U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

VEHICLE TECHNOLOGIES PROGRAM

Chevrolet Kodiak

2009 Duramax Diesel 6.6L V-8 Turbo (LMM)
Medium Duty

Diesel Power: Clean Vehicles for Tomorrow

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Prepared for the U.S. Department of Energy Vehicle Technologies Program

PURPOSE

The diesel engine has changed significantly over the last quarter-century, in terms of technology and performance. For this reason, the U.S. Department of Energy (DOE) has created this series of documents about the history of the diesel engine, its current uses in transportation vehicles, and the challenges it faces relative to increasing efficiency while meeting new emission standards at a competitive cost.

DOE's diesel engine research being conducted by the Office of Energy Efficiency and Renewable Energy is contained within the Vehicle Technologies Program. Research is conducted under two distinct partnership activities, the FreedomCAR and Fuel Partnership and the 21st Century Truck Partnership. The FreedomCAR and Fuel Partnership focuses on the high-risk research needed to develop cleaner and more fuel-efficient technologies for a full range of affordable cars and light trucks, while preserving the freedom of mobility and freedom of vehicle choice. The 21st Century Truck Partnership focuses on improving the efficiency, emissions, and safety of medium- and heavy-duty trucks and buses.

IMPORTANCE OF DIESEL RESEARCH

- If the U.S. doesn't pursue research essential for further engine improvements, foreign manufacturers may gain a competitive advantage in meeting new emissions and fuel-efficiency standards, eroding American diesel engine manufacturers leadership as worldwide suppliers.
- Diesel engines offer significantly higher efficiency than current gasoline spark-ignition engines; in some vehicles, fuel efficiency can be improved by 20% to 50% compared to gasoline. This provides the potential for reduced greenhouse gas emissions and reduced petroleum demand in the U.S., improving energy security.
- The diesel engine is a significant contributor to the U.S. economy; over 90 percent of the Nation's freight is transported by diesel-engine vehicles. The diesel engine is also being used for future high-efficiency, light-duty vehicles.
- The American diesel engine industry builds these engines for the U.S. market, and exports a significant portion of its output, providing employment and economic benefits to the states in which it operates and to the country as a whole.
- Concern over the effects of poor air quality on public health and economic welfare has prompted more stringent vehicle emissions regulation both here and abroad.
- Although the modern diesel engine is very clean, further research on diesel engine combustion, emission controls and fuels is needed to ensure that American diesel engines can meet these new regulations.

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CONTACTS

For more information on the programs and technologies discussed in this document, please visit the DOE Energy Efficiency and Renewable Energy Vehicle Technologies Program website at http://www.eere.energy.gov/vehiclesandfuels. Program contacts for Vehicle Technologies may be found at http://www1.eere.energy.gov/vehiclesandfuels/about/fcvt_org_charts.html.

For more information on the other work being undertaken by the Department of Energy's Office of Energy Efficiency and Renewable Energy, please visit http://www.eere.energy.gov or contact the EERE Information Center at 1-877-EERE-INF.

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Cover images (from top): Modern commercial vehicle diesel engine (top left). Photo courtesy of General Motors.

Modern heavy-duty diesel truck. Photo courtesy of Navistar, Inc.

Modern light-duty diesel truck. Photo courtesy of General Motors.

Biodiesel price sign. Photo courtesy of National Renewable Energy Laboratory.

THE HISTORY AND EVOLUTION OF THE DIESEL ENGINE

The diesel engine has a storied past and a bright future. Invented more than 100 years ago as a stationary power source, it has become the undisputed workhorse for shipping and trucking applications worldwide. Recent developments in engine design and emissions control have also made diesel passenger vehicles—long popular in Europe—a powerful alternative to gasoline vehicles in the U.S. market.

Modern diesel passenger vehicles offer higher fuel economy than comparable gasoline vehicles while providing similar handling and performance. Combined with the proven dependability of diesel technology and the wide availability of diesel fuel, diesel engines are an attractive option for reducing petroleum use and transportation-related carbon dioxide (CO_2) emissions. However, continual technological advances are needed to keep diesel emissions in compliance with ever-tightening regulations, allowing drivers to enjoy the advantages of diesel long into the future.

ORIGINS AND BASIC DESIGN

In 1893, German engineer Rudolf Diesel received a patent for a new internal combustion engine designed to be much more efficient than steam engines of the time and to use a variety of fuels, from coal dust to vegetable oils. In 1897, the first public demonstration of a working diesel engine involved a 20-horsepower model weighing more than four tons, similar to the engine in Figure 1.

Diesel's engine used a different combustion cycle than that of the spark-ignition engine invented by his contemporary, Nikolaus Otto. Both cycles (refer to Figure 2) consist of four piston strokes: intake, compression, power, and exhaust. However, they differ in how the fuel is supplied and ignited. In a typical gasoline spark-ignition engine without direct injection, the fuel is premixed with air and introduced into the cylinder during the intake stroke. Combustion begins when an electric spark ignites the fuel-air mixture late in the compression stroke. Gasoline engines require specific fuel and air mixtures for proper ignition. Power output is primarily controlled by limiting, or throttling, the air flow into the engine with a mechanical obstruction (throttle). In a diesel engine, fuel can be introduced into the combustion chamber under extremely high pressure during the intake or compression strokes, and combustion begins as the fuel-air mixture is spontaneously ignited by the cylinder's high temperature and pressure—without a spark. In contrast with gasoline spark-ignition combustion, diesel combustion does not require a uniform fuel-air mix-


Figure 1. Early Diesel engine (#2) located at MAN Diesel, Augsburg, Germany

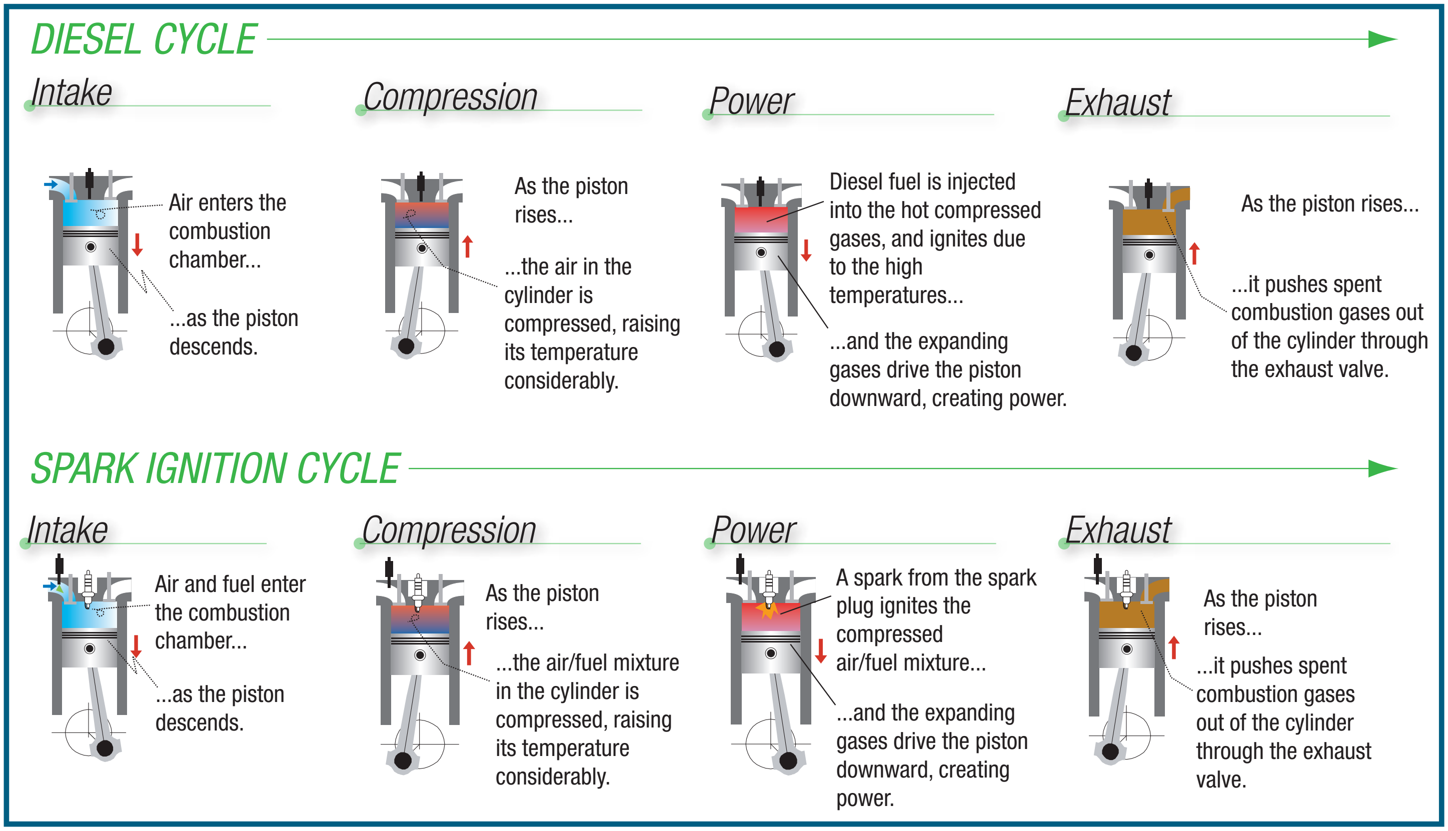

Figure 2. The Diesel and spark ignition four stroke cycles.

ture and can tolerate large amounts of excess air. Diesel engines primarily control power output by varying the amount of fuel supplied to the engine, eliminating the need for a throttle to control airflow.

In the past, a two-stroke version of the diesel engine was common for heavy-duty vehicle applications. These engines were popular because power is delivered during each crankshaft revolution, instead of every other revolution for a four-stroke engine, enabling greater power from a smaller engine. However, because two-stroke diesel engines generally have lower fuel efficiency and higher emissions than four-stroke engines, they are no longer manufactured for on-road vehicles. They are still common in large marine and locomotive applications, which have less stringent emissions requirements. For a more detailed description of diesel engine design and operation, see the Diesel Engine Technologies section of this series of documents.

INHERENT EFFICIENCY ADVANTAGES

High fuel efficiency is one reason the diesel engine is popular for many applications (Figure 3). Current diesel engines can convert about 40-50 percent of the fuel's energy into useful work, compared with about 25-35 percent efficiency for current gasoline spark-ignition engines. Researchers, including those supported by the U.S. Department of Energy (DOE), are striving to improve diesel engine efficiency to 55 percent across a wider variety of engines.

Diesel engines are inherently more efficient than gasoline spark-ignition engines primarily because of their higher compression ratio (the ratio of the cylinder's maximum volume to minimum volume), lean combustion, and lack of throttling. The compression ratio of most gasoline engines is between 8 and 12; for most diesel engines, it is between 14 and 20. The higher compression ratio allows much higher pressure within the combustion chamber, which translates into more mechanical work for a given amount of fuel. Gasoline engines cannot tolerate such high pressures owing to a phenomenon known as detonation, or 'knock,' which can lead to premature engine failure. This is not a problem in diesel engines because of their different combustion process, and more rigorous design.

Figure 3. Various diesel-powered vehicles. Photos courtesy of (top to bottom) Volkswagen Group of America; Chrysler LLC; Navistar Inc.; Deere & Company; and Caterpillar Inc.

Diesel engines also do not suffer from the throttling, or 'pumping,' losses experienced by gasoline spark-ignition engines. In a gasoline engine, both the fuel and the air entering the engine must be controlled. A throttle valve controls engine power by decreasing the air entering the cylinder. The throttle leads to development of a vacuum in the air intake system under most operating conditions, with stronger vacuums at lower power outputs. This vacuum makes the engine work harder to pump air into the cylinder. In contrast, diesel engine power is controlled simply by varying the amount of fuel injected into the cylinders with constant airflow. Thus, diesel engines do not require a throttle, and they experience no throttling losses. The diesel engine's efficiency advantage due to eliminating throttling losses is especially large at idle and low-load conditions, making it the technology of choice for transit buses and heavy-duty vehicles such as refuse haulers, which typically spend significant time in "stop-and-go" modes.

TWENTIETH CENTURY EVOLUTION

Early diesels tended to be large and heavy with very slow engine speeds, which restricted them primarily to stationary industrial applications. As the engine design was refined during the early 20th century, engineers developed new applications. The diesel engine's high efficiency and power led to early adoption in large ships and submarines, which could accommodate large engines. Beginning in the 1920s, engine designs became compact enough for large vehicles such as tractors, medium-duty trucks, and buses. In 1931, the diesel engine found an ideal application for its size and power—the Caterpillar Diesel Sixty tractor. The diesel tractor revolutionized farm work with its low-cost operation and high power output.

Significant diesel engine development occurred in Europe between World Wars I and II owing to gasoline shortages. Improvements in the size and power of diesel engines enabled Mercedes-Benz to begin producing its first diesel-powered passenger car, the 260D, in 1936. Although significant numbers of diesel trucks and buses were developed and widely used, early acceptance of diesel passenger vehicles was limited. After World War II, the diesel engine's efficiency and durability advantages, as well as advances in design tools and materials, made it an attractive power source for European passenger vehicles where fuel prices are traditionally higher than the U.S. This popularity continues to this day, as diesels are favored in many European light- and heavy-duty vehicle markets.

In the United States, the diesel engine has enjoyed the most success in the heavy-duty market. The diesel engine's fuel economy, power, and durability made it popular in the equipment that built the U.S. Interstate Highway System in the 1950s and in the trucks that used the interstates. Today, diesel engines continue to be the prime power source in most off-road construction equipment, farm machinery, and long-haul trucks.

Despite their success in other applications, diesel engines historically have not fared well in U.S. passenger cars . Diesel passenger cars achieved significant sales during the oil crisis of the 1970s, but customer acceptance remained low. Many diesel vehicles of this era suffered from poor reliability and were characterized as dirty and noisy. Following the oil crisis, the availability of low-priced gasoline further reduced the financial incentive for adopting the efficient diesel engine in the passenger car market. In addition, increasingly stringent U.S. emission standards made it difficult for manufacturers to develop cost-effective diesel passenger vehicles.

Regardless of setbacks in the passenger car market, the diesel has achieved significant success in the light-duty truck market In the early 1980's, GM and Ford introduced diesel engines for their pickup truck lines (Figure 4). The diesel versions quickly became favorites of demanding customers because of their increased towing capacity, good fuel economy, and reliability. By the end of the 1980s, all three major U.S. automakers offered high-power, high-torque diesel engines for their light-duty pickups. In July 2008, Cummins announced plans to produce a new generation of light-truck diesel engines based on work completed in conjunction with DOE. These engines are expected to be even lighter, more powerful, cleaner, and more economical than current engines.

Figure 4. First of a kind: the 1980 Ford F-250 light-duty pickup with a 6.9 liter diesel, first in a Ford pickup. Photo courtesy of Ford Motor Company.

Figure 5. Modern light-duty (top) and heavy-duty (bottom) diesel engines. Photos courtesy of Ford Motor Company (top) and Navistar Inc. (bottom).

TODAY'S CLEAN, GREEN DIESEL

Today's diesel engines (Figure 5) are much more advanced than those of just a decade ago—and tremendously improved compared with the unreliable, noisy, and polluting vehicles of the 1970s. Modern diesel engines are predominantly direct-injection, four-stroke engines with electronic controls that offer high efficiency, quiet operation, and low emissions. They are available in a wide variety of sizes for on- and non-road vehicles, from about 20 horsepower for agricultural and turf maintenance equipment to 3,000 horsepower or more for non-road equipment such as dump trucks. Diesel engines as large as 700 horsepower are available for on-road Class 8 tractor-trailers (greater than 33,000 lbs).

In 2008, passenger vehicles accounted for about 20 percent of U.S. CO_2 emissions. Higher fuel economy translates to lower CO_2 emissions, so increasing the share of diesel vehicles on the road reduces CO_2 emissions. Modern diesel passenger vehicles offer better fuel economy than most gasoline passenger vehicles while maintaining equivalent performance. For example, the model year 2010 diesel Volkswagen Jetta is the most fuel-efficient non-hybrid vehicle available in the United States, achieving 30 miles per gallon (mpg) city and 42 mpg highway fuel economy.

Modern diesel engines continue to offer their almost-legendary durability and dependability. Many owners report driving their light-duty diesel vehicles more than 300,000 miles with few problems, and it is not uncommon for heavy-duty diesel engines to operate for more than 1 million miles.

Their power, fuel efficiency, and durability also have brought diesel vehicles success in endurance and speed racing. In 2006 and 2007, Audi diesel vehicles finished first in the 24 Hours of Le Mans endurance race. In 2006, engine manufacturer JCB set the international land speed record for a diesel-powered vehicle by averaging more than 350 miles per hour (Figure 6).

Compared with their older counterparts, modern diesel engines produce significantly lower levels of harmful emissions, including hydrocarbons, carbon monoxide, nitrogen oxides, and particulate matter. Today's emission standards apply equally to all light-duty vehicles, so gasoline and diesel vehicles must meet the same standards. Advanced diesel combustion and emission-control technologies (such as the diesel particulate filter) continue to be developed and implemented widely to meet emissions standards.

LOOKING TO THE FUTURE

With their distinguished track record and inherent power and efficiency advantages, diesel engines are poised to meet the demands of the future. These demands include minimizing petroleum use, CO_2 emissions, and regulated emissions. Stricter emissions regulations may lead to widespread use of novel diesel emission-control technologies, and even entirely new combustion regimes (such as low-temperature combustion) are possible. The diesel engine must also adapt to new fuels such as biodiesel and synthetic diesel. Whatever the future holds, DOE is working with industry to drive the research and development necessary for the continued success of the diesel engine—one of the world's most important vehicle technologies.

Figure 6. The JCB DieselMax. Photo courtesy of JCB.

DIESEL ENGINE AND FUEL TECHNOLOGIES

Diesel engines have a been powerful, reliable, and efficient source of power for decades. Today, thanks to advanced technologies, they also offer environmental benefits and are becoming increasingly popular in the passenger vehicle market. Nonetheless, more engine and fuel research and development (R&D) are needed to improve the emissions and environmental impact of diesel engines while maintaining their high performance.

CUTTING GREENHOUSE GASES WITH DIESEL

Many experts believe that emissions of greenhouse gases (GHGs), particularly carbon dioxide (CO_2), are creating an atmospheric greenhouse effect linked to global warming. In 2008, the transportation sector accounted for more than 33 percent of U.S. CO_2 emissions, behind only the electricity generation sector (39 percent). Within the transportation sector, 61 percent of man-made CO_2 emissions come from passenger vehicles, 22 percent from heavy-duty trucks, and 13 percent from trains and ships. Between 1990 and 2008, U.S. transportation-related CO_2 emissions (Figure 1) rose 22 percent because of increased vehicle miles traveled (Figure 2). Because CO_2 emissions are proportional to the amount of fuel a vehicle uses, one way to reduce transportation-related CO_2 emissions is to increase vehicle fuel economy.

The fuel economy of diesel vehicles is 20 to 50 percent higher than that of comparable gasoline vehicles. Diesel engines already power nearly all U.S. heavy-duty vehicles—including trains, ships, and long-haul trucks—but only 4 percent of passenger vehicles. In contrast, about half the passenger vehicles in Europe are diesel powered partly because high European fuel costs make the diesel's higher fuel economy economically attractive. As higher fuel economy and lower CO_2 emissions become more important in the United States, increased use of diesel passenger vehicles could help reduce the nation's CO_2 emissions significantly.

CONTROLLING DIESEL EMISSIONS

Historically, the cost of controlling pollutant emissions has been a barrier to more widespread use of diesel passenger vehicles. Emissions of nitrogen oxides (NOx) and particulate matter (PM) have been particularly problematic. Nonetheless, revolutionary technological advances over the past 20 years have enabled greater control of diesel emissions while maintaining high performance and affordability.

As of 2004, U.S. Environmental Protection Agency (EPA) Tier 2 emission standards dictate that all light-duty vehicles, regardless of fuel type, meet the same emissions standards. This is a challenge for diesel engine developers because the excess-air operation of diesel engines precludes use of the three-way emission-reduction catalysts used by gasoline vehicles. The commercial vehicle engine sector has faced similar challenges as stringent heavy-duty emission regulations were phased in between 2007 and 2010.

These emissions challenges are being met via a combination of technologies. Combustion improvements reduce emissions generation inside the engine, and aftertreatment technologies reduce the engine emissions further before they are released to the atmosphere. These technologies are integrated using a systems approach. For example, a combustion technology that reduces emissions allows a complementary aftertreatment technology to be smaller, or a different aftertreatment type to be used, because a lower quantity of emissions must be controlled. The following sections summarize advances in combustion and aftertreatment technologies.

DIESEL ENGINE COMBUSTION AND CONTROL

Decades of work have produced a large body of knowledge about the diesel combustion process, although some details of the dynamics and variability are still not fully understood. Levels of harmful emissions leaving diesel engines have been reduced through com-

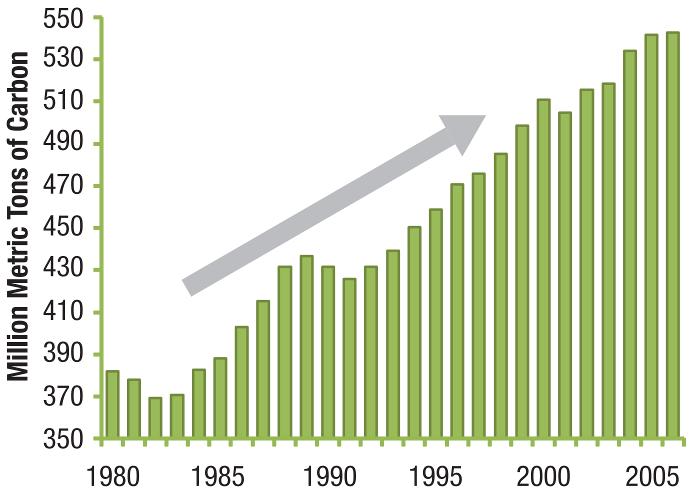

Figure 1. U.S. carbon emissions from transportation sources. Data from the U.S. Department of Energy, Energy Information Administration.

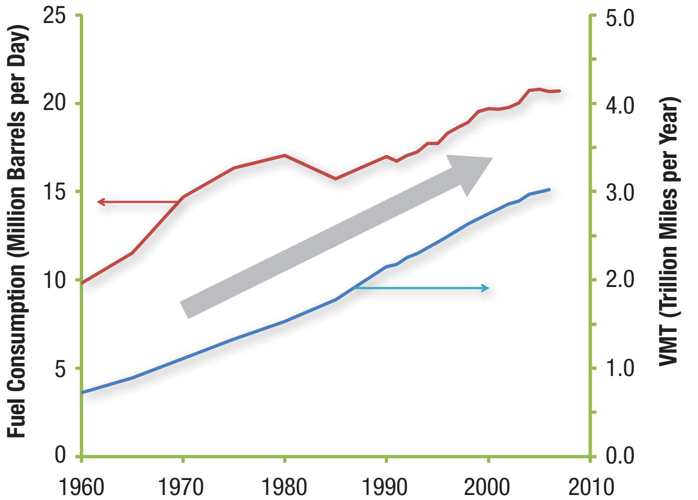

Figure 2. Trends in on-highway fuel consumption and vehicle miles traveled. Information from the U.S. Department of Transportation.

bustion-related advances in fuel injection, turbocharging, exhaust gas recirculation (EGR), and novel combustion technologies (Figure 3). Future details of these technologies are explained below.

Fuel Injection

Two major types of fuel injection systems are used in current diesel vehicles: common rail systems (CRS) and electronic unit injector (EUI). The quality and effectiveness of both systems are similar, and both inject fuel into the engine cylinders under very high pressure. The injection process is controlled electronically to deliver exact fuel volumes at optimal moments in the combustion cycle, which ensures maximum performance with minimum fuel consumption and emissions. However, CRS and EUI have differences in cost, packaging, and complexity that make them suitable for different applications.

In CRS, the fuel pump can pressurize the fuel to more than 30,000 PSI in a fuel rail that supplies all cylinders. Electronically controlled, high-performance magnetic—or, more recently, piezoelectric—valves precisely control injection times and durations for each cylinder. Functional separation of fuel pressure generation and fuel injection enables improvements in the fuel-delivery process compared with UIS. CRS are more similar to the fuel injection systems used in gasoline engines. This is beneficial for mass-produced engines because the fuel injection system can account for up to 30 percent of an advanced diesel engine's cost. Almost all new American and European passenger diesel engines and many heavy-duty now incorporate CRS.

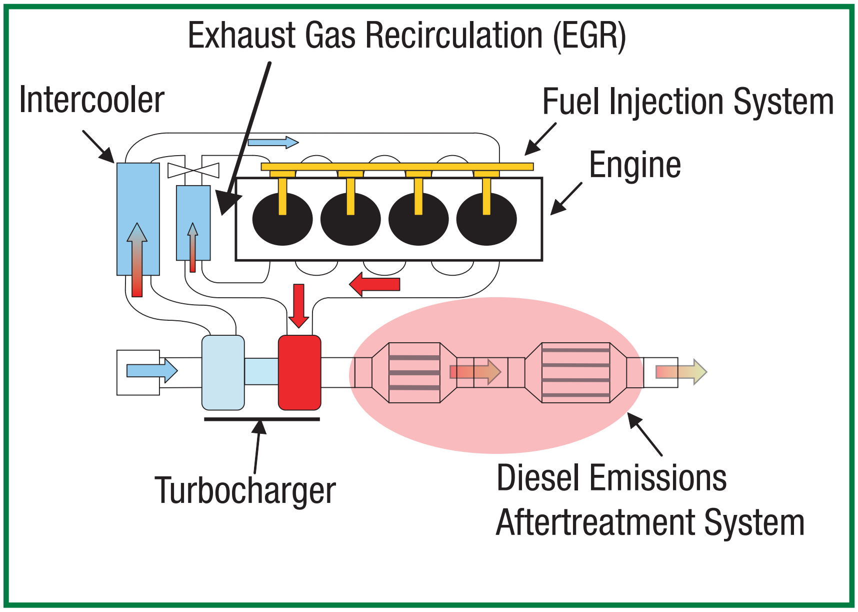

Figure 3. Schematic of the diesel engine and its major components.

With EUI, each engine cylinder has an injector contained in a single component (or unit), over 30,000 psi of pressure just before the injection event (the equivalent of a midsize car supported on an area the size of a fingernail). With EUI, the pressure drops after the injection event making the system less flexible for varying injection duration and timing than CRS. EUI are widely used in commercial vehicle diesel engine applications.

Since the mid-1980s, increasingly higher fuel injection pressures, which enable more rapid fuel-air mixing and evaporation, have reduced soot formation in diesel engines. Throughout the 1990s, managing fuel injection and other engine functions with sophisticated electronic control units (ECUs) enabled compliance with tightening emission standards. Considerable R&D also has focused on combustion chamber geometry for effective fuel-air mixing (combustion air swirl), injector shape and pressure for optimal fuel atomization, and injection-control strategies for advancing or retarding injection along with multiple injection pulses depending on load and speed.

Turbocharging

Turbocharging allows for use of smaller engines, which have lower frictional losses along with lower weight and size, resulting in better fuel economy and reduced emissions. Downsizing an engine and using a turbocharger to maintain the peak power rating is common for diesel engines but is also applicable to engines using gasoline and other fuels. Virtually all modern diesel engines are turbocharged.

Turbocharging uses the otherwise wasted energy in the exhaust gases to power a turbine that spins a compressor at very high speeds when extra power is desired. The compressor pressurizes the intake air, thereby increasing the oxygen introduced into the engine cylinders and allowing the engine to inject and burn more fuel and produce more power. Because compressing the intake air raises its temperature, many turbocharged engines use a heat exchanger called an intercooler to cool the intake air before it reaches the engine. This cooling creates a denser air charge and increased power. The lower intake air temperature also suppresses NOx formation during combustion.

A drawback of turbochargers, commonly known as turbos, is the time required to accelerate the turbo to rotational speeds sufficient to deliver pressurized air ("boost") to the engine. This delay, called "turbo lag," has been reduced or eliminated in modern engines using techniques such as variable geometry turbochargers (VGTs) and dual-stage turbocharger systems.

Also called variable nozzle turbochargers, VGTs control the boost pressure and help reduce turbo lag by placing movable vanes in the exhaust immediately in front of the turbine. The spaces between these vanes act as nozzles, directing exhaust gas into the turbine to optimize its rotational speed and acceleration for the engine conditions. The moveable vanes of VGTs are electronically controlled by the engine's electronic control unit, which makes VGTs highly flexible and responsive.

Dual-stage turbocharger systems use two different-sized turbos simultaneously. The smaller turbo quickly produces boost at lower engine speeds to provide responsive, lag-free power. However, this small turbo has a lower peak boost capability and cannot produce the necessary peak engine power, so a second, larger turbo is used at higher engine speeds to provide the necessary boost pressures. The result is an engine with responsiveness and high power.

Exhaust Gas Recirculation (EGR)

Exhaust gas recirculation has been used to suppress NOx formation in spark-ignition engines for more than 25 years and is one of today's most common emissions-control systems. With this technique, exhaust gases (mainly inert nitrogen, CO_2, and water vapor) are reintroduced into the engine intake air, diluting the fuel-air mixture in the combustion chamber and increasing its heat capacity, which reduces the temperature rise during combustion. NOx formation is suppressed in combustion environments with EGR because peak temperatures are kept below 3100ºF, the temperature above which NOx is readily formed.

Use of EGR is highly effective in gasoline spark-ignition engines because their exhaust consists primarily of inert gases. Diesel engines, on the other hand, operate at much leaner (excess air) fuel-air ratios than spark-ignition engines; thus their exhaust contains significantly more oxygen and less CO_2 and water vapor. To reduce NOx formation, diesel engines must use much higher proportions of recirculated exhaust gases in the intake air, especially at lower loads when the fuel-air mixtures contain the largest amount of excess air. To control both NOx and PM emissions accurately, the amount of recirculated exhaust gas and air entering the engine must be controlled precisely under all operating conditions.

Most current diesel engines operate with cooled EGR systems. These systems use a heat exchanger to reduce exhaust gas temperatures before introduction into the intake system, resulting in higher EGR rates and lower combustion temperatures, which results in even lower NOx formation. The cooling demand on this type of system is higher than on a gasoline engine owing to the higher EGR flow diesels require. The cooling is achieved in a similar manner, and with similar equipment, as in an intercooler for turbocharged engines. Despite their additional cost, cooled EGR systems are becoming increasingly common owing to more stringent emissions regulations.

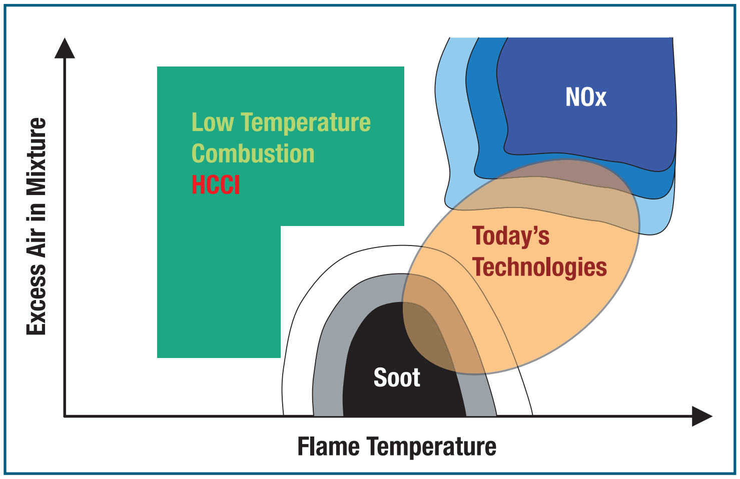

Figure 4. Diesel combustion regimes. Graphic courtesy of AVL Commercial Powertrain Systems.

Novel Combustion Technologies

Although conventional diesel combustion maintains relevance in current DOE research programs, advanced combustion concepts are also being studied (Figure 4). Examples include low-temperature combustion modes such as homogeneous charge compression-ignition (HCCI) and premixed charge compression-ignition (PCCI). These combustion strategies can be used alone or in a "mixed mode," e.g., low-temperature combustion modes are used at light to moderate loads, and conventional combustion modes are used for starting and at higher loads.

In HCCI, a homogeneous (uniformly mixed) fuel-air mixture is created in the combustion cylinder by injecting fuel during the intake stroke, in contrast to the heterogeneous (not uniformly mixed) mixture used in traditional diesel fuel injection. HCCI is similar to the fuel injection method used in gasoline engines, but it relies on the heat and pressure of the compressed gases to initiate combustion. HCCI's homogeneous charge eliminates fuel-rich (excess fuel) regions in the cylinder, so combustion occurs nearly simultaneously throughout the cylinder. This results in more complete, lower-temperature combustion and reduced NOx and PM formation compared with conventional diesel combustion.

A range of technical barriers must be solved before HCCI achieves the performance, cost, and reliability required for commercial applications. The most significant barrier is controlling ignition timing over the full range of engine speeds and loads. Other issues include developing a fuel-delivery system that can establish homogeneous charges under varying operating conditions, developing an effective cold-start system, and controlling the high levels of unburned hydrocarbons (UHC) and carbon monoxide (CO) that form under some operational modes. DOE sponsors much of the R&D work in this area, including laboratory and field testing of HCCI engines.

DIESEL EMISSIONS AFTERTREATMENT

Aftertreatment systems are installed in a vehicle's exhaust stream to reduce emissions of unburned hydrocarbons, carbon monoxide, nitrous oxides, and particulate matter. Robust aftertreatment systems are essential for achieving stringent current and future emission standards. DOE R&D efforts focus on improving durability and performance of these systems, while reducing their cost and minimizing their impact on vehicle fuel economy.

Aftertreatment was used on diesel vehicles beginning in the early 1990s to help meet EPA emission standards. Since then, the most common aftertreatment has been the diesel oxidation catalyst (DOC), which reduces HC and CO emissions and, to a lesser extent, PM emissions (mainly the soluble organic fraction). Emission regulations before 2007 were met successfully with a combination of improved combustion techniques and DOCs. However, DOC emission-reduction efficiencies are limited by the relatively low temperature of diesel exhaust, and meeting the EPA 2007 and 2010 emission regulations requires additional aftertreatment technology. Diesel aftertreatment technologies that are being used, or that will be used, include diesel oxidation catalyst, diesel particulate filters (DPFs), selective catalytic reduction (SCR), lean-NOx catalysts (LNC), and NOx adsorbers.

Diesel Particulate Filters (DPF)

PM emissions have historically been much higher in diesel engines than in gasoline engines due to the nature of the combustion process and fuel properties. Due to the low PM emissions from gasoline engines, there has been no need for their regulation to date. With diesel engines, PM control is necessary and is regulated for diesel cars and trucks. A DPF physically filters the exhaust stream, reducing PM emissions by more than 99 percent in many cases. DPFs control both the solid fraction of PM (i.e., the carbon "soot" and related black smoke). as well as the soluble organic fraction (SOF) of PM. DPFs have been commercialized for the passenger and commercial vehicle markets (Figures 5 and 6).

A common DPF structure is a ceramic monolith (engineered honeycomb-like structure) packaged in a metal housing similar to a conventional catalytic converter. Other filter material structures, such as woven wire mesh, are also used. The monolith consists of many parallel channels. Adjacent channels are alternately plugged at each end, forcing the exhaust gas through porous walls that capture PM. The flow restriction caused by increasing amounts of captured PM increases the exhaust backpressure over time, reducing engine performance and efficiency. As a result, accumulated PM is periodically oxidized into CO_2 in a process called "regeneration."

Regeneration can be passive or active depending on the application and DPF design. If the exhaust temperature is high enough, passive regeneration can be used to remove PM continuously. If the exhaust temperature is too low to support passive regeneration, active regeneration must be used to raise the exhaust temperature periodically. One way to raise the exhaust temperature is to introduce excess fuel into the exhaust stream, which reduces fuel efficiency slightly. Active regeneration is also more expensive and complex to implement than passive regeneration owing to the additional control and hardware requirements. It is achieved using engine-management techniques in passenger vehicles and occasionally using auxiliary exhaust fuel injection in commercial vehicles.

Adding a catalytic material to the DPF walls enables faster regeneration by lowering the required oxidation temperature. Some of the particulate matter in a DPF cannot be burned off and is known as "ash". Such material consists primarily of oil additives and contaminants. Ash slowly but continuously builds up in the DPF, eventually clogging it and permanently reducing engine performance through increased exhaust backpressure.

Figure 5. Diesel particulate filter used in the Ford SuperDuty diesel pickup application. Photo courtesy of Ford Motor Company.

Figure 6. Diesel particulate filter used in BMW light-duty diesel vehicles. Photo courtesy of BMW AG.

Selective Catalytic Reduction

Selective catalytic reduction is an aftertreatment technology used when EGR alone is insufficient to control NOx emissions (Figure 7). SCR has been used to reduce NOx emissions from large stationary engines and fossil fuel–burning equipment for more than a decade. In this process, the chemical compound urea ($[NH_2]_2CO$) is diluted with water and injected into the exhaust stream, where it decomposes to form ammonia (NH_3) and CO_2. The ammonia reacts with NOx to form harmless nitrogen gas and water vapor. Europe uses a 32.5-percent aqueous urea solution (AUS32) known by the trade name AdBlue. In the United States, the urea solution is referred to generically as diesel exhaust fluid (DEF).

A SCR system does add complexity to the vehicle. SCR systems include an onboard DEF storage tank, injection nozzles, exhaust catalyst, and associated control hardware. The storage tank and fuel lines must be heated because the water-diluted urea freezes at 12^{o}F. SCR can be more than 90-percent effective for NOx control and is not very sensitive to sulfur poisoning. Because ammonia emissions can be a byproduct of SCR, a downstream catalyst is added to oxidize any remaining ammonia in the exhaust.

Urea-based SCR has become the NOx-control technology of choice in Europe (Figure 8). In the United States, regulators were initially skeptical about SCR because of the need for developing a DEF distribution infrastructure and methods for restricting engine operation if a vehicle's DEF supply is depleted. However, owing to its superior performance and cost effectiveness, especially for large engines, many commercial vehicle engine manufacturers and several passenger vehicle manufacturers have chosen SCR to reduce NOx emissions. As a result, the EPA has developed safeguards with industry to ensure that SCR-equipped engines cannot be operated indefinitely without DEF. To help with the DEF infrastructure challenge, DOE has expanded its

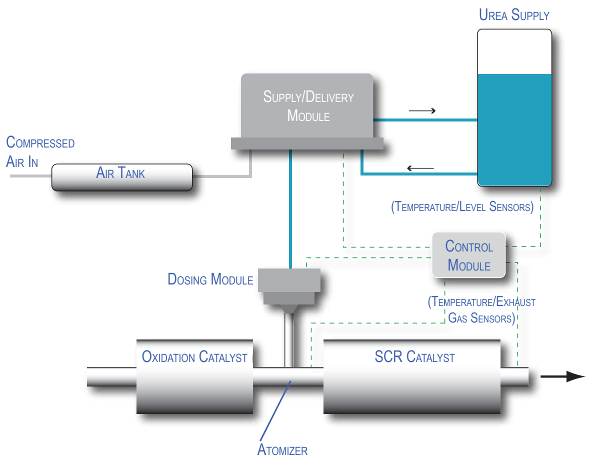

Figure 7. Urea SCR system, showing major components.

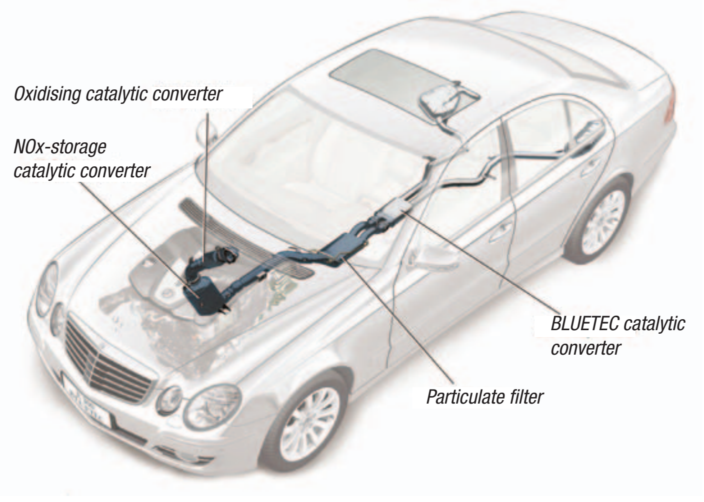

Figure 8. BLUETEC system schematic for Mercedes E-Class diesel vehicle. Schematic courtesy of Daimler AG.

Alternative Fueling Station Locator (www.afdc.energy.gov/afdc/fuels/stations_locator.html) to show the locations of retail DEF distributors.

Lean-NOx Catalysts (LNC)

Also known as HC-SCR and de-NOx, LNC are an alternative to selective catalytic reduction (SCR). These catalysts use unburned hydrocarbons to reduce nitrous oxides (NOx) instead of ammonia. Passive LNC use unburnt HC emitted in the engine exhaust, via engine-controlled air-fuel ratio enrichment, as the reducing agent. Active LNC use additional fuel injected upstream of the catalyst in the exhaust stream. LNC are sometimes combined with a diesel oxidation catalyst, creating a “four-way catalyst” for the simultaneous reduction of unburned hydrocarbons, carbon monoxide, nitrous oxides, and particulate matter.

Peak lean NOx conversion efficiencies (amount converted to harmless nitrogen and oxygen) range from 40 to 80 percent. In the past, the relatively narrow temperature range at which the LNC must operate resulted in low overall NOx conversion efficiencies for passive systems. Technological improvements and correspondingly higher NOx conversion efficiencies have made LNC economically viable for small diesel engines. The maximum engine displacement currently viable for LNC is approximately 3.0 L. For larger engines, SCRs systems are typically used for NOx control.

NOx Adsorbers

Also called lean NOx traps, NOx adsorbers are used to control NOx emissions from some direct-injection gasoline engines and small-displacement diesel engines. Unlike LNC, NOx adsorbers store NOx in the catalyst material under normal exhaust conditions. Periodic active regeneration cycles are initiated by adding reductant chemicals, usually excess diesel fuel, into the exhaust stream. This causes the catalyst to release the stored NOx, which is converted to nitrogen gas, and restores the adsorber’s ability to store NOx.

As with other NOx-control strategies that rely on catalytic treatment of exhaust gas, NOx adsorbers have durability issues associated with the high temperatures required for regeneration and sulfur poisoning. A major DOE R&D focus has been to minimize the 1–3 percent fuel economy penalty due to the fuel required for regeneration and to improve the durability and optimal temperature range. NOx adsorbers have demonstrated greater than 90 percent effectiveness in full-scale systems with fresh catalysts. The performance and durability of NOx adsorbers continue to improve, and some NOx adsorber technologies have been commercialized.

DEVELOPING ADVANCED DIESEL FUELS

Diesel fuels are another area of active research. Until the early 1990s, diesel fuel formulations—which included mainly paraffinic and aromatic hydrocarbons plus additives for cold-weather performance—remained relatively unchanged. Ignition quality was the most important diesel fuel property. Ignition quality correlates directly with a diesel fuel’s cetane rating: fuels with high cetane ratings exhibit less ignition delay during combustion and thus result in smoother and more controlled heat-release rates. Straight-chain paraffinic hydrocarbons have high cetane ratings. Aromatics are ring hydrocarbons and have low cetane ratings. Therefore, the general recipe for modern diesel fuels includes high paraffin content and proportionally lower aromatic content to achieve the required cetane number.

In the past few years, pollutant and GHG emissions became additional factors driving diesel fuel formulations. Fuels must now be developed to enable use of advanced emissions-control devices while maintaining ignition quality and other performance characteristics. Fuel feedstocks other than crude oil, most importantly renewable feedstocks, are being explored to reduce lifecycle GHG emissions. The following sections summarize advances in low-sulfur diesel, biodiesel, and synthetic diesel fuels (properties of these fuels are illustrated in Figure 9).

Low-Sulfur Diesel

Beginning with the Clean Air Act Amendments of 1990, the United States Environmental Protection Agency (EPA) tightened heavy-duty diesel emissions standards. Recognizing the link between engine emissions and fuel properties, EPA promulgated fuel-quality regulations for on-road diesel vehicles. These regulations required fuels to have a minimum cetane number and a sulfur content of no more than 500 parts per million (ppm). Sulfur in diesel fuel contributes to sulfate particulate and sulfide compound formation in the exhaust. Sulfur compounds in the exhaust poison catalytic converters used for exhaust emission control by blocking active reaction sites on the catalyst material.

Fuel Properties	**Ultra-Low Sulfur Diesel**	**Biodiesel**	**Fischer-Tropsch Diesel**
Specific Gravity	0.84-0.87	0.87-0.89	0.77-0.79
Cetane Rating	40-55	46-70	>70
Sulfur (ppm)	7-15	0-24	<1
HFRR Lubricity (mm)	0.40-0.55	0.27-0.32	0.40-0.64
Lower Heating Value (Btu/gal)	~129,500	~118,300	~129,500

Note: HFRR = High Frequency Reciprocating Rig, an ASTM wear test for fuel lubricity (requirement is less than 0.45 mm of wear)

Figure 9. Properties of various diesel fuels. Source: NREL Advanced Vehicles and Fuels Properties Database, http://www.nrel.gov/vehiclesandfuels/fuels_database.html.

EPA further reduced the diesel sulfur ceiling to 15 ppm by a rulemaking in December 2000 which took effect in October 2006 to support diesel emission regulations beginning in 2007. This sulfur reduction was crucial for increasing the durability of the aftertreatment devices diesel engines needed to meet emissions standards in 2007 and beyond. DOE and its National Laboratories led the research effort to determine the feasibility of producing and using low-sulfur diesel fuel. Fuels meeting the 15-ppm sulfur requirement are called ULSD. The processing cost to remove sulfur to this level is approximately $0.04/gallon. In addition, the lubricity of ULSD fuels is reduced because of the sulfur removal, and fuel additives are required (at additional cost) to adequately lubricate engine components.

Biodiesel

Biodiesel is the only diesel oxygenate used in significant quantities in the United States (Figure 10). Current, first-generation biodiesel consists of fatty acid methyl (or ethyl) ester-based fuels that can be produced domestically from vegetable oils, animal fats, or recycled yellow grease (waste fryer oil from restaurants). First-generation biodiesel is produced in batches and has been criticized for its lack of long-term sustainability because edible crops—mainly soybeans in the United States—are used as feedstocks.

To improve sustainability and production costs, second-generation biodiesel will use non-traditional or non-edible feedstocks including oil-producing plants such as mustard seed, rapeseed (canola), and algae. Second-generation fuel production methods include processing renewable feedstocks via conventional petroleum refining infrastructure, which enables higher throughput and results in fuel that is indistinguishable from conventional petroleum diesel.

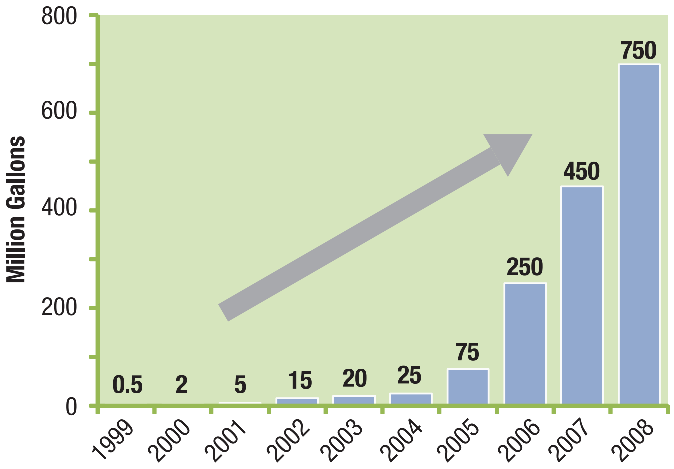

Figure 10. Biodiesel production history. Information from the National Biodiesel Board.

Biodiesel blends are safe, biodegradable, and reduce regulated air pollutants such as unburned hydrocarbons, carbon monoxide, and particulate matter. However, biodiesel can produce either a slight increase or decrease in NOx emissions depending on the engine and fuel used and on the duty cycle. Because it is derived from renewable feedstocks, biodiesel reduces lifecycle CO_2 emissions. One DOE study found that neat biodiesel (100 percent pure biodiesel or B100) reduced lifecycle CO_2 emissions 78 percent compared with petroleum diesel.

No sulfur, aromatics, or metals are present in B100. Because of its superior lubricity, biodiesel can be used as a lubricity additive in ULSD blends, although most refiners use cheaper petroleum-based additives. Biodiesel also has a slightly higher cetane rating than petroleum diesel (46–70 for biodiesel vs. 40–55 for petroleum diesel) and is an excellent blending agent for petroleum diesel. The two most common blends today are B5 (5 percent biodiesel) and B20 (20 percent biodiesel).

In the United States, B5 can be marketed as regular diesel and can be used in unmodified diesel engines. B20 offers a good compromise among issues related to cost, environmental benefits, material compatibility, and temperature stability. However, B20 has not been universally approved for all engines. Previously limited by inadequate biodiesel-quality standards, engine manufacturer acceptance of biodiesel blends up to B20 recently surged because of the acceptance of new biodiesel fuel specifications.

Historically, biodiesel has cost more per gallon than petroleum diesel. Government incentives help level the playing field by recognizing the environmental value of biodiesel. Starting in January 2005, a tax credit was instituted giving $0.01 per percent of agricultural product–based biodiesel in a fuel blend, and $0.005 per percent of recycled oil–based biodiesel. The incentive is taken by fuel blenders but is generally passed on to the consumer. With the tax credit included, the cost of B100 and biodiesel blends has been similar to, or even lower than, the cost of petroleum diesel according to DOE's Alternative Fuel Price Report (www.afdc.energy.gov/afdc/price_report.html).

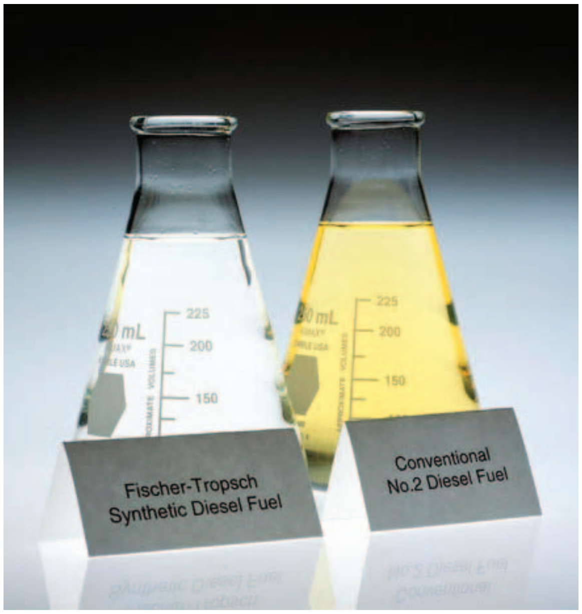

Figure 11. Synthetic diesel fuels. Photos courtesy of the National Renewable Energy Laboratory (above) and Choren Industries below).

Synthetic Diesel

Diesel fuels and other petroleum products are traditionally manufactured by refining crude oil. These products also can be produced synthetically from various carbon-bearing feedstocks such as natural gas (historically the most popular option), coal, and biomass (Figure 11).

The first and best-known synthetic fuel production technology is the Fischer-Tropsch (FT) process, which was developed in Germany in the 1920s. Because it transforms a gas into a liquid fuel, the FT process is a way to use "stranded" natural gas resources, i.e., resources that cannot be used locally or sent to other markets owing to a lack of natural gas distribution infrastructure.

With the exception of World War II Germany and South Africa during economic embargos, commercial use of FT fuels has been extremely limited. Nevertheless, several companies have continued FT R&D, leading to mature technological processes with improved economics. Today, the major players include some of the large oil and energy companies, such as ExxonMobil and Shell, and smaller companies such as Sasol. DOE and other government agencies also sponsor FT research for its potential alternative fuel applications.

Fuel from the FT process has ideal properties for diesel engines, including extremely high cetane ratings (Shell Gas & Power has achieved cetane ratings of 75–80), low aromatics, and negligible sulfur content. Several studies found that using synthetic fuel significantly reduced all regulated diesel emissions, including nitrous oxides and particulate matter, compared with using petroleum diesel.

Fischer-Tropsch fuels produced from natural gas or coal provide no greenhouse gas benefit relative to petroleum diesel (unless, in the case of natural gas, the gas would have been flared) because these feedstocks are non-renewable hydrocarbons. Only FT fuels produced using biomass feedstocks (called biomass-to-liquid, or BTL, fuels) provide a lifecycle GHG benefit. A lifecycle study by Volkswagen and DaimlerChrysler concluded that BTL fuel can reduce GHG emissions by 61–91 percent compared with petroleum diesel. In theory, almost any plant material can be used as a BTL feedstock, but dry forms of biomass such as untreated wood, agricultural waste, and energy plants are preferred.

Another benefit of FT fuels is the potential to adapt them to automotive requirements during the manufacturing process, enabling optimal combustion and virtually emissions-free operation. FT fuels also have a distribution advantage over other advanced fuels because they can be transported as liquid in the existing petroleum infrastructure and are compatible with existing diesel engines. The only adjustment that may be required is the use of lubricity additives to prevent fuel injection system wear. Despite their attractive characteristics, the high capital costs of FT processes and the market risks due to crude oil price fluctuation present barriers to wider commercialization of FT fuels.

MEETING THE R&D CHALLENGE

The diesel engine is the technology of choice for large trucks and buses and continues to gain acceptance in the U.S. light-duty vehicle market. The performance of today's diesel vehicles equals or surpasses the performance of comparable gasoline vehicles, and diesel emissions have improved substantially over the past decade, although challenges remain.

The R&D goals for diesel engine technologies are clear: improve the diesel engine's famed dependability and fuel economy, improve the combustion and aftertreatment systems to meet emissions standards beyond 2010, and make the diesel lifecycle more environmentally sustainable. To achieve these goals, DOE and industry R&D is focusing on diesel engine combustion, emissions aftertreatment, and advanced fuel technologies. Much progress has been made, but this ongoing work will ensure that the diesel engines of tomorrow will thrive in domestic and foreign vehicle markets, help reduce U.S. GHG emissions and petroleum dependence, and contribute to better air quality.

DIESEL ENGINES FOR THE PASSENGER VEHICLE MARKET

Diesel engines have been used in passenger vehicles for much of the past century and capture almost half of today's European market. Although diesel passenger vehicles have not had the same success in the United States, recent advances in diesel engine technology—and recent efforts to reduce petroleum consumption and greenhouse gas emissions—have boosted their appeal, from small cars with exceptional fuel economies to high-performance luxury sedans. To maintain the forward momentum in the face of ever-tightening emissions regulations, diesel engine technology must continue its extraordinary evolution into the 21st century.

THE EUROPEAN DIESEL MARKET

The diesel engine has been used for stationary applications since the 1890s, but it was not until the period between World Wars I and II that gasoline shortages spurred the development of diesel trucks and buses in Europe. After World War II, advances in design tools and materials paved the way for diesel engines in European passenger vehicles.

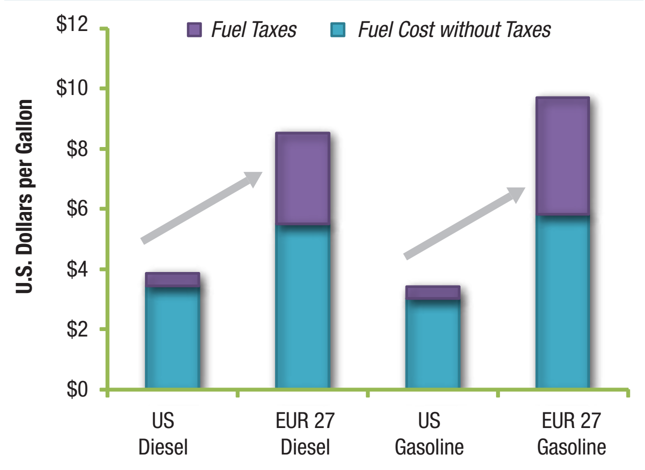

Figure 1. Comparison of fuel prices and taxes in the U.S. and Europe, 2007. Data from the U.S. Department of Energy's Energy Information Administration and the European Union.

In 2008, diesel vehicles accounted for about 52 percent of new passenger vehicles sales in the European Union, up from 32 percent in 2000, according to DieselNet. In some countries—such as Spain, Luxembourg, France, and Belgium—diesel vehicles accounted for more than 70 percent of passenger vehicle sales in 2008.

One reason for the popularity of diesel passenger vehicles in Europe is due to a fuel tax structure which favors diesel fuel (Figure 1). Diesel vehicles have better fuel economy than gasoline vehicles. For example, a 2010 diesel Ford Focus in the United Kingdom gets 51.3 mpg, almost 30 percent higher than its gasoline counterpart (39.8 mpg) with only a slight reduction in performance (Ford UK). In addition, diesel fuel is cheaper than gasoline in Europe, in part because of higher taxes on gasoline in most countries. However, increased diesel fuel prices over the past few years have reduced the fuel price advantage over gasoline.

Diesel vehicles are also more affordable in Europe than in the United States. One reason for this is the use of lower-cost emission-control technologies, made possible because emissions regulations prior to 2010 were less stringent in Europe. Other factors that make diesel vehicles popular in Europe are their high power and torque, excellent durability, and high resale value.

These benefits have led to widespread adoption of diesel passenger vehicles in Europe and a wide range of vehicle offerings, from subcompacts to large luxury sedans. The availability and popularity of diesel luxury vehicles shows the high level of sophistication and performance that the diesel engine has achieved in Europe. For example, diesel models accounted for 80 percent of BMW 5-Series sales and 73 percent of 7-Series sales in 2007, according to BMW. The performance of these large diesel sedans is similar to that of their gasoline counterparts, and their fuel economy is better. Diesels are also available for consumers who demand even higher performance. The most powerful production diesel engine in a European passenger vehicle in 2009 was the 493 hp, 758 lb-ft, twin-turbocharged V12 engine used in the Audi Q7 TDI (Figure 2).

THE U.S. DIESEL MARKET

Historically, cheap U.S. gasoline prices have made diesel vehicles economically unattractive because the cost savings from their increased fuel economy did not pay for the additional vehicle cost. However, automakers rapidly introduced new diesel passenger vehicles to the U.S. market in response to heightened fuel costs resulting from the oil embargos of the 1970s. Unfortunately, these models proved noisy and had poor durability. Coupled with weak emissions standards that allowed excessively dirty exhaust, customer acceptance of these diesel vehicles was low, and most disappeared from the market when gasoline prices dropped.

This bad experience created a stigma that still plagues the few automakers who continue to sell diesel passenger vehicles in the United States, even as technological improvements have virtually eliminated the issues of the past. Today, an increased U.S. focus on fuel economy has prompted automakers to renew their efforts to develop and promote diesel passenger cars.

Figure 2. The European Audi Q7 sport-utility vehicle, and its twelve-cylinder 6-liter diesel engine. Photos courtesy of Audi AG.

Figure 3. Comparison of fuel economy for current market hybrid and diesel sedans. Photos courtesy of Toyota Motor Company and BMW AG.

Figure 4. Comparison of fuel economy for current market hybrid and diesel sport-utility vehicles. Photos courtesy of Toyota Motor Company, BMW AG, and Daimler AG.

Figure 5. Comparison of fuel economy for current market hybrid and diesel small vehicles. Photos courtesy of Toyota Motor Company and Volkswagen Group of America.

The United States is one of the world's largest passenger vehicle markets. In 2008, 13.2 million vehicles were sold, dropping to 10.4 million in 2009. because of the economic downturn. Diesel vehicles accounted for about 3 percent of U.S. passenger vehicle sales in 2009. These diesel vehicles are among the most efficient in their classes (Figures 3-5). For example, in 2009 the diesel Volkswagen Jetta's fuel economy was rated at 30/41/34 (city/highway/combined mpg), behind only the hybrid-electric Toyota Prius (48/45/46) and hybrid-electric Honda Civic (40/45/42).

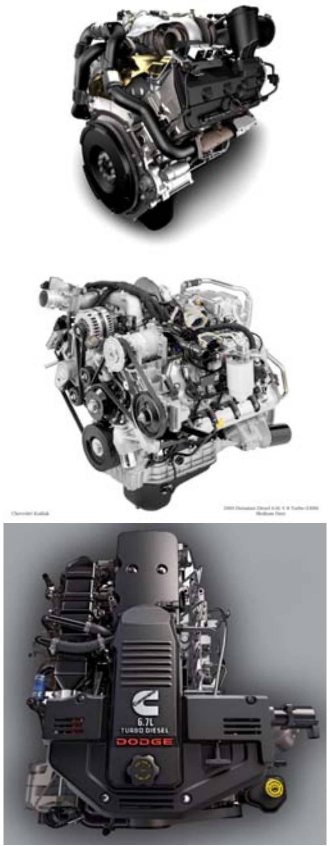

Figure 6. Modern light-duty truck engines used in light-duty pickups. Photos courtesy of (from top) Ford Motor Company, General Motors Corporation, and Chrysler LLC.

Regardless of setbacks in popularity in the passenger car market, the diesel engine has achieved significant success in the passenger truck market (Figure 6). In the early 1980s, GM and Ford introduced diesel engines for their pickup truck lines. The diesel versions quickly became favorites of demanding customers because their powerful engines offered higher towing capacity, good fuel economy, and reliability. By the end of the 1980s, all three major U.S. automakers offered high-power, high-torque diesel engines for their light-duty pickups.

The 2007 version of the Cummins light and medium truck and diesel engine was the first to meet the 2010 emissions regulations, three years ahead of requirements. The engine is used in Chrysler pickup products, and was certified to heavy truck standards using the optional chassis test procedure. In July 2008, Cummins announced plans to begin producing a new generation of light-truck diesel engines based on work completed in conjunction with the U.S. Department of Energy. These engines are expected to be lighter, more powerful, cleaner, and more economical than current engines.

The U.S. diesel passenger vehicle market may expand as consumers become more sensitive to fuel prices and greenhouse gas emissions. Newer and smaller diesel engines may enable manufacturers first to gain market share in the half-ton pickup truck and sport-utility vehicle (SUV) sectors, followed by increased acceptance of diesel engines in passenger cars. With increased customer acceptance and additional model offerings, diesel engines may replicate some of the success they have enjoyed in Europe.

MEETING THE EMISSIONS CHALLENGE

Historically, the high cost of controlling pollutant emissions has been a barrier to more widespread use of diesel vehicles. Emissions of nitrogen oxides (NOx) and particulate matter (PM) have been particularly problematic. Nonetheless, revolutionary technological advances over the past 20 years have enabled greater control of diesel emissions while maintaining high performance—positioning diesel passenger vehicles for reemergence in the U.S. market. However, further technological advances will be needed to meet more stringent emissions regulations in the future.

Vehicular emissions regulations were instituted for the first time in the early 1960s and formalized with the enactment of the Clean Air Act in 1970. Clean Air Act amendments in 1977 and 1990 tightened emissions standards for new light-duty vehicles, prompting intensive research and development by vehicle manufacturers. As a result, current light-duty vehicles are at least 95 percent cleaner than the unregulated vehicles of the 1960s.

In 1994, U.S. Environmental Protection Agency (EPA) Tier 1 standards included less stringent requirements on light-duty trucks than on passenger cars owing to their size and primarily commer-

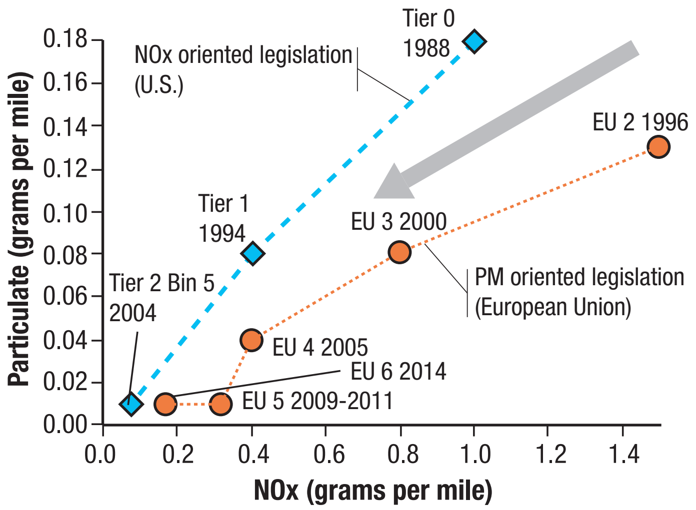

Figure 7. U.S. and European emission standards for light-duty diesel vehicles. The respective levels are reflective of the major policy and environmental drivers in the U.S. and Europe.

cial use. The Tier 2 standards implemented in 2004 for light-duty vehicles were stricter. Because of the increasing use of light-duty trucks and SUVs for personal transportation, EPA applied the same emissions standards to passenger cars, light-duty trucks, and SUVs. For the first time, the Tier 2 standards also required that diesel vehicles meet the same emission standards as gasoline vehicles.

The Tier 2 standards focus heavily on reducing NOx emissions, reflecting EPA's emphasis on controlling smog-forming emissions from a predominantly gasoline-fueled light-duty vehicle population. Europe has also begun to reduce both NOx and PM emissions, although not as rapidly as the U.S. (Figure 7). The U.S. Tier 2 standards are structured as follows:

- Manufacturers may certify particular vehicles to any of the eight permanent and two temporary "bins," or emissions levels, which creates flexibility in managing their fleet wide production of vehicles.
- The entire vehicle fleet sold by the manufacturer in a given year must meet an average NOx level of 0.07 grams per mile. This means that for every vehicle a manufacturer sells that is certified to one of the less stringent bins, at least one vehicle certified to a more stringent bin must be sold to ensure the fleet average remains in compliance.
- Passenger car and light-duty truck standards were phased in between 2004 and 2007. Standards for medium-duty passenger vehicles (personal transportation vehicles with a gross vehicle weight between 8,500 and 10,000 lb) were phased in between 2008 and 2009.

Tier 2 standards for light-duty trucks represent up to an 80 percent reduction in allowable NOx and PM emissions compared with Tier 1 levels. These new standards are a major driver of U.S. diesel engine emissions-control research. PM emissions limits have been met universally with the use of diesel particulate filters (DPFs). Most DPFs require time at high temperatures to burn off trapped PM emissions (i.e., to "regenerate"). Such regeneration reduces fuel-economy slightly if additional fuel must be used to reach sufficient temperatures. Light-duty vehicles usually spend less time at high power levels than do heavy-duty vehicles, and the resulting cooler exhaust temperatures make it more difficult to regenerate DPFs without using additional fuel.

Unlike PM control, NOx control is not performed by a single technology. Vehicle and engine manufacturers use various combustion and aftertreatment strategies to meet the Tier 2 NOx standards. Exhaust gas recirculation (EGR) is a combustion strategy that reduces NOx formation in the engine cylinders and decreases the emissions treated by complementary aftertreatment devices, thus lowering the aftertreatment system cost and the vehicle price. Lean-NOx aftertreatment and selective catalytic reduction (SCR) are two effective control strategies, often used in combination with exhaust gas recirculation. DPFs, EGR, lean-NOx catalysts, SCR and other emissions-reduction strategies are detailed in the Diesel Engine and Fuel Technologies document in this series.

	1976 VW Golf I	2003 VW Golf V
Number of Cylinders	4	4
Engine Displacement	1.5 liters	2.0 liters
Engine Power	50 hp	140 hp
Maximum Torque	62 lb-ft	236 lb-ft
Maximum Vehicle Speed	87 mph	126 mph
0-62 mph Acceleration	18 sec	9.3 sec
Fuel Economy	36 mpg	43 mpg
Vehicle Weight	1,716 lb	3,080 lb

Figure 8. Comparison of first generation Volkswagen Golf from 1976 with a modern Golf diesel offering. Information and photos courtesy of Volkswagen Group of America.

THE DIESEL ENGINE—TODAY AND TOMORROW

Light-duty diesel engines have come a long way over the past few decades and today perform as well or better than comparable gasoline engines—but with better fuel economy. The Volkswagen comparison in Figure 8 shows how much modern diesels have surpassed their predecessors as well. The modern engine has nearly three times the power and four times the torque of the older engine, and the modern vehicle accelerates twice as fast as its predecessor while getting better fuel economy.

Modern diesel passenger vehicles (like those in Figure 9) also will meet U.S. Tier 2 emissions standards, although challenges remain. These challenges include developing diesel emissions-control devices with long lives (at least 10–15 years and 150,000 miles) and minimizing the fuel-economy reduction and cost associated with some diesel emissions-control devices. With the combined efforts of industry and government, these challenges will be overcome, and tomorrow's diesel engines will power passenger vehicles with superior fuel economy and low emissions well into the 21st century.

Figure 9. The modern diesel comes in many shapes, for many applications. Photos courtesy of (clockwise from top right) BMW AG, Ford Motor Company (orange Focus, 2.2 liter diesel engine, and F-Series pickup), and General Motors Corporation.

DIESEL ENGINES FOR THE COMMERCIAL VEHICLE MARKET

Commercial vehicles don't get by on their looks. They are built to work hard. To maintain competitiveness, businesses demand commercial vehicles with superior performance and economics—from medium-duty pickup trucks to mammoth non-road construction vehicles to farm tractors of every size. So it's not surprising that performance and economic advantages drove widespread adoption of the diesel engine in commercial vehicles over the past century. In the last 15 years, strict new emissions standards have driven the technological developments needed to keep diesel commercial vehicles going strong into the future. Today, the world dependence on diesel fuel and pending rules for greenhouse gas emissions demand further advances in combustion engines.

DRIVING THE ECONOMY

Diesel engines power many of the vehicles that keep the U.S. economy moving. Simple and durable but oversized, early diesel engines were initially limited to large commercial equipment. By the 1950s, advancements to the diesel engine enabled their use in most of the non-road vehicles that were building the massive U.S. highway system as well as the trucks and buses using these new roads. Because of their efficiency and reliability, diesel engines also supplanted steam power in trains by the mid-1960s and enjoyed similar success in farm vehicles. Today, a diverse array of diesel commercial vehicles serves the U.S. economy.

Heavy-duty trucks and buses are among the most important applications. The growth of the U.S. economy depends largely on the ability to move freight efficiently. Over the past 40 years, per-capita freight increased 50 percent, and freight-transport distance increased more than 20 percent, while average freight cost per ton-mile decreased more than 10 percent (U.S. Departments of Transportation and Commerce statistics). As more Internet purchases are delivered directly to homes and more businesses adopt just-in-time inventory systems, efficient freight transport is becoming even more essential. Trucks transport almost two-thirds of U.S. freight tonnage (Figure 1), and diesel engines power more than 90 percent of trucks over 10,000 pounds. The extreme reliability of diesel engines enables diesel trucks to operate continuously for long periods—an economic necessity for many applications. It is common for many diesel over-the-road trucks to travel 50,000 miles or more annually and last for half a million miles or more.

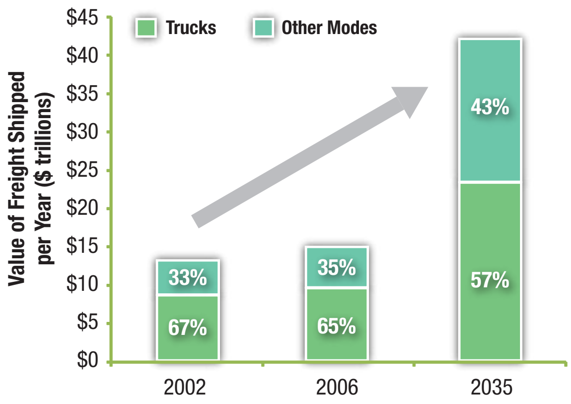

Figure 1. Freight tonnage by trucking relative to other modes. Information from the U.S. Department of Transportation, Freight Facts and Figures 2007.

In addition to hauling freight, diesel trucks serve a wide variety of applications such as collecting refuse, transporting construction materials, and plowing snow (Figure 2). Diesel transit buses provide 5.6 billion passenger trips per year (according to the American Public Transportation Association), and more than half the nation's children ride school buses, most of them diesel (according to the American School Bus Council).

Since the late 1980s, diesel engines have become increasingly popular in medium-duty vehicles (i.e., Class 3–6 vehicles, about 10,000–26,000 pounds gross vehicle weight rating). Diesel powers about half of today's Class 3–5 vehicles (10,000 to 19,500 pounds) and about 90 percent of Class 6 vehicles (19,501 to 26,000 pounds). Recently, higher diesel fuel prices (compared with gasoline) are reducing the economic advantage of medium-duty diesel vehicles, which have a higher initial purchase price than their gasoline counterparts. Minimizing the cost of the emissions-control systems needed to meet strict emissions standards—and thus keeping vehicle prices down—is critical to maintaining diesel market share in these vehicle classes (vehicle class definitions are shown in Figure 3).

Diesel engines are popular in U.S. non-road applications, powering nearly two thirds of farm vehicles and almost all large construction equipment. Diesel is also used widely in freight trains and some of the largest vehicles on the planet, such as the Caterpillar 797 mining dump truck with a 1,375,000 pound operating weight. As with on-road vehicles, emissions standards for non-road vehicles are tightening, and the combined cost of emissions controls and low-sulfur fuels likely will result in higher purchase prices and operating costs.

The U.S. military is another large market for the diesel engine. Sensitive to cost and durability, the military uses

Figure 2. Trucks come in many shapes and vocations. Photos courtesy of (left to right) Ford Motor Company, PACCAR Inc., Navistar Inc, Volvo Trucks North America, Inc., and Mack Trucks Inc.

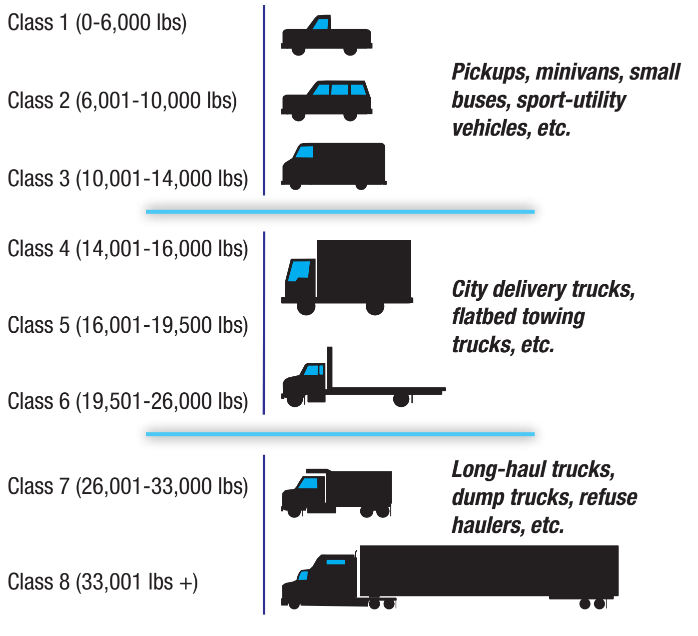

Figure 3. Truck weight classes and typical applications.

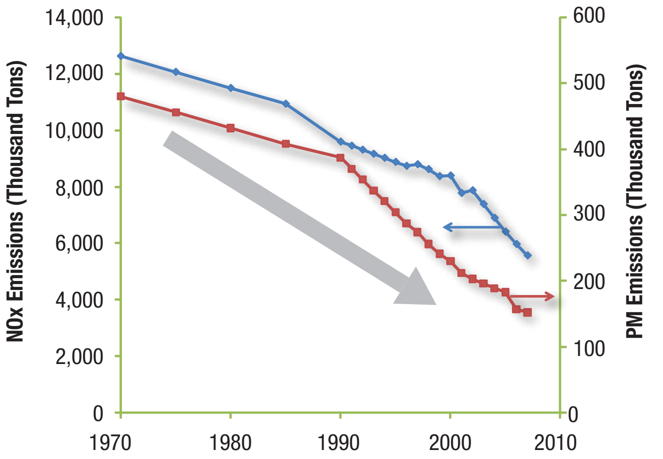

Figure 4. Trends in particulate matter and oxides of nitrogen emissions from highway vehicles (both light and heavy-duty). Information from the U.S. Environmental Protection Agency.

diesel vehicles to lower fuel use associated with combat and logistical missions. Commercially available, civilian-sector diesel engines and equipment are frequently capable of meeting the extreme requirements of military-specification vehicles. As in the civilian sector, the military is sharpening its focus on reducing vehicular emissions as well as costs.

HEAVY-DUTY DIESEL ENGINE EMISSIONS STANDARDS

Reducing emissions while maintaining performance and affordability is key to the continued success of diesel commercial vehicles in all sectors of the economy. Since 1970, government regulations and technological advances have reduced U.S. vehicular emissions of nitrogen oxides (NOx) by more than 55 percent and particulate matter (PM) by almost 70 percent, according to EPA data (Figure 4). Beginning in the early 1990s, the U.S. Environmental Protection Agency (EPA) began implementing increasingly strict emissions regulations for diesel engines, spurring further development of diesel emissions-control technologies (Figure 5).

Emissions Standards Before 2007

For model year 2004, emissions standards primarily aimed at reducing NOx emissions were applied to heavy-duty diesel engines. The standards gave manufacturers two options for certifying their engines: certify to a level of 2.4 grams per brake-horsepower-hour (g/bhp-hr) NOx plus non-methane hydrocarbons (NMHC), or certify to a level of 2.5 g/bhp-hr NOx plus NMHC and 0.5 g/bhp-hr NMHC. For the largest engines, these standards also included an increase in the useful life of the engine—the number of miles over which the emissions standards were enforced—to 435,000 miles.

By 2004, many major engine manufacturers had extensive experience meeting these standards, having agreed to meet them in October 2002, 15 months ahead of schedule[1]. They employed in-cylinder and air-management technologies such as advanced electronic fuel injection with rate shaping, cooled exhaust gas recirculation (EGR), and variable geometry turbocharging (VGT) to meet the standards. Further information on these technologies can be found in the second document of this series, Diesel Engine and Fuel Technologies.

Figure 5. Modern diesels provide power and efficiency while meeting stringent emission standards. Photos courtesy of (from top) PACCAR Inc., Volvo Trucks North America, Inc., and Navistar Inc.

Emissions Standards 2007–2010

Further emissions reductions occurred when the EPA promulgated stricter standards for model-year 2007 through 2010 heavy-duty diesel engines (Figure 6). The standards (shown in Figure 7), which included further restrictions on PM, NMHC, and NOx emissions, were phased in as an increasing percentage of engine manufacturers' sales between model years 2007 and 2010. Between 2007 and 2009, 50 percent of a manufacturer's engines had to meet the 0.2 g/bhp-hr NOx standard, and 50 percent could continue to meet the 2.5 g/bhp-hr NOx plus NMHC standard. Most engine manufacturers used these phase-

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[1] This accelerated schedule was part of the consent decree agreement reached by the EPA, the Department of Justice, the California Air Resources Board, and several engine manufacturers over engines from previous model years that were alleged to have employed "emissions defeat devices," i.e., devices that allowed engines to produce more emissions during actual operation than should have been expected based on emissions certification testing.

in provisions with averaging to certify engines to a NOx value about halfway between the two standards, or about 1.2 g/bhp-hr NOx.

The standards also include a 13-mode Supplemental Emissions Test (SET) with emissions limits equal to the EPA Federal Test Procedure (FTP) standards and Not-To-Exceed (NTE) limits of 1.25 or 1.5 times the FTP standards, depending on engine family. Crankcase emissions controls for turbocharged diesel engines are also regulated, with the expectation that no emissions from the crankcase will be released into the environment. The SET was also applicable to engines under the consent decree that were subject to the 2004 EPA emission standards.

These challenging standards required the development of various emissions-control technologies, including advanced combustion controls, diesel particulate filters (DPFs), cooled EGR, and NOx reduction technologies such as selective catalytic reduction (SCR). Using DPFs was the primary way manufacturers met the 2007 PM standard. For the 2010 standards, SCR has garnered the most interest for NOx reduction in commercial applications because of its prior use in Europe and its generally established reliability and performance. For details about these technologies, see the Diesel Engine and Fuel Technologies document in this series.

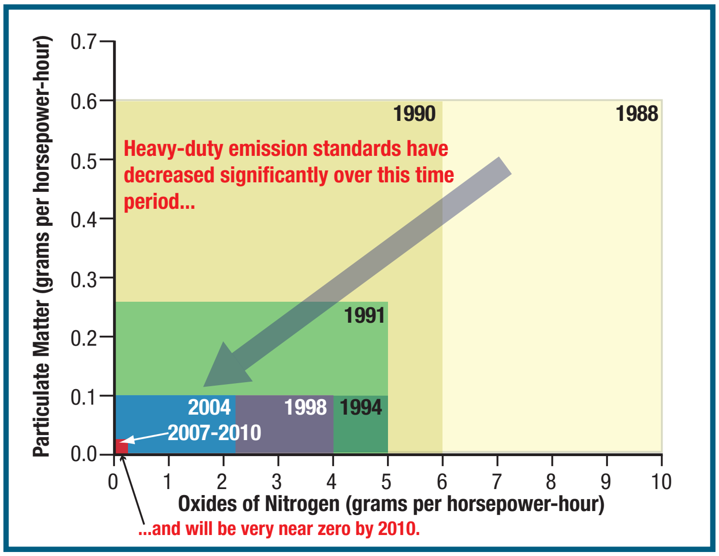

Figure 6. U.S. heavy-duty onroad vehicle emission standards (NOx and PM) through 2010.

Year	NOx (g/bhp-hr)	NMHC (g/bhp-hr)	NOx+NMHC (g/bhp-hr)	PM (g/bhp-hr)
2007[1]	0.20	0.14	2.5	0.01
2010[2]	0.20	0.14	---	0.01

1 - Between 2007 and 2009, 50% of a manufacturer's engines were to meet the 0.20 g/hp-h NOx standard and 50% were to meet the 2.5 g/hp-h NOx+NMHC standard.
2 - For 2010 and beyond all engines must meet the 0.20 g/hp-h NOx standard.

Figure 7. Heavy-duty emission standards for the U.S., 2007-2010.

The development of onboard diagnostics (OBD) for commercial vehicles is a critical component of the 2010 standards and future standards. The heavy-duty OBD requirements recently promulgated by EPA are similar to the OBD requirements in place for light-duty vehicles since 1996. All major emissions-control systems must be monitored and malfunctions detected before emissions exceed a set of thresholds. The aftertreatment devices (e.g., DPFs and NOx-reducing devices) must be monitored, and the driver must be notified of device failure. All emissions-related electronic sensors and actuators also must be monitored for proper operation. Initially, one engine family per manufacturer will be certified to the OBD requirements in the 2010–2012 model years. Beginning in 2013, all on-road engines for all manufacturers must be certified to the OBD requirements.

To enable engines to meet the new standards with advanced emission control devices, EPA, with assistance from DOE's research and development programs, promulgated a requirement to reduce the sulfur content in on-road diesel fuel to 15 parts per million (ppm). Fuel producers were required to supply this ultra–low sulfur diesel (ULSD) beginning in June 2006 to ensure the fuel was available for model year 2007 vehicles. The use of ULSD is essential because the aftertreatment devices needed to meet the emissions standards are extremely sensitive to deactivation by sulfur contamination. Low-sulfur fuels also reduce the portion of PM emissions made up of sulfate aerosols.

International Emissions Standards

The European Union has also implemented more stringent emissions standards for commercial vehicles, as shown in Figure 8. Euro IV standards went into effect for the 2005 model year and have a NOx limit of 3.5 grams per kilowatt-hour (g/kW-hr), equivalent to 2.6 g/bhp-hr. The Euro V standards, with implementation beginning in 2009, have a NOx limit of 2.0 g/kW-hr (1.5 g/bhp-hr). PM limits for Euro IV and Euro V are 0.2 g/kW-hr (about 0.15 g/bhp-hr). The Euro IV standards were expected to force the use of DPFs but they can typically be met with a combination of engine and catalyst technologies. More stringent Euro VI standards, to be implemented starting in 2014, are close to finalization. The Euro VI standards are comparable in stringency to the U.S. 2010 heavy-duty engine regulations.

Japan's commercial vehicle emissions standards (for vehicles over 3,500 kg or 7,700 pounds) have become increasingly strict as well (Figure 9). The 2005 emission regulations also included a new test cycle simulating Tokyo city traffic (JE05). For 2009, Japanese emissions standards reduced PM and NOx emissions by 43 and 65 percent respectively but NOx control remains significantly less stringent than U.S. standards.

Non-Road Emissions Standards

In its analysis of the 2004 non-road diesel emissons rulemaking, the EPA estimated that there are about six million non-road diesel vehicles and pieces of equipment in the United States, with about 650,000 more sold annually. Non-road, heavy-duty diesel vehicles and equipment, such as farm and construction vehicles, represent an increasing share of U.S. NOx and PM emissions. The EPA estimates that these sources produce almost half of mobile-source PM emissions and about a quarter of mobile-source NOx emissions. Moreover, emissions from these vehicles have not been declining as on-road vehicle emissions have.

The first U.S. standards for mobile non-road diesel engines were phased in between 1996 and 2000 with implementation of the Tier 1 (EPA designation for the era of regulations between 1996 and 2000) non-road standard (by comparison, the first on-road diesel engine standards went into effect in 1973). Since 1996, the difference between on-road and non-road emissions standards has shrunk rapidly. More stringent Tier 2 (2000-2006) and Tier 3 (2006-2008) non-road standards were phased in between 2000 and 2008.

The latest, Tier 4 (2008 and newer) EPA non-road diesel emissions standards were introduced in the Clean Air Nonroad Diesel Rule in 2004 (Figure 10). The Tier 4 standards will reduce emissions from construction, farm, and industrial equipment by more than 90 percent compared with Tier 3 standards. The standards will be phased in for new engines, starting with the smallest engines in 2008, until all but the very largest diesel engines meet NOx and PM standards in 2014. Some of the largest engines (750 hp or more) will have one additional year to meet the standards.

Tier 1–3 (1996-2008) emissions levels could be met via engine control alone, so advanced aftertreatment devices were not required. Meeting Tier 4 levels likely will require use of advanced aftertreatment devices similar to those on-road engines used to meet the 2007–2010 standards, including cooled EGR, improved combustion designs, improved fuel systems, electronic control of engine parameters, and DPFs. Advanced NOx control technologies such as SCR and lean-NOx adsorbers also may be required.

Tier	Year	NOx (g/kWh)	PM (g/kWh)
Euro IV	2005	3.5	0.02
Euro V	2009	2.0	0.02
Euro VI	2014	0.4	0.01

Figure 8. Heavy-duty emission regulations for the European Union, 2005-2014.

Year	NOx (g/kWh)	NMHC (g/kWh)	PM (g/kWh)
2005	2.0	0.17	0.027
2009	0.7	0.17	0.01

Figure 9. Heavy-duty emission regulations for the Japanese market, 2005-2009.

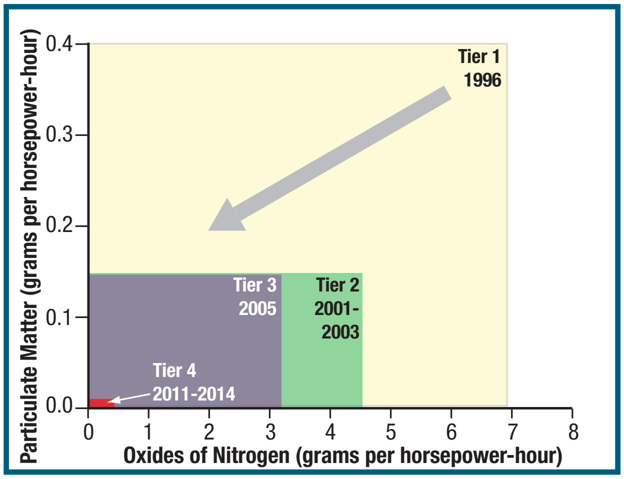

Figure 10. U.S. emission standards for non-road vehicles of 175 to 750 horsepower, typically found in farm tractors and other heavy equipment. (Standards for non-road vehicles vary by horsepower rating.)

Because additional taxes are paid for on-road diesel fuel, separate infrastructures exist for controlling on-road and non-road diesel fuel. Sulfur reductions in non-road diesel fuel occurred slightly behind reductions in the on-road fuel. During the period Tier 1–3 non-road standards were in place, non-road diesel fuel was limited to 5,000 ppm sulfur. To enable use of advanced aftertreatment devices, EPA reduced allowable non-road diesel fuel sulfur levels to 500 ppm in 2007 and then to 15 ppm in 2010.

TOMORROW'S DIESEL COMMERCIAL VEHICLES

The modern commercial vehicle diesel engine is efficient and durable, with advanced electronic controls and aftertreatment technologies that provide the reliable and clean operation that today's vehicles require. The stringent heavy-duty engine emissions standards that took full effect in 2010 are driving further development of advanced technologies such as diesel oxidation catalysts, SCR, lean-NOx catalysts, and NOx adsorbers. Future engines likely will also include optimized fuel-injection systems and combustion chamber designs to maximize combustion efficiency and limit the power and efficiency losses caused by aftertreatment systems. One remaining challenge is to implement these emissions-control strategies while improving vehicle efficiency and affordability. With the combined efforts of industry and government, this challenge can be overcome, and tomorrow's diesel engines will help clean, efficient, and affordable commercial vehicles drive the U.S. economy well into the 21st century.

The efficient, durable diesel engine has powered light- and heavy-duty vehicles for decades. Today, the high fuel economy of diesel vehicles is especially important for cutting U.S. petroleum use and greenhouse gas emissions. However, diesel technology is being challenged to meet strict new emissions standards while maintaining its high performance and affordability. Research and development (R&D) sponsored by the U.S. Department of Energy (DOE) is helping to meet this challenge. In collaboration with DOE's national laboratories and engine and vehicle manufacturers, the Vehicle Technologies Program within DOE's Office of Energy Efficiency and Renewable Energy is tackling the complementary R&D areas of advanced combustion, waste heat recovery, emissions aftertreatment, and fuel formulations.

ADVANCED COMBUSTION

Advanced diesel combustion promises higher engine efficiency, dramatically lower emissions, and lower engine costs than comparable alternatives. DOE is supporting research on low-temperature advanced combustion modes such as homogeneous charge compression-ignition (HCCI). These advanced modes can be used alone or in a "mixed mode," e.g., low-temperature combustion modes are used at light to moderate engine loads (power), and conventional combustion modes are used for starting and at higher loads.

In HCCI, well-mixed fuel and air (as in a gasoline engine) ignite spontaneously without a spark (as in a conventional diesel engine), potentially providing diesel-like efficiency and emissions cleaner than those from conventional diesel and gasoline engines. HCCI engines have demonstrated extremely low nitrogen oxides (NOx) emissions without use of aftertreatment. The challenge is to adequately control the HCCI ignition process, which depends on complex chemical reactions.

Developing an entirely new combustion process is daunting for any one organization, so DOE is leading partnerships of universities, fuel suppliers, engine and vehicle manufacturers, and international industry groups in this effort. The R&D activities of these groups range from simulating the complex thermodynamics and chemical kinetics of low-temperature combustion to developing and operating test engines in low-temperature combustion modes (Figures 1 and 2).

WASTE HEAT RECOVERY

An engine can lose up to 70 percent of its fuel energy as waste heat through its coolant and exhaust. DOE is studying ways to recover some of this waste heat and harness it for useful work.

Thermoelectric devices are solid-state materials that use temperature differences across different surfaces to generate electricity. Most famously used by the U.S. space program, thermoelectric devices can be placed in a vehicle's exhaust stream or coolant system to create the required temperature difference. The devices increase engine efficiency by using electricity to power accessories, such as power steering and water pumps, instead of using mechanical energy (and thus fuel) from the engine. Thermoelectrics also can boost the efficiency of hybrid-electric vehicles by converting waste energy into electricity that can be stored in the vehicle battery. DOE's thermoelectric R&D ranges from basic materials research to full-scale demonstration on commercial trucks.

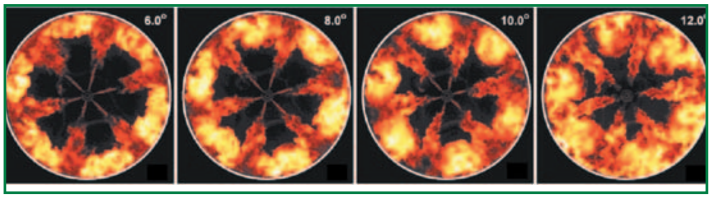

Figure 1. Series of in-cylinder diesel fuel spray combustion photographs at Sandia National Laboratories. Photos courtesy of Sandia National Laboratories.

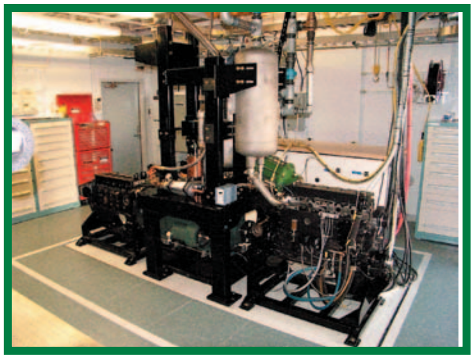

Figure 2. HCCI laboratory engine setup at Sandia National Laboratories. Photo courtesy of Sandia National Laboratories.

Combined cycles are another way to recover energy from waste heat. In a combined cycle, a power-producing engine maximizes efficiency by using more than one thermodynamic cycle. Combined cycles are common in large applications such as power generation. To date, an analogous approach for recovering waste heat for vehicle exhaust has been too expensive or too inefficient. DOE is investigating lower-cost and higher-efficiency combined-cycle strategies, such as an organic-Rankine cycle, that can use the typical temperatures found in vehicle exhaust. DOE is also sponsoring substantial research at various engine companies which make use of thermodynamic bottoming cycles for recovering thermal exhaust and/or EGR energy.

EMISSIONS AFTERTREATMENT

Although diesel engine manufacturers minimize emissions exiting their engines after combustion, a post-combustion emissions control system—known as an aftertreatment system—is needed to meet modern emissions standards. The diesel oxidation catalyst, which significantly reduces hydrocarbon and carbon monoxide emissions, has been used widely since the early 1990s and enabled diesel engines to meet emission standards before 2007. However, meeting the U.S. Environmental Protection Agency's (EPA) 2007 and 2010 standards requires use of advanced aftertreatment systems such as diesel particulate filters (DPFs), selective catalytic reduction, lean-NOx catalysts, and NOx adsorbers.

DOE's aftertreatment R&D (like the work in Figures 3 and 4) focuses on improving the durability and effectiveness of aftertreatment systems while lowering their cost. Projects include improving sensors and other measurement devices, developing new catalyst materials, identifying reasons that catalysts lose there effectiveness over time (aging), and developing models to use in systems analysis and controls development. DOE collaborated with industry and university partners to initiate the Cross-Cut Lean Exhaust Emissions Reduction Simulation (CLEERS) project, which improves the simulation tools used to develop lean-burn diesel engine technologies. Because engine combustion and aftertreatment are interrelated, much of DOE's aftertreatment R&D is integrated with its advanced combustion and fuel formulations R&D.

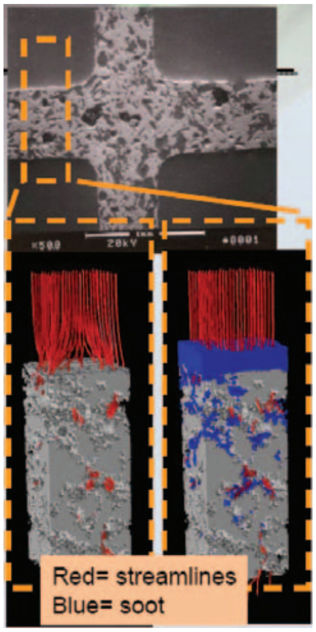

Figure 3. Microscale model developed at PNNL calculates flow field and particle deposition. Image courtesy of Pacific Northwest National Laboratory.

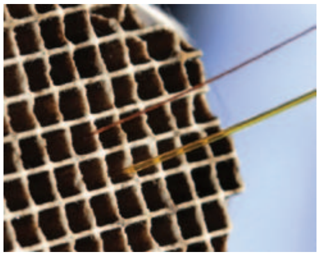

Figure 4. New understanding of catalyst reactions were achievable with DOE-supported innovations in research methods. Capillaries and optical fibers are able track chemistry and temperature in operating catalytic converters. Photo courtesy of Oak Ridge National Laboratory.

FUEL FORMULATIONS

Diesel fuel formulations—which included mainly paraffinic and aromatic hydrocarbons plus additives for cold-weather performance—remained relatively unchanged for many years except for two stages of sulfur reduction. The last reduction to a maximum of 15 ppm sulfur was implemented in 2006 in time for 2007 emissions regulations that required DPFs and NOx aftertreatment in some cases. Future fuel formulations may help diesel engines further reduce emissions, improve performance, and enable advanced combustion regimes.

DOE participates in many fuel R&D programs. Biodiesel—made primarily from soybeans or waste fats and oils—is already widely available in the United States. DOE is working with industry and other government agencies to develop biodiesel specifications and testing methods that fuel blenders can use and engine manufacturers can accommodate, ensuring consistent fuel performance and compatibility with vehicles of the past, present, and future. DOE is also working with biodiesel producers to increase the efficiency of their production processes, thereby further decreasing lifecycle greenhouse gas emissions. DOE-sponsored R&D also highlighted the negative impacts of sulfur on the durability and efficiency of diesel aftertreatment systems such as DPFs, DOCs and lean NOx traps.

Synthetic diesel fuels, such as those derived from pyrolysis oils or Fischer-Tropsch processes, are not readily available in the United States today, primarily due to high cost. There is a history of Fischer-Tropsch fuels in specific applications in the U.S., such as to aid sulfur reduction requirements in California. However, because synthetic fuels can be made to almost any specification and from various feedstocks (e.g., biomass and coal), they could become a widespread replacement for petroleum-based diesel fuel.

Figure 5. Ignition quality tester apparatus used to determine ignition delay for various fuels. Photo courtesy of the National Renewable Energy Laboratory.

DOE is supporting synthetic diesel fuel R&D to provide the U.S. consumer with fuel alternatives.

In addition, DOE supports R&D that advances the understanding of conventional diesel fuel (Figure 5). Although the diesel engine has existed for more than a century, there is still uncertainty surrounding fundamental aspects of the diesel combustion process. Government support is critical for many diesel fuel R&D efforts, such as large chemical kinetics studies of different fuels, because the scale of these efforts is prohibitive for even the largest private organizations.

CREATING A "SUPERTRUCK"

Various aspects of DOE's heavy-duty diesel R&D converge within DOE's "SuperTruck" project, which aims to demonstrate by 2015 a Class 8 long-haul truck that is 50 percent efficient and meets EPA 2010 emissions standards. In January 2010, DOE awarded more than $115 million to Cummins, Navistar, and Daimler for cost-shared efforts to develop and demonstrate SuperTrucks with advanced combustion techniques, improved aerodynamics, idle-reduction technologies, powertrain hybridization, and waste heat recovery systems. Awardees are required to demonstrate a 20 percent improvement in engine efficiency by 2015, which is equivalent to raising the peak engine thermal efficiency from 42 to 50 percent. The SuperTruck projects also will demonstrate a viable technology pathway to increasing peak engine thermal efficiency to 55 percent by 2017.

DOE DIESEL R&D HIGHLIGHTS

Diesel technology developed through DOE support affects almost every American every day. The following are just a few of DOE's recent diesel R&D highlights.

Advanced Combustion

DOE has created new fundamental insights into combustion through the use of optical engines coupled with multi-dimensional engine models. This knowledge discovery in combination with component and controls expertise is then used to further develop advanced combustion concepts for multi-cylinder realizations. DOE-supported research at laboratories and industry has given new understanding of the functions and degradation mechanisms of emission control catalysts. Development of new research tools such as the "SpaciMS" capillary probe allowed researchers to monitor chemical reactions inside operating Lean NOx traps and SCR devices and improve regeneration strategies and formulations. DOE labs were cited for contributions to the implementation of Cummins' lean-NOx trap system and the DPF developed by Dow for the Audi diesel-powered race car. DOE has expanded the fundamental understanding of combustion processes and sponsored the R&D responsible for the first public demonstration of an HCCI-powered vehicle.

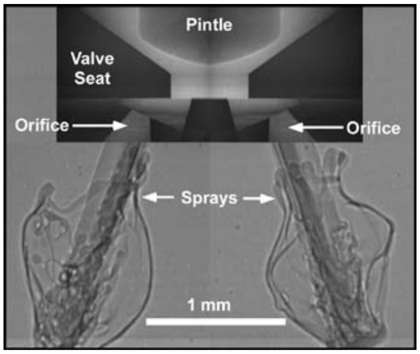

Figure 6. Ultrafast x-ray microimaging of fuel sprays from a direct-injection nozzle while the injector pintle motion was monitored in real time. Synchrotron X-rays from the Advanced Photon Source can penetrate the steel injector body and optically opaque sprays to better understand the fuel spray process for improving fuel efficiency and reducing emission of engine combustion. Photo courtesy of Argonne National Laboratory.

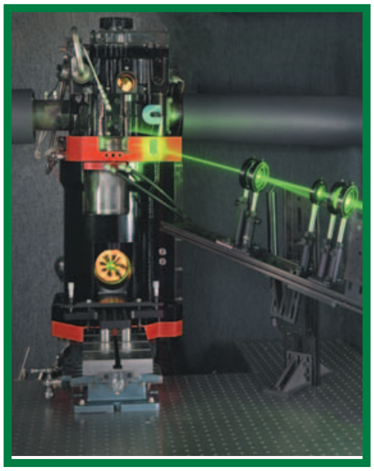

Figure 7. Optically-accessible single-cylinder research engine at Sandia National Laboratories. Photo courtesy of Sandia National Laboratories.

By supporting R&D at national laboratories and universities, DOE has guided the development of computer models that help researchers understand the impact of engine design changes on efficiency and emissions. In addition, national laboratories, universities, and industry developed the KIVA family of modeling software with DOE support. For example, national laboratories, universities, and industry developed the KIVA family of modeling software with DOE support. KIVA helps engine designers predict complex fuel and air flows, ignition, combustion, and pollutant-formation processes in engines. For commercial diesel engines, manufacturers have credited DOE with assisting their ~90% emissions reduction while maintaining efficiency.

A number of advanced materials developed with DOE support are now being used in truck diesels in the valvetrain and exhaust system. For example, the ORNL-developed CF8C-Plus stainless steel is now found in all of the new Caterpillar on-highway engines exhaust components.

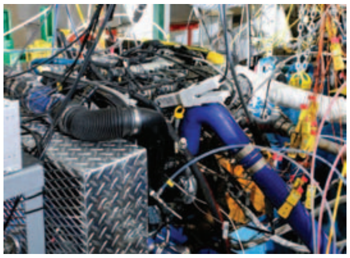

Figure 8. Diesel engine test setup at Oak Ridge National Laboratory for interfacing emission control devices to advanced combustion modes. Photo courtesy of Oak Ridge National Laboratory.

Emissions Aftertreatment

Progress in cost reduction is being made in the reduction of precious metals. Significant new insight is being gained into particulate matter morphology and composition which is crucial for developing effective DPF regeneration strategies and understanding the effect of bio-renewable fuels on this process.

Waste Heat Recovery

Thermoelectric devices have been used in the space program, but they were never demonstrated on a vehicle until DOE began working with industry partners. In 1995, a thermoelectric generator was demonstrated on a Class 8 commercial truck for the equivalent of 550,000 miles. Several vehicle manufacturers are developing commercial applications of this technology for introduction in the 2015 time frame with DOE support.

Fuel Formulations

Fuels research sponsored by DOE has led to greater confidence in biodiesel fuel quality. As recently as 2005, much of the biodiesel in the United States did not meet fuel-quality specifications and caused serious filter-clogging issues. In collaboration with partners including the National Biodiesel Board and ASTM International (an international standards organization), DOE's fuel-quality work spurred major improvements in biodiesel fuel specification compliance, making manufacturers more willing to endorse biodiesel use in their engines. Argonne National Laboratory's Advanced Photon Source was the first to show the details of the fluid dynamics inside a diesel fuel injector. The details, such as the formation of shock waves inside the injectore, will lead to better injector designs (Figure 5).

R&D Collaboration

DOE encourages R&D on technological improvements that can enter the marketplace in the near future. As part of this effort, DOE hosts the Directions in Engine-Efficiency and Emissions Research (DEER) conference, at which much of the nation's ground-breaking diesel R&D is shared with peers and presented to the public.

LEARN MORE

For more information about DOE's transportation R&D, visit the Vehicle Technologies Program Web site at www.eere.energy.gov/vehiclesandfuels.

PNNL researchers are applying their expertise and capabilities in surface chemistry, catalyst mechanisms, computational modeling, material synthesis, and aerosols to address challenges in diesel engine emissions. Work is focused in the areas of thermoelectrics, diesel engine performance simulation, sulfur traps, NOx sensors, and understanding of NOx adsorber sulfur poisoning.
http://www.pnl.gov

National Renewable Energy Laboratory advanced vehicle research focuses on hybrids and energy storage systems, performs non-petroleum and advanced petroleum fuels research, and maintains an Alternative Fuels Data Center to provide information on alternative fuels and the vehicles that use them. NREL also maintains the ReFUEL Laboratory with specialized testing and measurement equipment for heavy vehicle chassis and engine testing, with sensitive emissions measurement capability.
http://www.nrel.gov

Argonne has developed a diagnostic technique that uses X-rays to study fuel sprays. This technique provides highly quantitative characterization of fuel sprays that can be used to validate and improve computational spray models. Researchers are also exploring the use of X-rays as a tool to solve other problems in engine and emissions research.
http://www.anl.gov

INL conducts the Advanced Vehicle Testing Activity (AVTA) jointly with NREL to benchmark and validate the performance of vehicles featuring advanced technologies. The AVTA provides potential vehicle users with accurate and unbiased information on real-world vehicle performance by testing vehicles with industry partners and distributing the results.
http://www.inl.gov

LLNL researchers have developed chemical models for the combustion of a variety of common hydrocarbon fuels. These chemical kinetics models, known as HCT, combined with LANL's fluid mechanics code KIVA, have allowed for critical contributions to HCCI technology.
http://www.llnl.gov

SNL's Combustion Research Facility (CRF) researchers use advanced laser-based diagnostics in conjunction with experimental hardware to simulate realistic engine conditions. Hardware includes several optically-accessible engines and an optically-accessible combustion vessel. CRF researchers are also developing sensitive laser-based diagnostics for measuring real-time particulate matter in exhaust engine streams.
http://www.sandia.gov

LANL researchers developed a modeling code (KIVA) designed for performing internal combustion engine calculations. KIVA is a three-dimensional fluid mechanics code that simulates liquid and gaseous flow under steady state and transient conditions. KIVA has found widespread application in the automotive industry and universities for engine modeling.
http://www.lanl.gov

ORNL's Fuels, Engines and Emissions Research Center (FEERC) specializes in detailed characterization of internal combustion engine emissions and efficiency. The main research focus is the development of advanced engine, fuels, and emission control technologies. This includes the integration and management of advanced technologies for improved system efficiency with lowest possible emissions. ORNL also conducts a wide variety of research in other areas such as propulsion materials.
http://feerc.ornl.gov, http://www.ornl.gov

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