



2013

L. RAY BUCKENDALE LECTURE

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Systematic Development of Highly Efficient and Clean Engines to Meet Future Commercial Vehicle Greenhouse Gas Regulations

Donald W. Stanton
Cummins Inc.

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SAE 2013 Commercial Vehicle Engineering Congress
Rosemont, Illinois, USA
Tuesday, October 1, 2013

L. RAY BUCKENDALE LECTURE

This lecture, presented annually at the SAE Commercial Vehicle Engineering Congress, focuses on automotive ground vehicles for either on- or off-road operation in either commercial or military service. The intent is to provide procedures and data useful in formulating solutions in commercial vehicle design, manufacture, operation and maintenance.

Established in 1953, this lecture commemorates the contributions of L. Ray Buckendale, 1946 SAE President. L. Ray Buckendale, by his character and work, endeared himself to all who were associated with him. Foremost among his many interests was the desire to develop the potential abilities in young people. As he was an authority in the theory and practice of gearing, particularly as applied to automotive vehicles, it was in this field that he was best able to accomplish his purpose. To perpetuate his memory, SAE established this lecture to provide practical and useful technical information to young people involved in vehicle engineering.

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Donald Wayne Stanton

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58TH ANNUAL L. RAY BUCKENDALE LECTURE

Systematic Development of Highly Efficient and Clean Engines to Meet Future Commercial Vehicle GHG Regulations

Donald Wayne Stanton
2013-01-2421

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Systematic Development of Highly Efficient and Clean Engines to Meet Future Commercial Vehicle Greenhouse Gas Regulations

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ABSTRACT

With increasing energy prices and concerns about the environmental impact of greenhouse gas (GHG) emissions, a growing number of national governments are putting emphasis on improving the energy efficiency of the equipment employed throughout their transportation systems. Within the U.S. transportation sector, energy use in commercial vehicles has been increasing at a faster rate than that of automobiles. A 23% increase in fuel consumption for the U.S. heavy duty truck segment is expected from 2009 to 2020. The heavy duty vehicle oil consumption is projected to grow while light duty vehicle (LDV) fuel consumption will eventually experience a decrease. By 2050, the oil consumption rate by LDVs is anticipated to decrease below 2009 levels due to CAFE standards and biofuel use. In contrast, the heavy duty oil consumption rate is anticipated to double. The increasing trend in oil consumption for heavy trucks is linked to the vitality, security, and growth of the U.S. and global economies.

An essential part of a stable and vibrant U.S. economy is a productive U.S. trucking industry. Studies have shown that the U.S. gross domestic product (GDP) is strongly correlated to freight transport. As the economy grows, the freight tonnage increases as well as the annual vehicle miles traveled (VMT). Over 80% of all U.S. freight tonnage is transported by diesel power and over 75% is transported by trucks. The improved efficiency of heavy-duty engines and vehicles has been quickly overwhelmed by the increase in annual VMT. This results in heavy-duty vehicles consuming a growing share of the total transportation-related petroleum. Given the vital role that the trucking industry plays in the economy, improving the efficiency of diesel engines is a central focus of this paper.

Trucks are the mainstay for trade, commerce, and economic growth. Sustaining a U.S. trucking industry that is competitive in global markets requires innovation. 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.

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 diesel engines 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 provide guidelines and tools that allow a systematic approach to engine design and development that focuses 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 processes; however, the general principles may be applied to other diesel and natural gas engine applications, such as off-highway or power generation.

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 implementation of the new EPA/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 forward looking technology roadmaps in this paper provide a framework for improving engine efficiency over the next 10 to 15 years. The list of improvements consists of engine components, aftertreatment, and powertrain advancements.

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CHAPTER 1. THE ROLE OF EFFICIENT DIESEL ENGINES IN THE GLOBAL ECONOMY

1.1. 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 greenhouse gas (GHG) emissions, a growing number of national governments are putting emphasis on improving the energy efficiency of the equipment employed throughout their transportation systems.

Focusing on the U.S. energy landscape, [Figure 1-1](#) provides a view of the energy sources and their relative contributions to the total energy production. Also shown are the general sectors that consume the energy. Approximately 28% of the nation's energy is consumed by the transportation sector. Within this transportation sector, approximately 93% is fueled by petroleum with 4% fueled by natural gas and 3% by renewable fuels [3]. The high and often volatile price of current fuels provides economic motivation for making equipment more fuel efficient and for deploying advanced technologies. However, petroleum-derived fuels, such as diesel and gasoline, will remain the primary energy source for transportation services through at least 2050 [4]. There are many challenges to deploying alternatively fueled technologies. These technologies must compete against the extraordinary energy density and low production costs of petroleum-based fuels and adapt to, or compete with, the established fueling infrastructure.

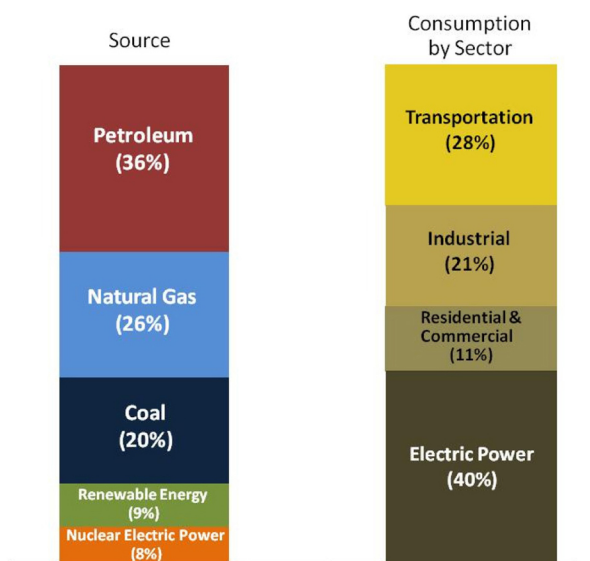


Figure 1-1. U.S. energy sources and consumption by sector for 2011 (Data Source [3]).

A further examination of the use of petroleum in the U.S. is shown in [Figure 1-2](#) 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 [5]. The first standard of this kind for medium-duty and heavy-duty vehicles was enacted in 2011 [6].

The projected impact of these government regulations on oil consumption for on-road vehicles is depicted in [Figure 1-3](#). The first observation is that energy use in trucks has been increasing at a faster rate than that of automobiles. A 23% increase in fuel consumption for the U.S. heavy duty truck segment is expected from 2009 to 2020. Also shown in [Figure 1-3](#), the heavy duty truck oil consumption is projected to grow between 2009 and 2050 while light duty vehicle (LDV - cars and light trucks) fuel consumption will eventually experience a decrease. By 2050, the oil consumption rate by LDVs is anticipated to decrease below 2009 levels due to CAFE standards and biofuel use. In contrast, the heavy duty oil consumption rate is anticipated to double. More recent studies have shown that the upward trend in oil consumption rate by heavy duty trucks will continue despite the new 2011 GHG regulations [3]. This increasing trend in oil consumption for heavy trucks is linked to the vitality, security, and growth of the U.S. economy.

An essential part of a stable and vibrant U.S. economy is a productive U.S. trucking industry. Studies have shown that the U.S. gross domestic product (GDP) is strongly correlated to freight transport [7]. As the economy grows, the freight tonnage increases as well as the annual vehicle miles traveled (VMT). Over 80% of all U.S. freight tonnage is transported by diesel power and over 75% is transported by trucks [7]. The improved efficiency of heavy-duty vehicles has been quickly overwhelmed by the increase in annual VMT. This results in heavy-duty vehicles consuming a growing share of the total transportation-related petroleum as supported by [Figure 1-3](#).

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

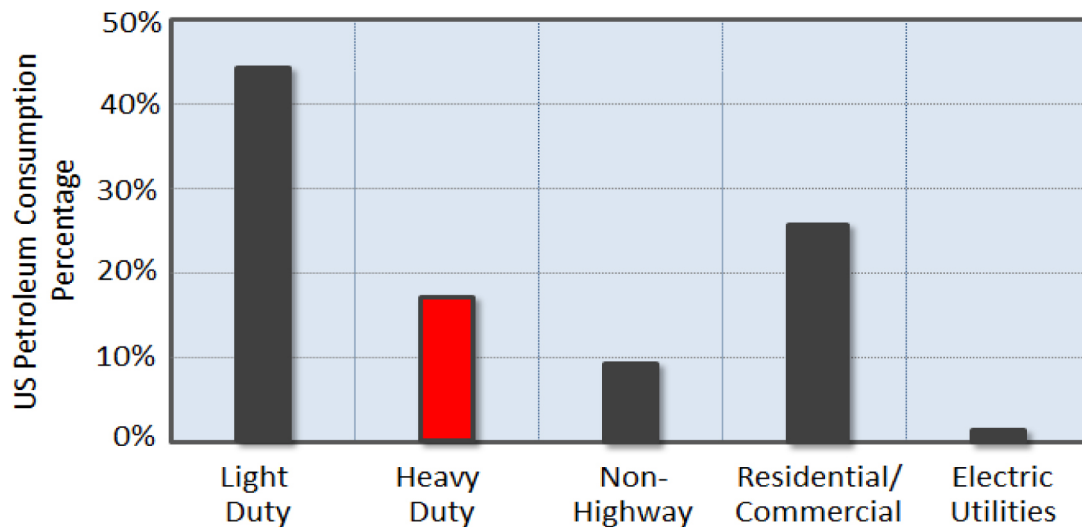


Figure 1-2. U.S. petroleum consumption by sector (Data Source: [2]).

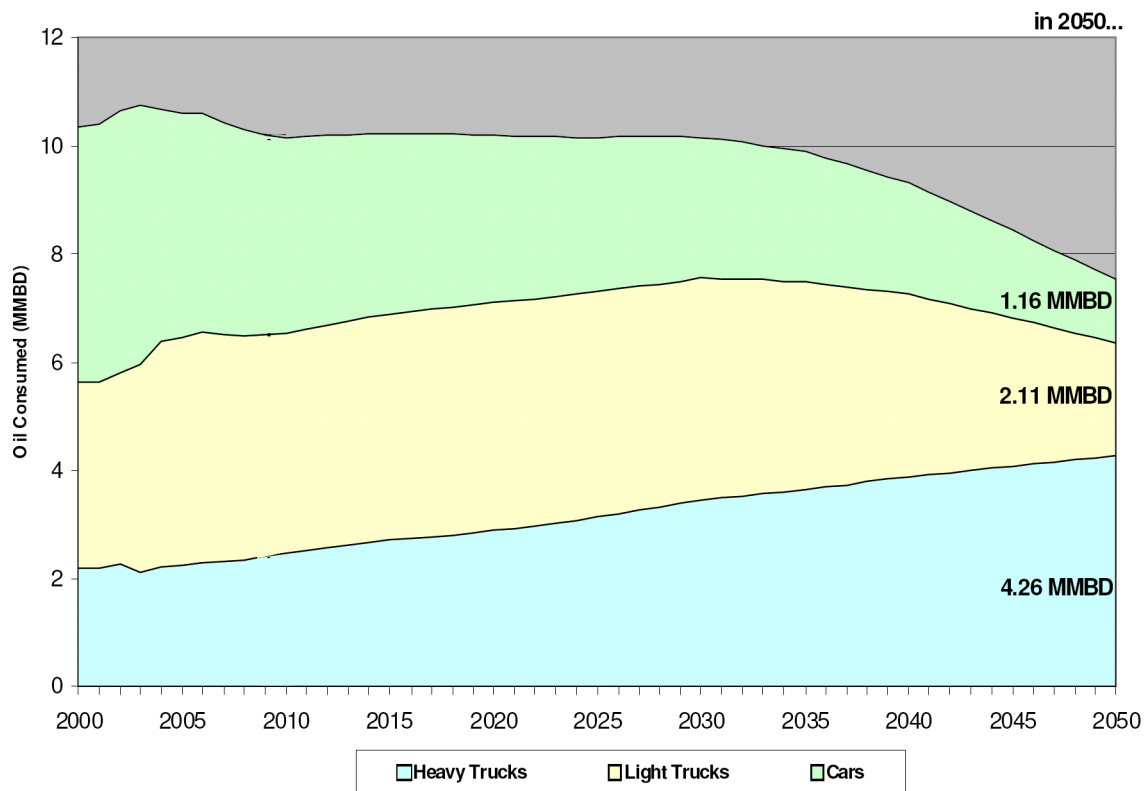


Figure 1-3. Oil consumption projections in the U.S. transportation sector by vehicle type (Source: [2]).

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, 8].

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

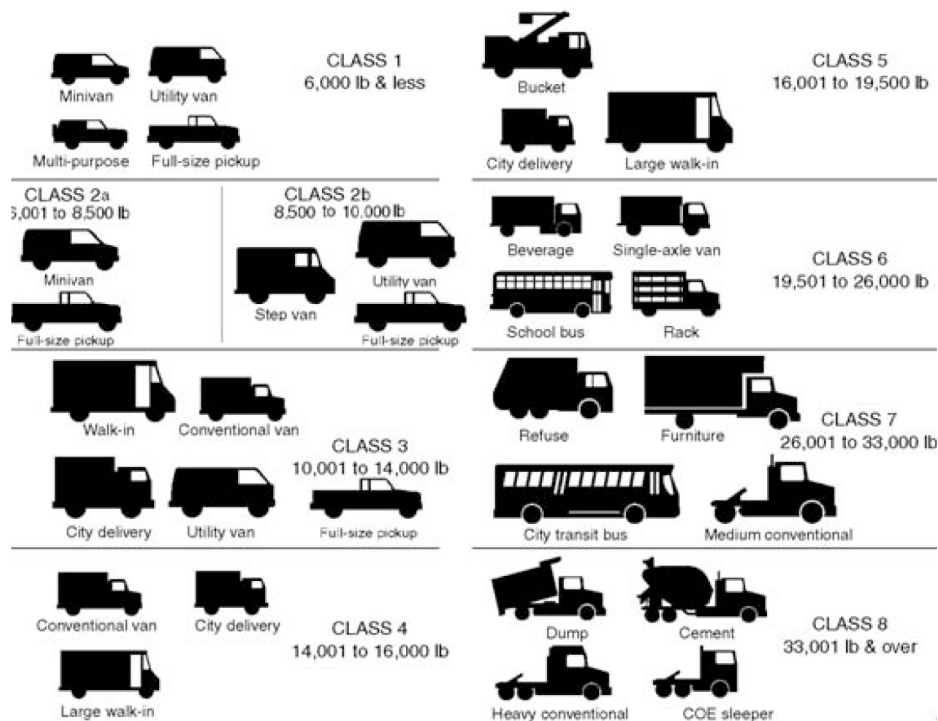


Figure 1-4. Commercial vehicle weight classes defined by the Federal Highway Administration (Source: [10]).

is to provide guidelines and tools 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 processes; however, the general principles may be applied to other diesel and natural gas engine applications, such as off-highway or power generation.

1.2. Classes of Commercial Vehicles

Commercial vehicles are diverse in terms of design and application such as pick-up trucks, delivery trucks, transit buses, dump trucks, tankers, bulk haulers, interstate line haul, and heavy-haul trucks. Figure 1-4 shows the classification scheme used for commercial vehicles by the National Highway Traffic and Safety Administration (NHTSA) and the different applications found in these classes. The vehicle classes are partitioned in terms of gross vehicle weight rating (GVWR). The GVWR is the maximum operating weight of a vehicle as specified by the manufacturer. Unlike the weight based classes in Figure 1-4, the designation of vehicle categories based on use is not uniformly applied (e.g. vocational, line-haul, etc.). The boundaries between light-duty and medium-duty, as well as medium-duty and heavy-duty, are not as well defined.

Light-duty trucks are considered as Class 1 and Class 2 vehicles less than 10,000 lb. This includes vehicles such as pickups, sport utility vehicles, and small vans. The majority of these vehicles (approximately 80%) are for personal use. The dominant engine type is spark-ignited gasoline. The fuel

efficiency of these vehicles, up to 8,500 lb, is governed under CAFE regulations for cars.

Vehicles in Class 3 through Class 6 are referred to as medium heavy-duty. A variety of diesel and gasoline engines are used. These commercial vehicles have single rear axles. Class 2b and 3 vehicles are sold as either complete or incomplete vehicles. A complete vehicle can be a chassis-cab (engine, chassis, wheels, and cab) or a rolling-chassis (engine, chassis and wheels). An incomplete-chassis could be sold as an engine and chassis without wheels.

The vocational vehicle segment includes a wide variety of Class 2b-8 vehicles ranging from 8,501 lb to greater than 33,000 lb GVWR. In 2005, sales of these vehicles were the second most numerous in the commercial truck market, with over 500,000 units sold, making up nearly one-quarter of all commercial truck sales [9]. Class 2b-8 vocational vehicles are typically sold as an incomplete chassis with multiple companies who complete the vehicle for sale. For example, an engine manufacturer, a body manufacturer, and an equipment manufacturer may all be involved in the production of the final vehicle. Manufacturers of vehicles within this segment vary widely.

Heavy-duty vehicles are Class 7 and 8. These commercial vehicles have two or more rear axles. In Class 8, combination trucks have a tractor with one or more trailers. The gross combination weight (GCW) limit is 80,000 lb with exceptions allowed in specific circumstances. Class 8 combination tractors operate as either regional-haul or line-haul trucks (also called long-haul). Tractors operating as regional-haul trucks are tractor trailer combination vehicles

used for routes less than 500 miles and primarily into metropolitan areas. They tend to travel at lower average speeds than line-haul trucks. Regional-haul combination tractors, therefore, generally do not include sleeping accommodations for the driver. Line-haul combination tractors typically travel at least 1,000 miles along a trip route. Line-haul operation occurs primarily on highways and accounts for approximately 70% of the fuel used by Class 7 and 8 combination tractors as shown in Figure 1-5. The most common trailer hauled by both regional and line-haul combination tractors is a 53-foot dry van trailer, which accounts for approximately 60% of heavy-duty Class 8 on-road mileage [11].

When considering EPA GHG regulations, all commercial vehicles are referred to as heavy-duty vehicles that fall into three regulatory categories: HD pickups and vans (typically Class 2b and 3), vocational vehicles (typically Class 2b-8), and line-haul tractors (typically Class 7 and 8).

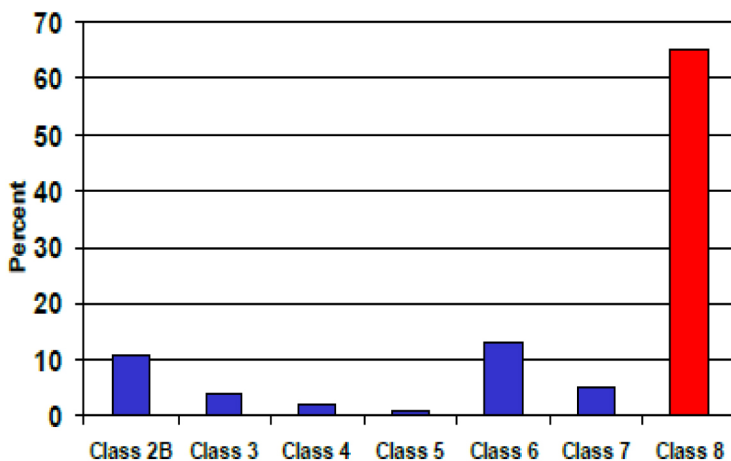


Figure 1-5. U.S. commercial vehicle fuel usage by weight class (Source [12]).

1.3. Macro Trends Impacting Commercial Vehicles

Identifying macro trends that influence global commercial vehicle markets is important to engine manufacturers to aid in technology development and product planning. These trends are globally sustained, economic activities that impact business, economy, society, and culture. They are indicators of the pace of change occurring worldwide. Six important macro trends influencing the future of engine and vehicle designs for commercial applications are:

- Globalization
- Urbanization
- Economic growth in emerging and developing markets
- Exhaust emission standards in world markets
- Energy availability and price

• Infrastructure spending

Globalization is the worldwide interconnected movement of people, goods, services, capital, information, and technologies. Globalization is not new, but it does provide changing opportunities to impact engine performance on a growing scale. As customer needs vary across regions and cultures, multinational engine manufacturers are adapting their engines to the individual markets. Market segmentation will be defined increasingly by a combination of two factors: how the vehicle is used and where the vehicle is used. The first dimension, how, takes into consideration the nature of the transport and the duty cycle patterns, such as load, type of freight, number of pickups and deliveries made, distance driven per day, etc. The second dimension, where, reflects the regulatory constraints which will vary across regions and countries, but also the degree of urbanization. Other geographical characteristics, such as national taxation policies, fuel quality, service network, and possible alternatives to oil, will play important roles as well.

The increasing pace of urbanization will lead to the merging of large city centers with suburbs resulting in expanding city limits. This will have a strong impact on the future of mobility. Consequently, there will be a growth of mega regions and corridors. Freight transport will be accomplished by increasing hub and spoke logistics infrastructure. Higher growth in the demand for city and regional-haul trucks (relative to heavy line-haul) is expected. The resulting urban congestion will likely drive growth in light commercial vehicles.

Economic growth in emerging and developing markets is changing the strategies of engine manufacturers. Several studies project that up to 60% of the commercial vehicle demand will come from emerging and developing markets by 2025 [13,14]. New engine and vehicle designs are being specifically developed for these markets. Low cost engines will sustain demand. However, greater technology content in the engine and aftertreatment system will grow as the emissions standards become increasingly stringent and fuel prices rise due to the growing energy demand.

Exhaust emission standards (criteria pollutants and greenhouse gas) are becoming prevalent throughout the world. The U.S., Europe, and Japan lead with the most stringent standards; however, other areas are following closely behind as shown in Figure 1-6. Emerging markets typically lag the developed market legislation, but efforts are being made to accelerate the progress. For example, China lags European standards by roughly 8 to 10 years. In many developing countries, the trend is toward a combination of national or regional standards, and local or city standards to deal with local air quality issues. Examples of local regulation can be found in Beijing, China and New Delhi, India. Emerging markets, such as China, are trying to implement emissions regulations to reduce the countries environmental impact but are limited by the access to good quality, low sulfur diesel fuel that will facilitate the reduction

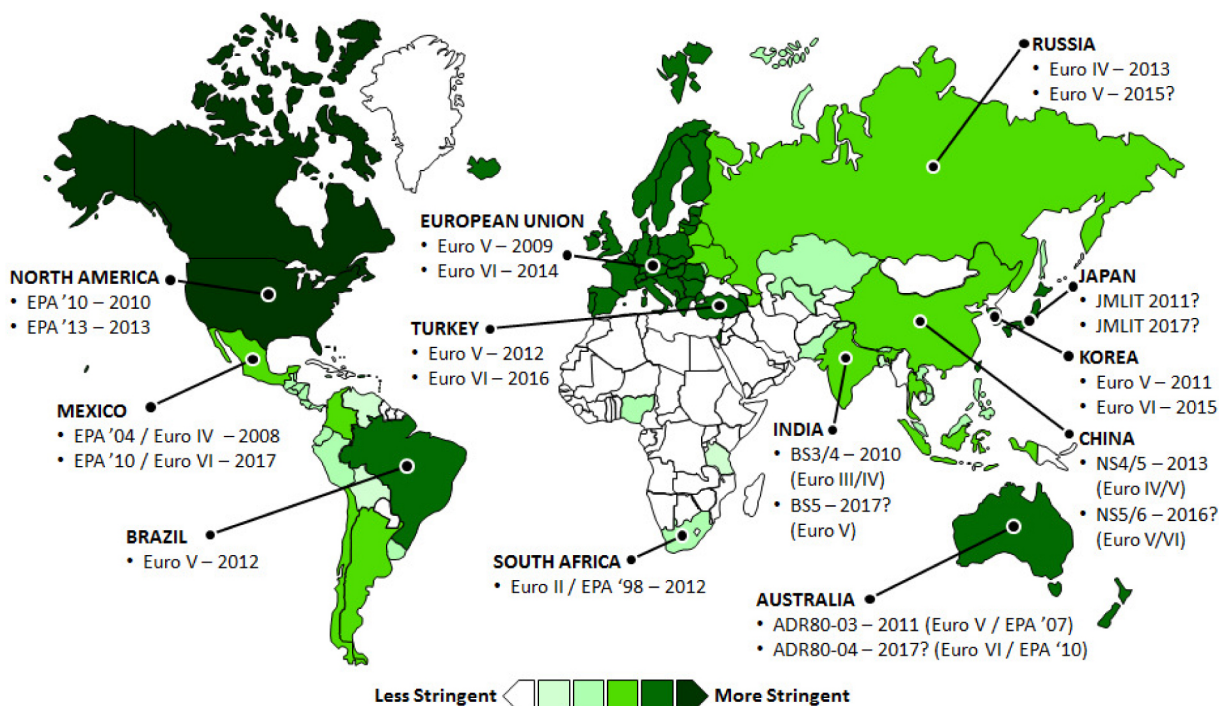


Figure 1-6. Worldwide emissions trends for on-highway diesel engines.

in emissions. As a consequence of the evolution in regional emissions regulations, the commercial vehicle industry faces the combined challenge of developing new technologies and serving an increasingly fragmented market.

As more countries continue to increase their industrial activities, the demand for energy will continue to rise. This demand is greatest in emerging markets. China accounts for the largest share of the growth in global energy use, with its demand expected to rise 60% by 2035, followed by India (where demand more than doubles) and the Middle East [15]. The projection of energy demand for the transportation sector is shown by geographical region in Figure 1-7. This growth in demand will continue to put upward pressure on price. The transportation sector already accounts for greater than half of the global oil consumption, and this share increases as demand for road freight rises quickly. Trucks are responsible for almost 40% of the increase in global oil demand [15]. With petroleum remaining the primary source of energy in the transportation sector for the next few decades, there is the need to seek alternatives, such as natural gas and renewable fuels, while developing engine technologies that accommodate these alternatives.

Infrastructure spending in emerging and developing markets is sustaining the demand for heavy-duty vehicles. The most dramatic example is China. China's economic growth and the build out of the highway system have spurred a boom in domestic Chinese commercial vehicle demand. Not only is the build-out of the infrastructure occurring at a fast pace, a new interstate system and new regulations are changing the way freight gets hauled. Consequently, engine

and truck manufactures have invested in state of the art manufacturing facilities.

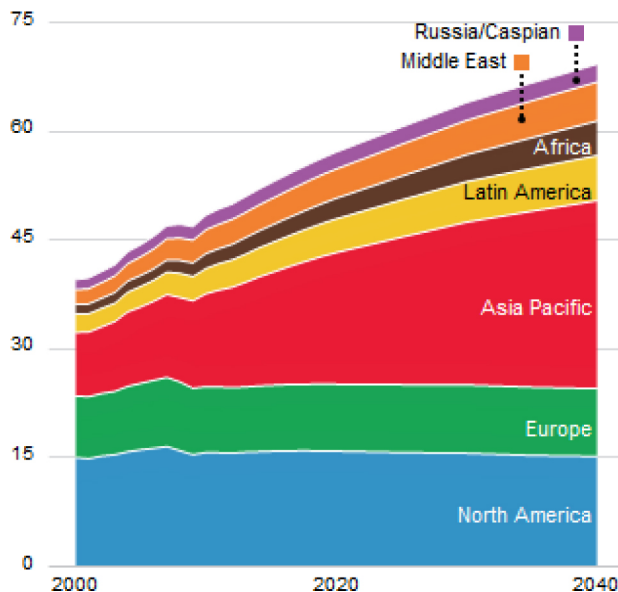


Figure 1-7. Global transportation energy demand in millions of oil-equivalent barrels per day (Source: [15])

The constraints driven by these macro trends will not drive market requirements uniformly. The legal requirements of different markets and the demands of customers will diverge. Engine manufacturers are responding to these macro trends by:



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1.4. Engine Product Requirements

Within the vehicle weight classes defined in [Figure 1-4](#), the range of applications illustrates the different uses associated with commercial vehicles across the transportation sector. This results in a broad range of duty cycles from high-speed highway operation with few stops to lower speed city and urban operation with numerous stops per mile. These complexities manifest the difficulties in developing engine technologies to reduce fuel consumption in all markets and for all duty cycles.

In Class 7 and 8, the largest use of heavy-duty trucks is for moving goods and materials with greater than 30% used in for-hire transportation of freight. Focusing further on Class 8 tractors, 86% are company-owned fleets and 14% owner-operator trucks [16]. The wide variety of applications and duty cycles create a challenge in determining the engine requirements.

Some customer requirements are common to all markets at some level:

- **Compliance with local regulations** - whether emissions, greenhouse gas / fuel economy, on-board diagnostics or other regulations.
- **Reliability** - the product functions as promised, every time with no unscheduled downtime. Reliability strongly impacts warranty expenses.

Other requirements are driven by the total cost of ownership (TCO). The TCO provides a cost basis for determining the total economic value of any commercial vehicle investment. It defines the cost of owning a vehicle from the time of purchase by the owner, through its operation and maintenance to the time it leaves the possession of the owner. A comparative TCO analysis between various models help consumers choose a vehicle to fit their needs and budget. These TCO requirements will vary dependent upon application and duty-cycle:

- **Fuel Efficiency** - with few exceptions customers are highly sensitive to fuel consumption. Applications with lower amounts of vehicle miles traveled will be less sensitive.
- **Initial Cost** - clearly a significant factor in all purchases, but for high fuel usage applications, such as prime power, HD truck, mine truck, other factors are often more important - for example, uptime, fuel consumption, and maintenance costs.

• **Maintenance** - maintenance requires downtime and incurs cost, for example, replacing filters or spark plugs, an oil change or the cleaning of a particulate filter to remove ash deposits.

• **Durability** - durability is sustained functionality as promised over the expected lifetime without major repair or replacement. It can be a strong influence on residual value, and therefore can be a key component of TCO.

• **Performance** - power and torque, response, gradeability, load acceptance and other performance requirements. In some cases performance can be traded at the cost of less work being performed per work period - again with an impact on TCO. Engine system weight can be a factor as added weight will reduce payload capacity.

• **Connected Systems** - increasingly customers are expecting products to communicate remotely with their business systems - for maintenance, service repair, optimization of operating costs, logistics, security, software upgrades etc.

• **Quality** - less tangible perhaps, however it is important that the customer be satisfied that they purchased a quality product. In this area ‘everything speaks’ - the product, the quality of machine integration, the product support, the ease of doing business, product warranty terms, and the people who interface with the customer.

A relative ranking of these customer requirements is shown in [Figure 1-8](#) for two applications, Class 8 line-haul and Class 3 delivery truck. Reliability has the highest ranking for both applications as customers need the uptime of the vehicle to be high in order to make money. For the Class 8 line-haul application, the annual mileage is typically between 120,000 to 180,000 per year for new trucks. Lifetime fuel cost makes up roughly 5 times the original truck cost, meaning that payback period on new fuel economy technologies can be very short. Truck fuel cost is the key driver for adopting new technologies and ranks second among the customer requirements. Technologies developed for the Class 8 market are typically implemented in three years or less, and quickly penetrate into the Class 6 and 7 markets because of the similarity of these vehicle classes. It is also interesting to note that initial cost is ranked 7th, but there is an initial price threshold that customers will not want to cross.

Initial cost has greater importance in the Class 3 delivery truck market segment and is ranked 2nd in [Figure 1-8](#). These vehicles often operate with less than 50,000 miles per year. In both applications, compliance with local regulations is the lowest ranking requirement. This becomes increasingly important to customers such as municipalities operating fleets of transit buses in cities with stringent emissions and noise regulations.

As fuel prices continue to rise, thus contributing more to the TCO of the vehicle, customers are beginning to rank fuel efficiency higher on the list of requirements across all vehicle weight classes. This is seen throughout the global commercial

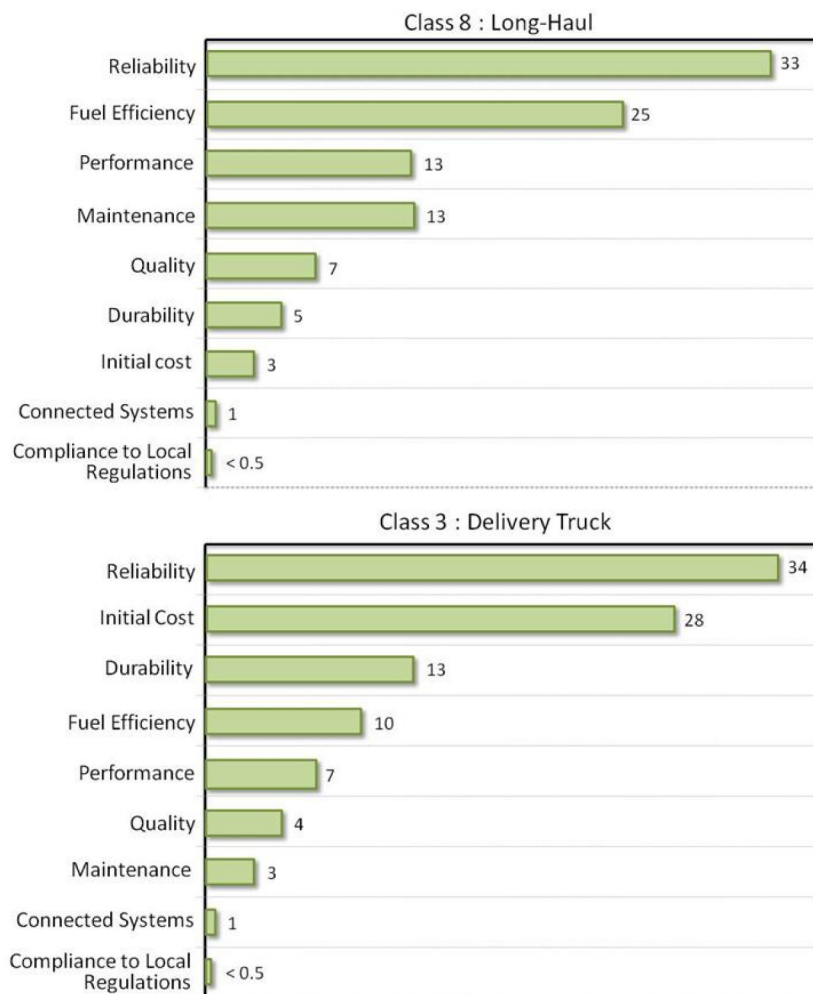


Figure 1-8. Relative ranking of customer requirements for Class 8 Long-Haul and Class 3 Delivery Truck.

vehicle markets, such as Europe where fuel prices are higher than the U.S., India and China where the amount of government subsidies for diesel fuel is waning.

1.5. Fuel Efficiency Definitions and Metrics

A number of metrics have been derived from customer requirements related to vehicle fuel efficiency. Commercial vehicles and the engines that power them are designed to transport freight, or payload. Therefore, the method to represent an attribute-based fuel consumption metric for the engine is to normalize the fuel consumption by the power required to operate the vehicle. The engine fuel consumption becomes a measure of the fuel flow rate per unit of power output. This is an indication of how efficiently the fuel is being converted to work. The most useful definition is brake specific fuel consumption (bsfc) and is determined using the measured power available at the engine shaft. The units for bsfc are lbm/bhp-hr or g/kW-hr.

The fuel efficiency of the engine is often referred to as the brake thermal efficiency (BTE). This is a dimensionless parameter defined as the engine output (measured as power at

the engine shaft) divided by the fuel energy input (fuel flow rate multiplied by the heating value of the fuel). The brake thermal efficiency and the bsfc are inversely proportional. Further details on the fundamental engine parameters influencing brake thermal efficiency and bsfc are given in Chapter 4.

For the vehicle, both fuel economy (FE) and fuel consumption (FC) are used to describe the efficiency of how fuel is used. Fuel economy is a measure of the distance a vehicle travels with a specified quantity of fuel and is expressed in miles per gallon (mpg). However, fuel consumption is a more useful metric. It is the amount of fuel consumed in driving a given distance. Common units are gallons per 100 miles or liters per kilometer. Engine and vehicle fuel consumptions are the fundamental engineering and regulatory metrics to properly evaluate fuel efficiency improvements.

Vehicle fuel consumption is equal to the reciprocal of fuel economy. This results in a non-linear relationship as shown in [Figure 1-9](#). A more useful relationship is shown in [Figure 1-10](#), where the percent decrease in fuel consumption is

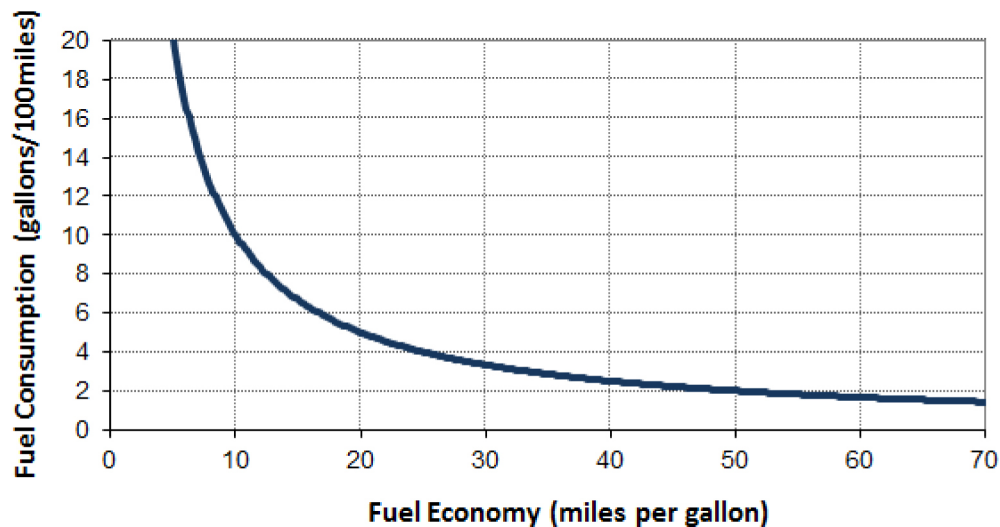


Figure 1-9. Vehicle fuel economy and fuel consumption relationship.

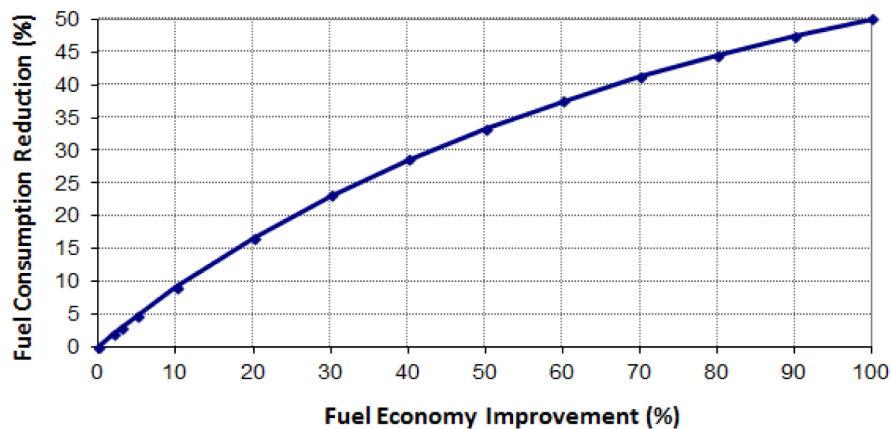


Figure 1-10. Relationship between percentage improvement in fuel economy to percentage reduction in fuel consumption.

related to the percent increase in fuel economy. This curve is independent of the value of fuel economy. It is often used as an engineering approximation relating the percent change in engine fuel consumption to an expected percent change in vehicle fuel economy.

In a similar fashion as the engine bsfc, the load specific fuel consumption (LSFC) of a vehicle is a way to normalize the fuel consumption by the payload. It becomes fuel consumption per weight with units of gallon/ton-100 miles. The FE, FC, and LSFC are significantly impacted by the payload. As the vehicle payload increases, the FC increased but the LSFC decreases.

Many operators track the freight efficiency of their vehicles. Freight efficiency is the payload multiplied by the FE and is expressed in ton-mpg. By tracking this metric, there is an incentive to decrease fuel consumption (or increase fuel economy) and reduce the vehicle weight. Engine designs that improve vehicle FC and reduce vehicle weight provide benefit to both grossed-out (at maximum vehicle weight) vehicles and cubed-out (at maximum cargo volume) vehicles.

Figure 1-11 illustrates the significant relationship between engine brake thermal efficiency (BTE) and the percentage increase in freight efficiency for a Class 8 line-haul application at 80,000 lb. Note, 42% BTE is a good industry representation of a 2009 vintage 15L diesel engine operating at a 65 mph highway cruise condition.

1.6. Structure of the Paper

This work focuses on diesel engine technologies for satisfying regulatory requirements particularly fuel efficiency and GHGs. The on-highway heavy-duty diesel engine in the U.S. market is used for illustration; however much of the technologies and key principles may be applied to other diesel engine applications, such as off-highway or power generation. The emphasis on fuel efficiency spans to all global commercial vehicle markets driven by government regulations and customer demands. Guidelines and tools that allow engine design and development for fuel efficiency improvement are presented.

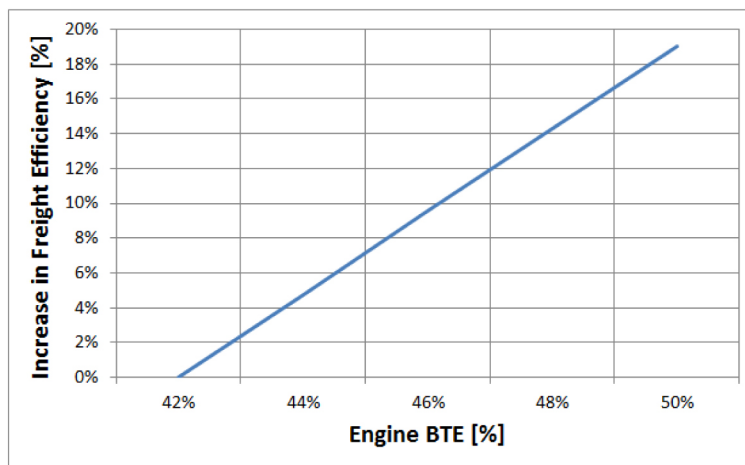


Figure 1-11. Engine BTE and the percentage increase in freight efficiency for a Class 8 line-haul application at 80,000 lb.

Chapter 2 provides an overview of the evolution of diesel engine emissions including criteria pollutants and GHGs. A review of the elements of the U.S. GHG regulation and their impact on engine technology selection and deployment is presented. The potential for GHG reductions in line-haul and vocational vehicle applications are analyzed. Several options that exist for the control of GHGs from commercial vehicles are surveyed with emphasis on the component-based approach adopted in the U.S. EPA GHG rulemaking.

Chapter 3 is an overview of the heavy-duty engine technologies deployed over the past 25 years to address the stringent emissions regulations with an assessment of their subsequent impact on engine fuel efficiency. This provides the background necessary for the exploration of future fuel efficiency improvements by analyzing engine and aftertreatment component technologies. Solutions have been developed that allow the heavy-duty, on-highway diesel engine to meet the extremely challenging emission standards as discussed in Chapter 2, while continuing to meet customer expectations for fuel economy, performance, reliability and durability. This level of innovation is made possible through the integration of a number of key technologies discussed in this chapter.

Chapter 4 identifies opportunities for additional engine fuel efficiency improvements through engine and vehicle energy analysis. The utility of the energy analysis technique is in comparing engine technologies, assessing trends, identifying boundaries of operation and building a general understanding of engine system efficiency. The technique provides a powerful mechanism for communicating engine energy losses, technology limitations, and establishing technology roadmaps. An overview of the technique provides a tool for the exploration of fuel efficiency improvements.

Chapter 5 provides a systematic approach to the development and deployment of engine and aftertreatment technologies that improve fuel efficiency. This system integration process is rooted in understanding the system

critical parameters and the fact that they must be rigorously managed. Success in system integration ultimately results from the application of system engineering tools which provide the discipline and structure that allow large teams to synchronize their work and their schedules. Consequently, a framework for the execution of system engineering that is specific to technology development is provided. This process is referred to as Technology Development for Six Sigma (TDFSS). TDFSS guides the process of knowing what is critical, how critical parameters are measured, and how they are interconnected. TDFSS is a system engineering and integration process that is used within an overarching technology development and product commercialization roadmap.

Chapter 6 is a forwarding looking technology roadmap for engine efficiency improvements. Based on the engine system energy analysis discussed in Chapter 4, key focal points for efficiency improvements are discussed for line-haul and vocational applications. The technologies are listed as improving mechanical efficiency, open cycle efficiency (gas exchange), closed cycle efficiency (compression, combustion, and expansion), and waste energy recovery. The list of improvements consists of engine components, aftertreatment, and powertrain advancements. The aggregate effect is a greater than 20% improvement compared to the 2010 product that serves as the baseline for the U.S. EPA GHG regulation for commercial vehicles. The feasibility of achieving the 20% fuel efficiency improvement is accomplished with an evaluation of an engine and vehicle demonstration. However, an economic viability assessment of each technology is beyond the scope of this work.

CHAPTER 2. EVOLUTION OF DIESEL ENGINE EMISSIONS REGULATIONS

For the past two decades, engine manufacturers have focused on reducing engine emissions to near zero levels

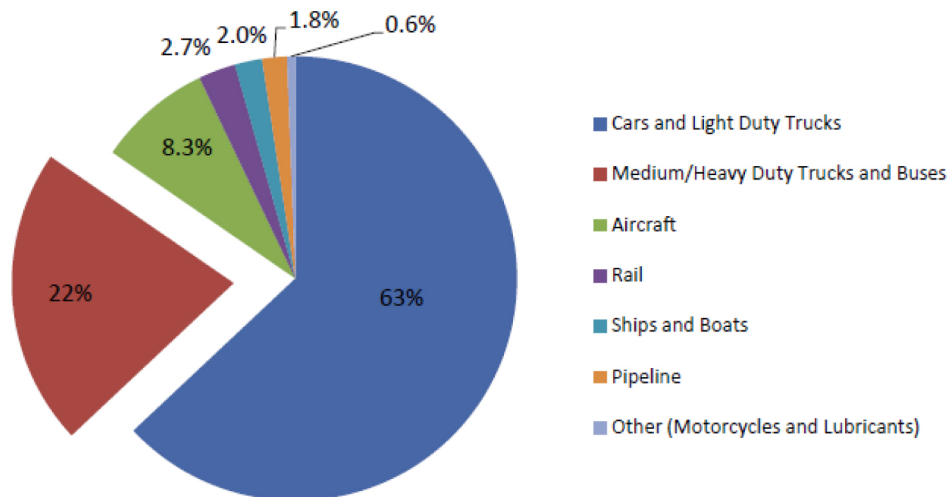


Figure 2-1. Sources of transportation related GHG emissions (Source: [6]).

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 [6,17]. It is instructive to review the elements of the U.S. GHG regulation and their impact on engine technology selection and deployment.

To begin, one source of potential confusion is the difference between regulations for criteria pollutants, GHG emissions, and Corporate Average Fuel Economy (CAFE), as well as the confluence of government agencies responsible for establishing and amending the standards; promulgating regulations concerning procedures, definitions and reports; and enforcing the standards and regulations.

The term ‘criteria pollutants’ is a reference to the U.S. National Ambient Air Quality Standards (NAAQS) that set ambient exposure limits for several diesel engine emissions including particulate matter, NO_x, and carbon monoxide [18]. The continuing evolution of regulations for criteria pollutants is managed by the EPA. The CAFE regulations are focused on passenger cars and light duty trucks (LDT) and are administered by the NHTSA, an agency within the U.S. Department of Transportation (DOT). However, the EPA is responsible for calculating the average fuel economy for each manufacturer. The GHG regulation for heavy-duty and medium-duty commercial vehicles and the engines that power them addresses both GHGs (CO₂, N₂O, and CH₄) and fuel consumption. In this regulation, the NHTSA developed fuel consumption standards under the authority of the 2007 Energy Independence and Security Act (EISA), while the EPA developed a GHG emissions program under the Clean Air Act [6]. This chapter focuses primarily on the regulation of criteria pollutants of diesel engines and the GHG regulations for diesel engines and commercial vehicles.

2.1. Potential for GHG Reductions

In the rulemaking, EPA highlights that heavy-duty trucks are the second largest source of GHG emissions in the transportation sector after light-duty vehicles (cars and light-duty trucks). The heavy-duty segment represents approximately 22% of all transportation related GHG emissions as shown in Figure 2-1. In addition, heavy-duty truck GHG emissions increased over 72% from 1990-2008 while GHG emissions from passenger cars increased approximately 20% over the same period [6].

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. The partitioning shown in Figure 2-2 is a logical and helpful way to analyze the potential contributions to CO₂ reduction.

In this partitioning, it is useful to consider the engine as the *Power Supply* and the vehicle as the *Power Demand*. As such the power produced by the engine will be equal to the power demanded by the vehicle. Other components and sub-systems that contribute to motive power, including the transmission, axles, hybrid energy storage with power components and waste heat recovery systems, would be considered with the engine as the Power Supply. The Power Supply system is active, in that it is responsive to operational demands, duty-cycle and ambient conditions, and has a complex and active control system that adjusts many parameters dynamically during operation.

Further 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,

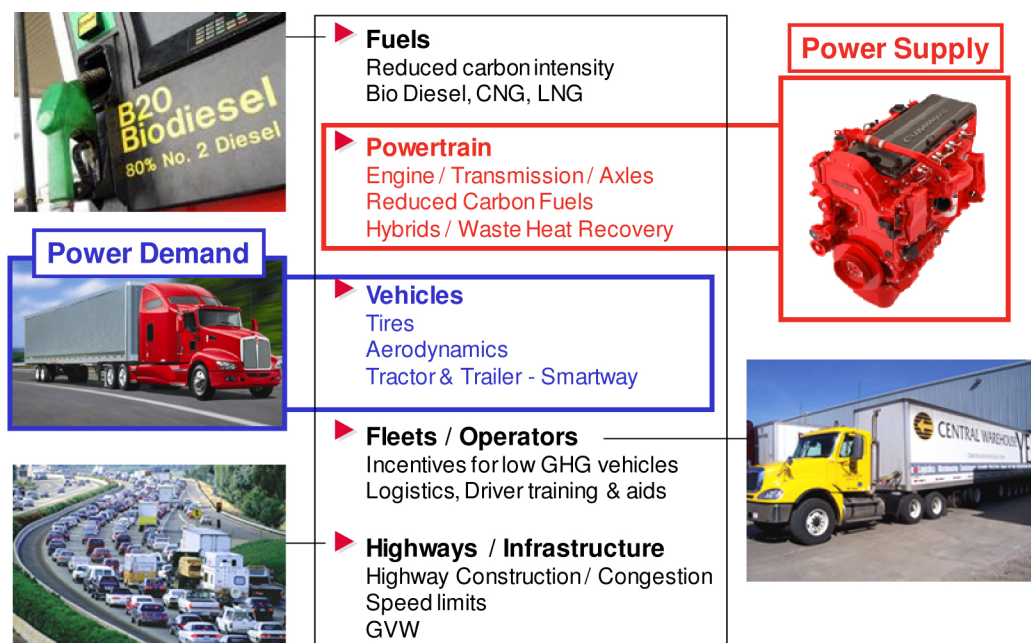


Figure 2-2. Goods movement system partitioning for control of CO₂ emissions. The vehicle provides the power demand (payload, aero, rolling resistance, accessories etc) which is met by the power supply provided by the engine and associated power sub-systems.

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 2-1 compares the critical parameters of line-haul and vocational applications.

Table 2-1. 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 2-3 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. Based on analysis of line-haul and vocational vehicle data, a reasonable generalization for vehicle power demand is:

- Aerodynamics dominate above 55 mph with a significant non-linear increase with speed
- Tire rolling resistance and drive line (i.e. engine, transmission, and axles) are the highest power demands between 40 - 55 mph and are often comparable in magnitude
- Engine power demand (i.e., heat transfer to the coolant, friction, gas exchange, etc.) dominates below 40 mph

The high annual mileage for line-haul vehicles contributes significantly to the 22% heavy-duty truck GHG emissions production shown in Figure 2-1. Based on a 2007 assessment by the U.S. Energy Information Administration (EIA), line-haul trucks are responsible for approximately 66% of the 22% heavy-duty truck GHG emissions production with approximately 21% from vocational, and 12% from pick-ups and vans - see Figure 2-4 [6].

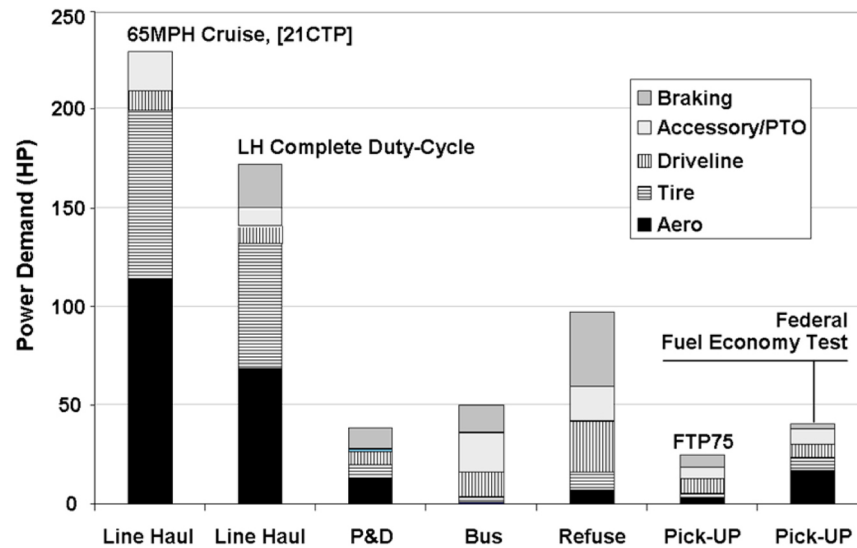


Figure 2-3. Breakdown of the power demand associated with line-haul and vocational applications. Line-haul 65MPH cruise data taken from 21st Century Truck Partnership report [7]. The power demand for the pick-up is reported for the FTP75 and Federal Fuel Economy Test - where the FTP75 has a greater amount of transients and lower vehicle speed than the Federal Fuel Economy Test.

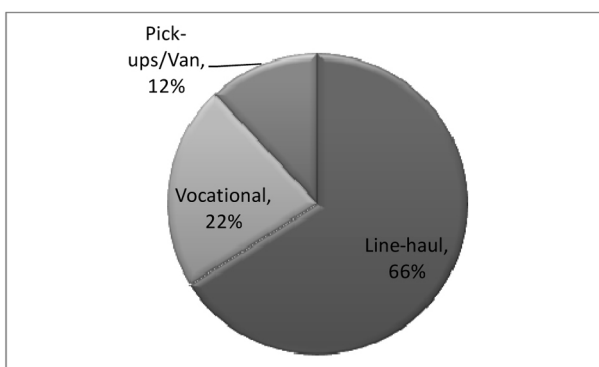


Figure 2-4. Contribution of vehicle type to the generation of GHGs from on-highway commercial vehicles.

Figure 2-5 shows the results of an analysis performed by Cummins of potential GHG reductions from line-haul and vocational vehicles in the U.S. 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 payloads. Engine improvements are possible and play a significant role [19, 20, 21].

For vocational applications, Figure 2-5 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 traveled, which gives little opportunity for improved aerodynamics or rolling resistance to achieve GHG reductions.

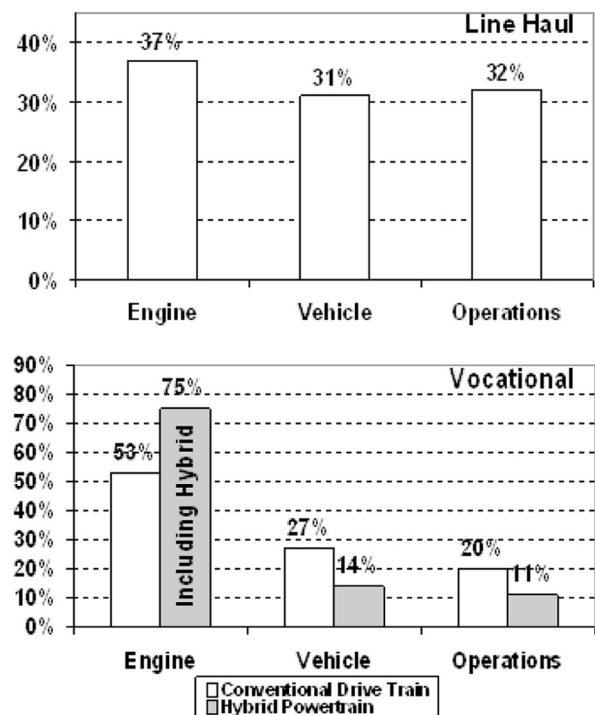


Figure 2-5. Relative contributions to total potential CO₂ savings for line-haul and vocational applications, showing the contribution from the vehicle, engine and operations as a percentage of the total CO₂ savings.

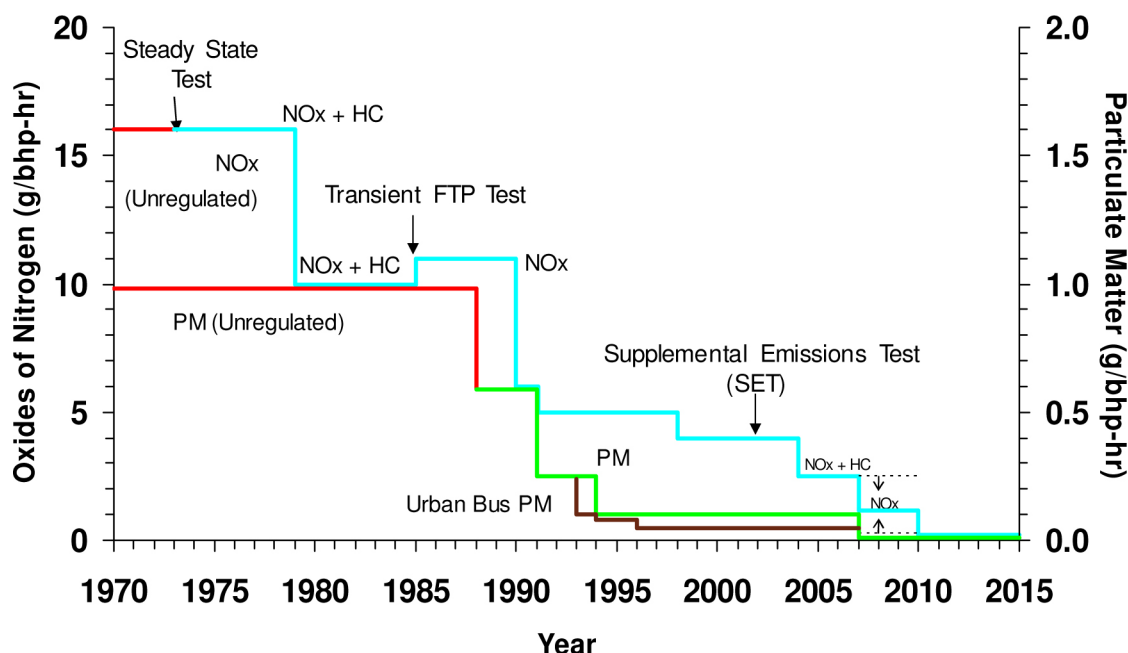


Figure 2-6. Evolution of the emissions reductions from heavy-duty, on-high way diesel engines.

2.2. Regulation of Emissions from Heavy Duty Engines - 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 2-6 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, see Figure 2-7. 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 2-8. This regulation also included a diesel fuel requirement that limited the sulfur content to 15 ppm, a reduction from the previous 500 ppm. The ultra low sulfur diesel fuel (ULSD) was mandated as a technology enabler for advanced exhaust emission catalysts that display a

sulfur-intolerance, such as catalytic diesel particulate filters (DPF) and NO_x selective catalytic reduction (SCR).

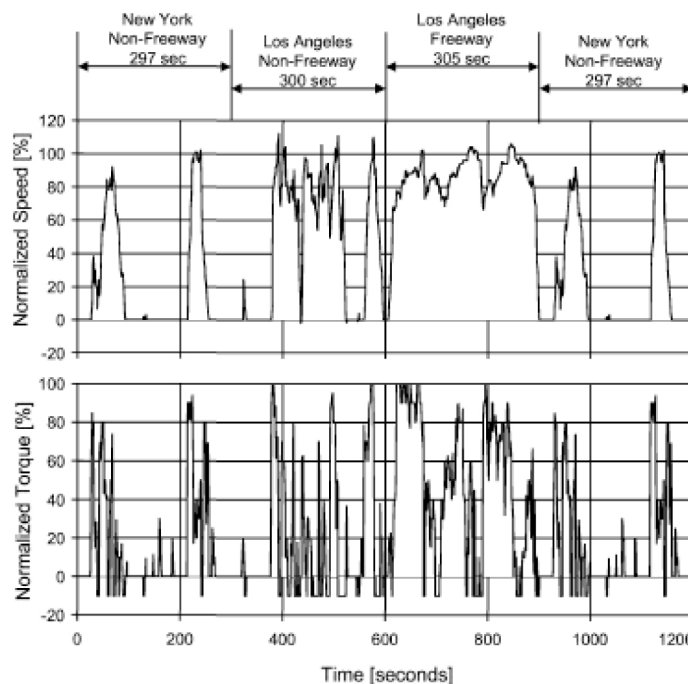


Figure 2-7. EPA transient emissions, engine dynamometer test cycle known as the Federal Test Procedure (FTP) cycle.

Starting in 2010, on-board diagnostic (OBD) systems were mandated for heavy-duty diesel engines where all major emissions control devices are monitored and malfunctions detected prior to emissions exceeding a set of emissions

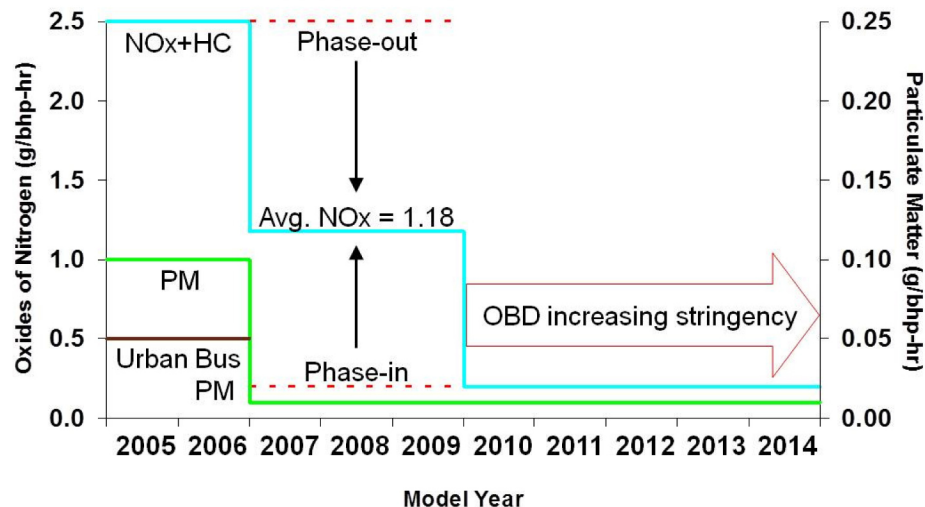


Figure 2-8. Overview of the 2010 EPA emissions regulation timeline, highlighting the 2007 phase-in and the introduction of on-board diagnostics (OBD).

thresholds. This self-monitoring capability is incorporated into the engine control system and alerts the vehicle operator regarding the malfunctioning system. The primary focus has been on aftertreatment systems including all emission-related electronic sensors and actuators. One engine family per manufacturer had to be certified to the OBD requirements in the 2010 through 2012 model years. However, by 2013, all on-highway engines for all manufacturers had to be certified to the OBD requirements. This phase-in was intended to spread the industry development effort over a number of years and to provide industry with a learning period prior to implementing the OBD requirements on 100% of their product line [22].

The heavy-duty emissions program could be used almost without change for the control of CO₂ from heavy-duty engines in line-haul and vocational applications. Using the existing emissions structure for CO₂ control removes the significant overhead associated with developing a new regulation from scratch. It also brings with it a set of provisions such as: test procedures, production line and in-use compliance audits, averaging, banking and trading flexibility, family emission levels, emissions useful life and many others.

2.3. Options for the Control of GHG from Commercial Vehicles

Several options exist for the control of GHGs from commercial vehicles. A few of the options employed in some form around the world include:

1. Regulatory programs which set limits for the contribution of system **components** to the total GHG emission of the vehicle system

- a. Conventional engines and drive trains
- b. Hybrid electric drive trains

2. Regulatory programs which set limits on the GHG emission of the **vehicle system**

- a. Based on test protocols and limits (i.e. chassis dynamometer certification)
- b. Based on hardware-in-the-loop simulation
- c. Entirely model-based

3. Voluntary reporting and labeling programs

These approaches each have trade-offs in terms of customer impact, effectiveness, cost, complexity, and alignment with the structure of the U.S. engine and vehicle industry. The approach adopted by EPA and NHTSA is essentially a components-based approach (option 1 above) for vocational trucks and line-haul tractors, and a complete vehicle approach (option 2a above) for pick-up trucks and vans based on chassis dynamometer testing [6, 23]. The U.S. GHG rule also allows for the certification testing of hybrid engines and powertrains as a complete unit - the so-called 'Power Pack Option'.

Option 1, 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.

Option 2a, vehicle system chassis dynamometer certification, is feasible for light-duty commercial vehicles such as pick-up trucks and vans that leave the production facility as 'complete vehicles'. It is less practical for medium-duty and heavy-duty vehicles, due to the significant capital expenditures involved and limited availability of such heavy-duty dynamometers with full emissions capability. Alternative measurement schemes, for example, based on

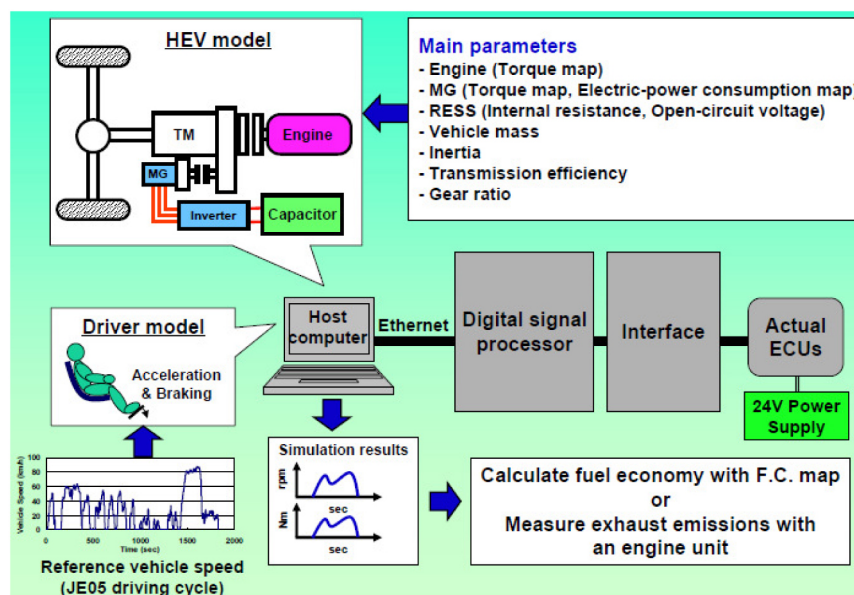


Figure 2-9. Outline of the HILS method for heavy-duty HEVs [24].

vehicle coast down, are relatively inaccurate and subject to noise factors such as wind direction, wind fluctuation and ambient conditions.

Option 2b above, hardware-in-the-loop procedure, uses hardware-in-the-loop simulation (HILS) to predict the emissions and fuel efficiency of commercial vehicles [24]. The HILS method was developed initially for Hybrid Electric Vehicles (HEVs) by a Japanese consortium led by the Japanese Automobile Research Institute (JARI), Hino Motors, Isuzu Motors, Mitsubishi Fuso Truck and Bus, Nissan Diesel and National Traffic Safety and Environment Laboratory (NTSEL). Comparison of calculated and measured data (vehicle speed, motor/generator power, rechargeable energy storage system power/voltage/current/state of charge, and fuel economy) was stated to be within 2%. A schematic of the HILS system for HD HEVs is shown in Figure 2-9.

Regulation of complete commercial vehicles has been proposed using only simulation models (option 2c above) - such as the *Powertrain System Analysis Toolkit* (PSAT) or *AUTONOMIE*. These are flexible simulation packages, developed by Argonne National Laboratory and sponsored by the U.S. Department of Energy (DoE) [25, 26]. While use of such models is certainly feasible, the final result will be no more accurate than the input data which represents the critical subsystems - engine, drivetrain, vehicle aerodynamics and rolling resistance - and driver characteristics. The complete vehicle modeling approach has the advantage of cost-effectiveness when a large number of chassis configurations are being certified. It has challenges relative to overall real-world fidelity and regulatory enforcement.

Option 3 above, voluntary reporting and labeling programs, can be used successfully, although achieving fidelity between the information presented to the potential

purchaser and real over-the-road experience can be challenging. This approach relies on market forces alone to drive fuel efficient technologies into the market place. This may be insufficient to drive the significant investments needed to reduce GHGs and improve fuel efficiency by meaningful amounts.

2.4. 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.

Since these are work vehicles, the unit of CO₂ emissions for a commercial vehicle program recognizes the work performed, for example [gCO₂/ton-mile]. Similarly, engine CO₂ emissions for line-haul and vocational are measured and reported in the same work units as criteria pollutants, i.e. [g/bhp-hr].

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 [22] and the more recent SmartWay program [27]. 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-

Table 2-2. Heavy-duty diesel engine standards for engines installed in vocational applications [6].

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

road vehicle fuel consumption data reveals the significant level of agreement [28]. For line-haul truck duty-cycles, CO₂ emissions from vehicle field data were within 3.7% of the CO₂ emissions predicted from the SET [28]. This particular study involved the collection of data from 8 line-haul trucks 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 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.

2.5. 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 described in Section 2.2.

A summary of the compression-ignition (diesel) engine standards is shown in [Table 2-2](#) and [Table 2-3](#). The definition of a compression-ignition (diesel) engine is based on the engine cycle rather than the ignition mechanism. The diesel engines are further categorized based on the GVWR of the intended application [6]:

- 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

Criteria pollutants and GHG regulations compliance must be demonstrated over the useful life of the engine, defined as [6]:

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

EPA and NHTSA 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 [6]:

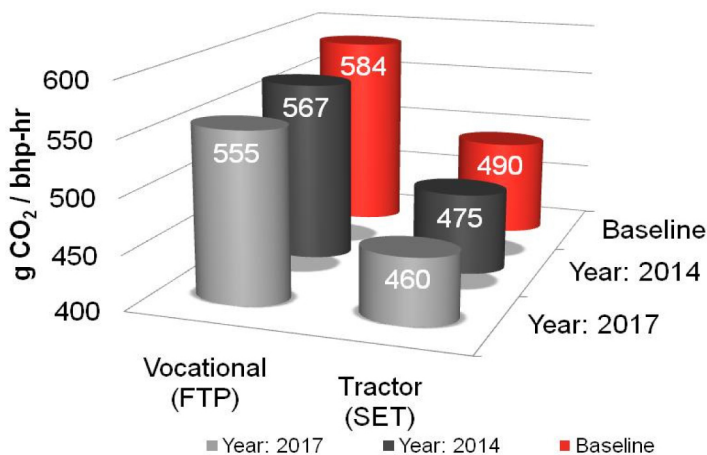
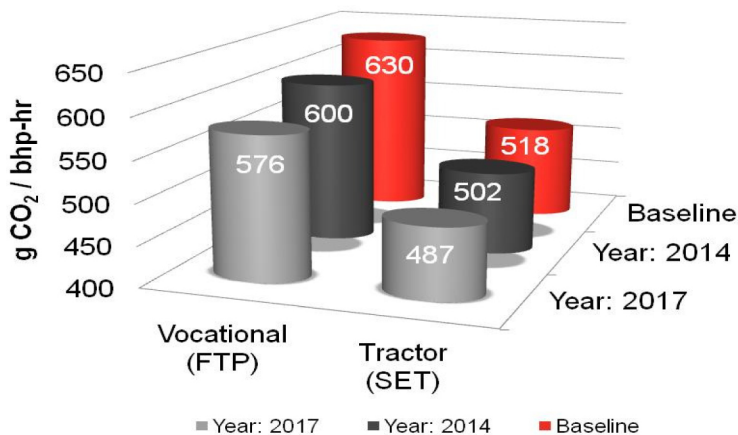
- Electronic control
- SCR/EGR/DPF exhaust aftertreatment system which achieves EPA 2010 criteria emissions standards
- Turbocharged with variable geometry turbocharger

Table 2-3. Heavy-duty diesel engine standards for engines installed in tractor applications [6].

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

- 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 2-10](#) and [Figure 2-11](#) for vocational and tractor applications. A summary of the percent reduction required for MY 2014 and MY 2017 is given in [Table 2-4](#). Early indications are that the MY 2014 reductions will be met by optimization of existing engine and aftertreatment technologies described in Chapter 3. This includes refinements of the formulation of the aftertreatment catalysts, thermal management, and engine calibration. This optimization process will result in a greater proliferation of engine and aftertreatment system hardware and software to minimize CO₂ for specific duty cycles. Striking the balance between product customization versus standardization will quickly become a focal point for engine manufacturers. The MY 2017 reductions will require the continued evolution of engine technologies discussed in Chapter 6.

**Figure 2-10. Comparison of Heavy HD diesel engine (HHDDE) baseline CO₂ levels and the regulated limits.****Figure 2-11. Comparison of Medium HD diesel engine (MHDDE) baseline CO₂ levels and the regulated limits.**

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 [6]:

- 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

2.6. Outline of the Vehicle GHG Standards

Heavy-duty combination tractors, the semi-trucks that typically pull trailers, are built to move freight. Consequently, freight transportation customers choose tractors primarily based on two major characteristics: the gross vehicle weight rating (GVWR), which establishes the maximum carrying capacity of the tractor and trailer; and cab type - sleeper cabs provide overnight accommodations for drivers. Operators also consider the tractor roof height when mating with trailers for the most efficient configuration. EPA and NHTSA have

Table 2-4. 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%

Table 2-5. CO₂ emissions and fuel consumption standards for MY 2017 combination tractors [6].

Category	EPA CO ₂ Emissions			NHTSA Fuel Consumption		
	g/ton-mile			gal/1,000 ton-mile		
	Low Roof	Mid Roof	High Roof	Low Roof	Mid Roof	High Roof
Day Cab Class 7	104	115	120	10.2	11.3	11.8
Day Cab Class 8	80	86	89	7.8	8.4	8.7
Sleeper Cab Class 8	66	73	72	6.5	7.2	7.1

Table 2-6. CO₂ emissions and fuel consumption standards for MY 2017 vocational vehicles [6].

Category	EPA CO ₂ Emissions	NHTSA Fuel Consumption
	g/ton-mile	gal/1,000 ton-mile
Light Heavy Class 2b-5	373	36.7
Medium Heavy Class 6-7	225	22.1
Heavy Heavy Class 8	222	21.8

adopted differentiated standards for nine sub-categories of combination tractors based on three attributes: weight class, cab type and roof height. The standards will phase into the 2017 levels shown in Table 2-5. These final standards will achieve from 9% to 23% reduction in emissions and fuel consumption from affected tractors over the 2010 baselines. For line-haul tractors, there is a composite CO₂ standard determined by a model, Greenhouse Gas Emissions Model (GEM) [29], which accounts for aerodynamics, rolling resistance, idling technology, weight and speed limiters.

Vocational vehicles consist of a very wide variety of truck and bus types including delivery, refuse, utility, dump, cement, transit bus, and many more. Vocational vehicles undergo a complex build process, with an incomplete chassis often built with an engine and transmission purchased from different manufacturers, which is then sold to a body manufacturer. In these rules, the agencies are regulating chassis manufacturers for this segment. The agencies have divided this segment into three regulatory subcategories - Light Heavy (Class 2b through 5), Medium Heavy (Class 6 and 7), and Heavy Heavy (Class 8). This is consistent with the engine classification described in Section 2.5. After engines, tires are the second largest contributor to energy losses of vocational vehicles as shown in Figure 2-3 for the P&D (pick-up and delivery), bus, and refuse applications. The final program for vocational vehicles for this phase of regulatory standards is limited to tire technologies (along

with the separate engine standards). The standards depicted in Table 2-6 represent emission reductions from 6% to 9% from a 2010 baseline.

For heavy-duty pick-up trucks and vans, a complete vehicle approach is utilized in lieu of a component-based approach. Heavy-duty pick-up trucks and vans must meet corporate average CO₂ and fuel economy standards. This approach is similar to light-duty vehicles; however, different standards exist for gasoline versus diesel vehicles. The agencies have established CO₂ standards in the form of a set of target standard curves, based on a “work factor” that combines a vehicle's payload, towing capabilities, and whether or not it has 4-wheel drive [6]. The standards will phase in with increasing stringency in each model year from 2014 to 2018. Both EPA and NHTSA are providing manufacturers with two alternative phase-in approaches. One alternative phases the final standards in at 15-20-40-60-100 percent in model years 2014-2015-2016-2017-2018. The other phases the final standards in at 15-20-67-67-67-100 percent in model years 2014-2015-2016-2017-2018-2019 [6].

2.7. Next Phase of 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, axle, and hybrid components 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.

CHAPTER 3. THE MODERN HEAVY-DUTY DIESEL ENGINE

Solutions have been developed that allow the heavy-duty, on-highway diesel engine to meet the extremely challenging emission standards as discussed in Chapter 2, while continuing to meet customer expectations for fuel economy, performance, reliability and durability. These engines are now on the road delivering the emissions benefits envisioned in the rulemaking as confirmed by a variety of studies [30, 31, 32]. This level of innovation was made possible through the integration of a number of key technologies. An overview of the prevailing on-highway diesel engine architecture and subsequent impact on engine fuel efficiency provides the background for the exploration of future fuel efficiency improvements.

3.1. Evolution of the Diesel Engine Architecture

The challenge posed by the stringent emission standards has led to the development and introduction of new technologies shown in [Figure 3-1](#) - all of which form a key part of today's low emission engine designs. A brief overview

of these technologies provides the background to understand the most common diesel engine and aftertreatment architecture that meets current U.S. regulations for emissions and on-board diagnostics.

Focusing on meeting the near-zero NO_x levels associated with the U.S. EPA 2010 emission standards, the general layout of a current heavy-duty, on-highway diesel engine with aftertreatment system is shown in [Figure 3-2](#). Such engines are turbocharged and use air-to-air charge cooling to increase charge density and reduce NO_x. They feature high pressure common rail (HPCR) fuel injection systems (1600-2500 bar) and full-authority electronic control. This engine has cooled Exhaust Gas Recirculation (EGR) technology to aid in the control of NO_x emissions. The electronic control system typically features several sensors to enable control of engine and aftertreatment performance and emissions under a wide range of operational and ambient conditions.

This vintage of diesel engine requires significant in-cylinder NO_x control and high performing NO_x aftertreatment. Similarly, control of tailpipe particulate matter (PM) requires both an optimized combustion system, in order to limit engine-out smoke levels, and an efficient diesel particulate filter. Furthermore, efficient operation of the NO_x and PM aftertreatment requires thermal management by the engine - which includes a degree of control over exhaust mass flow rate, exhaust temperature and exhaust oxygen. Thermal management is an essential element in the integration of engine and aftertreatment, and allows both the diesel particulate filter (DPF) and the selective catalytic reduction (SCR) to operate at peak efficiency over a wide range of duty cycles. A closer examination of the key technologies for the 2010 engine and aftertreatment system is provided.

3.1.1. Air-to-air charge cooling

As illustrated in [Figure 3-1](#), air-to-air charge cooling was introduced in the mid 1980's in order to reduce charge temperatures (hence flame temperatures), and to increase charge density, thereby providing more engine torque and power. Air-to-air charge cooling reduces intake manifold temperatures almost to ambient temperature. This is followed by compression heating in the turbocharger, producing large reductions in NO_x, of the order of 50% from unregulated levels. The charge air cooler (CAC) is a cooling matrix installed between the turbocharger compressor and intake manifold. The charge cooler is usually installed at the front of the truck - in front of the engine radiator so that it is cooled by the ambient air either by natural ram air from the forward motion of the vehicle, or with cooling fan assistance.

3.1.2. Electronic control systems

Electronic control systems were introduced in the late 1980s. Full-authority electronic controls were introduced initially to allow control of a new generation of electronic fuel systems. Subsequently, electronics have been used to

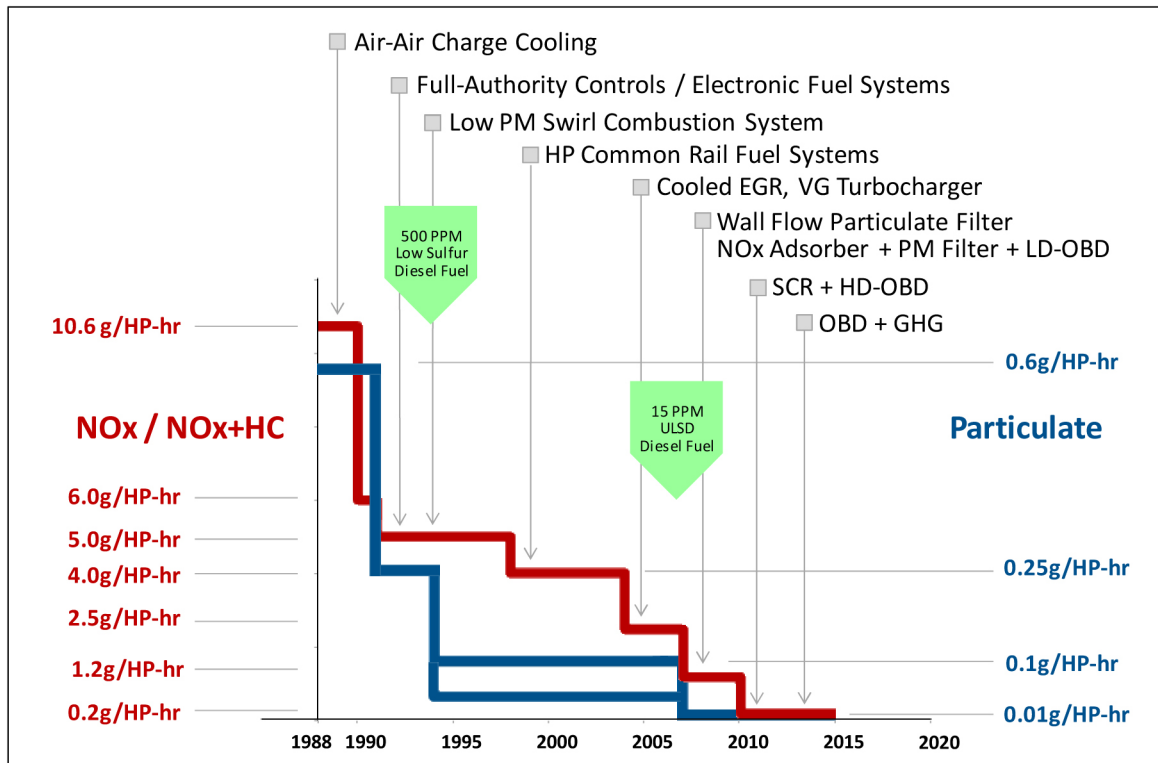


Figure 3-1. Evolution of diesel engine and aftertreatment technologies to meet emissions regulations.

control many aspects of the engine - turbochargers and EGR systems being notable examples. Electronics are also used to diagnose problems with the engine and aftertreatment systems, provide protection under extreme operating conditions, and support on-board diagnostics (OBD).

Electronic controls allow accurate supervision of all critical functions of the engine and aftertreatment systems, under the widest range of conditions. First generation controllers used relatively few sensors and actuators, and featured relatively simple algorithms that made extensive use of a limited number of look-up tables to produce outputs. Examples include controlling outputs such as injected fuel quantity and timing in direct response to inputs such as engine speed and accelerator pedal position. With growing requirements second generation controllers were developed that used several sensors and controlled a small number of actuators, such as fuel injectors and EGR valves. Such controllers made use of multiple look-up tables, featured limited closed-loop control and often made corrections to control outputs based on ambient temperature or altitude. Examples include EGR control based on EGR valve position with feedback, open-loop control of fuel system quantity and timing. Although the fuel system itself is effectively controlled open-loop, all engine controllers control engine speed or vehicle speed by means of a governor or cruise control.

Third generation controllers use a vast set of inputs determined directly from engine and vehicle mounted sensors, and indirectly from physical models often known as

virtual sensors. They feature closed-loop control of most critical variables - such as EGR flow rate, air flow rate, or DEF dosing - which is necessary to limit the amount of variation in performance and emissions from engine-to-engine, and with variation in climate and duty-cycle. Third generation controllers have smart actuators where the electronic control module (ECM) communicates with the actuator over a serial data-link. Smart actuators feature local microcontrollers which can decode control inputs from the data-link and execute control and diagnostics algorithms local to the actuator. Examples include EGR valves, turbochargers, and hydrocarbon and DEF dosers for aftertreatment.

3.1.3. Combustion system

In the modern diesel engine, significant effort is expended to optimize the piston bowl shape, intake air motion (swirl), fuel injector nozzle configuration (number of orifices, size of orifices and the targeting of the fuel injection angle relative to the piston profile), and the number and quantity of fuel injection events to achieve desired engine out emissions and performance. This collection of hardware is referred to as the combustion system.

With all combustion systems, the charge (EGR and air) is compressed through a relatively high compression ratio (typically between 16.5:1 and 19:1) to raise the charge temperature prior to fuel injection. Although many schemes exist for early pilot, pilot, post and late-post fuel injection events, the main fuel injection event occurs close to piston top-dead-center (TDC). The high pressure fuel systems in use

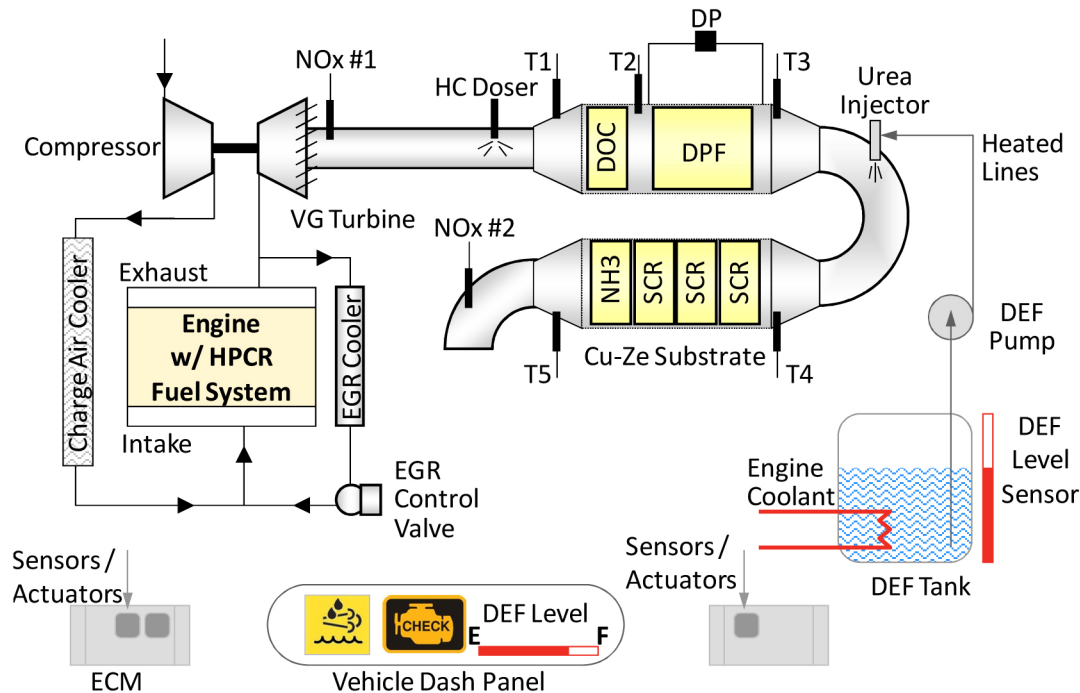


Figure 3-2. Engine and aftertreatment system architecture employed in 2010 on-highway vehicle applications.

today operate at fuel pressures between 1600 bar and 2600 bar, to create a highly atomized fuel spray and short injection duration (less than 30°CA). The fuel rapidly vaporizes in the hot charge in the cylinder, and begins to mix with the surrounding charge. The introduction of swirl (ordered charge rotation inside the cylinder) in the early 1990s allowed a step improvement in engine-out particulate emission and removed the need for the early deployment of PM filter technology.

During the 1990s, the understanding of diesel combustion was significantly advanced through the work of Dec et al [33]. This effort characterizes the various phases of combustion from liquid fuel injection at the injector nozzle orifice to the edge of the combustion plume as shown in the Figure 3-3. One important consequence of this work was the development of high fidelity computer modeling of the stages of diesel combustion including spray atomization, detailed chemical kinetics and emissions formation - computed in a detailed three-dimensional representation of the intake and exhaust ports and in-cylinder geometries. These tools continue to be used to design and optimize combustion systems. A 3-D rendering of the combustion plume interacting with the piston surface is shown in Figure 3-4. The grey surface represents the top surface of the piston called the piston bowl. The fuel injector (not shown) is centrally located and has eight fuel sprays. The yellow shapes are the diffusion flames (one for each combustion plume) interacting with the piston bowl. The complexity of the changing shape of the diffusion flame is revealed; however, the fundamentals shown in Figure 3-3 remain true. Of particular importance, NO_x is formed in the high temperature diffusion flame region at the interface between the fuel rich

plume and the surrounding charge. Since NO_x production is essentially an exponential function of flame temperature, in-cylinder control of NO_x has been accomplished through control of factors which directly influence flame temperature, such as cooled EGR, intake manifold temperature, and fuel injection characteristics.

3.1.4. Variable geometry turbocharger

The variable geometry turbocharger (VGT) was first conceived in the mid-1980s, and after a period of development and optimization was introduced into series production in the late 1990s [34]. A conventional turbocharger consists of a turbine stage in the exhaust stream of the engine which drives a compressor stage installed in the intake system (see Figure 3-2).

The primary goal of the turbocharger is to increase charge density (boost), enabling increased engine power. The combination of charge compression by a turbocharger and air-to-air charge cooling has allowed 3 to 4 fold increases in diesel engine power density over the past 40 years. The amount of intake air compression achieved depends on the characteristics of the turbine stage. The turbine develops power by expanding exhaust gases through a stator or nozzle ring and rotor. The two key parameters of the turbine are its swallowing capacity and isentropic efficiency. Swallowing capacity is a term used to describe the overall flow restriction caused by the turbine, and hence the upstream pressure head created. The higher the pressure head, the higher the expansion ratio through the stage, and the higher the turbine power developed. The isentropic efficiency determines how

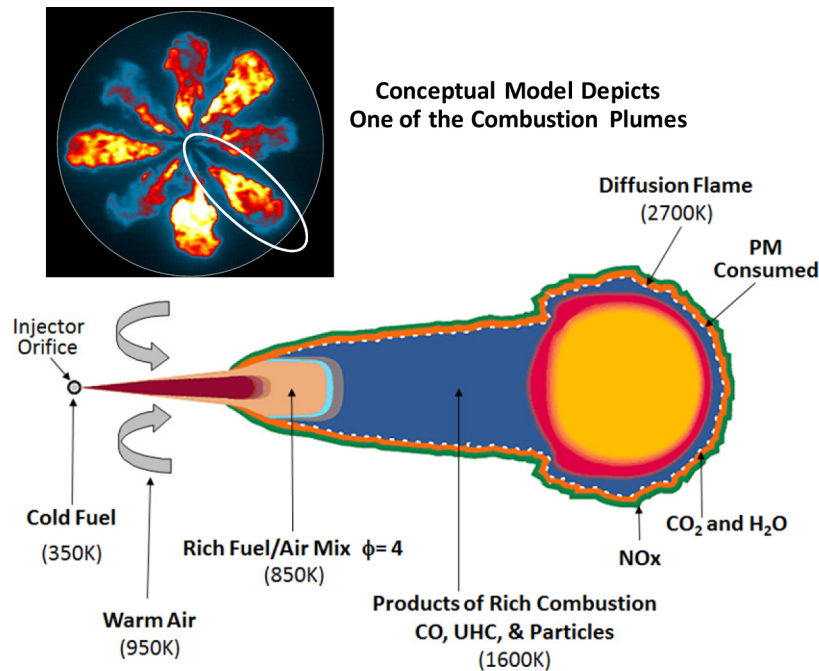


Figure 3-3. Features of diesel diffusion flame combustion based on the Sandia/Cummins collaboration [33].

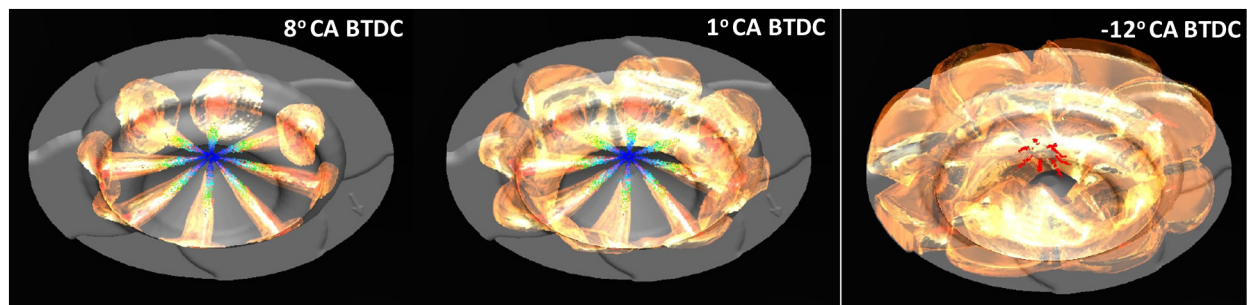


Figure 3-4. Simulation results at three instances during combustion using Computational Fluid Dynamics (CFD) computer modeling.

much of the available turbine power is actually achieved in the stage.

Given that the swallowing capacity of the turbine is a critical parameter in determining turbocharger power, interest in variable geometry turbocharging was a natural evolution from the initial 'fixed' geometry turbocharger (FGT) designs. The first evolution of variable geometry was the development of the turbine wastegate. The wastegate is essentially a controlled bypass path around the turbine stage. By allowing part of the exhaust gas to by-pass the turbine rotor, the power of the turbine stage could be modulated from its maximum power by opening the wastegate. The wastegate allowed turbine stages with small swallowing capacities, which could produce high boost pressures at low engine speeds with the wastegate closed. At higher engine speeds, the wastegate would be opened to prevent over-boosting and protect the engine from damage [35].

A truly variable geometry turbocharger allows the turbine swallowing capacity to be adjusted during engine operation, without the need to by-pass any of the exhaust gas. This allows the turbine power to be modulated in response to real-time operating conditions, for example, during a hard acceleration the VGT can be closed to speed up the compressor to increase air flow. At low engine speeds the VGT can be closed down to generate high air flows to provide high engine torque levels. At higher engine speeds the VGT can be opened to reduce air flow for optimum engine operation without risk of damage.

A number of VGT concepts have been proposed, which include swing vane designs and sliding nozzle designs. Today, the VGT serves several purposes in engine performance and emission control:

- Air flow for torque and performance
- EGR delivery and control

