

Diesel Engine Technologies Enabling Powertrain Optimization to Meet U.S. Greenhouse Gas Emissions

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ABSTRACT

The world-wide commercial vehicle industry is faced with numerous challenges to reduce oil consumption and greenhouse gases, meet stringent emissions regulations, provide customer value, and improve safety. This work focuses on the new U.S. regulation of greenhouse gas (GHG) emissions from commercial vehicles and diesel engines and the most likely technologies to meet future anticipated standards while improving transportation freight efficiency.

In the U.S., EPA and NHTSA have issued a joint proposed GHG rule that sets limits for CO₂ and other GHGs from pick-up trucks and vans, vocational vehicles, semi-tractors, and heavy duty diesel engines. This paper discusses and compares different technologies to meet GHG regulations for diesel engines based on considerations of cost, complexity, real-world fidelity, and environmental benefit. In addition, the paper describes powertrain integration aspects for vocational and semi-tractor engines with technologies including advanced SCR, waste heat recovery (Rankine) cycles and downspeeding. Innovation in component technology coupled with system integration is enabling engine manufactures to move forward with the development of high efficiency clean diesel products with a long term goal of reaching a greater than 50% brake thermal efficiency (BTE) for the engine plus aftertreatment system.

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INTRODUCTION

Worldwide energy use in the transportation sector is projected to increase over the next four decades [1]. There are many expectations that oil prices will remain relatively high, and analysis indicates that petroleum and other liquid fuels are the world's slowest-growing energy sources [1,2]. With increasing energy prices and concerns about the environmental impact of GHG emissions, a growing number of national governments are putting emphasis on improving the energy efficiency of the equipment employed throughout their transportation systems.

An examination of the use of petroleum in the U.S. is shown in Figure 1 where approximately 63% of the oil is used for mobile, on-road applications (light duty and heavy duty vehicles) with the remainder going to non-highway, industrial, residential-commercial, and electrical utilities. For on-road applications, vehicle efficiency improvements are viewed as the fastest route to reduce oil consumption and are the focus of on-going U.S. Department of Transportation (DOT) and EPA regulations. Initial efforts have been aimed at light duty vehicles (LDV) consisting of passenger cars and

light trucks. The primary drivers of fuel economy are the CAFE and GHG tailpipe emissions regulations. The CAFE standards are currently set through 2016, with further increases through 2025 announced [3]. The first standard of this kind for medium-duty and heavy-duty vehicles was enacted in 2011 [4].

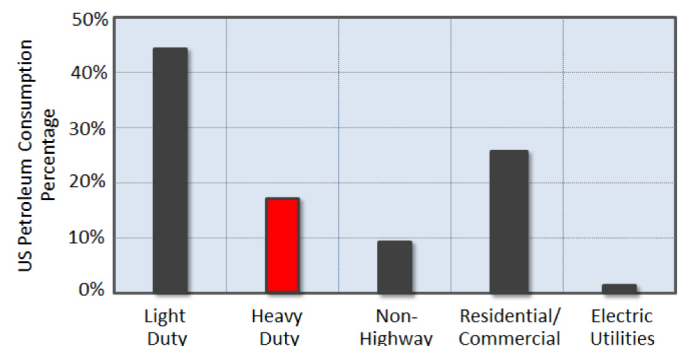


Figure 1. U.S. petroleum consumption by sector (Data Source: [1]).

Trucks are the mainstay for trade, commerce, and economic growth. Sustaining a U.S. trucking industry that is competitive in global markets requires innovation. Unlike passenger vehicles, the trucking industry cannot simply downsize the vehicle and still transport the freight with improved efficiency. The truck manufacturing and supporting industries are faced with numerous challenges to reduce oil consumption and greenhouse gases, meet stringent emissions regulations, provide customer value, and improve safety. A key part of the strategy to meet these requirements is to improve the efficiency of the internal combustion engine (ICE) powering the trucks. The performance, low cost, and fuel flexibility render the ICE the leading candidate to power commercial vehicles for many decades. This sentiment has been echoed by recent studies on future powertrain technologies [1, 5].

Historically, diesel engine technologies have taken more than 10 years after first introduced to diffuse throughout the commercial vehicle marketplace. This rate is faster when fuel economy provides a business advantage to the vehicle's owner. Increased efficiency and reduced emissions of ICEs can be realized through technologies that improve engine design and better integrate systems. Engine manufacturers have a growing need to refine the capability to innovate, design, develop, and validate engine efficiency improvements. Therefore, the primary purpose of this paper is to highlight technologies that allow engine design and development to focus on satisfying regulatory requirements, achieving greater fuel efficiency, and improving transportation freight efficiency. The on-highway heavy-duty diesel engine is used to illustrate the technologies; however, the components may be applied to other diesel and natural gas engine applications, such as off-highway or power generation.

US GHG REGULATION OVERVIEW

For the past two decades, engine manufacturers have focused on reducing engine emissions to near zero levels while maintaining or slightly increasing fuel efficiency. With the advent of the joint EPA and NHTSA commercial vehicle GHG regulations in 2011, the need to reduce fuel consumption has been explicitly linked to the ability to manufacture and sell engines. The rulemaking sets limits for CO₂ and other GHGs from pick-up trucks and vans, vocational vehicles and semi-tractors, and heavy-duty diesel engines [4, 6]. It is instructive to review the elements of the U.S. GHG regulation and their impact on engine technology selection and deployment.

Potential for GHG Reductions

It is reasonable to look at the commercial vehicle industry as part of an integrated system to find opportunities for GHG reduction. The system consists of fuels infrastructure, powertrain components, vehicles, operations and highway infrastructure. Natural dividing lines within the system could

be used to form the basis of regulatory or other initiatives aimed at reducing system-wide fuel consumption and CO₂ emissions. Analysis of the power demand of specific duty-cycles highlights the differences between vocational and line-haul applications. Interstate line-haul trucks operate at high average speeds, with high load factors, high annual mileage, high accessory loads and high rolling resistance. For such vehicles, both chassis and engine performance are significant factors for control of CO₂ emissions.

Vocational vehicles typically operate at lower average speeds in and around urban areas. They have lower rolling resistance, with modest accessory loads and considerably lower annual mileage. [Table 1](#) compares the critical parameters of line-haul and vocational applications.

Table 1. Comparison of line-haul and vocational applications. The table shows typical values for factors that largely determine CO₂ emissions.

Parameter	Line Haul	Vocational
Average Speed	40-55 MPH	20-40 MPH
Cruise Speed	60-70 MPH	-
Idle Time	5-35%	30-55%
Annual Mileage	100-225k	15-60k
Average GVW	50-80k LBS	20-40k LBS
No. of Wheels	18 – 26	4 – 16
Accessory Loads	Sleeper, HVAC	PTO, HVAC
Cruise Power	180 - 250 HP	-
Ave Duty-Cycle Power	100-200 HP	20-125 HP
Peak Power	400-500 HP	200-500 HP

[Figure 2](#) shows a breakdown of the power demand associated with on-highway vehicles - comparing a typical interstate line-haul truck with typical vocational applications. The graph demonstrates clearly the unique nature of the line-haul truck. The vocational applications require far less power to overcome aerodynamic and rolling resistances and generally operate with lower accessory loads.

[Figure 3](#) shows the results of an analysis of potential GHG reductions from line-haul and vocational vehicles in the US. The analysis shows that for line-haul the engine, vehicle, and vehicle operations can contribute about equally to future GHG reductions. In this analysis, operational improvements were expected to come from higher vehicle weights in Class 8 (for example 96,000 lbs GVW compared with 80,000 lbs today), speed limiters, and improved highways. Vehicle improvements were projected to come from enhanced aerodynamics, reduced tire rolling resistance, idling technologies and weight reduction giving higher pay loads. Engine improvements are possible and play a significant role [8].

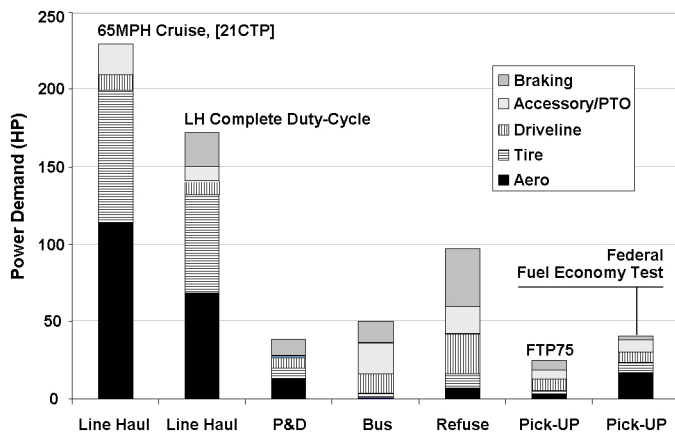


Figure 2. Breakdown of the power demand associated with line-haul and vocational applications. Line-haul 65MPH cruise data taken from 21st Century Truck Partnership report [7].

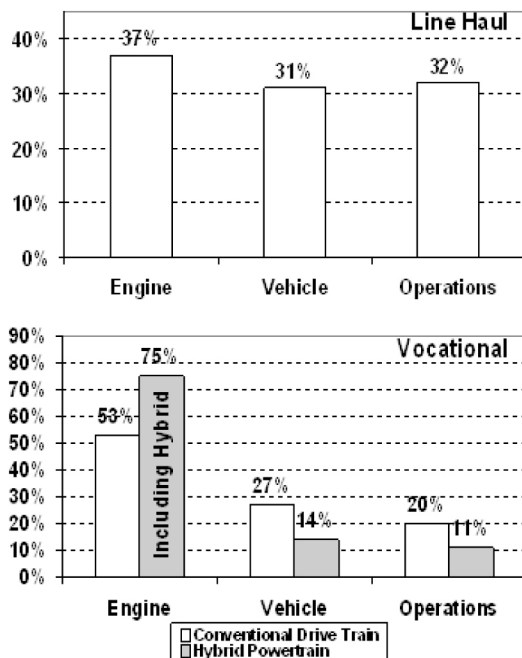


Figure 3. Relative contributions to total potential CO₂ savings for line-haul and vocational applications, showing the contribution from the vehicle, engine and operations as a percentage of the total CO₂ savings.

For vocational applications, Figure 3 also shows that the engine provides by far the biggest potential for GHG reductions. This is because of the stop-and-go nature of vocational applications (transit bus, refuse trucks, delivery trucks etc) and the relatively low annual mileage, which gives little opportunity for improved aerodynamics or rolling resistance to achieve GHG reductions.

Component-Based Approach for Vocational Trucks and Line-Haul Tractors

Despite the complexity associated with a wide range of vehicle applications and body types, duty-cycle analysis reveals a natural segmentation into two categories: (1) line-haul and (2) vocational, work trucks and buses (noted for brevity as ‘vocational’). This segmentation is helpful for regulating GHGs and has been adopted in the rulemaking with implementation using a component-based approach. A components-based approach sets separate limits for the specific vehicle components that directly impact CO₂ production, such as engines, tires, vehicle aerodynamic features, etc. This provides certain and clear targets for technology development and investment to promote continual improvements across all vehicle types and for the life of the vehicles.

In addressing the complexities, the component-based approach builds on the historical and successful constructs of existing regulatory protocols to address GHGs: the EPA heavy-duty emissions regulations [9] and the more recent SmartWay program [10]. For line-haul engines, the EPA heavy-duty engine Supplemental Emission Test (SET) is a good match for predicting in-use CO₂ emissions. For vocational engines, the approach applies the EPA heavy-duty engine transient emissions test - Federal Test Procedure (FTP) - for CO₂ measurement. An analysis comparing CO₂ emissions from these certification test procedures to over-the-road vehicle fuel consumption data reveals the significant level of agreement. For line-haul truck duty-cycles, CO₂ emissions from vehicle field data were within 3.7% of the CO₂ emissions predicted from the SET [8]. This particular study involved the collection of data from 8 line-haul trucks powered with Cummins engines with data acquisitions systems to allow fuel to be tracked at 1 second intervals during normal operation. In a similar test involving field-monitored vocational trucks, the FTP transient engine test data predicted CO₂ emissions to within 4% of the on-road results. Here, the data were gathered for 9 vehicles, including school bus, refuse truck, and pick-up and delivery equipped with a variety of Cummins engine displacements (6.7L, 8.3L, and 11L).

Engines in both of these categories will continue to be regulated for criteria pollutants against both the SET and FTP as today. Other elements of current regulation under the Clean Air Act, including lead-time and stability, would be applied for GHG regulations as well.

Hybrid and other waste energy recovery technologies are also recognized in the GHG regulatory structure. The approach associates all components and subsystems that provide motive power to the vehicle into a ‘Power Supply’ category. Through some modifications, the existing emission regulations can accommodate the regulation of GHGs from the range of power supply systems.

A component-based regulatory approach provides for the cost-effective development and deployment of technologies that will significantly reduce fuel consumption and CO₂ emissions. It addresses the source of CO₂, i.e. the engine, directly while also addressing other opportunities for CO₂ reduction from vehicle components and operations where those effects are significant.

Outline of the Engine GHG Standards

Model year (MY) 2014 - 2018 vehicles and the engines that power them are covered under the GHG regulation. This constitutes all on-road vehicles at a GVWR of greater than 8,500 lbs. MY 2012 - 2016 light-duty vehicles covered by the CAFE standards are excluded.

There are three categories of vehicles: combination tractors, vocational vehicles, and heavy-duty pick-ups and vans. The rule sets separate standards for engines used in vocational trucks and line-haul tractors based on the existing protocols and definitions used to regulate criteria pollutants (NO_x and PM). Consequently, heavy-duty diesel vehicles are not chassis certified. Instead, the engines are certified based on dynamometer testing.

A summary of the diesel engine standards is shown in [Table 2](#) and [Table 3](#). The diesel engines are further categorized based on the GVWR of the intended application [4]:

- Light heavy-duty diesel engines (LHDDE): 8,500 lbs < LHDDE < 19,500 lbs (14,000 lbs < LHDDE < 19,500 lbs in California)
- Medium heavy-duty diesel engines (MHDDE): 19,500 lbs ≤ MHDDE ≤ 33,000 lbs
- Heavy heavy-duty diesel engines (including urban bus): HHDDE > 33,000 lbs

Table 2. Heavy-duty diesel engine standards for engines installed in vocational applications [4].

Category	Year	CO ₂ Emissions	Fuel Consumption
		g/bhp-hr	gallon/100 bhp-hr
LHD Engines	2014	600	5.89
	2017	576	5.66
MHD Engines	2014	600	5.89
	2017	576	5.66
HHD Engines	2014	567	5.57
	2017	555	5.45
HH Gasoline Engines	2016	627	7.06

Table 3. Heavy-duty diesel engine standards for engines installed in tractor applications [4].

Category	Year	CO ₂ Emissions	Fuel Consumption
		g/bhp-hr	gallon/100 bhp-hr
MHD Engines	2014	502	4.93
	2017	487	4.78
HHD Engines	2014	475	4.67
	2017	460	4.52

Criteria pollutants and GHG regulations compliance must to be demonstrated over the useful life of the engine, defined as [4]:

- LHDDE: 10 years / 110,000 miles
- MHDDE: 10 years / 185,000 miles
- HHDDE: 10 years / 435,000 miles / 22,000 hours

The agencies have derived the baseline engine configuration for each regulatory category by examining engines in the existing fleet to represent the typical 2010 model year. The baseline engine architecture utilizes [4]:

- Electronic control
- SCR/EGR/DPF exhaust aftertreatment system which achieves EPA 2010 criteria emissions standards
- Turbocharged with variable geometry turbocharger
- 2200 bar fuel injection pressure
- Single fixed overhead valve
- Belt driven accessories

The 2010 baseline CO₂ levels, representing an industry average, for HHDDE and MHDDE are shown in [Figure 4](#) and [Figure 5](#) for vocational and tractor applications. A summary of the percent reduction required for MY 2014 and MY 2017 is given in [Table 4](#).

In addition to the engine CO₂ standards, EPA has adopted standards for N₂O and CH₄ emissions. N₂O and CH₄ are important GHGs that contribute to global warming, more so than CO₂ for the same amount of emissions. While today's gasoline and diesel engines emit relatively low levels of N₂O and CH₄ emissions, EPA's standards will act to cap emissions to ensure that manufacturers do not allow the N₂O and CH₄ emissions of their future engines to increase significantly above the currently controlled low levels. The specific regulated levels are [4]:

- Engine Testing (tractors & vocational): N₂O = 0.10 g/bhp-hr; CH₄ = 0.10 g/bhp-hr
- Chassis testing (pick-ups and vans): N₂O = 0.05 g/mi; CH₄ = 0.05 g/mi

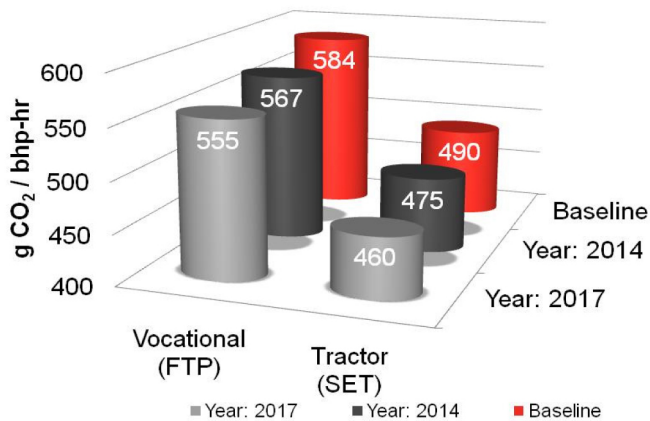


Figure 4. Comparison of Heavy HD diesel engine (HHDDL-) baseline CO₂ levels and the regulated limits.

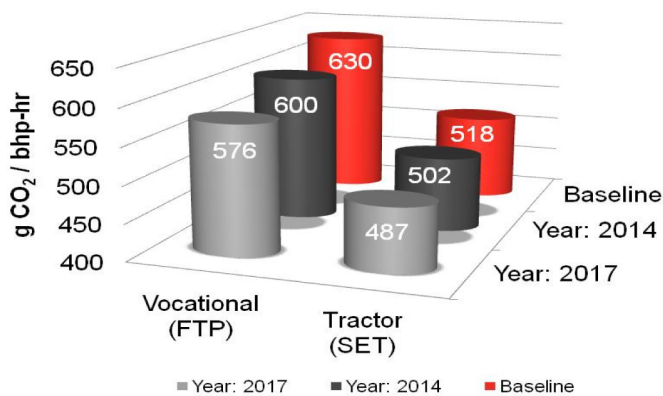


Figure 5. Comparison of Medium HD diesel engine (MHDDE) baseline CO₂ levels and the regulated limits.

Table 4. Percentage reduction in CO₂ emissions for heavy HD and medium HD diesel engines - listed by application type.

	HHDE		MHDDE	
	2014	2017	2014	2017
Vocational	3%	5%	5%	9%
Tractor	3%	6%	3%	6%

Next Phase of U.S. GHG Regulations

In the current phase of GHG regulation, EPA and NHTSA have relied on a mix of components-based limits and complete vehicle based limits. The engine manufacturer certifies the engine for criteria pollutants and GHGs (CO₂, N₂O, and CH₄). For vocational applications, the chassis manufacturer certifies the vehicles for tires. The tractor manufacturer certifies the vehicle for aerodynamics, weight reduction, tires, idling and speed limiters. Finally, the vehicle manufacturer of pick-up trucks and vans certifies the complete vehicle.

The agencies are considering a next phase of rules for model years beyond 2018, as there are more opportunities to reduce GHG emissions and fuel consumption. The next phase will include updating the assessment of actual GHG emissions and fuel usage from commercial vehicles. The agencies also seek to align with similar programs developed outside the U.S. to help lessen the product development burden of the engine and vehicle manufacturers.

Further assessments will be conducted to document the efficacy of the component-base approach for setting limits on specific vehicle components. Having separate standards for engine and vehicles will continue to address the sources of CO₂ generation in a manner similar to criteria pollutants. This guarantees reductions across all vehicles and for the life of the vehicles.

The commercial vehicle industry has provided feedback regarding the need to expand the component technologies recognized under the rulemaking. For example, having a powertrain certification option will allow for engine, transmission, and axle integration improvements. Also, trailers are not covered under the current rules, due to the agencies' limited experience working in a compliance context with the trailer manufacturing industry. Because trailers do impact the fuel consumption and CO₂ emissions from combination tractors, EPA and NHTSA are working to include them in a future rulemaking.

Evolution of HD Diesel Engine Efficiency - a Success Story

The regulation of oxides of nitrogen (NO_x) and particulate matter (PM) from heavy-duty on-highway diesel engines was first discussed in the late 1970s. Figure 6 shows the successful 30 year history of regulation of criteria pollutants from heavy-duty diesel engines.

At that time, EPA and the industry faced similar complexity in addressing engine emissions across a wide range of vehicle applications, duty-cycles and engine technologies as confronted for GHGs today. The issue was resolved by creating a laboratory engine test cycle that was synthesized from actual operating data taken over a number of representative duty-cycles, vehicles and engines. While the Federal Test Procedure (FTP) was not specifically representative of any individual duty-cycle, it was deemed adequately representative of all of them [9]. This approach, essentially 'Engine-in-the-Loop' simulation, has been used to successfully regulate criteria pollutants since the late 1980s. In 2002, a Supplemental Emissions Test (SET), based on European experience, was added. The SET is a steady-state test that measures emissions of NO_x, PM, hydrocarbons (HC) and carbon monoxide (CO) over a broad area of the engine operating range from the maximum torque speed to the rated power speed and from 25% load to full load.

In 2007, the phase-in of the 2010 emissions began as illustrated in Figure 6. This regulation also included a diesel fuel requirement that limited the sulfur content to 15 ppm a