from incorporating technologies that go beyond Phase 1 standard setting technologies. A Phase 1 compliant vehicle incorporates those technologies used to meet the Phase 1 standards and represents a 6 to 24 percent improvement over the 2010 baseline vehicle. (Chapter III, Table III-10, identifies the Phase 1 technologies for each of the vehicle categories.)

For each category, staff conducted an extensive literature search for over 20 technologies that could be used to reduce fuel consumption of heavy-duty trucks. Technologies were evaluated for their technology readiness (research and development, prototype, field demonstration, introduced commercially, or widely commercial) and applicability. The percent FCR shown in the table correspond directly to potential reduction in CO_2 emission reductions, and can be used to help inform the

Phase 2 GHG standard setting process. However, any recommendations staff makes to U.S. EPA regarding the inclusion of additional technologies in setting the Phase 2 standards will only be made after the potential incremental cost of adding those technologies has been evaluated.

Table ES-3: Potential Additional Fuel Consumption Reduction from a Phase 1 Compliant Vehicle that Incorporates All Applicable Technologies

Category	Potential Additional FCRs beyond Phase 1
Heavy-Duty Tractor-Trailer (Class 7-8) Long Haul	8%-36%
Heavy-Duty Tractor-Trailer (Class 7-8) Short Haul	8%-33%
Heavy-Duty Vocational (Class 3-8)	10%-28%
Heavy-Duty Diesel Pick-ups and Vans (2b/3)	3%-23%
Heavy-Duty Gasoline Pick-ups and Vans (2b/3)	10%-27%

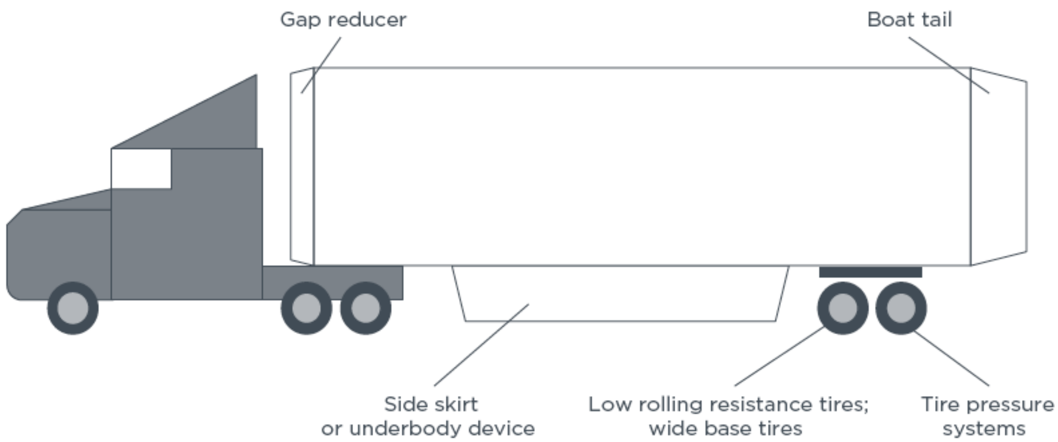
8. What technologies are available to make trailers more fuel-efficient?

Improvements in trailer efficiencies can have significant FCR benefits for tractor-trailer overall efficiency. Aerodynamic technologies for box-type trailers, which can be combined to achieve significant fuel reduction benefits, include side skirts, boat tails, and gap reducers, as well as underbody devices (see figure ES-1). Side skirts are the most commonly used aerodynamic trailer devices today. Applied to box-type trailers used in long haul service, these devices can achieve from 3 to 7 percent reduction in fuel use. In addition, boat tail devices can achieve significant reductions ranging from 3 to 5 percent. Based on recent interviews with fleet-owners conducted by the International Council on Clean Transportation (ICCT), these technologies have payback periods of 1-2 years in most cases. The average tractor trailer ratio of the fleets interviewed was one tractor to 2.7 trailers.

Tire pressure systems and low rolling resistance (LRR) tire technologies available today can reduce the rolling resistance of trailers and can result in a 1 to 3 percent reduction in fuel consumption.

The requirements of both California's Tractor-Trailer GHG regulation and U.S. EPA's SmartWay Program have increased the demand and development of aerodynamic technologies and low-rolling resistance tires for trailer applications. Both tractor-trailer fleets and technology manufacturers have indicated that the reliability and durability of side skirt technologies have improved over the years. Although trailers were not included in the Phase 1 GHG regulations, ARB staff anticipates the Phase 2 program will include trailer GHG standards based on the application of aerodynamic technologies and LRR tires.

Figure ES- 1: Trailer Fuel Saving Technologies



ICCT 2014

Trailers are dominated by the box-type (dry van) variety, but there are a wide variety of trailer types including flatbeds, container chassis, refrigerated vans and more. The FCR benefit of the aerodynamic and tire technologies will vary by trailer-type and usage. Tire technologies are applicable to nearly all types of trailers. Aerodynamic technologies vary in applicability depending on the trailer type. Side skirts can apply most trailer types, but gap reducers, underbody devices and boat tails apply primarily to box type trailers. In addition to Class 7/8 tractor-trailers, both tire and aerodynamic devices can be used on smaller pup trailers.

9. What technology demonstration projects are ongoing or planned?

U.S. DOE is co-funding several demonstration projects, with the most significant being the SuperTruck Program. The SuperTruck program is cost-shared with industry. Total project funding to date is approximately $284 million, with DOE contributing approximately 130 million. The four teams - Cummins/Peterbilt, Daimler, Volvo, and Navistar - are focusing on measures to improve the overall efficiency of long-haul Class 8 trucks to be demonstrated at the full-vehicle system level. Relative to an approximate 2010 baseline technology, the program seeks a 50 percent increase in overall tractor-trailer freight efficiency and a 20 percent increase in engine efficiency [i.e., achieving 50 percent brake thermal efficiency (BTE) relative to an approximate 42 percent baseline] by 2015. Two of the four SuperTruck teams – Cummins/Peterbilt and Daimler - have exceeded the program goals and will be providing U.S. DOE final reports on their projects by summer 2015. The other two teams, Navistar and Volvo, are on track to meet the program's goals in 2016. The technologies developed under the SuperTruck program are considered high-risk investments and without the program, they wouldn't be expected to begin entering the market over the next decade. Many of the technologies being demonstrated in SuperTruck are included in this technology assessment and are being evaluated by U.S. EPA as they develop the Phase 2 standards. Information published by the four teams regarding the FCR potential of specific technologies is referenced in this report (Gravel, 2015).

From 2011 to 2014, U.S. DOE invested $230 million in its Advanced Vehicle Research and Development plan in an effort to further accelerate the development of critical vehicle technologies. These investments include $55 million in 2014 focused on two major topic areas: fuel efficiency improvements in passenger vehicles and commercial trucks, and electric vehicles technologies. U.S. DOE funded projects, most of which are currently ongoing, include developing and demonstrating dual-fuel technologies, high-efficiency engine and powertrain systems, and advanced lubricants and coatings. For example, a joint project between U.S. automakers focusing on weight reduction led to the introduction of lightweight magnesium components and the development of a magnesium engine cradle which is 60 percent lighter than a steel cradle and 35 percent lighter than an aluminum cradle (U.S. DOE, 2010).

U.S. DOT is currently developing a pilot deployment program to test new and emerging connected vehicle technologies. The first wave of pilot deployments is set to start up in the fall of 2015 with the second wave beginning in 2017 (U.S. DOTb). Current connected vehicle projects are focused mostly on vehicle safety features, however, some potential pilot programs with environmental implications could include, but are not limited to, transit/freight signal priority systems and cooperative adaptive cruise control systems.

California is also helping to lead development and implementation of connected vehicle technologies. Caltrans and the auto industry have been testing connected vehicle technologies in real world traffic on a stretch of El Camino Real (State Route 82) in Palo Alto since 2005. They are also developing truck platooning technology and plan to test it on a Southern California freeway in 2016. Partners in this Federal Highway Administration funded program include California Partners for Advanced Transportation Technology, a research and development program of the University of California, Berkeley; Volvo; and Peloton Technology.

10. What are the next steps?

This technology assessment represents a crucial early step in the development of the California program to further control GHG emissions from heavy-duty trucks. Staff will use the results of this technology assessment as part of the technical foundation for the development of California's Sustainable Freight Strategy and State Implementation Plans, as well as for the development of California Phase 2 standards, with the goal of harmonizing with the federal program. Upon release of U.S. EPA's NPRM, staff will evaluate the federal proposal to determine if it fully addresses California's needs and advances progress in meeting the State's aggressive climate and air quality goals. After staff has had the opportunity to conduct a thorough evaluation of the federal proposal, they will be able to determine what, if any, program revisions may be necessary to address California's unique air quality and climate needs. In preparation of this, ARB has already begun engaging stakeholders in its own California Phase 2 rule development process with the intent of bringing a California proposal to the Board for consideration in late 2016 or early 2017.

The Phase 2 NPRM will provide updated FCR and cost information for many of the technologies evaluated in this report. Once released and the information is publically available, staff will reevaluate the FCR estimates in this report and evaluate the cost-effectiveness of the technologies expected to be implemented in response to the proposed Phase 2 standards. If staff determines that further cost-effective CO2 emission reductions are achievable by implementing additional technologies beyond those anticipated to be used to meet the Phase 2 standard requirements, staff may provide comments to that effect to U.S. EPA as part of the formal Phase 2 rulemaking process.

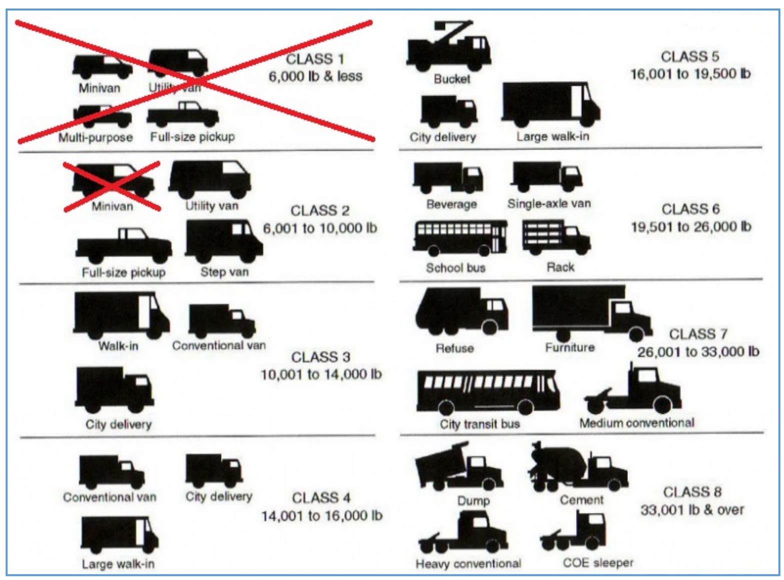
I. INTRODUCTION AND PURPOSE OF ASSESSMENT

ARB's long-term objective is to transform the on-and- off-road mobile source fleet into one utilizing zero and near-zero emission technologies to meet air quality and climate change goals. The focus of this technology assessment is to identify engine and vehicle technologies that can reduce fuel consumption and greenhouse gas (GHG) emissions from Class 2b through Class 8 on-road heavy-duty vehicles (gross vehicle weight of 8,501 pounds (lbs) and up), shown in Figure I-1. Cleaner combustion technologies reduce GHG and, in some cases, criteria pollutant emissions. Vehicle and drivetrain technologies reduce energy demand, thereby reducing both GHG and criteria emissions and making zero emission vehicles (ZEVs) more feasible.

These technology and fuels assessments support ARB planning and regulatory efforts, including:

- California's integrated freight planning,
- State Implementation Plan (SIP) development,
- Funding Plans,
- Governor's ZEV Action Plan, and
- California's coordinated goals for greenhouse gas and petroleum use reduction.

Figure I- 1: Truck Classes



The technologies assessed in this report are separated into two major categories:

1. Engine/Powerplant and Drivetrain Optimization Technologies (Engine Technologies); and
2. Vehicle and Trailer Efficiency Technologies (Vehicle Technologies).

In this report, each technology is assessed for its potential reduction in fuel consumption (which results in a corresponding reduction in GHG emissions) in consideration of cost and its state of commercial development.

The remainder of this section describes U.S. Environmental Protection Agency's (U.S. EPA) Phase 1 heavy-duty vehicle GHG standards. Section II of this report describes key engine and vehicle technologies that can reduce fuel consumption from Class 2b through Class 8 on-road heavy-duty trucks in the post-2020 timeframe. These technologies are discussed in more detail in Appendix A. Section III provides FCR estimates from a 2010 baseline for suites of key technologies applied to each of the six vehicle classifications. It provides estimates for the potential post-Phase 1 fuel consumption reductions that are still available after Phase 1 technologies are fully deployed. Section IV discusses demonstration projects and section V identifies potential next steps.

Heavy-duty vehicles are currently required to comply with the requirements of ARB Tractor-Trailer GHG regulation and U.S. EPA Phase 1 heavy-duty vehicle GHG standards. In 2008, the ARB approved the Tractor-Trailer GHG regulation, which became effective January 1, 2010. The regulation reduces the fuel consumption of long-haul tractor-trailers by improving the aerodynamic performance and reducing the rolling resistance of long-haul tractor-trailers. In 2011, U.S. EPA and the National Highway Traffic Safety Administration (NHTSA) adopted GHG emission standards for heavy-duty vehicles. These standards are referred to as “Phase 1” standards because of U.S. EPA’s and NHTSA’s intent to subsequently establish a second more stringent set of standards, referred to as Phase 2.

The Phase 1 standards were primarily designed to introduce off-the-shelf technologies in heavy-duty engines and vehicles. U.S. EPA created separate engine and vehicle standards. U.S. EPA/NHTSA anticipate that, to comply with the Phase 1 engine standards, most heavy-duty diesel engines will incorporate technologies that reduce engine friction, improve accessory efficiency, optimize fuel injection, and for combination tractor engines, add turbo compounding to recover some of the waste heat energy and convert it to mechanical power. To comply with the Phase 1 vehicle standards, heavy-duty tractors will use a combination of improved aerodynamics, reduced rolling resistance, weight reduction and automatic engine shut-off systems to reduce idling emissions. Vocational vehicles will rely mostly on reductions in rolling resistance, while heavy-duty pick-ups and vans will use reductions in rolling resistance, along with incremental improvements in transmission efficiencies, aerodynamics, and mass reduction (U.S. EPA, 2011c).

The 2010 baseline and Phase 1 vehicle standards for heavy-duty tractors and vocational vehicles, expressed as grams carbon dioxide (CO_2) reduction per ton-mile (gCO_2/ton-mile) are presented in Tables I-1 through I-4. For heavy-duty pick-ups and vans, the standards are expressed as CO_2 targets based upon the load capacity and production volume of each vehicle model. U.S. EPA estimates a 15 percent reduction in CO_2 emissions by 2018 for diesel-fueled vehicles and a 10 percent CO_2 reduction for gasoline-fueled vehicles (U.S. EPA, 2011d). The technologies to meet these standards are reflected in the 2017 model year compliant engine and vehicle.

Table I- 1: 2010 Baseline Combination Tractor CO_2 Emission Levels (gCO2/ton-mile)

	Class 7	Class 8	
	Day	Day	Sleeper
Low Roof	116	88	80
Mid Roof	128	95	89
High Roof	138	103	94

Table I- 2: Phase I HD Combination Tractor CO_2 Standards (gCO2/ton-mile)

	2014-2016 Model Year			2017+ Model Year		
	Class 7	Class 8		Class 7	Class 8	
	Day	Day	Sleeper	Day	Day	Sleeper
Low Roof	107	81	68	104	80	66
Mid Roof	119	88	76	115	86	73
High Roof	124	92	75	120	89	72

Table I- 3: 2010 Baseline Vocational Vehicle CO_2 Emission Levels (gCO2/ton-mile)

LHD Class 2b-5	MHD Class 6-7	HHD Class 8
408	247	236

Table I- 4: Phase I Vocational Vehicle CO_2 Standards (gCO2/ton-mile)

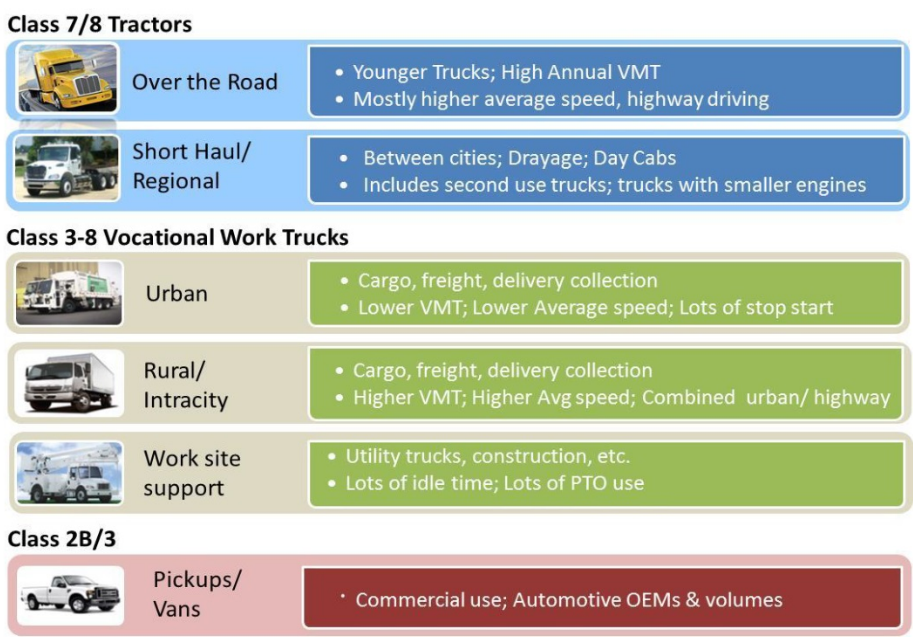
Model Year	LHD Class 2b-5	MHD Class 6-7	HHD Class 8
2014-2016	388	234	226
2017+	373	225	222

In contrast to the off-the-shelf technologies used to meet Phase 1 standards, the Phase 2 standards currently under development are expected to spur the further development of technology and will reflect anticipated technology advances in the post-2020 timeframe. U.S. EPA's NPRM for Phase 2 heavy-duty greenhouse gas standards is scheduled to be released in the spring of 2015. Many of the technologies that are the subject of this technology assessment are also being evaluated by U.S. EPA in setting the Phase 2 standards.

Core questions staff sought to answer for each identified technology include:

- How does the technology work?
- What, if any, implementation issues or challenges exist?
- What is the potential fuel consumption reduction (FCR)? The FCR is expressed as the percent reduction from a 2010 baseline engine. Section III provides an estimate of the potential FCR still available after Phase 1 technologies are deployed as part of 2017 MY heavy-duty vehicles.
- What is the technology readiness level (research and development, prototype, demonstration, introduced commercially, or widely commercially available)?
- To which vehicle classes are the specific technologies applicable? Classes are based on the California Hybrid, Efficient and Advanced Truck (CalHEAT) Research Center vehicle classifications shown in Figure I-2.

Figure I- 2: CalHEAT Vehicle Classifications for Class 2b-8 Heavy-Duty Vehicles



II. OVERVIEW OF ENGINE AND VEHICLE TECHNOLOGIES

Table II-1 identifies the key engine and vehicle technologies that can reduce fuel consumption from Class 2b through Class 8 heavy-duty vehicles in the post-2020 timeframe, and include the FCR for each. The technologies summarized in Table II-1 are separated into two categories: Engine/Powerplant and Drivetrain Optimization Technologies (Engine Technologies), and Vehicle/Trailer Efficiency Technologies (Vehicle technologies). Gasoline technologies used in heavy-duty pick-ups and vans are presented and discussed within the Engine Technologies category. Staff conducted a thorough literature search and review for each technology listed. A detailed summary of the staff's findings for each technology can be found in Appendix A. There is a subset of engine technologies that are identified as "future engine technologies". These technologies are all in the research and development stage.

The goal of this assessment was to assess the potential fuel consumption benefit of these technologies from a 2017 baseline vehicle. However, most of the information found in staff's literature search discussed fuel consumption benefits from a typical 2008 through 2010 model year diesel engine. (A detailed description of the technologies used in a 2010 baseline engine is contained in Section III.) Therefore, to approximate the benefit from a 2017 baseline, staff assessed the potential benefit of a suite of key technologies for defined truck categories from a 2010 baseline. Then, staff subtracted out the benefits gained from the Phase 1 rule for that vehicle category. The remaining benefits approximate the potential future reductions available after full implementation of the Phase 1 rule in 2017.

<u>NOx/GHG (fuel efficiency) Trade-Off</u>

One of the concerns associated with the implementation of these technologies is their impact on NOx emissions. The potential tradeoff between reducing fuel consumption and reducing NOx emissions is well known. Technologies that reduce fuel consumption by improving combustion efficiency typically result in increased combustion temperatures which may result in higher engine out NOx emissions. However, the presence of aftertreatment technologies on the vehicle can mitigate the increase in NOx emissions from the engine. For engines that run lean (e.g., diesel engines), selective catalytic reduction (SCR) systems are used to control NOx emissions. For stoichiometric engines (e.g., gasoline or natural gas engines), three-way catalysts are used. Both aftertreatment devices can be designed for the optimization of the engine for fuel efficiency while ensuring NOx emission compliance.

While aftertreatment systems are crucial for meeting future more stringent NOx standards, some of the technologies that reduce fuel consumption may also have the potential to reduce engine-out NOx emissions or improve the conversion efficiency of NOx aftertreatment systems. Low-temperature combustion cycle engines (e.g. homogeneous charge compression ignition - HCCI, premixed charge compression ignition - PCCI, and reactivity charge compression ignition - RCCI) have the potential to reduce engine out NOx without relying solely on SCR systems to meet stringent NOx standards. Technologies that result in the retention of exhaust heat energy during periods of low-load/low-speed operation (e.g. stop-start); or provide efficiency gains during periods of high temperature combustion (e.g. cylinder deactivation) have the greatest potential for improving FCR without increasing NOx emissions in the presence of an aftertreatment system. In the future, radically different engine designs offer potential engine-out NOx reduction inherent in their design and operation. For example, the natural exhaust gas retention inherent in opposed-piston engines reduces pumping work while controlling NOx at low loads. Further discussion of the NOx and GHG (fuel efficiency) trade-off can be found in the ARB companion report Technology Assessment: Lower NOx Heavy-Duty Diesel Engines.

Table II- 1: Key Technologies Evaluated*

	Key Technologies	Potential FCR[1]	Technology Readiness[2]	Applicability (Vehicle Classes)
Engine Technologies	Advanced Transmissions and Engine Downspeeding	0-10%	Introduced Commercially	All Classes
	Waste Heat Recovery	2.5-8%	Technology Dependent	Class 8 Long Haul Tractor
	Engine Downsizing	1-4.5%	Introduced Commercially	All Classes
	Stop-Start	5-10%	Introduced Commercially	Class 7/8 Short Haul; Class 3-8 Urban Vocational; Class 2b/3
	Automatic Neutral Idle	N/A	Introduced Commercially	Class 3-8 Urban, Rural, Worksite Support Vocational; Class 2b/3
	Combustion and Fuel Injection Optimization	1-4%	Introduced Commercially	Class 7/8 Long Haul Tractor and Short Haul; Class 3-8 Urban, Rural, and Worksite Support Vocational; Class 2b/3
	Higher-Efficiency Aftertreatment	1-4%	Introduced Commercially	Class 7/8 Long Haul Tractor and Short Haul; Class 3-8 Urban, Rural, Worksite Support Vocational; Class 2b/3
	Reduced Friction	0.5-4%	Introduced Commercially	All Classes
	Auxiliary Load Reduction	0.5-4%	Demonstration	All Classes

	Key Technologies	Potential FCR[1]	Technology Readiness[2]	Applicability (Vehicle Classes)
Engine Technologies (cont.)	Air Handling Improvements (Turbocharging, EGR, Variable Value Actuation)	1-4.5%	Widely Commercial	Class 7/8 Long Haul Tractor and Short Haul; Class 3-8 Vocational Urban, Rural, Worksite Support; Class 2b/3
	Cylinder Deactivation	2-3%	Widely Commercial	Class 2b/3
	Stoichiometric GDI	2-3%	Widely Commercial	Class 2b/3
	Lean-Burn GDI	10-14%	Introduced Commercially	Class 2b/3
Future Engine Technologies	*Camless Engines*	N/A	Research and Development	All Classes
	Opposed Piston Engines	N/A	Research and Development	All Classes
	Free Piston Engines	N/A	Research and Development	All Classes
	Low Temperature Combustion Cycles (HCCI/PCCI/RCCI)	Up to 20%	Research and Development	All Classes
Vehicle Technologies	Aerodynamics	3-16%	Widely Commercial	Class 7/8 Long Haul Tractor; Class 3-8 Rural; Class 2b/3
	Lightweighting	0.75 - 3.2%	Introduced Commercially	All classes to a varying degree with an increased benefit for smaller vehicle classes

	Key Technologies	Potential FCR[1]	Technology Readiness[2]	Applicability (Vehicle Classes)
Vehicle Technologies (continued)	Low-Rolling Resistance Tires	1-14%	Widely Commercial	All classes; better FCR in applications with higher speeds
	Automatic Tire Inflation	1%	Widely Commercial	All classes
	Vehicle Speed Limiters	0.7-1% per mph reduction	Widely Commercial	Class 8 Long Haul Tractor
	Axle Efficiency Improvements	2.5%	Widely Commercial	Class 8 Long haul; Class 8 Short Haul; Class 3-8 Urban, Rural, Worksite Vocational
	Idle Reduction	1.3%-9%	Technology Dependent	Class 8 Long Haul Tractor
	Improved Air Conditioning Systems	~ 1%	Technology Dependent	All Classes
	Connected Vehicles			
	Predictive Cruise Control	1%-3%	Introduced Commercially	Class 8 Long Haul Tractor
	Platooning	10%-21%	Demonstration	Class 8 Long Haul Tractor

N/A = Not Available
*See appendix for references and a more detailed discussion of each technology
1. Fuel Consumption Reduction Estimate based on a 2010 baseline.
2. “Technology Dependent” means the technology category refers to more than one specific technology and that they have differing technology readiness classifications. Please see Appendix A for the specific technology readiness classifications for each specific technology.

III. FUEL CONSUMPTION REDUCTION POTENTIAL FOR TECHNOLOGY SUITES BY CLASS

When used in the applicable truck classifications, technologies presented in Section II (discussed in more detail in Appendix A) significantly reduce fuel consumption and GHG emissions. The following section identifies the suites of technologies that are applicable to each of the CalHEAT truck categories. Using the results from the literature search, staff estimated the FCR associated with each technology, and provided an estimate for the potential reduction in fuel consumption through the application of these technologies on 2017 model year compliant vehicles. Staff believes most of these technologies could be in use by 2025.

The technologies identified each have a percent fuel reduction associated with them. The overall percent FCR estimated for a suite of technologies is not assumed to be additive, but is assumed to the combined percentage (one technology reduces the emissions remaining after the previous technology was applied, etc.), which is the methodology used by the National Academy of Sciences (NAS) (NAS, 2010).

It is important to note that although a cost analysis is not included as part of this report, the costs associated with each technology will be offset in whole or part by the cost savings associated with reduced fuel consumption. The U.S. EPA's NPRM for the Phase 2 rulemaking will provide peer-reviewed technology costs estimates for the suites of technologies similar to those identified in this technology assessment for the 2020 through 2030 timeframe. Once the NPRM is released and the technology cost information is publically available, staff will evaluate the cost-effectiveness of the technologies expected to be implemented in response to the proposed Phase 2 standards. If staff determines that further cost-effective FCR's are achievable by implementing additional technologies beyond those used to meet the Phase 2 standard requirements, staff will provide comments to that effect to US EPA as part of the formal Phase 2 rulemaking process.

A. TECHNOLOGY SUITES BY VEHICLE CLASS

1. Heavy-Duty Class 7-8 Tractors

Heavy-duty class 7 and 8 tractors are segregated into two categories: long haul tractors and short haul or regional tractors. Long haul tractors are typically sleeper cab tractors that have annual vehicle miles traveled (VMT) over 100,000 miles. Most of their miles are traveled at highway speeds. Short haul and regional tractors typically have lower annual VMT than long haul tractors, spending more time traveling on city streets making local deliveries. Examples include drayage tractors and local delivery day cab tractor-trailers. It is important to note that the benefits associated with the long haul and short haul or regional tractor technology suites are largely based on how the tractor is used. To that extent, the FCR benefit of a technology installed on a long haul tractor may not continue to be realized if that same tractor is used later in short haul service.

Long Haul Tractors

The two main areas of energy loss associated with long haul tractors are engine and aerodynamic losses. The remaining sources of energy loss include rolling resistance, auxiliary loads, drivetrain, braking, and idling as shown in Figure III-1.

Figure III- 1: Sources of Energy Loss for Long Haul Tractors

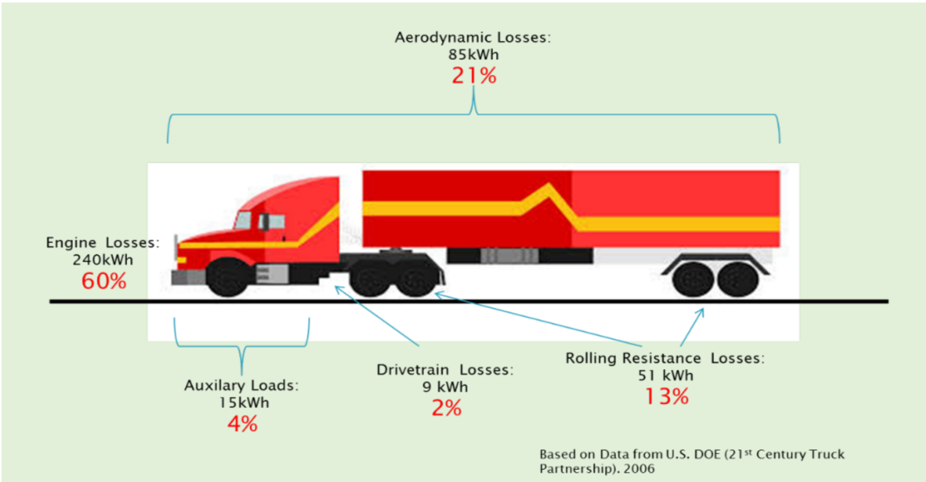


Table III-1 identifies the key technologies applicable to long haul tractors (and trailers) that address all of the above areas of energy loss.

Table III- 1: Key Technologies for Heavy-Duty Long Haul Tractor-Trailers

	Key Technologies	FCR Benefit (%) (2010 Baseline)
Engine Technologies	Combustion and Fuel Injection Optimization	1%-4%
	Air Handling Improvements	1%-4.5%
	Reduced Friction	1%-4%
	Downsizing	1%-4.5%
	Higher Efficiency Aftertreatment	2%-4%
	Waste Heat Recovery	2%-8%
	Advanced Transmissions/ Engine Down Speeding	2%-8%
	Auxiliary Load Reduction	0.5%-4%
Vehicle Efficiency Technologies	Aerodynamics	9%-16%
	Low-Rolling Resistance Tires	2%-14%
	Automatic Tire Inflation Systems	1%
	Predictive Cruise Control	1%-3%
	Axle Efficiency	2.5%
	Idle Reduction	1%-9%
	Air Conditioning System Improvements	1%
Totals		**25%-60%**

As shown in Table III-1, staff estimates that for long haul tractor-trailers, the total reduction in fuel consumption available from the application of the technologies listed is 25 to 60 percent per tractor-trailer. The FCR estimates are measured from a 2010 baseline vehicle. The largest potential benefits come from improved aerodynamics (9 to 16 percent), low-rolling resistance tires (2 to 14 percent) and waste heat recovery (2 to 8 percent). Aerodynamics and low-rolling resistance tires would achieve the greatest benefit in long-haul applications where a fully aerodynamic sleeper cab tractor-trailer is equipped with wide-base low-rolling resistance tires. Waste heat recovery (WHR) systems based on the Rankine cycle are being demonstrated as part of the SuperTruck program (discussed in Section IV). WHR systems show the potential to reduce fuel consumption by up to 10 percent. Lightweighting was not included in Table III-1 due to the significant amount of weight that must be removed to achieve minimal FCR improvements. Advanced Combustion Cycles (i.e. low temperature combustion (LTC) strategies, including RCCI, PCCI, and HCCI), have the potential for up to a 20 percent FCR, but were not included in Table III-1. These technologies were excluded because they have not yet been demonstrated on a long haul tractor application. However, they may become commercially ready in the near future as the SuperTruck teams continue to evaluate technologies (such as LTC) that will achieve the goal of 55 percent brake thermal efficiency.

Recent interviews of fleet owners and manufacturers (22 total companies) conducted by the International Council on Clean Transportation (ICCT) illustrate the cost effectiveness of van trailer aerodynamic devices and the acceptance by the trailer industry. Table

III-2 is a summary of these interview responses for van trailer aerodynamic technology costs and levels of adoption. The average tractor-trailer ratio of the fleets interviewed was 2.7 (ICCT, 2014).

Table III- 2: Summary of Interview Responses on Trailer Technology Levels of Adoption

<table>
<tr><th>Technology</th><th>Fuel Savings</th><th>Typical payback time</th><th>Adoption in New Trailer Sales</th></tr>
<tr><td>Side skirts - average</td><td>3%</td><td>1-2 years</td><td rowspan="2">40%</td></tr>
<tr><td>Side Skirts - best</td><td>7%</td><td><1 year</td></tr>
<tr><td>Boat tails - average</td><td>3%</td><td>2-3 years</td><td rowspan="2">3%</td></tr>
<tr><td>Boat tails - best</td><td>5%</td><td>1-2 years</td></tr>
<tr><td>Gap reducers</td><td>1%-2%</td><td>2-5 years</td><td>Minimal</td></tr>
<tr><td>Underbody devices</td><td>2%-5%</td><td>2-5 years</td><td>3%</td></tr>
</table>

<u>Short Haul/Regional Tractors</u>

Short haul or regional class 7 and 8 tractors typically are used to transport freight locally. Because they are not used to haul freight long distances, most are day cab tractors. Many are used as drayage tractors or local delivery tractors that make several delivery stops per day. Typically, short haul or regional tractors operate less than 100,000 miles per year and travel at slower average speeds than their long haul counterparts.

Table III-3 identifies the key technologies applicable to short haul or regional tractors and the associated FCR benefit.

Table III- 3: Key Technologies for Heavy-Duty Short Haul/Regional Tractor-Trailers

	Key Technologies	FCR Benefit (%) (2010 Baseline)
Engine Technologies	Combustion and Fuel Injection Optimization	1%-4%
	Air Handling Improvements	1%-4.5%
	Reduced Friction	1%-4%
	Downsizing	1%-2%
	Higher Efficiency Aftertreatment	1%-2%
	Advanced Transmissions/ Engine Downspeeding	0%-8%
	Auxiliary Load Reduction	1%-3%
	Stop-Start	5%-10%
Vehicle Efficiency Technologies	Aerodynamics	2%-5%
	Low-Rolling Resistance Tires	2%-14%
	Automatic Tire Inflation Systems	1%
	Axle Efficiency	2.5%
	Air Conditioning Improvements	1%
Totals		**18%-47%**

Staff estimates that for short haul/regional tractors, the total reduction in fuel consumption available from the application of the technologies listed is 18 to 47 percent (2010 baseline).

Although many of the key technologies listed are the same technologies identified for long haul tractors, both the FCR potential and the cost estimates are lower for short haul tractors than long haul tractors. This is primarily due to the reduction of aerodynamic improvements (2 to 5 percent), the exclusion of waste heat recovery (2 to 8 percent), and removal of overnight idling reduction technologies (1 to 9 percent) from the short haul tractor technology lists. Both aerodynamic improvements and waste heat recovery result in the largest benefits when the truck duty cycle spends the vast majority of vehicle miles traveled at freeway speeds. Short haul tractors spend a significant amount of their vehicle miles traveled on urban roadways and therefore staff reduced or excluded these two technologies from the category as a whole. The aerodynamic technologies applicable to short haul were assumed to be limited to tractor improvements (i.e., roof fairing, aerodynamic hood, aerodynamic bumper, aerodynamic mirrors, and fuel tank fairings). Additional differences between the long haul and short haul tractor technology mix includes the addition of stop-start technologies (5 to 10 percent) for short haul applications. Stop-start was added due to the nature of their short haul duty cycle, which includes a significant amount of stop and go driving. Another difference is the cost and effectiveness of advanced transmission/downspeeding technologies. Automated manual transmissions are more applicable to long haul tractor applications where shifting is less frequent. Advanced automatic transmission technologies are more applicable to short haul applications and preferred by drivers because of smoother shifting at low speeds due, in part, to their power shift abilities.

2. Heavy-Duty Class 3-8 Vocational Work Trucks

Heavy-duty Class 3 through 8 vocational work trucks are segregated into three categories based on how they are used: urban vocational work trucks, rural/intercity trucks, and worksite support trucks. Both urban and rural/intercity trucks are primarily used for hauling and delivering freight, as well as collection (i.e., garbage trucks). Urban trucks typically have lower VMTs, lower average speed, and more "stop-start" activity than their rural/intercity counterparts. Worksite support trucks are typically utility or on-road construction-related trucks (i.e., boom trucks) where a significant amount of time is spent at idle as a result of power-take-off use.

Urban Vocational Work Trucks and Worksite Support Trucks

Table III-4 identifies the key technologies applicable to both urban vocational work trucks and worksite support trucks, and lists the associated FCR benefits.

Table III- 4: Key Technologies for Heavy-Duty Class 3-8 Urban Vocational Work/Worksite Trucks

	Key Technologies	**FCR Benefit (%) (2010 Baseline)**
Engine Technologies	Combustion and Fuel Injection Optimization	1%-4%
	Air Handling Improvements	1%-4.5%
	Reduced Friction	1%-4%
	Downsizing	1%-2%
	Higher Efficiency Aftertreatment	1%-2%
	Advanced Transmissions/Engine Downspeeding	2%-10%
	Auxiliary Load Reduction	1%-3%
	Stop-Start	5%-10%
Vehicle Efficiency Technologies	Lightweighting	3.2%
	Low-Rolling Resistance Tires	2.5%
	Automatic Tire Inflation Systems	1%
	Axle Efficiency	0%-2.5%
	Air Conditioning System Improvements	1%
Totals		**19%-40%**

Urban vocational work trucks and worksite support trucks share enough common characteristics such that the suite of key technologies evaluated in this technology assessment is identical. However, staff believes that the differences in duty cycles between these two categories of trucks will result in differing levels of fuel consumption benefits due to the inclusion of hybrid technology. There is a separate technology assessment report addressing hybrid technology, so hybrid technologies are not included in this assessment. The National Academy of Sciences estimates that 25 to 40 percent fuel consumption gains can result from the application of hybrid technologies in vocational work trucks, with the largest potential gains coming from the worksite support truck category.

Both truck categories operate at lower speeds and generally travel less miles per year than their rural/intercity counter parts. However, there are distinct differences between urban vocational trucks and worksite trucks. Worksite trucks spend a lot of time at idle, powering equipment through power-take-off interfaces. Urban vocational trucks spend a lot of time traveling at slow speeds and include many stop-start applications.

As shown in Table III-4, staff estimates that for urban vocational trucks and worksite support trucks, the total reduction in fuel consumption available from the application of the technologies listed is 19 to 40 percent. The largest potential fuel consumption improvements come from the application of stop-start technologies and advanced transmissions and downspeeding.

As urban and worksite vocational vehicles travel most of their miles on city roads making frequent stops, significant fuel consumption gains can be had through technologies that reduce engine load at idle. Stop-start technology turns the engine off at idle. This reduces fuel consumption and facilitates the retention of exhaust heat in the SCR system which can improve the NOx conversion efficiency of the SCR system. Stop-start technology can reduce fuel consumption 5 to 10 percent, depending on the vehicle's duty cycle during actual operation. An alternative to stop-start technology is auto neutral idle technology, which effectively shifts the vehicle into neutral at stops and reduces the idling load of the engine while leaving the engine on during stops. However, the potential FCRs associated with neutral idle are less than for stop-start, and neutral idle technology may result in the cooling of the SCR catalyst at idle operation.

The advanced transmission technologies for urban vocational vehicles and worksite support trucks include advanced automatic transmissions and dual clutch technologies. Both types of transmissions allow the vehicle to shift under power which improves both drivability and fuel efficiency of the vehicle. Advanced transmission gearing and shift logic allows for downspeeding. By downspeeding, the engine generates the required horsepower at lower engine speeds and higher torques than would occur through use of a standard transmission. Downspeeding results in FCR benefits due to reduced engine friction at lower piston speed, reduced relative heat transfer, and increased thermal efficiency of the engine. Lightweighting was not included for the Class 8 tractor assessment due to minimal FCR gains; however, lightweighting can result in significant FCR benefits for smaller, lower classes. For class 3-6 vocational vehicles, a 3.2 percent FCR benefit can be achieved. It should be noted however, that as diverse as the class 3-8 vocational truck sector is, this FCR benefit will vary significantly and likely will not be cost effective for the larger classes. For simplicity, staff determined it best to apply the 3.2 percent FCR benefit to the whole truck sector and note the caveat for larger truck classes.

Table III- 5: Fuel Consumption Reduction from Lightweighting (TIAX, 2009)

Truck Class	FCR (%)	Weight Reduction (lbs)
8	1.25	2500
3-6	3.2	1000

Rural/Intercity Trucks

Table III-6 identifies the key technologies applicable to rural/intercity vocational work trucks and the associated FCR benefit.

Table III- 6: Key Technologies for Heavy-Duty Class 3-8 Rural/Intercity Vocational Work Trucks

	Key Technologies	FCR Benefit (%) (2010 Baseline)
Engine Technologies	Combustion and Fuel Injection Optimization	1%-4%
	Air Handling Improvements	1%-4.5%
	Reduced Friction	1%-4%
	Downsizing	1%-2%
	Higher Efficiency Aftertreatment	1%-2%
	Advanced Transmissions/Engine Downspeeding	2%-10%
	Auxiliary Load Reduction	1%-3%
Vehicle Efficiency Technologies	Aerodynamics	4%-6%
	Lightweighting	3.2%
	Low-Rolling Resistance Tires	3%
	Automatic Tire Inflation Systems	1%
	Axle Efficiency	0%-2.5%
	Air Conditioning System Improvements	1%
Totals		**18.5%-38%**

Staff estimates that for rural/intercity trucks, the total reduction in fuel consumption available from the application of the technologies listed is 18.5 to 38 percent (2010 baseline). The largest potential fuel consumption benefits come from aerodynamic improvements and advanced transmissions. Aerodynamic technologies, including side skirts and roof fairings or nose cones, would greatly reduce the drag of straight trucks used in intercity delivery operations. As with urban trucks, advanced transmission technologies could also result in potentially significant FCRs due to increased shift efficiency and downspeeding.

Heavy-Duty Class 2b/3 Pickups and Vans

Unlike the heavy-duty class 3 through 8 vocational work trucks, the majority of class 2b and 3 pickups and vans are powered by gasoline engines. For this category, ARB staff developed separate lists for key technologies for gasoline and diesel engine vehicles. Table III-7 identifies the key technologies applicable to gasoline-powered pickups and vans and the associated FCR benefit. Table III-8 is a similar table for diesel-powered pickups and vans. Noticeably missing from the list of technologies is hybrids. There is a separate technology assessment report addressing hybrid technology (Technology Assessment: Heavy-Duty Hybrid Vehicles), so hybrid technologies are not included in this assessment. The National Academy of Sciences estimates that fuel consumption can be reduced 18 percent fuel consumption through the application of hybrid technologies in heavy- duty pick-ups and vans.

Table III- 7: Key Technologies for Heavy-Duty Class 2b and 3 Pickups and Vans (Gasoline)

	Key Technologies	FCR (%) (2010 Baseline)[1,2,3,4]
Engine Technologies	Reduced Friction[1]	1%-4%
	VVA[2]	1%-3%
	Cylinder Deactivation[3]	2%-3%
	Stoichiometric GDI[4]	2%-3%
	Downsizing (w/ turbocharger)	1%-2%
	Advanced Transmissions/Engine Downspeeding	2.7%-9.5%
	Auxiliary Load Reduction	1%-3%
	Stop-Start	5%-10%
Vehicle Efficiency Technologies	Aerodynamics	3%
	Lightweighting	0%-0.75%
	Low-Rolling Resistance Tires	1%-2%
	Automatic Tire Inflation Systems	1%
	Air Conditioning System Improvements	1%
Totals		**20%-37%**

[1,2,3,4] - The benefits associated with the first four technologies listed:1) reduced friction, 2) variable valve actuation, 3) cylinder deactivation, and 4) stoichiometric GDI engines represent the incremental benefit of each technology building on the next technology. For example, the benefit of cylinder deactivation is 2 to 3 percent improvement over a port-injected, naturally aspirated engine that has variable valve actuation and reduced friction. The benefits for the remaining technologies are relative to a stoichiometric GDI engine baseline.

As shown in Table III-7, staff estimates that for gasoline pick-ups and vans the total reduction in fuel consumption available from the application of the technologies listed is 20 to 37 percent (2010 baseline). The largest potential fuel consumption improvements come from the application of stop-start technologies and advanced transmissions. Lean burn GDI engine technology has the greatest potential for FCR for gasoline engines at 10 to 14 percent, but was not included in Table III-7 due to difficulties in meeting NOx emissions regulations during long periods of lean burn operation. .

Table III- 8: Key Technologies for Heavy-Duty Class 2b and 3 Pickups and Vans (Diesel)

	Key Technologies	FCR Benefit (%) (2010 Baseline)
Engine Technologies	Combustion and Fuel Injection Optimization	1%-4%
	Air Handling Improvements	1%-4.5%
	Reduced Friction and Auxiliary Load Reduction	1%-4%
	Downsizing	1%-2%
	Higher Efficiency Aftertreatment	1%-2%
	Advanced Transmissions/Engine Downspeeding	2.7%-9.5%
	Auxiliary Load Reduction	1%-3%
	Stop-Start	5%-10%
Vehicle Efficiency Technologies	Aerodynamics	3%
	Lightweighting	0%-0.75%
	Low-Rolling Resistance Tires	1%-2%
	Automatic Tire Inflation Systems	1%
	Air Conditioning System Improvements	1%
Totals		**18%-38%**

As shown in Table III-8, staff estimates that for diesel pick-ups and vans, the total reduction in fuel consumption available from the application of the technologies listed is 18 to 38 percent (2010 baseline). As with gasoline pick-ups and vans, the largest potential fuel consumption improvements come from the application of stop-start technologies and advanced transmissions. Additionally, these diesel-powered pick-ups and vans rely on some of the same diesel engine and vehicle technologies as their larger counterparts; namely air handling improvements, turbocharger efficiency improvements, and higher efficiency after treatment SCR and diesel particulate filter (DPF) systems.

Comparison to Phase 1

The percent FCR totals presented above represent the potential fuel FCRs that are available from 2010 baseline vehicles. As discussed earlier in this report, U.S. EPA established Phase 1 GHG emissions standards that improve upon this 2010 baseline. In the following paragraphs, staff compares the potential FCRs identified in this technology assessment to the potential fuel consumption benefits that U.S. EPA estimated from implementation of the Phase 1 rule. The difference in the FCR from Phase 1 and this technology assessment represents the starting point for the evaluation of the potential FCRs that could be achieved via Phase 2 standards.

Phase 1 standards are fully implemented for most heavy-duty vehicles by the 2017 model year (2018 model year for Class 2b-3). Table III-9 summarizes the estimated potential FCR percentages resulting from full implementation of the Phase 1 standards.

Table III- 9: Estimated Phase 1 Fuel Consumption Reduction from 2010 baseline

Category	Phase 1 FCR from Baseline
Heavy-Duty Tractor-Trailer (Class 7-8) (Long Haul)	17%-24%
Heavy-Duty Tractor-Trailer (Class 7-8) (Short Haul)	10%-14%
Heavy-Duty Vocational (Class 3-8)	6%-9%
Heavy-Duty Pick-Ups and Vans	10% (gas) 15% (diesel)

In establishing the engine and vehicle standards on which these potential reductions are based, U.S. EPA derived baseline engine and vehicle configurations for each heavy-duty truck category by examining engines and vehicles in the fleet which represent the typical 2010 model year vehicle and engine. Table III-10 describes the 2010 model year baseline engine and vehicle configurations and identifies the technologies that, when applied to these vehicles, would result in compliance with the Phase 1 standards.

The Phase 1 technologies listed in Table III-10 are also included in this technology assessment because staff believes further development of these technologies over the next five years will result in an increase in their FCR potential.

Table III- 10: Phase 1 Baseline Technologies (2010); Phase 1 Technologies (establishing 2017 baseline) (U.S. EPA, 2011c)

Category	2010 Baseline	Phase 1 Technologies
Heavy-Duty Tractor-Trailer (Class 7-8)	Engine • Electronic control • SCR/EGR/DPF exhaust aftertreatment which achieves 2010 MY criteria emission standards • Turbocharged with variable geometry turbocharger • 2200 BAR injection pressure • Single overhead valve • Belt driven accessories Vehicle • Conventional aerodynamic tractor	Engine • Improvement in cylinder and exhaust manifold design, turbo efficiency, fuel pump efficiency, fuel injector optimization, H2O pump efficiency, engine friction reduction, turbocompounding Vehicle • Improvement in aerodynamics, rolling resistance reduction, weight reduction • NO TRAILER IMPROVEMENTS
Heavy-Duty Vocational (Class 3-8)	Engine • (Same as above)	Engine • (same as above) Vehicle • rolling resistance reduction
Heavy-Duty Pick-Ups and Vans	Engine (gasoline) • V8 • Electronic control • Naturally aspirated • Fixed valve timing Engine (diesel) • 2010 compliant • Electronic control • 6 speed automatic transmission	Engine (gasoline) • Low friction lubes, engine friction reduction, Stoichiometric GDI, 8 speed automatic, improved accessories, electric power steering, mass reduction, A/C Engine (diesel) • Low friction lubes, * speed automatic, aerodynamics, after treatment optimization mass reduction, A/C Vehicle Aerodynamic improvements, rolling resistance reduction

To estimate the potential for further reduction in fuel consumption from heavy-duty vehicles, staff subtracted out the Phase 1 FCR benefits (Table III-9) from the potential FCR benefits identified in this technology assessment. The difference is an indicator of the potential FCRs and potential incremental cost associated with future, more stringent engine and vehicle standards. To utilize the Phase 1 category results for the more segregated CalHEAT categories, staff calculated maximum and minimum FCR values for five Phase 1 categories: heavy-duty tractor-trailer long haul, heavy-duty tractor-trailer short haul, vocational, diesel-fueled pick-ups and vans, and gasoline-fueled pick-ups and vans. For the vocational vehicle classes, staff weighted the FCR percentages by the percentage contribution of each truck class category to overall CO_2 emissions (CalHEAT, 2013).

Tables III-11 to III-15 show the potential for fuel consumption improvement for each of the five Phase 1 vehicle categories: Heavy-Duty Tractor-Trailer (Class 7-8) (Long Haul), Heavy-Duty Tractor-Trailer (Class 7-8) (Short Haul), Heavy-Duty Vocational (Class 3-8), Heavy-Duty Diesel Pick-ups and Vans (Class 2b-3), and Heavy-Duty Gasoline Pick-ups and Vans (Class 2b-3). The first row in each table labeled “Tech Assessment” shows the potential FCR from implementing the suites of technologies identified in this technology assessment. The second row labeled “Phase 1” shows the potential FCR benefit from implementation of the Phase 1 rule. The third row labeled “Difference” shows the incremental Post-Phase 1 FCR benefits from implementing the full suite of technologies identified for each category.

As shown in Tables III-11 through III-15, additional fuel consumption improvements of up to 36 percent and 30 percent, respectively, are potentially available for the tractor-trailer and vocational sectors, with a potential 27 percent reduction available from the class 2b/3 sector.

Table III- 11: Heavy-Duty Tractor-Trailer (Class 7-8) Long Haul Potential Additional FCR Post-Phase 1

	Potential FCR
Tech Assessment	25% - 60%
Phase 1	17%- 24%
Difference	**8%-36%**

Table III- 12: Heavy-Duty Tractor-Trailer (Class 7-8) Short Haul Potential Additional FCR Post-Phase 1

	Potential FCR
Tech Assessment	18% - 47%
Phase 1	10%- 14%
Difference	**8%-33%**

Table III- 13: Potential Heavy-Duty Vocational (Class 3-8) Additional FCR Post-Phase 1

	Potential FCR
Tech Assessment	19%-39%
Phase 1	6%-9%
Difference	**13%-30%**

Table III- 14: Heavy-Duty Diesel Pick-ups and Vans (Class 2b-3) Potential Additional FCR Post-Phase 1

	Potential FCR
Tech Assessment	18%-38%
Phase 1	15%
Difference	**3%-23%**

Table III- 15: Heavy-Duty Gasoline Pick-ups and Vans (Class 2b-3) Potential Additional FCR Post-Phase 1

	Potential FCR
Tech Assessment	20%-37%
Phase 1	10%
Difference	**10%-27%**

IV. Demonstration Projects

U.S. Department of Energy (U.S. DOE) has two significant truck technology demonstration projects underway: The SuperTruck Program and the Advanced Vehicle Research and Development Plan. Additionally, the U.S. Department of Transportation (U.S. DOT) is also investing significant resources into establishing a nation-wide connected vehicle program.

SuperTruck Program

U.S. DOE SuperTruck Program demonstrates the FCR potential for long haul tractor-trailers. The program set efficiency goals for both engines and vehicles. For engine efficiency, the goal was to achieve 50 percent brake thermal efficiency (BTE) by 2015. The baseline engine was representative of a 2009 model year engine which typically had a BTE of about 42 percent. The vehicle efficiency goal was to demonstrate a 50 percent improvement in freight efficiency by 2016. Freight efficiency is expressed as ton-miles/gallon. A 50 percent improvement in freight efficiency is equivalent to a 33 percent improvement in load specific fuel consumption (ICCT, 2013c).

To date, U.S. DOE has awarded approximately $130 million distributed amongst four SuperTruck teams: Cummins (with a Peterbilt tractor body); Daimler; Navistar; and Volvo. Each team was required to contribute matching funds. Table IV-1 presents the strategies that each team was investigating to meet the SuperTruck program goals in 2013 (ICCT, 2013c).

Table IV- 1: Original SuperTruck Team Strategies (2013)

Strategy	Cummins	Daimler	Navistar	Volvo
Engine Downsize	NO	YES	NO	YES
Engine Down-speeding	YES	YES	NO	YES
Transmission	AMT	AMT	Dual-Mode Hybrid[1]	DCT
Hybridization	NO	Mild	Full[1] (series/parallel)	NO
Waste Heat Recovery	YES (mechanical)	YES (electric)	NO	YES
Turbocompounding	NO	NO	YES (electric)	YES (mechanical)

1. By 2015, dual-mode/full hybrid approach was replaced with non-hybrid waste heat recovery approach (Gravel 2015)

Each team started out emphasizing different areas. Cummins put emphasis on improving engine efficiency by integrating improved component technologies in the overall combustion process and aftertreatment systems and recapturing exhaust energy via a waste heat recovery system. Daimler explored engine downsizing and hybridization. Navistar had worked to improve tractor-trailer aerodynamics and hybridization. Volvo had focused on improving truck and engine efficiency integration. Transmission efficiency had been a focus of all four teams with Cummins and Daimler incorporating automated manual transmissions and Volvo incorporating a dual clutch transmission. Navistar and Daimler were also evaluating hybrid technology applications. Daimler evaluated a parallel mild hybrid system that can provide propulsion and generate electrical power through regenerative braking. Navistar evaluated a more substantial series hybrid system where the electric motor can propel the vehicle at speeds less than 50 miles per hour and work in parallel with the engine at higher speeds. (An in-depth evaluation of hybrid and hybrid related technologies can be found in the ARB companion report Technology Assessment: Heavy-Duty Hybrid Vehicles.) (ICCT, 2013c.)

Currently, all four teams have narrowed their strategies, no longer exploring full-hybridization technologies. Two of the four SuperTruck teams – Cummins/Peterbilt and Daimler - have met the program goals and will be providing U.S. DOE final reports on their projects by summer 2015. Cummins achieved a 76 percent improvement in freight efficiency – far exceeding the goal of 50 percent. Cummins also developed and demonstrated a 51 percent improvement in BTE. Additionally, in an over 312 mile roundtrip from Fort Worth to Vernon, Texas, the Cummins SuperTruck demonstrated 10.7 miles per gallon (Cummins, 2014). The engine and vehicle technologies incorporated into the Cummins SuperTruck are many of the same technologies identified in this Technology Assessment. Figure IV-1 lists the key technologies ARB staff has identified for long haul tractors.

Figure IV- 1: Cummins SuperTruck Technologies*

ENGINE TECHNOLOGIES

1. Advanced Transmissions/Engine Downspeeding (AMT)
2. Advanced Combustion Cycles (LTC)
3. Waste Heat Recovery (Bottoming Cycle)
4. ~~Engine Downsizing~~
5. ~~Stop-Start~~
6. ~~Automatic Neutral Idle~~
7. Combustion and Fuel Injection Optimization (Calibration Optimization; Piston Bowl Geometry, Peak Cylinder Pressure)
8. Higher efficiency aftertreatment (Advanced Catalyst Coating)
9. Reduced Friction (Seals, oil viscosity) Auxiliary Load Reduction (More efficient lube and H2O pumps)
10. EGR/Turbo/Air Handling Improvements
11. ~~Variable Valve Actuation/ Cylinder De-activation (Variable Valve Actuation)~~

VEHICLE EFFICIENCY TECHNOLOGIES

1. Aerodynamics
2. Lightweighting
3. Low-Rolling Resistance Tires (Single-wide)
4. ~~Automatic Tire Inflation System~~
5. ~~Vehicle Speed Limiters~~
6. Predictive Cruise Control (GPS Route Manager)
7. Axle Efficiency (6x2)
8. Idle Reduction (Li Ion Battery APU)
9. Improved Air Conditioning System

* Those that are not part of the current Cummins SuperTruck are shown in strikeout format.

Daimler recently announced it demonstrated an impressive 115% freight efficiency improvement and a 50.2% improvement in BTE. Over a similar 312 mile roundtrip the Daimler SuperTruck demonstrated a 12.2 miles per gallon. Both Navistar and Volvo continue to develop and demonstrate their SuperTruck strategies. Volvo should complete its project by winter 2016. To date, Volvo has demonstrated a 48% improvement in BTE and a 43% improvement in freight efficiency. Navistar should complete their project by Fall 2016. To date, Navistar has demonstrated a 48.3% improvement in BTE. Both Navistar and Volvo are on track to meet both the SuperTruck BTE improvement and freight efficiency improvement goals. (Gravel, 2015)

<u>Advanced Vehicle Research and Development Plan</u>

In 2011, U.S. DOE announced the funding of the Advanced Vehicle Research and Development Plan, grants totaling more than $175 million that will support forty projects over a 3-5 year timespan in hopes of accelerating the development of advanced vehicle technologies and improving the fuel efficiency of next generation vehicles (Energy.Gov, 2011). Combined with additional investments by the grantees, project support totals more than $300 million in eight different areas: advanced fuels and lubricants, lightweighting materials, light weight multi-material prototypes, advanced cells and design technology for electric drive batteries, advanced power electronics and electric motor technology, thermoelectric and enabling engine technologies, fleet efficiency, and advanced vehicle testing and evaluation. These grants fund research and development projects into many of the technology fields listed in this heavy-duty technology assessment including $1.5 million to Wisconsin Engine Research Consultants to further the development of RCCI engines, $1.5 million to Cooper Tire & Rubber Company to develop and demonstrate a new fuel efficient tire class, and $10 million to Chrysler Group LLC to fund the demonstration of a cost-effective light weight, multi-material vehicle targeting a 50 percent weight reduction.

An additional $55 million has been invested by U.S. DOE in 2014 for 31 new projects in an effort to further accelerate the development of critical vehicle technologies (Energy.Gov, 2014). These investments focused on two major topic areas: fuel efficiency improvements in passenger vehicles and commercial trucks, along with critical technologies for electric vehicles. The U.S. DOE-funded projects in the fuel efficiency sector put emphasis on developing and demonstrating dual-fuel technologies, accelerating the growth in cost-competitive, high-efficiency engine and powertrain systems, and the introduction of advanced lubricants and coatings for future vehicles. For example, George Washington University received $1 million to develop SAE 0W-16 low viscosity lubricants, while Chrysler Group LLC and Ford Motor Company each received about $1.5 million dollars to develop aftertreatment systems with new catalysts that demonstrate 90 percent conversion efficiency of NOx during an FTP cycle near 150°C and to demonstrate low temperature catalyst materials that are sufficiently durable to meet full useful life emission targets, respectively. This comprehensive approach to vehicle efficiency research and development will help ensure technologies are available to meet the new fuel efficiency standards and stricter emission regulations.

<u>Connected Vehicles</u>

Programs designed to improve transportation safety have led to many advances in connected vehicle technologies including the continued development of vehicle-to-vehicle (V2V) communication and vehicle-to-infrastructure (V2I) communication (U.S. DOTa). Using V2V communication, heavy-duty trucks can communicate important safety and mobility information from one vehicle computer to another that can help save lives, ease traffic congestion, and improve the environment. For example, vehicles can potentially communicate traffic conditions to upcoming commuters to warn them of a potential accident and enable upcoming vehicles the opportunity to divert to a secondary route. Through the use of V2I communication, predictive cruise control systems use global positioning system information to predict uphill and downhill gradients on a given drive route, allowing the truck to optimize gearing, braking and acceleration and thereby reducing fuel consumption. The field of connected vehicles is broad and expanding with the ultimate future goal of a completely autonomous vehicle fleet. Most of the connected vehicle applications are still in the early stages of planning and development making their implementation beyond the scope of this technology assessment.

U.S. DOT is currently developing a pilot deployment program to test new and emerging connected vehicle technologies (U.S. DOTb). The first wave of pilot deployments is set to start up in the fall of 2015 with the second wave beginning in 2017. Current connected vehicle projects are focused mostly on vehicle safety features, however, some potential pilot programs with environmental implications could include, but are not limited to, transit/freight signal priority systems and cooperative adaptive cruise control systems. Development of a connected vehicle wireless system has typically focused on the light passenger vehicle sector with further deployment into the heavy-duty sector as the technologies improve their market penetration. A timescale for complete infiltration of a connected vehicle system into the commercial automobile community is unknown at this time. The current funding initiatives set forth by federal and state agencies hope to speed up the implementation and development of this full scale connected vehicle system.

California is also helping to lead development and implementation of connected vehicle technologies. The California Department of Transportation (Caltrans) is working with U.S. DOT, FHWA, and NHTSA and other American Association of State Highway and Transportation Officials (AASHTO) members to develop standards, evaluate technology, and move towards infrastructure deployment. In 2014, NHTSA announced their decision to consider mandating vehicle to vehicle (V2V) communications to be installed on new light duty vehicles. They are currently considering a similar decision for heavy-duty vehicles. Caltrans and the auto industry have been testing connected vehicle technologies in real world traffic on a stretch of El Camino Real (State Route 82) in Palo Alto since 2005. They are also developing truck platooning technology, which builds on prior truck development work from 2003 and 2009 projects, and intend to test it on the I-710 in Southern California or another suitable freeway corridor in 2016. Partners in this FHWA funded program include California Partners for Advanced Transportation Technology (PATH), a research and development program of the University of California, Berkeley; Volvo; Peloton Technology

Two connected vehicle technologies, predictive cruise controls and platooning, are discussed in more detail in Appendix A.

V. NEXT STEPS

Staff will use the results of this technology assessment as part of the technical foundation for the development of the Sustainable Freight Strategy. In January 2014, the ARB adopted Resolution 14-2, directing staff to develop the Sustainable Freight Strategy that, among other things, would consist of a set of recommendations for near-term actions (by the ARB and others) to move California towards a sustainable freight transportation system. One of the goals of the strategy is to ensure the cleanest, most efficient trucks are available for fleets moving freight. To do this, ARB staff will need to identify the FCR technologies that can be deployed in the freight moving truck fleet and assess the impact that these technologies will have on fuel consumption. This technology assessment will be a tool used by ARB staff to help meet this goal.

Staff will also reevaluate the potential FCRs presented in this report after the NPRM for the Phase 2 GHG regulation is released in the spring of 2015. The Phase 2 standards will establish a new technology baseline for heavy-duty trucks. The NPRM will provide critical cost and cost-effectiveness information that staff will consider when evaluating the stringency of the Phase 2 standards. The determination of how extensively Phase 2 incorporates technologies evaluated in this technology assessment will assist CARB in establishing whether federal Phase 2 meets California's needs and determining the potential for further reductions beyond the federal Phase 2 requirements, in order to meet California specific goals.

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California Environmental Protection Agency

AIR RESOURCES BOARD

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APPENDIX A: TECHNOLOGY SUMMARY

ENGINE/POWERPLANT AND
DRIVETRAIN OPTIMIZATION
AND
VEHICLE EFFICIENCY

June 2015

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Table

Figure

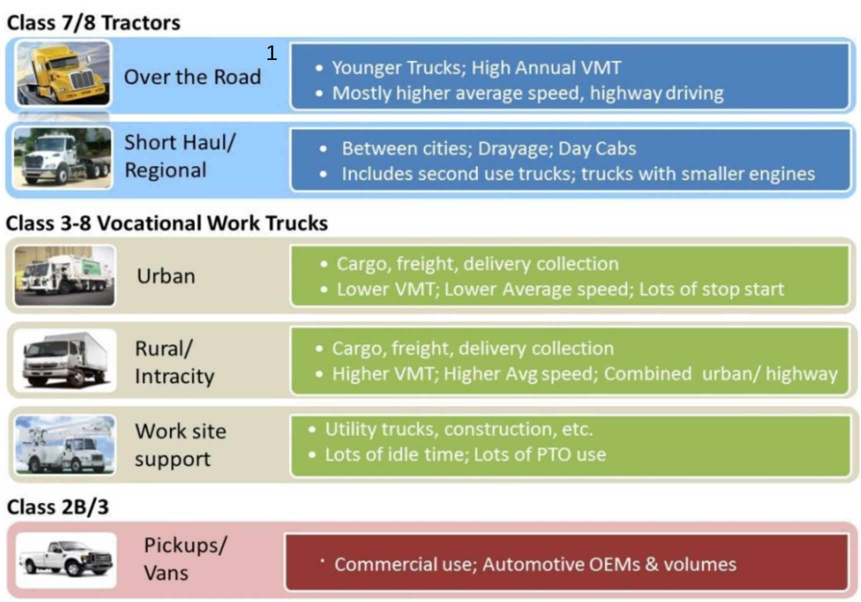
I. INTRODUCTION

This appendix to the Technology Assessment for Engine/Powerplant and Drivetrain Optimization and Vehicle Efficiency provides a more detailed overview of each of the technologies identified in the main report. This assessment is based on staff's findings from a literature search and review for heavy-duty engine and vehicle technologies that reduce fuel consumption. The technologies summarized herein are separated into two categories: Engine/Powerplant and Drivetrain Optimization Technologies (Engine Technologies), and Vehicle Efficiency Technologies (Vehicle Technologies). Reference numbers correspond to numbers found in the list of references in Chapter VI, References, of main report.

Core questions staff sought to answer for each identified technology include:

- How does the technology work?
- What, if any, implementation issues or challenges exist?
- What is the potential fuel consumption reduction (FCR)? The FCR is expressed as the percent reduction from a 2010 baseline engine, unless otherwise noted.
- What is the technology readiness level (research and development, pilot/demonstration, introduced commercially, and widely commercial)?
- To which vehicle class or classes is the specific technology applicable? Truck classes are based on the California Hybrid, Efficient and Advanced Truck (CalHEAT) Research Center vehicle classifications shown below in Figure A-1.

Figure A- 1: CalHEAT Vehicle Classifications for Class 2b-8 Heavy-Duty Vehicles



1. "Over the Road" is equivalent to "Long Haul"

The remainder of this appendix is organized as follows. Section II describes engine technologies that have been demonstrated. Section III describes engine technologies that are in the research and development stage. Section IV describes vehicle technologies.

II. ENGINE TECHNOLOGIES

A. Advanced Transmissions and Engine Downspeeding

	Applicability	**Potential FCR: 0-10%**
Advanced Automatic Transmission	Class 7/8 Short Haul Class 3-8 Vocational Class 2b/3 Pickups/Vans	0-5%[TIAX, 2009] 2-3%[TIAX, 2009] 2.7-4.1%[TIAX, 2009]
Automated Manual Transmission	Class 7/8 Long Haul Class 2b/3 Pickups/Vans	2-3%[Lutsey, 2014] 5.5-9.5%[TIAX, 2009]
Dual-Clutch Transmission	Class 7/8 Short Haul Class 7/8 Long Haul Class 3-8 Vocational	3-8%[Lutsey, 2014] 3-8%[Lutsey, 2014] 8-10%[Dorobantu, 2014]
Technology Readiness Level	Introduced Commercially	

Currently, most class 2b through 8 heavy-duty vehicles use one of three types of transmissions: a manual transmission (MT), automatic transmission (AT), or an automated manual transmissions (AMT). For class 7 and 8 long haul tractors, the most prevalent transmission type is a MT, with AMT's projected to occupy an estimated 30% market share by 2014 (Berg, 2012). For class 2b through 8 trucks used in primarily urban applications, ATs are widely used. A fourth category of transmissions, dual clutch transmissions (DCTs), have just recently been made commercially available for heavy-duty truck applications and are therefore not widely used in any class of trucks. The use of advanced transmissions (e.g., advanced ATs, AMTs, and DCTs) facilitates downspeeding of the engine. By downspeeding, the engine is made to run at lower speeds and with high torques. For the same power, the engine is operated at higher specific load which results in higher efficiency and reduced fuel consumption. The reasons for increased fuel efficiency are reduced engine friction due to lower piston speeds, reduced relative heat transfer, and increased thermodynamic efficiency.

Advanced Automatic Transmission (AT)

An AT typically has five to seven gears with a torque converter and a lock-up clutch. The transmission utilizes the torque converter at low-engine and vehicle speeds and lock-up mode at high speeds. The torque converter permits upshifts under full engine power. There can be a fuel economy advantage in performing full-power shifts because the engine can continue to operate at an efficient point during and after their shifts. Drivers of trucks that make frequent starts and stops may prefer ATs over AMTs because of their smooth shifting in and out of lower gears. The major disadvantage associated with ATs is related to the inefficiency of the torque converter. A significant portion of the input power from the engine is lost as heat in the torque converter.

Advanced ATs have more elaborate shift strategies with up to ten gears and the ability to reduce or eliminate the torque converter load when the vehicle is stopped. As with all transmission technologies, the FCR associated with the use of an advanced AT is highly dependent on vehicle type and typical duty cycle.

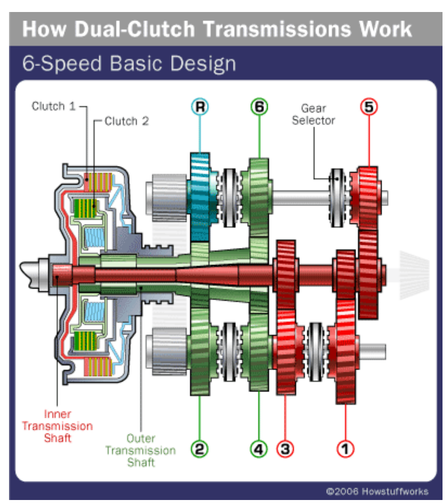
Automated Manual Transmission (AMT)

The AMT is basically a manual transmission that has a control module and actuators taking over shifting and clutch operation from the driver. The AMT controller can match the performance of a skilled driver using a manual transmission which results in reduced fuel consumption benefits for most fleets. As a result, AMTs are gaining market share over manual transmissions in the Class 8 long haul tractor category. The FCR potential will vary and is based on the tractor's duty cycle. Benefits will be seen in duty cycles involving hilly terrain or some urban driving. For vocational applications, the frequent shifting may result in drivability issues, so AMTs are a less popular option.

Dual-Clutch Transmission (DCT)

Like AMTs, DCTs are also computer controlled. Figure A-2 illustrates the basic design for a DCT with 6 forward gears and a reverse gear. There are two transmission shafts: the red one has the odd numbered gears and the green one has the even numbered gears. One is always engaged meaning there is always power to the wheels, even during shifting, similar to an AT. When it is time to shift, there is an instantaneous transfer of power through the engagement and disengagement of the two clutches. DCT's have been used in automobile production for several years. Heavy-duty vehicle applications are now coming out for commercial production. Eaton recently announced the launch of the Procision, a new medium-duty dual-clutch transmission claiming it can deliver 8 to 10 percent better fuel economy than a similarly equipped vehicle with an AT (Dorobantu, 2014). For Europe, Volvo launched its I-Shift Dual Clutch technology for heavy-duty long haul trucks.

Figure A- 2: Six-Speed Dual Clutch Transmission



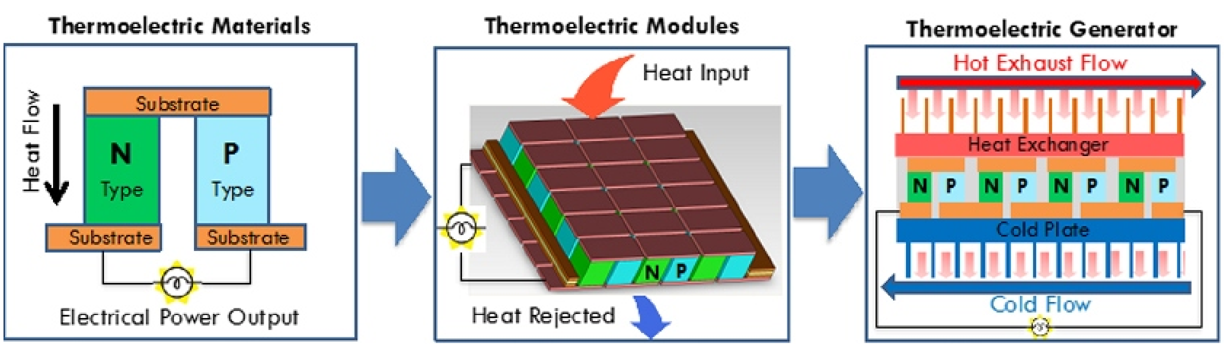
B. Waste Heat Recovery

	Applicability	Potential FCR: 2-8%	Technology Readiness
Bottoming Cycle	Class 8 Long Haul Tractor	2-8%(Lutsey, 2014)	Field Demonstration
Turbocompounding mechanical		2.5-5%(NAS, 2010)	Introduced Commercially
Turbocompounding electrical		4-5%(NAS, 2010)	Introduced Commercially
Thermoelectricity		N/A	Research and Development

Waste Heat Recovery (WHR) is a technology that captures waste heat from the operation of a piece of equipment or machinery with a recovery unit and converts it into emission-free energy through a heat exchange process. In general, a diesel engine converts about 45 percent of its fuel into useful energy versus a gasoline engine's 30 percent efficiency (U.S. DOE, 2014a). The rest of the fuel's energy is lost to waste heat, engine and driveline inefficiencies, idling, and/or used to power accessories (CEC, 2014). In a WHR system, the thermal energy losses are captured and turned into electrical or mechanical energy. Types of WHR include thermoelectricity (TE), turbocompounding (TC), and bottoming cycles (Rankine cycle).

TE is the direct conversion of temperature differences to electric voltage and vice versa. A thermoelectric device, as shown in Figure A-3, creates voltage when there is a different temperature on each side. Plates of thermoelectric material connected together form a TE-module. The efficiency of TE depends on the material used as well as the temperature drop across the device.

Figure A- 3: Thermoelectric Waste Heat Recovery System

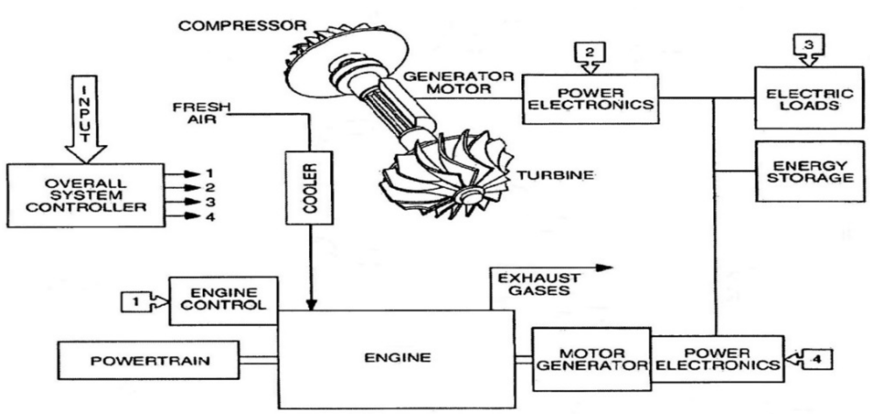


The TE materials used in thermoelectric generators are semiconductors with high electrical conductivity and low thermal conductivity, allowing the direct conversion of thermal energy into electrical energy. To generate electrical energy, waste heat is applied to the junction of two electrically opposed materials that are cooled at the opposite end. The temperature differential across the module creates a voltage potential that is extracted as useful power.

A TE module consists of multiple leg pairs, each made of n-type and p-type TE materials, which are connected electrically in series and thermally in parallel to form a TE module. An N-type semiconductor carries current mainly in the form of negatively-charged electrons, in a manner similar to the conduction of current in a wire. A P-type semiconductor carries current predominantly as electron deficiencies called holes. A hole has a positive electric charge, equal and opposite to the charge on an electron. In a semiconductor material, the flow of holes occurs in a direction opposite to the flow of electrons. The modules are then incorporated into a heat exchange assembly with a hot and cold side forming a thermoelectric generator ("TEG").

TC refers to the use of a turbine to recover energy from the exhaust system of an engine and reintroduces that energy back into the engine. In mechanical TC, the energy recovered from the exhaust gases is converted into kinetic energy and fed back into the engine via a high ratio transmission (gearbox). In electrical TC, as shown in Figure A-4, the energy is converted to electrical power and then electrically transmitted to the engine by a power electronics module. The success of both types of TC depends on the successful redesign of the engine's turbocharger, which must be made more efficient (by 5-10 percent) in order to prevent an excess of back pressure in the exhaust system when the turbogenerator is fitted (Bowman, 2014).

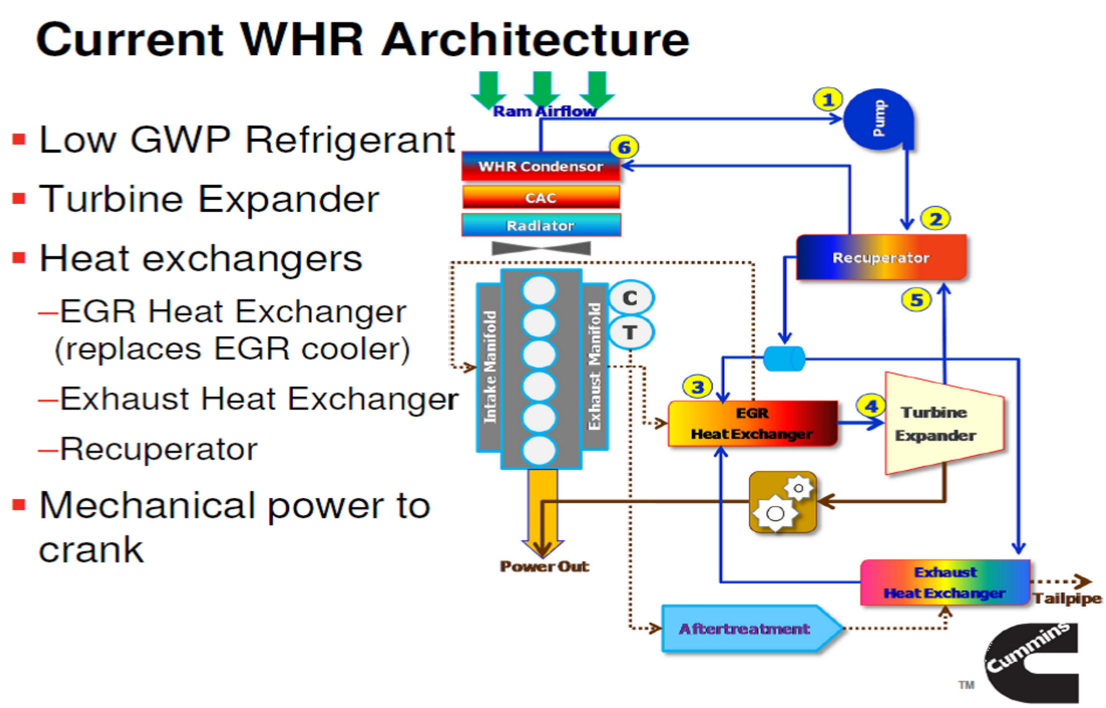
Figure A- 4: Electric Turbocompound Waste Heat Recovery System



With electric TC, a high-speed motor/generator is added to the turbocharger rotating group. In this way, recovered exhaust energy not used by the turbine to boost engine compression is converted to electricity, which can be stored in batteries, flywheels, and/or ultra-capacitors. When needed, this power can be used to meet electrical demands or routed to a second electric motor/generator to increase engine output. Conversely, this second motor/generator can be used to further augment energy efficiency through electro-dynamic braking, also known as a Kinetic Energy Recovery System (KERS).

In a Rankine-based WHR system (bottoming cycle), as shown in Figure A-5, heat exchangers transfer waste heat energy to a power fluid, turning the fluid into steam/vapor. The pressure will then drive a turbine expander which can be either directly tied to the crankshaft of the engine or linked to an alternator to generate electricity. A condenser then rejects unused heat energy from the power fluid before starting a new cycle. Sources of energy to power a Rankine-based WHR system include the exhaust gas recirculation (EGR) stream, exhaust stream, charge air stream, and engine coolant circuit. Up to a 10 percent FCR is possible (U.S. EPA, 2011d).

Figure A- 5: Rankine (Bottoming Cycle) Waste Heat Recovery System



Cummins Presentation, "Roadmap to Energy Conversion Efficiency at Cummins" at 2013 ERC Symposium, June 5, 2013

The Rankine cycle is a thermodynamic cycle traditionally using steam as the working fluid to generate power in steam turbines. Organic Rankine Cycle turbomachines work with the same principle, but use a specific organic working fluid instead of water. These machines transform thermal energy into mechanical or electrical energy. The recovered heat will be used to reheat and vaporize the organic fluid that will then be expanded in a turbine supplying a generator. The fluid is then condensed in a closed cycle to start the cycle again. Cummins, Daimler, and Volvo are developing Organic Rankine waste heat recovery systems as part of their SuperTruck efforts.

C. Engine Downsizing

Potential FCR	1-4.5%(NAS, 2010; TIAX, 2009; Lutsey, 2014)	
	1-4.5%(Lutsey, 2014) 1-2%(21CTP; Allison, 2012)	Class 8 Long Haul All other Classes
Technology Readiness Level	Introduced Commercially	
Applicability	All Classes	

Many improvements in vehicle efficiency reduce road load power requirements. These vehicle efficiency improvements may result in large diesel engines operating in lower efficiency regions of the engine map. Through engine downsizing (i.e. replacing a 15 liter (L) engine with a 13-11 L engine), the engine can continue to operate in its optimal, higher-efficiency engine region even with these vehicle efficiency improvements. The lower displacement engine usually has lower peak torque and peak power levels, which may negatively affect vehicle functionality. For duty cycles that require the elevated peak power and torque levels of the larger engine classes (e.g., steep grade climbing), a turbocharger can be equipped to the smaller displacement engine to meet these peak power demands. The reduced weight and friction losses as a result of the smaller engine enable a reduction in fuel consumption for the same amount of power. In general, downsizing is facilitated by coupling the engine with an advanced transmission (e.g., dual clutch) that minimizes torque loss during shifting and thus reduces the need for higher torque to complete the shift process.

Outside of hybrid applications (see Technology Assessment: Heavy-Duty Hybrid Vehicles), engine downsizing is currently not widely done. Concerns of sacrificing vehicle functionality and the lack of smaller engines that meet medium and heavy-duty engine warranty requirements have limited penetration of downsized engines within the market. Additionally, as larger displacement engines are generally thought to be more durable, the market has gone mostly to the larger engine, except in very weight sensitive applications (bulk haulers, tankers, etc.) (NAS, 2010). One potential benefit of downsizing is that downsized engines are expected to increase exhaust temperatures at a quicker rate, which may improve aftertreatment performance. An analysis by Frost & Sullivan, a consultancy, indicates that 15 L engines will continue to dominate the Class 8 engine market through 2018, but are expected to lose market share to 11 L to 14 L engines (NAS, 2014).

D. Stop-Start

Potential FCR	5-10%[IEA, 2012]
Technology Readiness Level	Introduced Commercially
Applicability	Class 7/8 Short Haul; Class 3-8 Urban Vocational; Class 2b/3

Stop-start systems automatically shut-down the engine during idle. The engine then restarts when a certain action is taken by the operator. Those actions can include, but are not limited to:

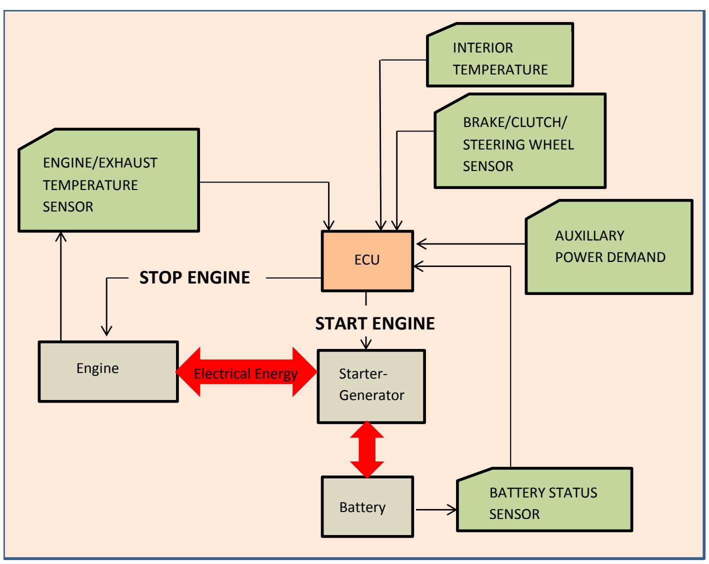
- the driver's foot leaving the brake pedal;
- depressing the clutch;
- movement of the steering wheel.

The engine can also be restarted independent of operator action, if the vehicle requires the engine to be running to perform certain tasks, such as:

- battery recharging or auxiliary power demand;
- interior vehicle temperature sensor triggers air conditioning.

Figure A-6 provides a diagram of a stop-start system. The electronic control unit (ECU) determines when to start and stop the engine based on various inputs.

Figure A- 6: Stop-Start System



The time between idle and restart will vary based on manufacturers' preprogramed settings that are subject to conditions listed above. Once the conditions are correct or power is demanded, the engine restarts. Stop-start systems are most advantageous for vehicles which spend significant amounts of time waiting at traffic lights or frequently come to a stop in traffic, e.g., garbage trucks or delivery trucks (IEA, 2012). Stop-start systems are feasible on vehicles with manual and automatic transmissions. The shut-down of the engine during idle results in reduced fuel consumption and GHG emissions. For diesel engine applications, stop-start systems also help maintain the temperature of SCR catalysts during periods of idle. Since the engine is shut-off, there is no flow of low-temperature exhaust traveling through the SCR and effectively cooling it. As part of its Phase 2 rule development, U.S. EPA is gathering data to quantify the cooling rate during idle, as well as the heat-retention resulting from implementation of stop-start systems on vocational vehicles.

E. Automatic Neutral Idle

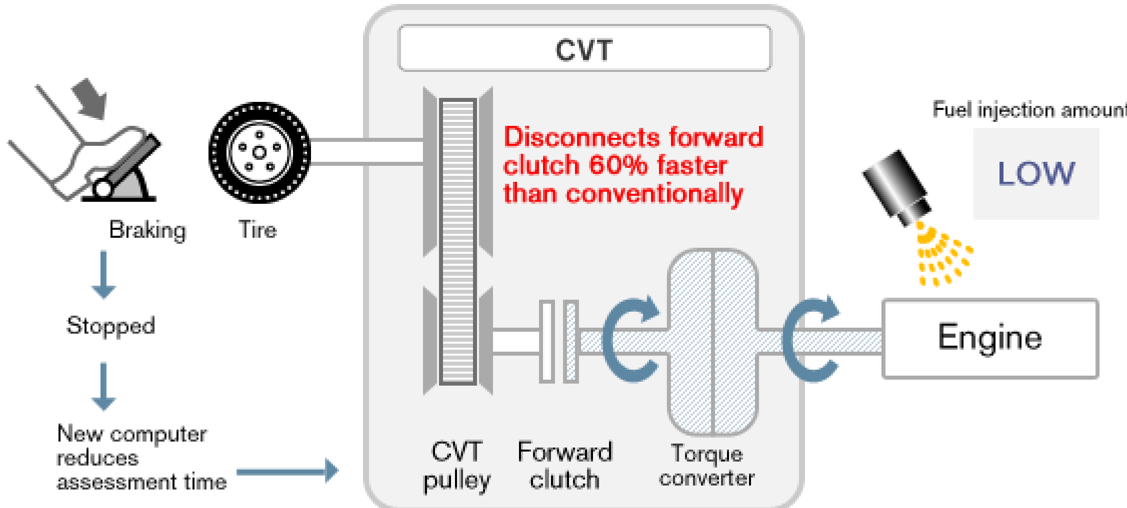
Potential FCR	N/A
Technology Readiness Level	Introduced Commercially
Applicability	Class 3-8 Urban, Rural, Worksite Support Vocational; Class 2b/3

Neutral-idle technologies are applicable to trucks with automatic transmissions. Trucks with traditional automatic transmission/torque converter systems idle in gear or in park, which results in higher fuel usage than their manual transmission counterparts. Neutral-idle control disengages the engine from the gearbox components when specific conditions are met. These conditions can include, but are not limited to, the following:

- The transmission is in drive.
- The foot brake is pressed.
- The vehicle is stopped.
- The accelerator pedal is not pressed.
- The transmission fluid temperature is greater than 0ºC or 32ºF.
- The road grade is not steeper than 15 degrees.

Allison is one manufacturer that markets neutral-idle technology for its vocational vehicle automatic transmissions. For bus applications, Allison markets a park-brake auto-neutral system that automatically puts the vehicle in neutral when the parking brake is engaged. As the engine is still running during neutral-idle conditions, the fuel consumption (FC) benefit is not as significant as that of stop-start technology, however, there is a FCR compared to a standard (in-gear) idling mode. It should also be noted that unlike a stop-start system, the neutral-idle technology does not prevent the cooling of the SCR catalyst at idle operation. In developing the requirements for the Phase 2 rule, U.S. EPA is gathering more information on the cooling rate of SCR during the idle periods of an engine tested in accordance with the FTP. This will allow them to better quantify the cooling rate, and applicability, of neutral-idle technology on heavy-duty diesel engines when setting the Phase 2 engine standards. Figure A-7 below shows a schematic of a neutral-idle system for a Nissan passenger car with a CVT, continuously variable transmission.

Figure A- 7: Schematic of a Neutral-Idle System



(Nissan)

F. <u>Combustion and Fuel Injection Optimization</u>

Potential FCR	1-4%(Jardin, 2012; Lutsey, 2014; NAS, 2010)
Technology Readiness Level	Widely Commercial
Applicability	Class 7/8 Long Haul Tractor and Short Haul; Class 3-8 Urban, Rural, and Worksite Support Vocational; Class 2b/3

Combustion and fuel injection optimization is a broad category, and can include modifications to all of the following parameters in order to improve the fuel combustion rate:

- Compression ratio
- Expansion ratio
- Combustion chamber shape
- Injection spray pattern
- Injection pressure
- Injection timing
- Injection rate shaping
- Air/fuel mixing and ratio

- Peak cylinder pressure limit

Combustion chamber design improvements result in optimized air/fuel mixing and improved air management. Improved materials and structural designs allow for higher compression ratios resulting in higher in-cylinder pressure. These modifications result in a more precise control rate of combustion resulting in increased brake thermal efficiency and reduced fuel consumption. Unfortunately, this can result in higher in-cylinder NOx production because of the higher cylinder pressures and associated peak combustion temperatures. Measures to counteract the NOx increase include improved aftertreatment SCR conversion rate, fuel injection optimization, and improved engine controls.

Modifying the fuel injection spray pattern and injecting it under high pressure conditions of an improved combustion chamber environment is critical for a cleaner, more efficient fuel burn. Common rail systems with high pressure injectors (3,000 bar) are capable of finely tuned spray patterns. Piezoelectric nozzles are capable of multiple injections at high pressures. The FCR benefit of these improvements is estimated at 1 to 4 percent (Jardin, 2012; NAS, 2010).

G. Higher-Efficiency Aftertreatment

Potential FCR	1-4%(Lutsey, 2014; U.S. EPA, 2011d)
	2-4%(Lutsey, 2014) Class 7/8 Long Haul
	1-2%(U.S. EPA, 2011d) All other
Technology Readiness Level	Introduced Commercially
Applicability	Class 7/8 Long Haul Tractor and Short Haul; Class 3-8 Urban, Rural, Worksite Support Vocational; Class 2b/3

In order to meet current 2010 PM (0.01 g/bhp-hr) and NOx (0.20 g/bhp-hr) standards, most heavy-duty diesel engines are outfitted with a DPF to reduce PM and an SCR system to reduce NOx. Improved scrubbing efficiency within the SCR system to further reduce engine-out NOx along with better combustion system optimization can allow NOx and fuel consumption to both be reduced further. For example, improved engine timing which can improve the overall combustion process and allow for an improvement in FC inherently leads to higher engine-out NOx emissions, but combined with improved NOx aftertreatment efficiency, a system can still meet the stringent NOx emissions standards, thus helping solve the potential GHG-NOx tradeoff.

Another way to improve fuel efficiency of the engine is to reduce the backpressure these aftertreatment devices create. In trapping PM, the DPF must restrict the flow of exhaust. To a lesser extent, the SCR system also restricts exhaust flow. Backpressure can be reduced by using a thinner-walled DPF and by improving the SCR cell density.

Additionally, as SCR system-effectiveness is improved, DPFs may be optimized to reduce regeneration frequency.

Both of these changes discussed above would result in fuel consumption improvements. Overall, aftertreatment improvements are expected to deliver a 1 to 2 percent FCR in the near future.

H. Reduced Friction

Potential FCR	0.5-4%(Argonne, 2006; Lutsey, 2014; NAS, 2010; U.S. EPAb)	
	0.5-2%(Lutsey, 2014)	Class 7/8 Long Haul
	1-4%(Argonne, 2006, NAS, 2010, U.S. EPAb)	All Others
Technology Readiness Level	Widely Commercial (All)	
Applicability	All Classes	

Low Viscosity Oils

The viscosity of an oil mixture, i.e., its tendency to resist flow, governs the fluid film thickness between operating surfaces (Totten & George, 2006), and thus plays a vital role in monitoring frictional forces within the operating gears. Conventional mineral oils with higher viscosities may not be able to effectively slip between and lubricate the moving parts within a gear system, especially in newer truck components that are designed with close tolerances and tight fits. Without proper lubrication, the moving parts within the axle system will grind together, increasing wear, stresses, and frictional energy loss. Additives such as viscosity modifiers and friction modifiers are mixed with the base oil to improve viscosity/temperature characteristics and reduce frictional energy losses. Viscosity modifiers are polymers that adjust their shapes depending on the associated temperature. The polymer coil expands at high temperatures into long molecular chains, increasing the viscosity of the system and maintaining the required fluid film thickness. At low temperatures, these chains curl up into tight balls, taking up less space within the oil solution, negating their impact on the viscosity of the overall system. In essence, these molecules are active at high temperatures helping to resist reductions in viscosity as temperature increases (PCEO, 2013). Then they become inactive at lower temperatures when their assistance is no longer needed.

With improvements in the viscosity index, low-viscosity oils can still maintain the same level of protection within the internal gear system at engine operating temperatures relative to those higher viscosity oils used in previous generations, yet have the added benefit of reduced flow resistance, helping to minimize parasitic energy losses within the vehicular system. This helps to extend engine life and deliver maximum fuel economy because the engine doesn't have to work as hard to move the oil around. Cold start performance can benefit significantly from low viscosity oils, frequently reducing oil starvation times in diesel engines from 1 minute down to 20 seconds (ETSAP, 2010) for a zero-weight diesel formulation. Emissions performance will also benefit as the engine consumes fuel more efficiently.

Multi-weight synthetics, such as diesel 0w-40, also offer the benefit of improved high temperature performance. The composition and structure of synthetic oil allows the molecular weight of suspended particles to be precisely determined, providing synthetic oils with greater viscosity stability in diesel engines and protection against oxidation in gasoline engines over a much wider temperature range than conventional motor oils. This also has the benefit of slowing down the depletion rates of friction modifiers and detergent additives in the oil. Because of this, oil change intervals can be extended significantly (e.g., from 300 hours to 500 hours) (Deere, 2014) for many diesel engine applications. It is estimated that the use of synthetics can improve fuel economy from 0.5 to 2 percent, which in turn would improve emissions performance by a proportionate amount. Combined with the advanced anti-friction techniques mentioned in the next sections, up to a 4 percent FCR can be seen.

Anti-Friction Coatings

Anti-friction coatings are another means of improving engine efficiency by creating a smoother, harder surface on metallic moving parts such as pistons and bearings. The smoother surface makes the components less susceptible to abrasion and wear in addition to reducing frictional losses. Anodizing is a technique that has been available for many years to improve the surfaces of aluminum components. More recent coating technologies include manganese phosphate deposition, molybdenum nickel chromium plating, diamond-like-carbon (DLC) coating, and nitride coating, all of which exhibit low coefficients of friction and high micro-hardness, making them extremely effective in vehicular applications. A typical friction coefficient for metal DLC coating is in the range of 0.1 to 0.2 (ETSAP, 2010). High luster polishing has also been shown to significantly reduce the coefficient of friction on iron and steel components such as piston rings and valve train buckets and tappets.

Valve train applications of manganese phosphate on buckets (and presumably on tappets) have been demonstrated to reduce frictional losses between 5 and 14 percent, and DLC coated and polished surfaces showed an improvement of between 17 and 25 percent (Deere, 2014). Similarly, DLC coating and polishing have been demonstrated to improve the frictional performance of pistons rings, although the benefit was less than that for treated valve train components (Deere, 2014). Ceramic coated rollers and pivot pins have also shown promise in reducing friction, but can be somewhat less resilient to shearing forces than steel counterparts. Ceramic also tends to increase the wear of metal components with which it comes into contact and tends not to retain oil as well as steel, although ceramic is typically able to survive at higher temperatures longer than steel without lubrication and without degradation (Hauzer, 2014).

Optimized Component Geometries

Optimizing the geometry of engine components such as pistons, rings, and cylinder bores can also contribute significantly to a reduction in engine friction. Piston crowns can be designed in such a way that they redirect more of the combustion energy into the cylinder walls to ensure less blow-by, and greater overall efficiency, during the power stroke of the engine. While this would appear to create additional friction between the piston rings and cylinder wall due to the increased lateral pressure, it would, in reality, reduce friction by allowing fewer rings to be utilized (from three to two) to achieve a proper seal. Ring tension could be relaxed, further reducing overall friction especially during the intake and exhaust strokes when pressure levels aren't as high. (Deere, 2014)

More precise bore cylindricity and honing pattern designs can also reduce engine friction by removing unwanted sources of asperity and abrasion. These optimization strategies coupled with appropriate anti-friction coatings and synthetic lubrication have the potential to reduce inefficiency enough that a smaller engine may be able to do the same work of an inefficient larger engine (downsizing). Such downsizing could have a profoundly positive effect on emissions performance.

Another significant reduction in diesel engine friction could come from the geometrical optimization of the oil and water pumps. Typically both pumps are mechanical, gear-driven, and use a rotating paddle mechanism to transport their respective fluids throughout the engine. The pumps are designed to provide adequate pressure ensuring that oils and coolant can be delivered to even the smallest and most tightly-toleranced moving parts within the engine. The primary purpose of the water pump is to keep the engine from overheating, but the oil pump is responsible for cooling, lubricating, and the transport of combustion residue away from the cylinders, valves, and pistons.

For the most part, diesel oil and water pumps are designed to run off the camshaft through the use of a gear system that transfers proportional rotation to the fluid fan mechanism. The fan mechanism is usually an arrangement of fixed pitch paddles that are sufficient to swirl fluids at the necessary velocities to keeps fluid pressure within an acceptable range from idle to redline. These paddles, however, are not necessarily designed to maximize flow rate efficiency. Paddle geometry (i.e., shape, pitch, and deflection) can significantly affect fluid dynamics. Many of the oil pumps in use today in on- and off-road diesel engines use paddles that have square edges and which are largely oriented perpendicular to the direction of fluid flow. This works well to rapidly circulate fluids, but the resulting dynamic drag puts additional load on the camshaft making the engine work harder, especially at higher engine speeds. This increase in loading also increases frictional losses between the pump and camshaft as their interfacing gears will mesh harder and teeth will contact each other more frequently.

To address these inefficiencies, variable pitch paddles and clutched fan mechanisms could be employed to increase flow rate efficiency and reduce the differential pressure range of the circulating fluids. Variable pitch paddles could be designed with an initial perpendicular orientation to provide maximum flow at low engine speeds, but then to adjust to a more open pitch orientation at higher engine speeds in response to increasing pressure. The increasing pressure itself could be used to modulate the paddles automatically, resulting in a self-regulating mechanism and achieving a more constant flow rate throughout the engine's operating cycle. A clutched fan could achieve the same results, but instead of being self-regulating via paddle modulations, the clutch would employ controlled slippage to achieve ideal flow rates. Clutched fans are commonly employed to cool radiators on many modern automotive engine applications. Because only a minimum pressure differential is required to ensure adequate circulation, it is desirable to keep the pressure range as tight as possible to minimize parasitic losses. Pumps optimized for fluid dynamics could be designed with wider teeth gearing to decrease frictional resistance, improve fuel efficiency, and lower emissions.

Belt driven pumps also have the potential to reduce frictional losses by taking the gear mechanism out of the equation altogether. Belt driven water pumps are often employed in automotive applications, but gear driven water pumps are the norm for on- and off-road diesel applications, primarily to extend service intervals and for better off-road durability. Belt driven pumps are almost always external to the engine block. Concerns regarding belt slippage and loss of belt tension would need to be addressed before belt driven oil and water pumps become a more attractive option for on- and off-road diesel engine manufacturers (Deere, 2014).

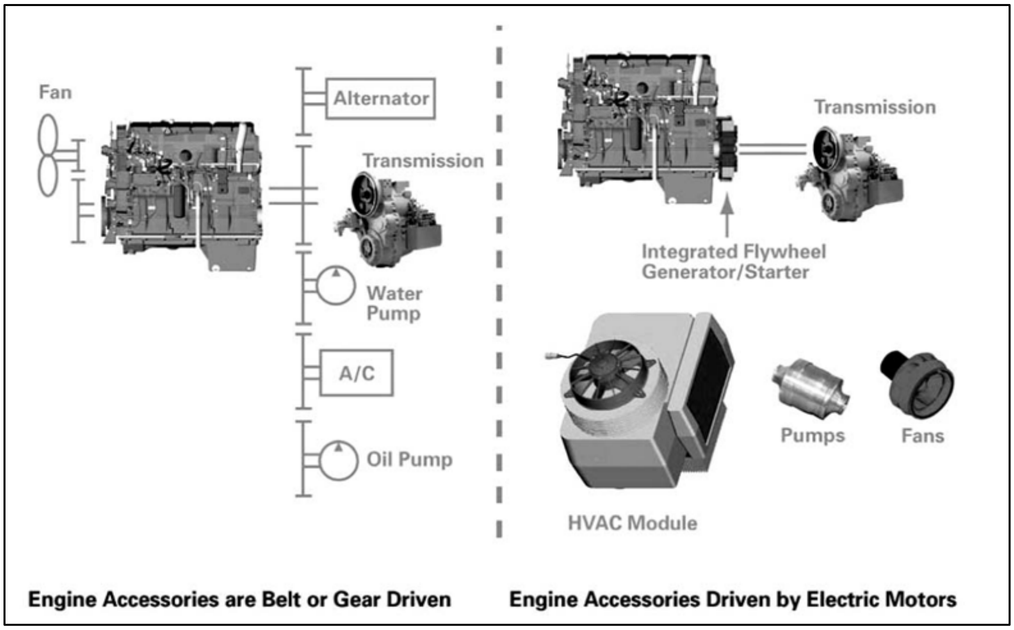
I. <u>Auxiliary Load Reduction</u>

Potential FCR	0.5-4%(Lutsey, 2014; TIAX, 2009)
	0.5-4% Class 7/8 Long Haul 1-3% All Other
Technology Readiness Level	Demonstration
Applicability	All Classes

Auxiliary loads include accessories needed to run the engine or provide power to vehicle systems, such as cooling fans, alternator, actuators, power steering pumps, air brake compressors, water pumps, fuel pumps, and vehicular environmental comfort loads such as the air conditioning compressor, ventilation, and heating system. Vehicles currently have auxiliary loads that are primarily mechanically belt-driven off the engine and can represent up to 9 percent of the energy used in the truck. The energy required can be reduced by converting them from mechanical to electric power. Electrically-powered accessories such as the air compressor or power steering operate only when needed, but these accessories impose a parasitic demand all the time when they are belt driven. Some electric power allows the auxiliary load to run at speeds independent of the engine speed, such as the cooling fans or water pump, which can reduce power consumption. They also allow the engine to be shut down during idling (CalHEAT, 2013).

Currently, conversion of accessories to electric power is still in the demonstration stage for non-hybrid heavy-duty vehicles. Figure A-8 illustrates the difference between mechanical and electric engine accessories. Electrified accessories are one factor of a broader electrification strategy, such as hybridization or electric waste-heat recovery. In addition, due to low production volumes, unit prices remain high. The fuel consumption benefit of electrified accessories has been estimated to range anywhere from 1 to 3 percent (Lutsey, 2014; TIAX, 2009). This benefit is duty-cycle dependent with more benefits in urban driving and short-haul conditions; line-haul applications will benefit less. When implemented as part of a broader electrification package, accessory electrification can result in more FC benefits than as a standalone approach.

Figure A- 8: Difference between Mechanical and Electric Engine Accessories



CONVENTIONAL TRUCK MORE ELECTRIC TRUCK

Source: Assembly Bill 32 (Measure T-6) and Goods Movement, 2011 (U.S. DOE's More Electric Truck)

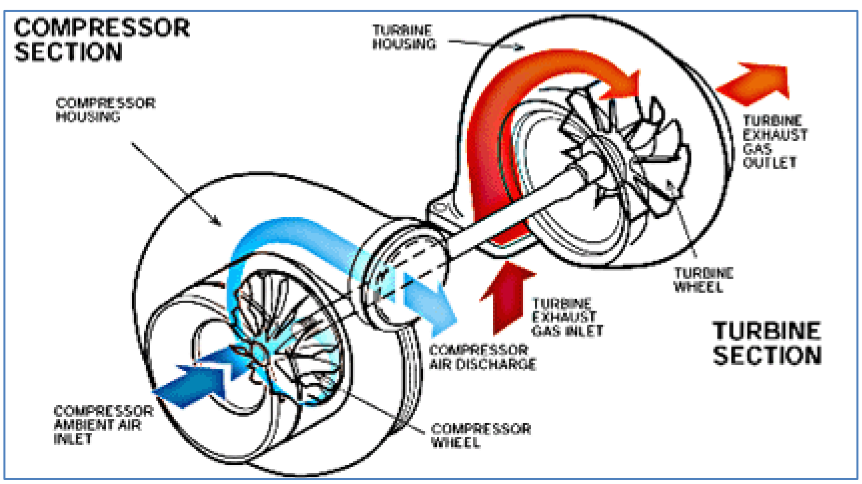
The United States Department of Energy (U.S. DOE), through Argonne National Laboratory (ANL), established the Caterpillar More Electric Truck (MET) program, which was initiated in 2000 and ended in 2007. The MET program's intent was to reduce engine loads by using electrified accessories including heating, ventilating, and air conditioning (HVAC), water pump, brake air compressor, oil pump, and cooling fan. The study showed that current technology can result in a 1.3 percent reduction in fuel consumption on the road due primarily to the electric water pump and electric brake air compressor, and a 2.7 percent reduction in fuel consumption during steady state conditions due to the electric cooling fan with a revised cooling system (Lutsey, 2014).

J. Air Handling Improvements (Turbocharger, EGR, and VVA)

Potential FCR	1-4.5%(Czarnowski & Shutty, 2011; ICCT, 2013a; TIAX, 2009)	
Turbocharger	1-2%(Czarnowski & Shutty, 2011; Jääskeläinen)	All
EGR	1-1.5%(TIAX, 2009)	All
VVA	1-3%(TIAX, 2009)	All
Technology Readiness Level	Widely Commercial	
Applicability	Class 7/8 Long Haul Tractor and Short Haul; Class 3-8 Urban, Rural, Worksite Support Vocational; Class 2b/3	

Higher efficiency air handling (air and exhaust transport) can be accomplished through improvements in turbocharger design and EGR systems. A turbocharger is a forced air induction device that compresses the air entering an engine cylinder (see Figure A-9). A turbine placed in the engine's exhaust stream is used to drive a radial compressor that compresses the air. By compressing the air, more fuel can be added. As a result, a turbocharged engine produces more power overall than the same engine without turbocharging. This can significantly improve the power-to-weight ratio for the engine and enable engine downsizing.

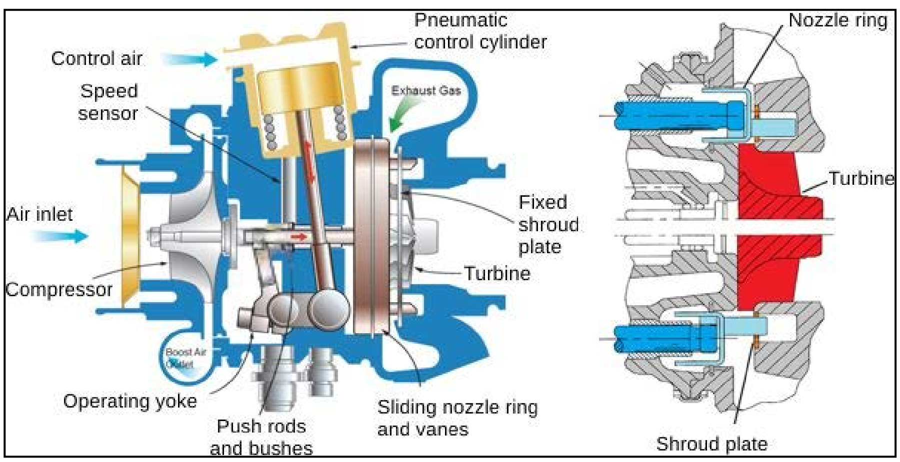
Figure A- 9: Turbocharger



Dual-stage turbocharging with intercooling would allow higher turbocharging efficiency for diesel engine applications with high compression ratios. Systems can be set up to allow the two turbochargers to work in series at all times, or to operate sequentially, where the turbocharger boost is modulated as required by engine operation. These high-efficiency turbocharging systems produce a positive pressure differential (ΔP) between the intake and exhaust manifolds (i.e., the intake manifold pressure is higher than the exhaust manifold pressure). As a result, an EGR pump or turbocompound system would most likely be required to facilitate EGR flow. Improving the efficiency of the turbine or compressor could improve the fuel efficiency of the engine by 1 to 2 percent (U.S. EPA, 2011d).

Light-duty truck diesel engine research has shown that up to 2 percent fuel consumption improvement can be gained from optimized variable geometry turbochargers (VGT) and dual-loop EGR systems over the federal test procedure (FTP) cycle (Czarnowski & Shutty, 2011). Staff believes similar gains in fuel consumption benefit can be made for heavy-duty diesel engine applications. Compared to a fixed geometry turbine, the variable geometry turbine allows significant flexibility over the pressure ratio/flow relationship across the turbine and by extension, the engine. This flexibility can be used for improving low speed torque characteristics, reducing turbocharger lag and in diesel engines, driving EGR flow. A variable geometry turbine can also be an important component of high pressure loop (HPL) EGR systems. By coordinating the position of the turbine vanes and the EGR valve, it is possible to minimize pumping losses while ensuring adequate EGR flow and air-fuel ratios (Jääskeläinen). Most heavy-duty diesel engines utilize a moving wall VGT due to the high pressures they require. Figure A-10 shows the basic components of a moving wall VGT.

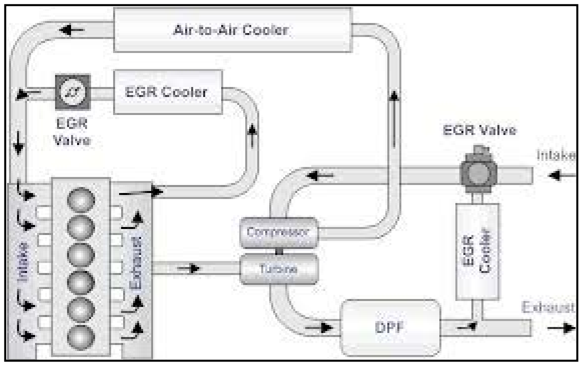
Figure A- 10: Basic Components of Moving Wall VGT



Right: Turbine nozzle closed (top) and open (bottom) (Cummins)

Dual-Loop EGR, show in Figure A-11, has both a high pressure loop and low pressure loop (LPL). In these systems, it is common to use the LPL at high engine loads, and the HPL at lower engine loads, with a combination of the two in the transition region (Khair & Jääskeläinen).

Figure A- 11: Dual-Loop EGR



(Dieselnet)

Variable valve actuation (VVA) allows the intake and exhaust valves to be adjusted independently from the crankshaft angle and can be used to better optimize engine performance at varying loads, helping to improve both fuel consumption and reduce emissions. Poppet valves within the engine system are used to control the flow of intake and exhaust gases into and out of the combustion chamber. The timing, duration, and lift of these valves have significant impacts on engine performance and are controlled by the camshaft. Conventional engine designs offer a fixed valve train system with the timing optimized for a given engine speed and load. This results in a trade-off between low-speed torque and high-speed power as both cannot be ideally optimized.

The simplest form of VVA is the use of cam phasers to modify the timing of the valve events to adjust the characteristics of the engine at varying speed and load ranges. Cam phasing advances or retards valve lift events by rotating the camshaft, typically over a range of about 60 degrees relative to the crankshaft angle (Tracy, 2013). However, cam phasing cannot adjust the camshaft lift or duration. To achieve variable duration of the lift sequence, more complex systems such as multiple cam profiles or oscillating cams must be used. Changing the cam profile by altering the camshaft lobes can not only affect how far the valves open (valve lift), but also adjust the duration of how long the valves stay open.

More advanced VVA systems use electromagnetic and hydraulic camless actuators and offer the greatest control over valve timing. As discussed in more detail in the camless engine section, research is currently in progress to improve the reliability of electromagnetic and hydraulic systems. Current VVA technology shows FCR of around 1 percent.

K. Cylinder Deactivation

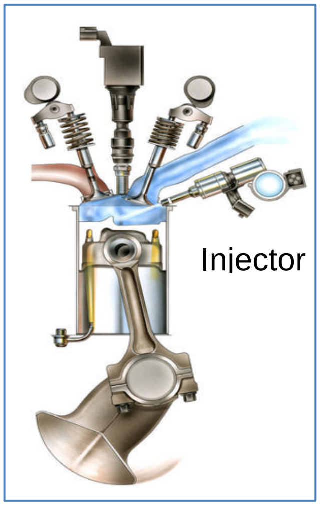
Potential FCR	2-3%(TIAX, 2009)
Technology Readiness Level	Widely Commercial
Applicability	Class 2b/3

Cylinder deactivation is a process by which both the intake and exhaust valves of a particular set of cylinders are kept closed throughout the whole engine cycle. This technology is taken advantage of during partial engine load, where only about 30 percent of an engine's potential power is typically used (Gable). With a portion of the engine cylinders deactivated, the remaining cylinders function normally, running at a higher specific power load to reach the desired engine load. This reduces pumping losses that are associated with increased throttling during partial engine load conditions leading to fuel consumption benefits of about 2 to 3 percent. Of note, cylinder deactivation is not a highly implemented fuel reduction technology in turbocharged diesel engines due to surge problems associated with the turbocharger during the switch over process.

L. Stoichiometric Gasoline Direct Injection

Potential FCR	2-3%(TIAX, 2009)
Technology Readiness Level	Widely Commercial
Applicability	Class 2b/3 gasoline

Figure A- 12: GDI System



Gasoline direct injection (GDI) engines inject fuel directly into the combustion chamber instead of into the intake port like traditional port fuel injectors. Figure A-12 illustrates a GDI system. The stoichiometric ratio of fuel to air used continues to allow the use of a three way catalyst to maintain low engine-out emissions typical of a gasoline engine. Throttling is still needed to maintain a consistent air/fuel ratio. Stoichiometric GDI results in efficiency gains over the more common port fuel injection engine. Fuel consumption improvements arise due to improved internal cooling of the cylinder air/fuel charge which leads to a higher knock margin. This allows for higher compression ratios, improving thermodynamic efficiency. Stoichiometric GDI engines are also more tolerant of EGR, so higher compression ratios can be used without a NOx penalty (NAS, 2010). Coupled with injector technologies that introduce multiple injections per cycle, improvements in air/fuel mixing, as well as residual exhaust gas tolerance, stoichiometric GDI engines generally have a higher power density than port fuel injected engines. Based on data used to support the U.S.

EPA's Phase 1 rulemaking, the estimated FCR of stoichiometric GDI engines is about 1 to 2 percent.

M. Lean-Burn Gasoline Direct Injection

Potential FCR	10-14%(NAS, 2010)
Technology Readiness Level	Introduced Commercially
Applicability	Class 2b/3 gasoline

A GDI engine can operate in an ultra-lean combustion mode during cruising situations when little acceleration is required. This approach results in the engine operating in a mode similar to that of a diesel engine by minimizing the throttling of the intake air and controlling the engine load by varying the air/fuel ratio. Like a diesel engine, a lean-burn GDI engine will most likely be turbocharged. In this case, the fuel is injected in the latter stages of the compression stroke just prior to ignition. This allows a small amount of fuel to be placed near the spark plug. The effective air/fuel ratio is very lean resulting in significant fuel savings. Lean-burn GDI engines have not reached broad application in the market due to difficulties in meeting NOx emissions regulation during long periods of lean operation. In lean-burn conditions, the three-way catalyst is no longer effective. As a result, NOx reduction strategies would be similar to those for a diesel engine, which would include the use of SCR. Based on data used to support the U.S. EPA's Phase 1 rulemaking, the estimated effectiveness of a turbocharged lean-burn GDI engine is about 10 to 14 percent relative to a port-injected engine with variable valve timing (NAS, 2010).

III. FUTURE ENGINE TECHNOLOGIES

Future engine technologies are all technologies currently in the research and development stages.

A. Camless Engines

Potential FCR	As much as 20%
Technology Readiness Level	Research and Development
Applicability	All Classes

Conventional valve trains generally have fixed valve lift and timing during the combustion cycle. Conventional designs use rocker arms and springs to open and close the valves. Such systems result in large parasitic power losses as friction from the camshaft and cam belts consume energy from the system and generally deliver only one timing speed. Camless engines bring about new engine advances that allow for independent control and scheduling of valve lift and duration. To achieve this freedom, the use of timing belts to link the crank motion to the valve timing is removed through the use of electromagnetic or electrohydraulic actuation. This allows for the optimization of valve motion to the desired engine power output. More torque is made available improving volumetric efficiency, which helps to reduce harmful emissions while improving fuel consumption. Camless engines would eliminate the need for throttling operations in gasoline engines, reducing the pumping losses seen in traditional engines. Camless engines would also require less engine oil lubrication demands (i.e., since these engines do not require a timing belt or camshaft gears). The elimination of the timing belt and camshaft gears not only diminishes frictional energy losses, but decreases the overall engine weight as well (Mackoski, 2001). Camless technology is thought to have the potential to deliver as much as 20 percent better fuel efficiency over a conventional engine (Free Republic, 2006). Technical issues with the actuators and the software used to run the system are currently being addressed to improve the repeatability of the process, power consumption, and vibration noise (Mackoski, 2001). Over twenty years of research examining camless valve train technologies has resulted in significant growth and development within the field, however; camless vehicles are not yet commercially available.

Electromagnetic Systems

In camless systems, instead of a timing belt, electromagnets can be used to open and close the intake and exhaust valves. A magnetic field is generated and a current is passed through an armature coil which runs perpendicular to the magnetic field. Depending on the direction of the current supplied to the armature, the valve is driven toward the open or closed position. Varying the strength of the current through the armature or changing the strength of the magnetic field enables control of both the opening and closing of the valves (Mackoski, 2001). Currently, large energy losses have been seen as load demands increase due to the required increase in current supply to the armature coil or strength of the magnetic field. To maximize the benefits of electromagnetic camless technology, these energy losses must be reduced.

Electrohydraulic Systems

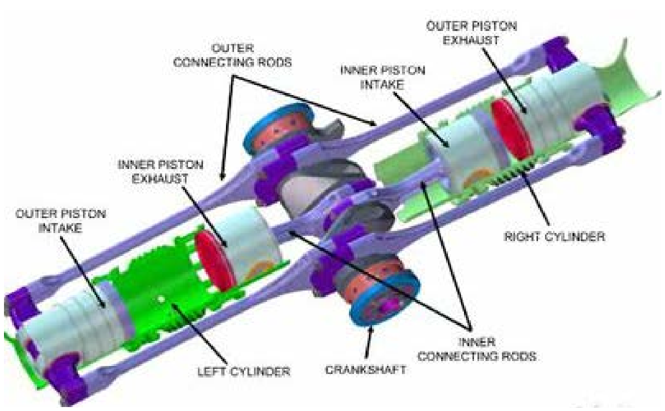
Unlike electromagnetic systems, hydraulic systems use a combination of compressed hydraulic fluid and fast-actuating solenoid valves to control the timing of valve opening and closing. The system incorporates high and low pressure fluid reservoirs. During valve opening, the high pressure solenoid is opened and the increase in net pressure accelerates the engine valve open. The process of closing the engine valve is similar, but in this case the low-pressure solenoid is opened creating a pressure gradient that forces the valve shut. Valve lift is controlled by varying the duration of the solenoid voltage pulse, while adjusting the high pressure within the solenoid system allows for adjustment to the valve acceleration, velocity, and travel time (Schechter & Levin, 1996). Control system development and energy loss due to high power consumption are challenges that engine developers are currently working to improve. Typically, electrohydraulic systems are only being developed for diesel truck engines as it is thought the technology will not have the speed necessary for higher revving passenger vehicle engines (Mackoski, 2001).

B. Opposed Piston Engines

Potential FCR	15-24%
Technology Readiness Level	Research and Development
Applicability	All Classes

In an opposed piston engine, each cylinder has two pistons that come together at top dead center and then expand outward upon combustion. Opposed piston engines are two-stroke, compression ignition engines. As shown in Figure A-13, the right cylinder is completing the compression stroke and the left cylinder is completing its expansion stroke. The pistons cyclically expose the exhaust and intake ports without the use of a camshaft or valve train resulting in a smaller, lighter weight engine that reduces heat and frictional losses (Fromm et al., 2012). Higher thermal efficiency is seen from the opposed piston design due to leaner air/fuel ratio requirements and a shorter combustion duration. Current research suggests that a possible 15 to 24 percent FCR is possible with the use of opposed piston designs (Regner et al., 2014) depending on the specific application.

Figure A- 13: Opposed Piston Engine



(Ecomotors)

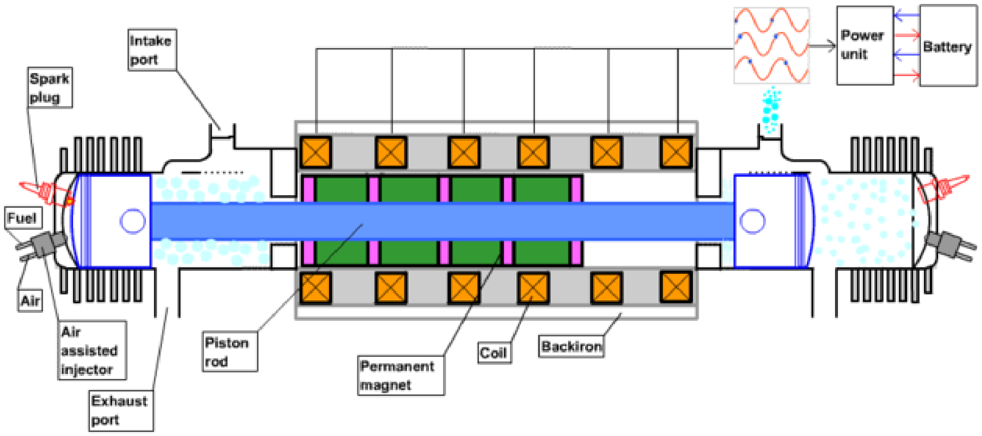
As a two-stroke engine, the opposed piston design has historically suffered from durability, thermal management and oil consumption issues resulting in higher hydrocarbon and particulate matter emissions, challenging engine designers who must reach the ever increasing emission stringencies required of automobiles. Further research and testing is needed to convince automakers that the opposed piston design can be trusted to continually meet emission standards. Achates Power Inc., based in San Diego, California, is working on opposed piston engine research and development and is showing significant advancement in both technology and emission control. Their testing of prototype engines in medium- and light-duty applications has shown that high thermal efficiency and lower tailpipe emissions are possible, primarily due to 1) an increased surface area to volume ratio in the combustion chamber which results in better heat transfer and less heat rejection, 2) the reduced heat rejection leads to less parasitic loss to cooling fans and reduces radiator size and aerodynamic drag, 3) less fuel burned in a relatively larger cylinder volume resulting in a leaner and more efficient combustion process relative to a four cylinder engine, and 4) natural exhaust gas retention reducing pumping work due to natural exhaust gas retention which helps control NOx at low loads (Achates, 2014). Ecomotors is another company that is designing an opposed piston engine targeted for sale in China. Most automakers see the opposed piston engine as a potential post-2020 technology. The timescale for implementation are difficult to predict at this time.

C. Free Piston Engines

Potential FCR	N/A
Technology Readiness Level	Research and Development
Applicability	All Classes

The free piston term is used to distinguish a linear engine design from one with a rotating crankshaft. The piston is considered "free" because its position is determined by the interaction between the gas and load forces acting upon it and its motion is not restricted by a crankshaft (Mikalsen et al., 2009). There are inherent advantages of the free piston design relative to the traditional 4-stroke automotive engine. The lack of a crankshaft allows for variable piston stroke lengths depending on the desired engine output load. These variable compression loads allow for better efficiencies when the engine is at partial load. Additionally, the elimination of the crank mechanism reduces the number of parts and complexity of the engine design. This leads to a reduction in frictional losses due to less moving parts, reduced manufacturing costs, and an increased lifetime. Moreover, as a two-stroke engine, the free piston engine design has an inherent specific power advantage over traditional 4-stroke engines. In addition to running on gasoline and diesel fuel, free piston engines have also been demonstrated to run on alternative fuels such as crude oil and vegetable oil (Flynn, 2005). Fuel consumption is reported to be around 20 percent lower than a conventional engine; however, these findings must be further substantiated through tests and demonstrations. Figure A-14 shows a free piston engine that is set up to generate electricity. The magnet attached to the piston rod generates a current as it travels back-and-forth in the coil. The electricity generated can be supplied to the battery system of an electric or hybrid vehicle and used as a range extender when battery power is depleted. Earlier renditions of the free piston motor in the 20^{th} century converted the combustion energy into compressed air, which was then used to power a turbine.

Figure A- 14: Free Piston Engine used to Generate Electricity



(Sandia)

Accurate control of piston motion currently represents one of the biggest challenges of free piston engine development. The stroke length is limited by the need for sufficient compression; hence, there are limitations in the frequency control and power output (Flynn, 2005). As the free piston engine does not have the energy storage capacity to drive the engine for several revolutions like the flywheel in a conventional engine, misfiring can be a concern as well (Flynn, 2005). Despite this, the large potential FC benefits associated with the free piston engine keeps engine research designers hopeful that a breakthrough is within reach.

D. Advanced Combustion Cycles – Low Temperature Combustion

Potential FCR	Up to 20% (WARF, 2014; TIAX, 2009)
Technology Readiness Level	Research and Development
Applicability	All Classes

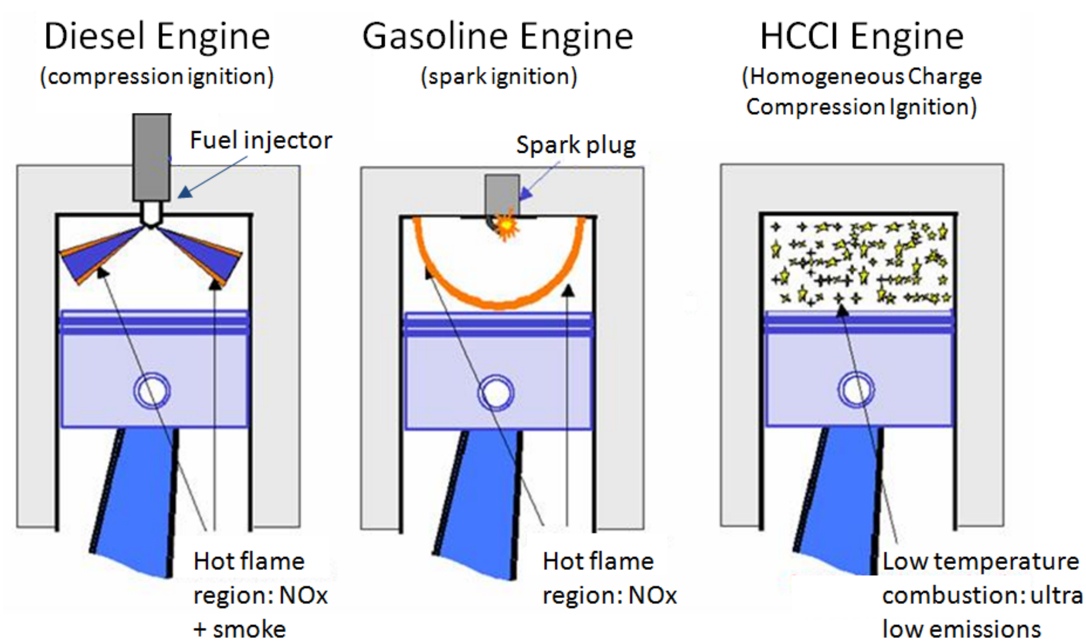
Advanced combustion cycles are currently in development to combine the thermal efficiency of diesel compression combustion engines with the lower emission levels of gasoline spark ignition combustion engines. Low temperature combustion engines like homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), and reactivity controlled compression ignition (RCCI) are engine design concepts that offer potential to see vast improvements in engine efficiency without the need to install expensive aftertreatment systems to meet emission standards. Large future benefits can be gained if continued progress is made in the research and development of these systems. At this time, it is difficult to assess the potential FC benefits.

HCCI

In an HCCI engine, the best of gasoline engine and diesel engines are combined. Fuel is homogeneously mixed with air similar to a spark-ignited gasoline engine, however, at a very lean air/fuel ratio. The fuel is then combusted through compression ignition, similar to that of a diesel engine. This lean air/fuel ratio allows for diesel like thermal efficiencies to be reached since fuel is not wasted as in a rich-burn spark ignition system. Efficiency is also improved due to the elimination of throttling losses, high compression ratios, and a short combustion duration.

Ignition timing can be difficult to control and high HC/CO emission output has been observed. The rapid combustion that occurs at high loads can also lead to large NOx levels, increased noise, and can potentially damage the engine (KAUST, 2014). However, researchers are currently working to address these concerns and improvements are being made. For example, cold start capability has been seen as a problem with the engine design. However, this has potentially been solved through the use of glow plugs or spark ignition to get the engine running. A time frame for the commercialization of this technology remains unclear, but progress is being made. Figure A-15 below shows a diagram of HCCI.

Figure A- 15: Homogeneous Charge Compression Ignition Diagram



(National Instruments, 2014)

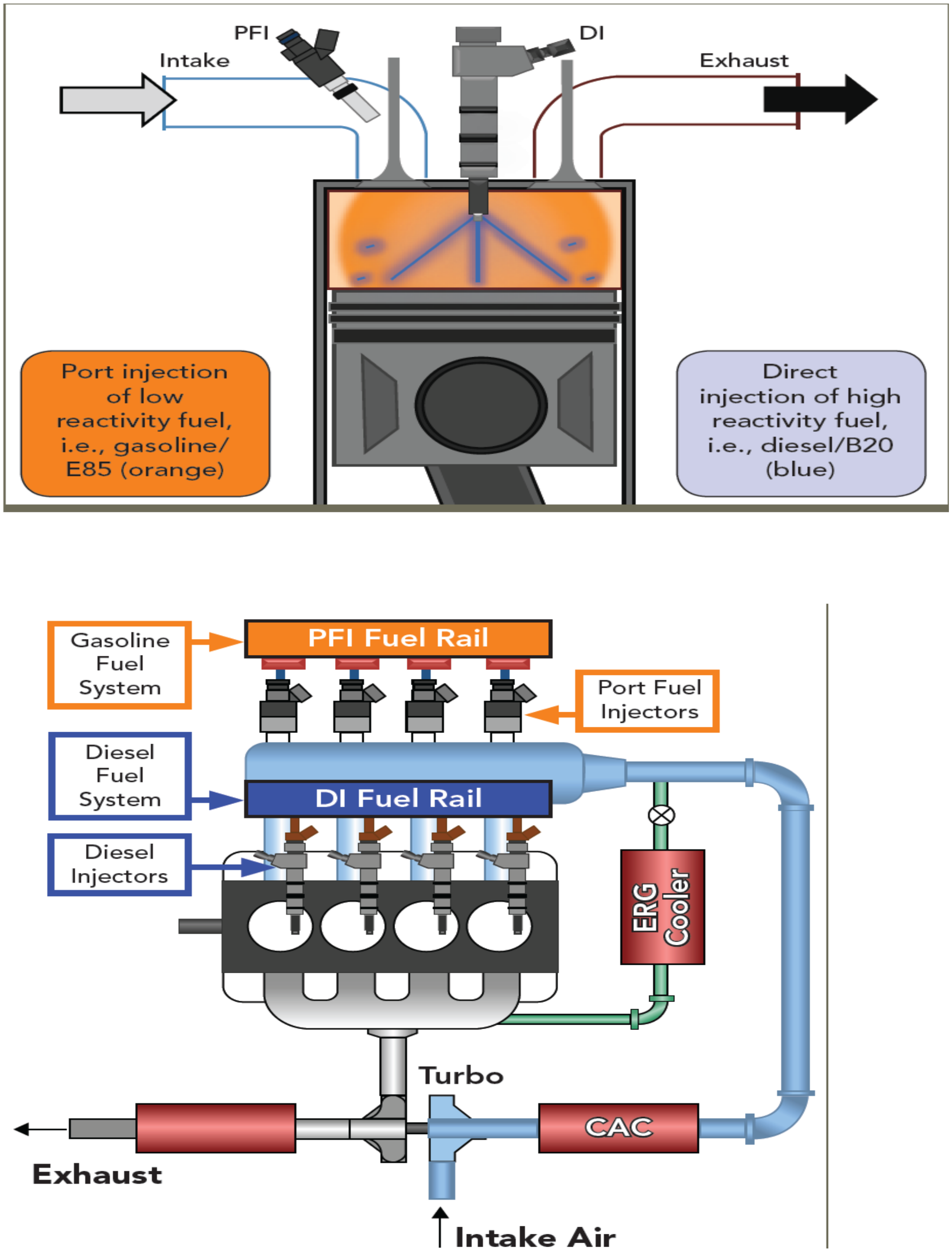
PCCI

PCCI is an attempt to better control the ignition timing problems associated with HCCI by injecting a late fuel pulse in the compression stroke that dictates the onset of ignition (National Instruments, 2014). Fuel is premixed with air in the cylinder creating HCCI-like conditions as the compression stroke reaches top dead center (TDC). Near TDC, the late fuel pulse is then directly injected into the cylinder. This fuel-rich late injection burns before the lean air/fuel mixture already present in the cylinder, allowing more control over when and where combustion begins in the cylinder. Additionally, the burn duration is lengthened relative to an HCCI engine which increases the specific power of the engine. Of note, the PCCI engine produces higher NOx and PM emissions relative to the HCCI engine.

RCCI

An evolution of both HCCI and PCCI, RCCI attempts to get further control over the LTC combustion process through the use of multiple fuels of different reactivities. Multiple injections of varying fuels are used in an effort to optimize combustion phasing, duration, and magnitude throughout the engine cycle (WARF, 2014). A low reactivity fuel is injected early in the engine cycle mixing homogenously with the intake air. Later in the cycle, a higher reactivity fuel is injected into the cylinder. Examples of fuel pairings include gasoline (low reactivity) and diesel (high reactivity) or ethanol (low reactivity) and diesel (high reactivity). This strategy creates pockets of differing air/fuel ratios within the cylinder enabling the manipulation of combustion rate and timing. By tailoring the relative amount of fuel charge and combustion timing, RCCI offers enhanced thermal efficiency (60 percent relative to a standard diesel engine (Ashley, 2014)), while simultaneously reducing emissions of CO_2, NOx, and PM. As with the other LTC systems mentioned here, RCCI is still very much in the developmental stage with large uncertainties with regard to the timing of full demonstration and deployment into the industrial sector. These systems offer large potential for improvements in fuel consumption and emission control, but are likely still at least a decade away from impacting the transportation sector. Figure A-16 shows a diagram of an RCCI system.

Figure A- 16: Reactivity Charge Compression Ignition Diagram



(Curran et al., 2013)

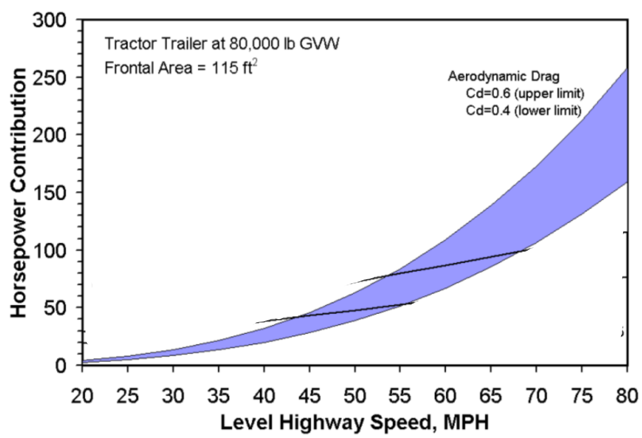
IV. VEHICLE EFFICIENCY TECHNOLOGIES

A. Aerodynamics

Potential FCR	
Long Haul Tractor-Trailer	9-16%(NAS, 2010; NAS, 2014)
Short Haul Tractor-Trailer	2-5%(U.S. EPA, 2011d)
Straight Truck	4-6%(TIAX, 2009)
Pickup and Van	3%(TIAX, 2009)
Technology Readiness Level	Widely Commercial
Applicability	Class 7/8 Long Haul Tractor; Class 3-8 Rural; Class2b/3

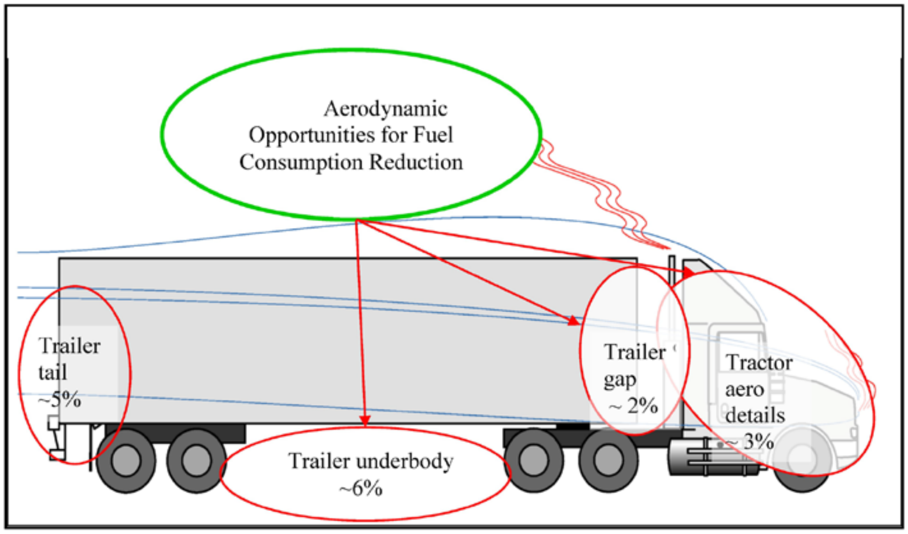
Reducing aerodynamic drag plays a big role in reducing the fuel consumption for vehicles that operate at higher speeds. Figure A-17 illustrates the horsepower needed to overcome the impact of aerodynamic drag on a tractor-trailer traveling at increasing speeds.

Figure A- 17: Horsepower Required to Overcome Aerodynamic Drag and Rolling Resistance



As shown, if the aerodynamic drag coefficient (Cd) is reduced from 0.6 (which is roughly equivalent to a modern SmartWay verified aerodynamic tractor and trailer) to 0.4 (which is equivalent to an advanced "next generation" aerodynamic tractor-trailer), the horsepower required to overcome aerodynamic drag is reduced from 110 to about 60 horsepower at 65 mph. This would equate to roughly a 16 percent reduction in fuel consumption (Wood et al.). For tractor-trailers, improvements in fuel consumption can be achieved in four major areas: the tractor body, tractor-trailer gap, trailer underbody, and the rear of trailer. These areas are shown in Figure A-18. As shown, for a tractor-trailer with a Cd of 0.625, there is the opportunity to reduce fuel consumption by about 3 percent through improved tractor aerodynamics and about 13 percent from improved trailer aerodynamics.

Figure A- 18: Tractor-Trailer Combination Truck Illustrating Regions of Potential Fuel Consumption Reduction; Combined Cd Base of 0.625 (NAS, 2010)



Tractor aerodynamics can be improved in many ways, as illustrated in Figure A-19. Both the U.S. EPA's SmartWay voluntary program and ARB's Tractor-Trailer GHG regulation have influenced the demand for more aerodynamic tractors by fleet owners. The differences amongst a classic tractor with few aerodynamic features, a SmartWay-verified tractor which incorporates all of the features shown, and the next-generation tractor are shown in Figure A-20. The next generation tractor shows the type of innovations to tractor design that are being developed through the SuperTruck projects.

Figure A- 19: Sleeper Cab Tractor with Aerodynamic Features Identified (NAS, 2010)

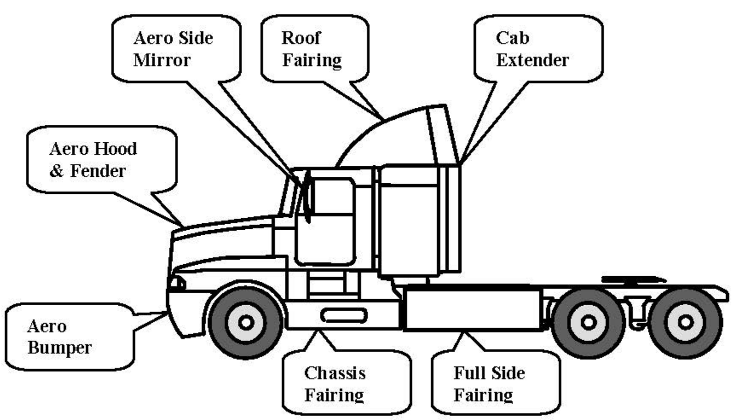


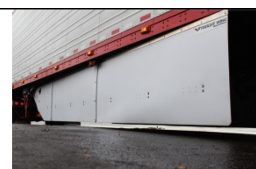
FIGURE 6-4 Sleeper tractor with aerodynamic features identified. SOURCE: NRC, 2010, Figure 5-5.

Figure A- 20: Classic, SmartWay, and Next Generation Tractors

Classic Tractor | "SmartWay" Aerodynamic Tractor | "Next Generation"

Trailer aerodynamics can be improved through the installation of aerodynamic devices. As with tractors, the SmartWay program and the Tractor-Trailer GHG regulation have influenced the growing market for these devices. The most common aerodynamic technology being added to van trailers is the side skirt. Other devices such as rear trailer fairings, under trailer devices, and gap fairings are also being installed. Examples of these devices are shown in Figure A-21.

Figure A- 21: Trailer Aerodynamic Devices

Side Skirts	
Gap Fairing	
Rear Trailer Fairing	
Under Tray Device	

Recent interviews of fleet owners and manufacturers (22 total companies) conducted by the International Council on Clean Transportation (ICCT) illustrate the cost effectiveness of van trailer aerodynamic devices and the acceptance by the trailer industry. Table A-1 is a summary of interview responses on van trailer aerodynamic technology fuel savings and levels of adoption (ICCT, 2014a). As shown, 40 percent of new trailers are sold with trailer side skirt technologies. Other technologies are not as well accepted, but are also resulting in FCR benefits.

Table A- 1: Summary of Interview Responses on Trailer Technologies

<table>
<tr><th>Technology</th><th>Fuel Savings</th><th>Adoption in New Trailer Sales</th></tr>
<tr><td>Side skirts - average</td><td>3%</td><td rowspan="2">40%</td></tr>
<tr><td>Side Skirts - best</td><td>7%</td></tr>
<tr><td>Boat tails - average</td><td>3%</td><td rowspan="2">3%</td></tr>
<tr><td>Boat tails - best</td><td>5%</td></tr>
<tr><td>Gap reducers</td><td>1%-2%</td><td>Minimal</td></tr>
<tr><td>Underbody devices</td><td>2%-5%</td><td>3%</td></tr>
</table>

Aerodynamic technologies for Class 3-8 vocational straight trucks are currently being demonstrated by fleets that use these trucks in rural/intercity delivery activities. Front gap fairings, side skirts, and wheel covers are being applied. At least two trailer aerodynamics manufacturers, Freight Wing Laydon, and Wabash Composites, currently market side skirts for trailers that can be customized to fit delivery trucks (see Figure A-22). ARB currently has a contract with National Renewable Energy Laboratory (NREL) for evaluating the fuel consumption benefit of vocational vehicles and pup (27 foot long trailers pulled in tandem) trailers with and without aerodynamic technologies installed. The devices being tested as part of this project include front/roof fairings, side skirts, and wheel covers.

Figure A- 22: Front Gap Fairing and Side Skirts on Straight Trucks and Pup Trailers

B. Lightweighting

Potential FCR	0.75-3.2% (NAS, 2010)
Technology Readiness Level	Introduced Commercially
Applicability	All classes to a varying degree with an increased benefit to lower classes (See Table A-2)

Reducing a vehicle's mass improves fuel consumption by lowering the energy demands needed to overcome climbing grades, acceleration, and a vehicle's rolling resistance. Mass reductions are applicable across all vehicle subsections including, but not limited to, the engine, exhaust system, transmission, chassis, brakes, and suspension. Mass reduction can be accomplished through multiple avenues. Material substitution, where a lower density/higher strength material such as aluminum, magnesium alloy, or carbon fiber composite, can reduce the overall mass of the vehicle when replacing traditional steel components. Optimizing the structural design of various systems can additionally lead to a reduction in the total amount of material used. As an additional benefit, smaller, lighter engines and transmissions can potentially be used due to lower power requirements which will result in further mass reduction to the overall vehicle system. The energy to overcome climbing grades, acceleration, and rolling resistance is essentially linearly dependent on truck weight, therefore there is large variability in the overall benefit of lightweighting in the various vehicle sets. For example, a 0.5 percent FC benefit in class 8 trucks results from a 1000 pound weight reduction, whereas, a 0.75 percent FC benefit can be achieved on a class 2b/3 truck with only a 300 pound weight reduction (NAS, 2010).

Table A- 2: Variability in Percent Reduction from Lightweighting

Class	FCR (%)	Weight Reduction (lbs).
8	1.25	2500
3-6	3.2	1000
2B/3	0.75	300
Refuse	1	500

C. Low-Rolling Resistance Tires

Potential FCR	1-14%(TIAX, 2009)
Class 8 Over-the-Road	2-14%(TIAX, 2009)
Class 6 Urban	2%
Urban Bus	1%
Technology Readiness Level	Widely Commercial
Applicability	All classes, better FC in applications with higher speeds

Tire rolling resistance can account for about 1/3 of the power required to propel a long-haul truck at highway speeds (NAS, 2010). This resistive force is defined as the coefficient of rolling resistance (C_{rr}) and is found to be nearly linearly proportional to the load on the tire, where $C_{rr} = \frac{resistive\ axial\ force}{normal\ force}$. C_{rr} is a dimensionless unit, typically ranging from 0.004 to 0.008 in modern trucks (NAS, 2010).

Rolling resistance is a component of three main sources: hysteresis losses within the tire, frictional drag, and aerodynamic drag. Through recent technology advancements, these energy draining components have been reduced, leading to a more fuel efficient tire. Improved rubber formulations and sturdier side wall casings have reduced the amount of sidewall flexing and heat loss that is a result of the inherit hysteresis effect in moving tires. New tread designs, in addition to shallower tread depth, have improved both aerodynamic and frictional losses that occur during the drive process. Although shallower tread depth in the past was associated with reduced tire life, improvements in rubber durability have offset the reduction in tread depth enabling tire lifetime to not change significantly.

Fuel savings via low rolling resistance tires is highly duty-cycle dependent. Rolling resistance increases with speed, thus greater fuel savings can be seen for fast moving long haul trucks than for those vehicles working in the stop-and-go urban sector. Table A-3 shows the estimated conversion from C_{rr} to FC percent benefit for the various truck drive cycles. As can be seen from the table, long haul trucks have the lowest $\frac{C_{rr}}{FCR\ \%}$ ratio demonstrating that they gain the greatest fuel consumption benefit from switching to low rolling resistance tires. FCR of up to 14 percent can be seen in the trucking sector relative to a standard tire model (TIAX, 2009).

Table A- 3: Change in C_{rr} Necessary to Achieve a 1% Reduction in Fuel Consumption (NAS, 2010; TIAX, 2009)

Truck Class	Ratio of (C_{rr} %)/(FCR %)
Class 8 Long Haul	≈ 4
Class 6 Urban	≈ 10
Bus Urban	≈ 20

* Numbers generated using rolling resistance data

Further improvements in fuel consumption can be seen by switching from a dual tire configuration to a wide base single (WBS) tire. Through the elimination of two sidewalls and bead areas relative to the dual tire setup, WBS tires can cut flex related rolling resistance in half. Additionally, a weight savings ranging from 800 to 1,000 pounds can be realized by switching to WBS tires. Table A-4 presents the average $C_{rr,}$ C_{rr} improvement, and fuel consumption benefit for Class 8 tractor-trailer tires.

Table A- 4: Tire Options for Class 8 Tractor-Trailers (TIAX, 2009)

Tire Options	Avg C_{RR}	C_{RR} Imp.	FC Benefit
Standard Duals Package	0.0068		
Low rolling resistance duals	0.0061 to 0.0062 (Est)	10%	2 to 4%
Wide base singles (WBS) (Tractor Only)	0.0055	19%	3 to 6%
Wide base singles (WBS) (Tractor + Trailer)	0.0055	19%	6 to 9%
Next generation WBS	0.0045	34%	11 to 14%

D. Automatic Tire Inflation

Potential FCR	1%[U.S. EPAa]
Technology Readiness Level	Widely Commercial
Applicability	All classes; mostly trailers, limited for tractors

Tires represent the second largest financial expense for most fleets (Meritor). Through road side inspection surveys, it was found that only about 50 percent of tires checked were within 5 percent of their recommended pressures. Underinflated tires have been shown to increase the tire footprint on the roadway leading to more friction and heat production which increases the rolling resistance of the tire. Additionally, more flex in the sidewalls of the tires increases energy loss due to a larger hysteresis effect. These complications result in a reduction in fuel consumption and reduce the overall lifetime of the tire in question. Automatic tire inflation (ATI) systems are designed to monitor and continually adjust the level of pressurized air in tires, automatically keeping tires properly inflated even while the vehicle is in motion. A vehicle with an ATI system installed should not require any special attention from the drivers. This eliminates the need to check tire pressure manually, which saves time and labor while ensuring consistent and proper tire inflation (U.S. EPAa).

Currently, ATI systems are largely separated into two fundamental types, centralized or distributed, depending on how the air is supplied to the system. The most common type of ATI system is a centralized system that utilizes the vehicle's brake compressor to supply air (see Figure A-23). The system utilizes hollow axles to run lines from the air tank to the wheel end to deliver air to the tires. These types of systems are currently limited to trailer applications due to the availability of the hollow axle to deliver air (the system currently cannot be used on tractor drive axle due to the inability to run air lines through the axle, which contains a drive shaft within the housing). A second type of ATI system is a distributed system that utilizes pumps either within individual tires or with one system per wheel end (See Figure A-24). Unlike centralized systems, this technology is not dependent on a vehicle air tank and the availability of hollow axles. The system can be used on both drive (tractor) and trailer axles. Both systems can also deflate tires to correct for pressure rises when the temperature increases (NAS, 2010). At present, the availability of these systems is extremely limited (NACFE, 2013a). ATI systems lead to a fuel consumption benefit of about 1 percent (Park, 2012). These systems can also improve overall roadway safety by reducing the amount of tire blowouts caused by underinflation problems.

Figure A- 23: Centralized ATI System

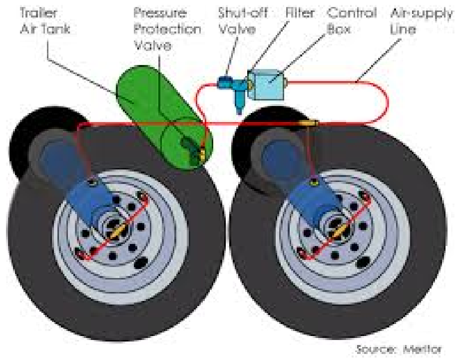
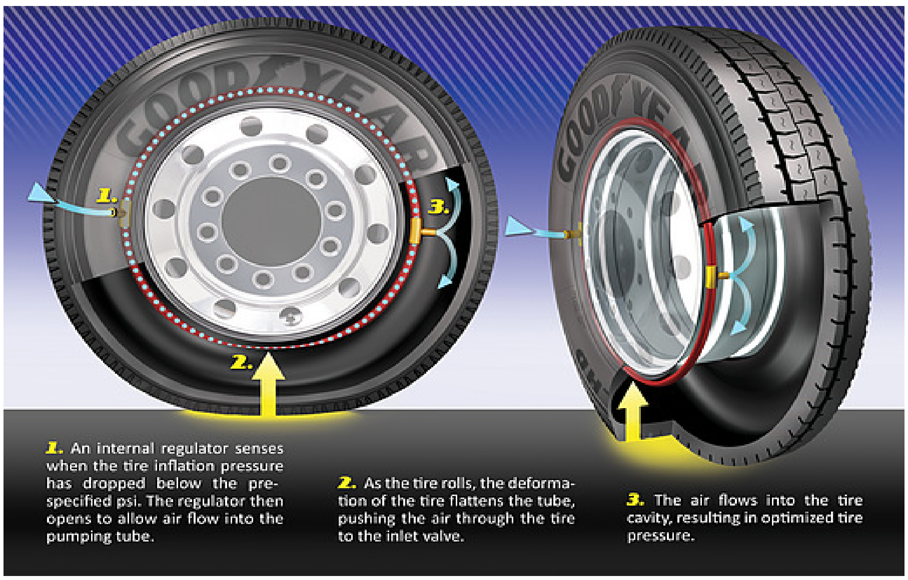


Figure A- 24: Distributed ATI System



(Source: Goodyear)

E. Vehicle Speed Limiters

Potential FCR	0.7-1% per mph reduction(NAS, 2010)
Technology Readiness Level	Widely Commercial
Applicability	Class 8 Long Haul Tractor

Road speed limiters establish a top end speed at which a vehicle can travel and are currently standard features on heavy-duty trucks; however, it is up to the vehicle owner to decide whether or not to take advantage of the setup. Fleets that use speed limiting technology today typically set maximum speed allowances between 65 to 70 mph. Many fleets, however, do not use them at all. A fuel consumption benefit of about 0.7 to 1 percent per mph reduction is expected for an aerodynamically optimized long haul tractor-trailer. Thus, for example, a FCR of 3.5 to 5 percent results from a fleet lowering its governed speed from 65 to 60 mph, whereas a 7 to 10 percent FC benefit occurs for a fleet reducing its governed speed from 70 to 60 mph (NAS, 2010). In Europe, all trucks have speed limiters that are set by the factory to a specific speed determined by law.

F. Axle Efficiency Improvements

Potential FCR	2.5%(NACFE, 2014a)
Technology Readiness Level	Widely Commercial
Applicability	Class 8 Long Haul Tractor and Short Haul; Class 3-8 Urban Rural, and Worksite Support Vocational

Traditionally, North American class 8 tractors are equipped with three axles - a forward, unpowered, steer axle, and two rear-drive axles which are often referred to as a “live tandem” axle system. Thus, 4 wheels are powered by the engine making this a 6x4 configuration (6 total wheels, 4 drive wheels). A 6x2 configuration on a six-wheeled tractor has the same wheel configuration, but only one of the rear axles is a drive axle, with the other rear axle constituting as a dead axle. This means only 2 wheels are powered by the engine. There are two possible configurations on a 6x2 system, differentiated by the location of the non-driving rear axle. The first and most common 6x2 system is the “tag tandem” where the forward-rear axle is driven and the rear-rear axle is the “non-driver” or “tag” axle. Alternatively, a “pusher tag” 6x2 system has the non-driven axle in the forward-rear location and the drive axle in the rear-rear location (NACFE, 2014a).

Studies by the North American Council for Freight Efficiency have recently shown that the 6x2 configuration offers fuel consumption savings ranging from 1.9 to 3.5 percent with an average savings of 2.5 percent relative to the 6x4 configuration. When combined with additional technologies such as an overdrive transmission and dual-tires, this complete package represents a 6 percent FCR (Berg, 2014; NACFE, 2014a). Additionally, 6x2's offer about a 400 to 450 pound reduction in weight to the overall chassis as the additional dead axle in a 6x2 is significantly lighter than the additional drive axle in a 6x4 configuration. The lack of internal gearing in the dead axle of a 6x2 configuration also contributes to a FCR (compared to a 6x4 configuration) since there are no lubrication needs and therefore no frictional energy losses normally associated with gearing. (Berg, 2013a; NACFE, 2014a). The reduced internal gearing and drop in the total number of driveline components is expected to lead to a decline in labor and maintenance relative to a 6x4 configuration.

6x2 configurations account for only about 4 percent of new line haul tractor sales in the U.S. The total U.S. market penetration is 2.3 percent, yet is beginning to show slow growth. Suppliers suggest the 6x2 configuration will increase to as high as 18 percent of total class 8 tractor sales in 5 years (Berg, 2013b). Several factors are limiting the growth of acceptance of the 6x2 configuration within the U.S. By far the largest concern voiced in the trucking industry is a reduction in traction relative to the 6x4 configuration (NACFE, 2014a). However, these concerns are likely overstated. Many conditions where a loss of traction might be noticed in a 6x2 configuration, (e.g., deep snow, loose gravel, ice, etc.), will also inhibit traction in a 6x4 configuration. Any potential shortcomings of a 6x2 configuration can also be mitigated with the use of load shifting technologies to increase the weight on the drive axle at low speeds (NACFE, 2014a). Electronically controlled air suspension systems exist that will automatically increase traction to the drive axle when a low traction situation is detected. Traction increase is accomplished by briefly decreasing pressure in the tag axle suspension air bags. The 6x2 configuration is readily used in Europe, not only in line-haul applications, but in heavy load applications such as garbage trucks, dump trucks, and snow plows as well.

Increased tire wear on the single drive axle is also a concern raised by the fleet industry as all the torque and engine braking power passes through only a single set of tires in a 6x2 instead of two in the traditional 6x4. However, this can be offset by using less expensive trailer tires on the additional tag axle which also provide the benefit of a lower rolling resistance.

Current resale values of the 6x2 configuration are less than their 6x4 counterparts in the U.S. (Berg, 2013b; NACFE, 2014a). This resale penalty is one reason fleets cite for not purchasing 6x2 tractors. However, as 6x2 technology is better understood by the trucking industry and these systems become more accepted in the U.S., it is expected that this resale penalty will significantly reduce or be virtually eliminated by the time a fleet is ready to sell their tractors.

G. Idle Reduction

Potential FCR	1.3-9%(NAS, 2010; TIAX, 2009)
Technology Readiness Level	Technology Dependent
Applicability	Class 8 Long Haul Tractor (Sleeper Cabs)

Throughout the U.S., about 10 percent of a truck's time is spent idling (NACFE, 2014b). Sleeper cab idling periods account for about 9 percent of total fuel consumption, constituting about three billion gallons of fuel. Through regulatory measures requiring an auxiliary power unit (APU) and a 5 minute maximum idling period, the amount of fuel consumed under idling conditions in California is drastically lower than in other parts of the country. Table A-5 shows the amount of fuel consumed while idling at various engine speeds ranging from about 0.5 gallons/hour at 650 RPM up to about 1.2 gallons per hour at 1200 RPM (NACFE, 2014b). APU devices lower the amount of fuel consumed during overnight idling periods benefitting the truck operator through cost savings while simultaneously reducing pollutant emissions.

Table A- 5: Main Engine Idling Fuel Consumption

Main Engine Speed (Revs/Minute)	Average Fuel Consumption
650 RPM	≈ 0.5 gallons/hour
1000 RPM	≈ 1.0 gallons/hour
1200 RPM	≈ 1.2 gallons/hour

The following sections summarize important idle reduction technologies that can be used to reduce the amount of fuel wasted during idling and include some zero-emission technologies. For a detailed analysis, refer to the 2014 NACFE Idle Reduction Confidence Report (NACFE, 2014b). Other idle reduction technologies discussed in the 2014 NACFE Idle Reduction Confidence Report that are not included in this assessment include thermal storage systems, automatic engine stop-start systems, and fuel operated coolant heaters. For the technologies summarized here, the combination of battery APUs and solar power or truck stop electrification offer the largest potential for zero and near-zero emissions. The penetration rates of both solar power and truck stop electrification are low; significant growth is necessary to achieve higher penetration of zero-emission technologies in the future.

Fuel Operated Air Heaters

Technology Readiness Level	Widely Commercial

Fuel operated air heaters burn diesel fuel to provide heat to the sleeper cabin area when the engine is powered off. Small and lightweight (6 to 8 pounds), they are usually mounted either behind or under the sleeper cabin with fuel pumps attached directly to the truck's fuel tank. These units can burn as little as 0.02 gallons per hour, up to a maximum of 0.13 gallons per hour. They offer substantial fuel cost savings relative to engine idling. This unit can be considered a bare-bones idle reduction technology as drawbacks include an inadequacy to provide air conditioning or electrification to the cabin area and can drain a truck's main battery unit with long-term use. These systems usually have to be equipped with other APU technologies during the hot summer months and are often sold as a package with battery HVAC systems.

Diesel APUs

Technology Readiness Level	Widely Commercial

Diesel APUs offer all the necessary functions needed during extended shut-off periods by providing heating, cooling, and electrification to the sleeper cabin. They burn between 0.1 to 0.5 gallons of fuel per hour depending on design and operation requirements and typically weigh between 400 to 500 pounds. Diesel APUs are equipped with generators that supply 120 volt AC power directly to the cab and as a result, do not drain a truck's battery system. These systems require more in-use maintenance than other idle reduction technologies such as periodic oil changes, filter changes, tune-ups, and replacement of belts, hoses, etc.

Battery HVAC/APUs

Technology Readiness Level	Widely Commercial

Battery APUs provide climate control and electrification to the interior cabin while the engine is shut down and can be recharged through off-board AC power (shore power) or by capturing energy produced by the truck engine's alternator as the truck is running. Battery APUs are sufficient for overnight downtime as they typically provide between 8 to 10 hours of functionality before having to be recharged. They require about 1 to 3 hours to recharge during engine-on mode and weigh between 400 and 500 pounds.

Current research is heavily focused on improving the lifetime and storage capacity of battery technology, while at the same time, driving manufacturing costs down. With steady improvements in the future, battery APUs have the potential to become an important idle reduction technology that can provide significant emission benefits.

Solar Energy Capture

Technology Readiness Level	Demonstration

On-vehicle solar energy capture through the use of roof-mounted solar panels can be used to create DC power to run a battery HVAC system or recharge it after overnight use. With the use of solar energy, the life of a battery HVAC system can be extended to at least 14 hours when run during daytime hours. This can become important for operators who decide to take daytime breaks to avoid traffic congestion. There is potential to use the combination of solar energy and battery APUs to power the cabin throughout the entire 34-hour rest period required by the federal Hours of Service (HOS) rules if the battery HVAC system is run throughout the night and then recharged during the day at the same time solar energy is being used to supply electricity to the cabin. Idle downtime in the trucking industry can potentially become a zero-emission technology through the combination of these systems instead of relying on the main engine's fuel supply and alternator to recharge the battery system.

Truck Stop Electrification

Technology Readiness Level	Commercial, although more investment infrastructure is needed

Truck stop electrification is an idle-free electrification option that allows trucks to plug into 120V AC power supplies at various truck stops and rest areas. The electrification infrastructure is currently not adequate to support the trucking industry and is the biggest obstacle to penetration. Due to this lack of infrastructure, truck operators cannot rely on electrification sites alone and must purchase additional idle APU technology to use when these sites are unavailable. Besides powering APU systems, truck stop electrification can also be used to power hybrid electric transport refrigeration units on refrigerated van trailers. Most hybrid electric TRUs are 460 V, 3-phase electric power, thus, truck stops only equipped with 120 V, single phase power would not be compatible. Large investments in publically accessible electric power infrastructure and the number of 460 V and 120 V power plug pedestal units available at current operating sites are needed for truck stop electrification to become a viable alternative to non-electric APU and TRU technologies.

H. Improved Air Conditioning Systems

Reflective Glazing

Potential FCR	Less than 1%
Technology Readiness Level	Widely Commercial
Applicability	All Classes

Up to 75 percent of the thermal energy emitted into a vehicle passes through the windows with more than 40 percent entering through the front windshield (ARB, 2009a; Roessler & Heckmann, 1992). Thus, minimization of this heat parameter can lead to reductions in the cooling loads on HVAC systems within an operating vehicle. Glazing manufacturers have focused on the rejection of IR (infrared) wavelengths to improve thermal comfort within vehicular interiors. It has become the major focus of solar-control glazing technology in vehicles (Devonshire & Sayer, 2002) as IR radiation accounts for about half of the solar wavelength distribution reaching the earth's surface. It is imperative to minimize the loss of visible light associated with these glazing materials as enhanced reflection of visible light can reduce the visibility of the vehicle operator and/or inhibit the visibility of oncoming drivers. Federal regulations require a minimum of 70 percent luminance transmittance within vehicular windshields. Ceramics and transparent metallic coatings that specifically reflect wavelengths within the IR region such as indium, tin oxides, and noble metals are doped onto the window surface to reduce the amount of IR radiation penetrating into the interior cabin.

There are two methods for applying the IR reflective material onto window surfaces. The first approach is to bond the reflective coating directly into the glass itself. This process, known as sputtering, involves processing the glass through a vacuum chamber to create a thin layer of high reflective material about 5 to 30 µm thick on the glass surface (Johnson, 2009). Due to extensive capital and operation costs, this sputtering process is rarely used within the U.S. automotive industry. An alternative technique sputters the reflective coating onto a clear polyethylene terephthalate (PET) film. The laminate film is then placed between the two panels of a laminated windshield, eliminating the expensive procedure of coating the glass itself (Johnson, 2009). This allows automotive glass manufacturers to purchase "off the shelf" products from dealers specializing in industrial sputtering processes instead of investing in expensive capital which would only be one part of their overall production line.

An additional type of glazing technique takes advantage of IR adsorptive materials, such as iron oxide, that collect IR wavelengths while allowing visible light to pass through unaffected. The heat produced from this absorption process is then dissipated outward via convection (Huber, 1988), removing some of the solar radiation that would otherwise pass straight through the windshield into the vehicle's interior. Emission of this energy is scattered in all directions, thus some of the absorbed energy is still transmitted into the vehicle interior. This makes absorbing materials less effective at reducing thermal radiation than a purely reflective substance (Beecham, 2013).

As of 2009, manufacturers offered reflective products which allowed no more than 50 percent of the total solar energy into the vehicle (ARB, 2009a). PPG Industries glass technology group developed a technology, called Sungate EP, which allows only 3 percent of the IR energy to be transmitted through the glass (BASF). Only 33 percent of the total solar energy is transmitted through the glass, most of which is from the visible spectrum. Solar absorbing products are widely available as well, some of which allow no more than about 60 percent of the total solar energy into the vehicle (ARB, 2009a).

Studies have shown significant temperature drops within the interior cabin space through the use of solar reflective films. When glazing was applied to all window surfaces during a solar soak test, interior temperatures dropped up to 4.6^{0}C with respect to a same model vehicle where no reflective glazing was applied (Rugh et al., 2011). A drop of up to 2.5^{0}C was determined when glazing was only applied to the front windshield. A/C system capacity could be reduced by 4 percent in a passenger vehicle through the use of only a solar reflective windshield, resulting in fuel economy improvements for a conventional vehicle of about 0.7 to 1.1 percent (Rugh et al., 2013). When solar reflective glazing was combined with solar reflective paint and solar powered ventilation, the temperature within a passenger vehicle's interior was reduced by 10 to 12 ^{0}C, with a dashboard temperature reduction of 18.6^{0}C (Rugh et al., 2007).

Performance metrics for glazing technologies in passenger vehicles are detailed in ARB's Cool Cars staff report from 2009 (ARB, 2009a). Assessing the performance metrics and emission reductions for heavy-duty vehicles is more difficult. Passenger vehicles and heavy-duty vehicles possess similar technologies, however, the differing geometries and glass ratios will likely lead to slightly varying results for the heavy-duty sector. Additionally, the duty cycles between passenger vehicles and heavy-duty vehicles are different. Many heavy-duty applications require extended idling times while being loaded or unloaded, queuing, or during mandated rest periods. In hot and cold temperatures, these longer breaks will result in uncomfortable cabins regardless of thermal temperature controls such as reflective glazing and will require the use of HVAC systems for an extended period of time. In these situations, thermal management systems such as glazing provide little to no benefit. Additionally, the fuel consumption penalty for the use of HVAC systems in heavy-duty vehicles is likely less than in a smaller passenger vehicle due to the larger engine design. Thus, the HVAC load is a smaller percentage of the overall engine workload. Therefore, the overall fuel consumption benefit of reflective glazing will be less in heavy-duty operations. Although the performance metrics and emission reduction potentials are difficult to predict for heavy-duty applications, it is safe to say the benefits of thermal comfort applications in a heavy-duty vehicle will be less than in a passenger vehicle, with an estimation of FCR below 1 percent.

Reflective Paints

Potential FCR	Less than 1%
Technology Readiness Level	Widely Commercial (light hues); Research and Development (dark hues)
Applicability	All Classes

Solar reflective paint formulations take advantage of the fact that over 50 percent of the solar radiation impacting surfaces is not visible to the human eye (ARB, 2009a). Humans can only visualize light reflected in the visible region, from a wavelength of about 400-700 nm. However, about 50 percent of the radiation impacting surfaces is infrared (IR), a region which heavily influences heat buildup within a vehicle. By adding pigments to paint formulations that reflect IR wavelengths, the solar reflective properties of the vehicle surface can be enhanced. Current opaque formulations (e.g., a deep black color) only reflect about 5 percent of the incoming solar radiation (ARB, 2009a). In theory, by doping paint formulations to reflect all IR radiation, a vehicle's paint surface can be improved to reflect at least 50 percent of the incoming solar radiation without affecting the color seen by the human eye. This can lead to lower temperatures within the cabin, potentially allowing operators to reduce their dependency on HVAC systems during hot weather conditions.

There are currently two types of technologies used to improve the reflectivity of vehicle paints, IR-reflective paints and IR-transmissive paints (Doggett, 2009). IR reflective pigments, typically inorganic metal oxides, are mixed into the base coat to improve the reflectivity of the paint mixture. IR reflective pigments have been used to good effect in the housing industry to reduce solar absorption in roofing materials. This technology can also readily be applied to vehicle surfaces, especially in light hues (e.g., white and silver). However, problems arise when trying to improve IR reflectance in darker hues, such as jet black. Currently, manufacturers are unable to maintain the dark black color when adding IR reflective pigments to the paint mixture. Carbon black, which strongly absorbs in both the visible and IR regions, is currently used by the automotive industry to formulate dark hues such as black and brown. By adding IR reflective pigments to the paint mixture, the carbon black pigment is diluted and results in a "dulling out" of the desired color (Doggett, 2009), a trait not desirable to a consumer looking for a vivid dark color scheme. Current research shows promise for improvements in the reflectivity of darker hues. The BASF chemical company has developed "cooler" black pigments, such as Paliogen Black and Sicopal Black, which achieve reflectivity values in excess of 30 percent (BASF). These reflective black paints have a color that is similar to jet black; however, when compared side to side, they still cannot match the vibrant jet black color scheme.

IR-transmissive paints contain a transparent pigment that allows IR and near IR light to pass through the base layer to the primer. This primer, usually light colored to increase the reflective properties, then reflects some of the IR light away from the vehicle surface. IR-transmissive paints allow the automotive industry to get much closer to the desired color scheme. With a light primer layer under a dark colored base, any chip or dent that occurs over the vehicle's lifetime will appear as a light-colored spot. Therefore, automakers tend to use a primer color that is very similar to the base coat (Doggett, 2009), as light colored splotches are very unappealing to the consumer.

Hoke and Greiner concluded that each 0.1 increase in the solar reflectance parameter (ρ) of a passenger vehicle shell results in a cabin air soak temperature reduction of about 1^{0}C (Hoke & Greiner, 2005). To put this into perspective, a white vehicle shell has a ρ of 0.50, whereas a black shell has a ρ of 0.05. Studies testing black and silver sedans showed similar interior temperature results and estimated the load on the HVAC system was 13 percent lower in the silver sedan relative to the black sedan (Levinson et al., 2011). A solar reflective film made of an IR reflecting product (CI-100T) was applied to a vehicle's exterior roofing resulting in a 6.7^{0}C reduction in roof temperature and a 1^{0}C reduction in interior vehicle temperatures during a typical experimental soak test (Rugh et al., 2001). Models have predicted that switching from a black shell (ρ=0.05) to a cool-colored shell (ρ=0.35) increases fuel economy through the reduction of A/C usage by about 1.1 percent in passenger cars, thus decreasing CO_2 emissions by about 1.1 percent as well (Levinson et al., 2011).

As with reflective glazing, it is difficult to extrapolate emission reduction parameters from passenger vehicles and apply them to the heavy-duty sector. In addition to the different vehicle shell geometries, the reduction of HVAC systems to total engine load for the heavy-duty sector will reduce the benefits of solar reflecting paints. Refer to the reflective glazing section for more details on the differences in thermal comfort loads between passenger and heavy-duty vehicle differences. The majority of thermal load enters through the windows, mitigating the advantage of reflective paints. During operation, wind motions increase convective heat loss from the vehicle's exterior which further reduces the thermal impact of solar reflective coatings (Rugh et al., 2001). Emission reductions due to reflective surfaces are still less than the benefits potentially gained from reflective glazing. A larger portion of commercial trucks are also already white in color compared to the passenger vehicle sector, reducing the potential benefits gained from IR reflective paints in the commercial truck sector. The one percent FCR measured in passenger vehicles can be taken as an upper limit for the reductions possible in the heavy-duty sector; however, the emission benefits are likely smaller than one percent.

Improved Cabin Insulation

Potential FCR	N/A
Technology Readiness Level	Widely Commercial
Applicability	All Classes

More efficient insulation decreases the amount of energy transfer between the interior cabin area and the outside environment. With less energy transfer between the cabin interior and the outside environment, less energy is required to maintain a specific temperature within the cabin. This decreases the amount of work done by the HVAC system and/or a TRU, thus reducing the amount of fuel consumed during this auxiliary process.

Insulation, such as glass-fiber, mineral wool, cellulose, and polystyrene, is a low conductance material used to resist energy transfer from one surface to another, and thus, is used to retard the transfer of heat from a warm body to a cooler body (U.S. DOE, 2012). The thermal resistivity (R) of a material is defined by the ratio of the temperature difference across the insulator (ΔT) and the heat flux per unit area time (Q_A), where $R = \frac{\Delta T}{Q_A}$, with units of ft^2 ^0F hr/Btu. An R-value of 1 is equivalent to 1 ft^2 ^0F hr/Btu. Imperial units, as used in the U.S., can be converted to SI units (meters squared kelvin per watt (m^2K/W)) through multiplication by a conversion factor of 0.17611. The R-value depends on the type of insulation, its thickness, and its density. For information regarding the R-values of various insulating materials, refer to the tables located in reference 35. R-values are additive properties; consequently, accumulation of more individual layers improves the overall resistance to flow. For example, doubling the insulation should cut heat loss in half. Sometimes, insulation properties are referenced by using the "U value", referred to as the overall heat transfer co-efficient, where U is the reciprocal of the R-value ($U = \frac{1}{R}$). It is common practice in the U.S. to use the R value to describe the effectiveness of an insulating material.

It is important to note that a given R-value is the upper limit to an insulator's effectiveness. When real world factors such as air infiltration, extreme temperatures and thermal bridging are present, installed insulation can lose more than half of its R-value (SIPA). R-values may deteriorate over time due to the aging of the insulator material. Nevertheless, R-values can be used as a general baseline to determine the effectiveness of a specific insulating material.

Insulation with an R-value above 30 is commonly used in residential homes and buildings. However, this technology has not made the transition to long-haul trucks. As of 5 to 10 years ago, sleeper cabs were built with minimal insulation (R-values ranging from 1 to 1.5 (Lust, 2008; Dometic, 2008)). Even "cold weather packages" offered in new trucks usually only have insulation values of R-2. The Technology and Maintenance Council (TMC) currently recommends insulation with R-values ranging from 4.2 to 4.6 for long-haul trucks (Dometic, 2008).

Modeling studies have estimated that increasing the insulation value to an R-10 configuration can reduce thermal load requirements by up to 30 percent (Lust, 2008). The National Renewable Energy Laboratory (NREL), in combination with U.S. DOE, has developed the CoolCab project to further assess the energy savings associated with improved insulation (Lustbader et al., 2012). Thick R-19 insulation (6.5 inches thick) installed to the interior cab in the sleeper walls, floor, and roof resulted in a 26 percent savings in heating loads. During a 10-hour daytime rest period A/C test, this heat transfer reduction resulted in an overall A/C load reduction of 20 percent. In a second test, insulation was also added to the structural channels increasing the energy savings up to 36 percent for heating loads with a 34 percent reduction in energy demands on the A/C system. Baseline insulator parameters are not specified for the tests, however, it is assumed that minimal insulation was used in the baseline truck, likely with R-value ranging from 1 to 1.5. The experimental tests suggest less energy savings that model predicted values. This is potentially due to the fact that the R-19 insulation, as stated above, cannot produce 100 percent efficiency in real world situations. The model calculations likely assumed no defects in the insulation, thus represent an upper limit to the level of energy savings, not what a real world R-10 insulator would produce.

Packages including insulation with R-values of at least 4.6 are available (NY Insulate). At this point, advanced insulation packages like those R-19 packages tested during the CoolCab project are still in the demonstration stage. Fuel and emissions savings due to improvements in insulation are likely to be minimal. As with any application process, it is difficult to completely cover the entire cabin space with insulation. Small gaps along supporting structures within the cabin space lead to areas of increased energy transfer with the outside world, limiting the effectiveness of insulation. It is estimated that this technology will account for less than 1 percent reduction in CO_2 emissions. This technology can potentially be sold more as a convenience to truck operators who wish to be more comfortable as they drive and sleep than as a fuel savings device.

HVAC Refrigerant

Potential FCR	0% * Results in GHG benefit, not FC benefit
Technology Readiness Level	Demonstration
Applicability	All Classes

The current refrigerant used in vehicle HVAC systems is HFC-134a; a refrigerant with a global warming potential (GWP) of about 1,300 (i.e., 1,300 times the potency of CO2). As this refrigerant leaks out of the HVAC system, these molecules are emitted to the atmosphere and contribute to the warming of the planet. Through the use of improved refrigerants with lower GWP values, the harmful leakage from HVAC refrigerants can be reduced. Two potential alternative refrigerants can be used to replace HFC-134a. These candidates include HFC-152a, which has a GWP of 120, and R-744 (CO_2), with a GWP of 1. By switching to one of these two alternative refrigerants, the harmful effects of HVAC leakage can be reduced by 1 to 2 orders of magnitude. The emission reductions associated with replacing the current refrigerant far outweigh the reductions of trying to reduce the leakage rate within the HVAC system itself. Although this strategy is not a fuel saving technique, it is an important and easy upgrade to reduce the amount of harmful global warming potential gases emitted from vehicles to the atmosphere.

I. Connected Vehicles

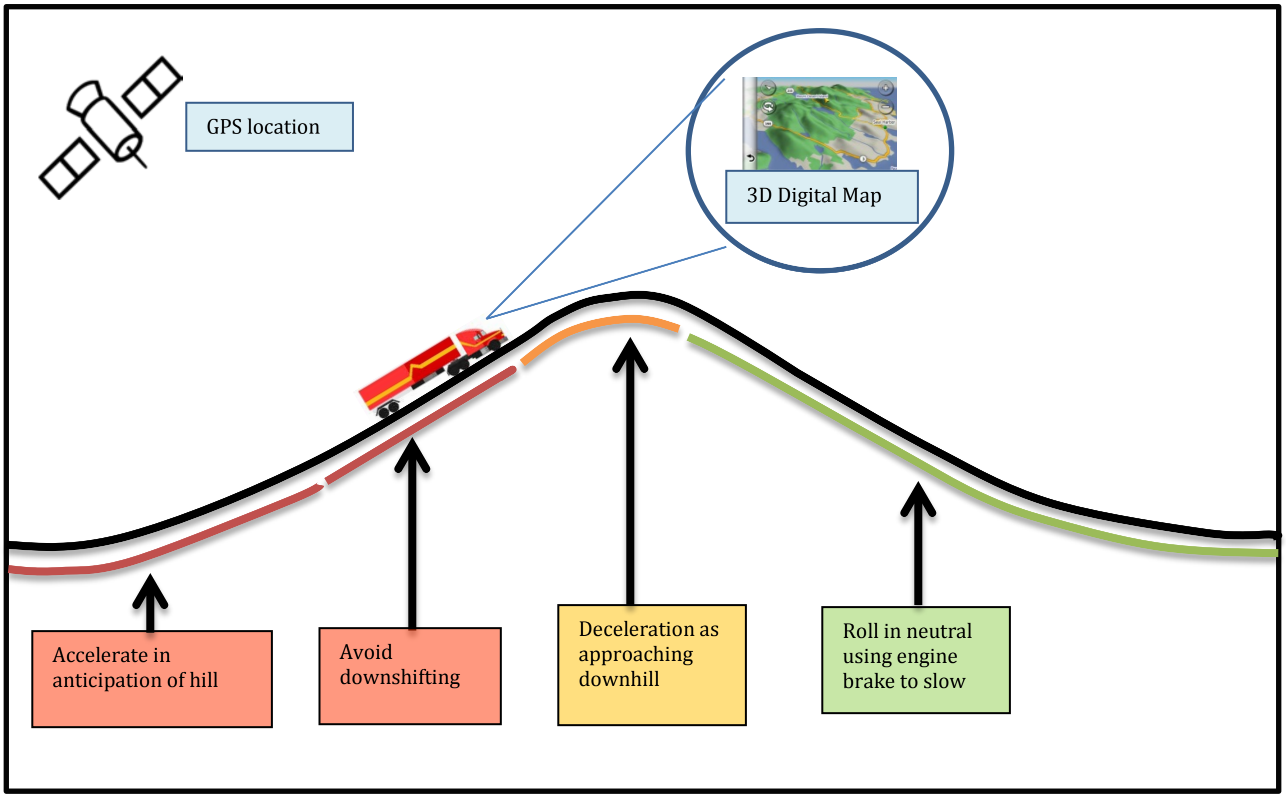
A big push in the improvement of transportation safety has led to many new advances including the continued development of vehicle-to-vehicle (V2V) communication and vehicle-to-infrastructure (V2I) communication (U.S. DOTa). Such advances in safety already included in some new passenger vehicle models include forward collision warning and lane change warnings. Using V2V communication, vehicles ranging from passenger vehicles to heavy-duty trucks and buses can communicate important safety and mobility information from one vehicle computer to another that can help save lives, ease traffic congestion, and improve the environment. For example, vehicles can potentially communicate traffic conditions to upcoming commuters to warn them of a potential accident and enable upcoming vehicles the opportunity to divert to a secondary route. Through the use of V2I communication, vehicles can potentially communicate with traffic signals to help improve traffic flow through urban areas while wireless communication between vehicles and a pedestrian's cell phone can help ensure the safety of individuals near roadways. The field of connected vehicles is broad and expanding with the ultimate future goal of establishing a completely autonomous vehicle fleet. Most of the connected vehicle applications are still in the early stages of planning and development making their implementation well beyond the scope of this technology assessment. Predictive cruise control and platooning, two connected vehicle technologies that have applications to the long haul heavy-duty sector, are discussed below.

Predictive Cruise Control (PCC)

Potential FCR	1-3%[NAS, 2010; TIAX, 2009]
Technology Readiness Level	Introduced Commercially
Applicability	Class 8 Long Haul Tractor

PCC systems use maps and GPS to predict uphill and downhill gradients on a given driving route. On board electronics calculate the optimum vehicle speed to maximize fuel economy by taking advantage of the momentum of the truck while navigating uphill and downhill grades by adjusting the engine and transmission output automatically. As an example, a truck will accelerate before a hill to improve its climbing capacity. The truck then curbs its speed before reaching the apex of the climb and allows its momentum to carry it to the top and onto the downhill portion of the route. Figure A-25 illustrates how GPS positioning information and digital 3D mapping technology could be used to predict upcoming route terrain, subsequently adjusting engine output accordingly to maximize fuel economy. Through these subtle computerized engine and transmission optimizations, a fuel consumption benefit ranging from 1 to 3 percent relative to classic cruise control systems has been observed in demonstrations, with more benefits occurring on routes with larger variations in road topography (NAS, 2010; TIAX 2009). It is most effective in the long haul sector that travels on rural roadways.

Figure A- 25: How Predictive Cruise Control Works to Maximize a Trucks Kinetic Energy When Approaching a Hill



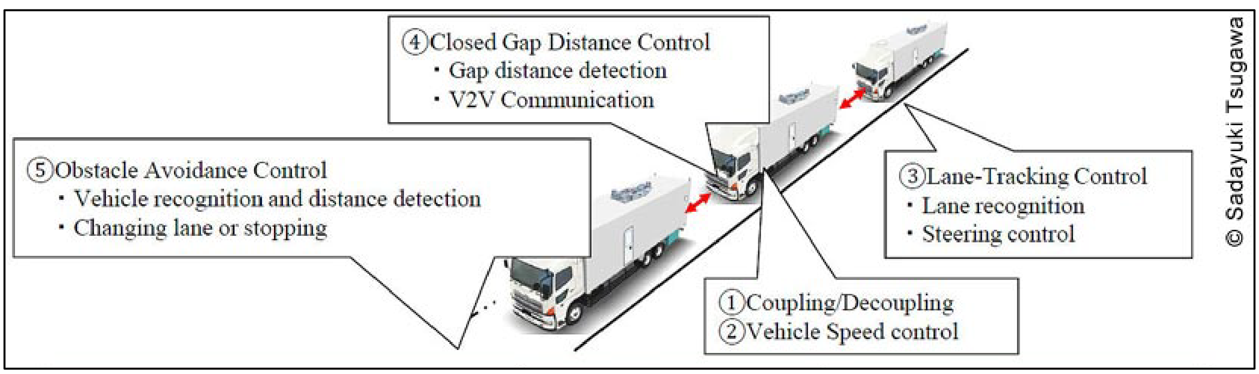
<u>Platooning</u>

Potential FCR	10-21%(NAS, 2010; TIAX, 2009)
Technology Readiness Level	Demonstration
Applicability	Class 8 Over the Road Tractor

Platooning is a type of cruise control technology that allows vehicles to travel closely together in formation to reduce the effects of aerodynamic drag resistance. Using wireless technology, the lead truck controls the entire platoon. Inter-vehicle communication devices send speed updates about every 20 milliseconds and automatically adjusts the speed and gap space between each vehicle in the convoy. Figure A-26 shows a diagram of platooning. Key operational conditions that must be addressed include coupling and decoupling from the platoon, vehicle speed control, lane tracking control, closed gap distance control, and obstacle avoidance control. Vehicle gap space typically ranges from about 7 feet for passenger vehicles and 30 feet for larger class 8 vehicles. The lower drag resistance associated with a reduced gap size has produced FCR ranging from 10 to 21 percent (NAS, 2010; TIAX, 2009; TNO, 2014) in trail vehicles. Due to improved aerodynamic flow at the tail end of the vehicle, the lead vehicle also experiences an FC benefit ranging anywhere from 3 to 10 percent. In October 2013, Peloton Technology Inc., in combination with CR England, demonstrated an average fuel consumption reduction of 4.5 percent for the lead truck and a 10 percent benefit for the following truck traveling at 65 mph with a 36-foot following distance (NACFE, 2013c). Also, in 2013, Japanese demonstrations showed truck fuel consumption improvements averaging 15 percent or more while travelling at 50 mph at a following distance of 4 meters (BBC, 2013).

Public acceptance is critical for successful implementation. Driver discomfort issues are likely to occur with such small gap spaces between vehicles. Some operators may not be willing to trust a computer to drive their vehicle at high speeds within short gap distances. Driver training and education programs may be a way to facilitate acceptance within the community. Requirements for how quickly a platooning vehicle can respond to unforeseen emergencies, and which entity shall be held responsible should a platooning vehicle be involved in a traffic accident, are considerations that need to be addressed. New traffic regulations may be warranted to deal with some of the predicted challenges. However, given additional time and research, these challenges should be overcome. Large scale demonstration projects on public roads are possible by 2015 with goals of full implementation within the next decade.

Figure A- 26: Platooning Diagram



(DOT, 2012)