American Energy Innovation Council

CASE STUDIES ON THE GOVERNMENT'S ROLE IN ENERGY TECHNOLOGY INNOVATION

Advanced Diesel Internal Combustion Engines

By Jeffrey Rissman and Hallie Kennan

EXECUTIVE SUMMARY

Modern diesel engines are hugely important to the U.S. economy, especially in the transportation industry, where they are widely used in trucks and other heavy-duty vehicles. Truck transportation, which is dominated by diesel engines, directly employed over 1.3 million people and contributed $275 billion to national GDP in 2011. The widespread adoption of cleaner, more efficient diesel engines, and the associated energy security benefits, was accelerated by tremendous technological advances made through research at national labs and by government-led coalitions.

The diesel engine was invented in the 1890s, but it only began to play a major role in the U.S. economy during and after construction of the Interstate Highway System in the 1950s. Following the 1973 oil embargo, the government placed a new emphasis on technological development to improve fuel efficiency and reduce dependence on foreign oil. Over the following decades, there were three main mechanisms by which the government supported the improvement of diesel engines: performing basic combustion research, creating engine simulation tools, and establishing research partnerships with private industry.

EXECUTIVE SUMMARY (Continued)

Basic Combustion Research: In the 1970s and 1980s, the extent to which engine manufacturers could refine their products was limited by a lack of fundamental knowledge about the combustion process. Basic research is risky and long-term, so it is difficult for private companies to justify to their shareholders. To address this need, the government founded the Combustion Research Facility (CRF), which began operations in 1981, and the Advanced Combustion Engine R&D program (ACE R&D), which started in 1986. These programs brought together researchers from national labs, universities, and the private sector to achieve advances in fundamental understanding of combustion.

Simulation Tools: The CRF and ACE R&D programs also developed computer software capable of simulating the combustion process, such as KIVA codes and the Cross-Cut Lean Exhaust Emissions Reduction Simulation (CLEERS). These tools were used by engine manufacturers such as Caterpillar, Cummins, General Motors, Ford, and Chrysler to develop cleaner and more efficient engines.

Research Partnerships: In addition to the efforts above, the DOE played a critical role in bringing together private companies, government labs and agencies, and academia through partnerships that continued to refine engines through the 1990s and 2000s. These include the Partnership for a New Generation of Vehicles (PNGV) in 1993, the 21st Century Truck Partnership in 2000, the FreedomCAR and Fuel Partnership in 2002, and U.S. Drive in 2011. Additionally, DOE has convened smaller partnerships, such as the Cooperative Research and Development Agreement between Cummins, catalyst maker Johnson Matthey, and Pacific Northwest National Laboratory, to achieve rapid technical progress. These partnerships achieved advances that improved vehicle efficiency, reduced harmful emissions, and reduced dependence on foreign oil.

As a result of government-supported research, heavy-duty diesel trucks went from 37% efficiency in 1981 to 42% efficiency in 2007. Truck fuel economy increased almost 20%, from a low of 5.4 miles per gallon in 1981 to 6.4 miles per gallon in 2010. From 1990 to 2009, per-mile emissions of harmful nitrogen oxides (NOx), carbon monoxide, and particulate matter from the U.S. heavy truck fleet declined 67–81%, dramatically reducing adverse health impacts from diesel engines.

Today, diesel engines use an array of technologies developed through the CRF and ACE R&D programs. Government-led diesel research is ongoing; the ACE R&D program's 2015 goals include improving overall efficiency of diesel passenger vehicles to 45% and commercial vehicles to 50%.

From 1986 through 2007, the CRF and ACE R&D programs generated over $70 billion in economic benefits to the United States while improving fuel efficiency, reducing emissions, and reducing U.S. reliance on foreign oil. The history of advanced diesel engines shows that government support of energy R&D is not wasteful and can generate a positive return on investment for the country while simultaneously achieving important health, environmental, and national security benefits.

As a result of government-supported research, heavy-duty diesel trucks went from 37% efficiency in 1981 to 42% efficiency in 2007.

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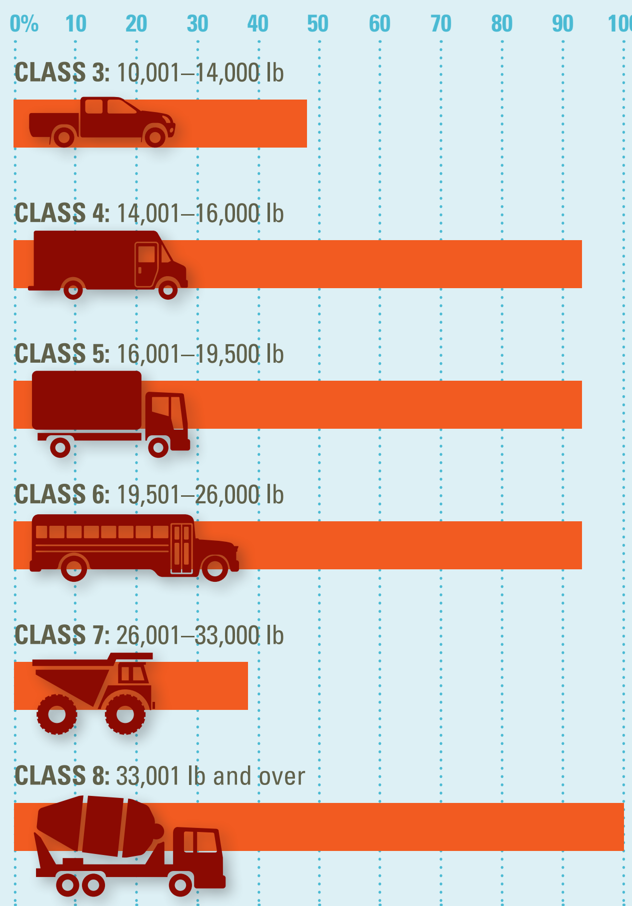
Introduction

In 2010, petroleum sources accounted for 95% of energy consumption in the transportation sector.[1] Vehicles running on conventional fuels are tremendously important sources of energy demand and greenhouse gas emissions, and they likely will remain so for years to come. Ensuring that conventional fuel vehicles run as cleanly and efficiently as possible is key to protecting the well-being of America's people and environment.

Diesel engines are the workhorses of the American truck industry; in 2010, 73 percent of all trucks weighing over 10,000 pounds ran on diesel.[2] Figure 1 shows the classification of medium- and heavy-duty trucks along with estimates of the share of each truck class that was powered by diesel in 2010.[3]

Figure 1: **Truck Classification**

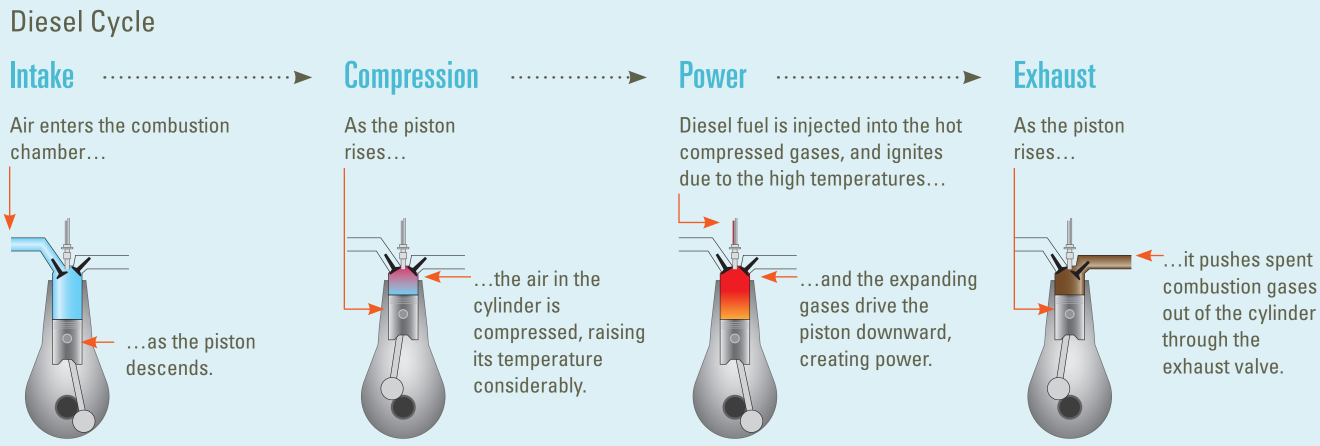
(Percent per class powered by diesel in 2010)



A strong truck transportation industry is vital for interstate commerce, contributes to a strong economy, and helps to create and maintain American jobs. In 2012, the truck transportation industry employed over 1.3 million people, accounting for approximately 30 percent of the total employment in the transportation industry.[4] Truck transportation had a gross output of $275 billion in 2011, accounting for nearly one-third of the transportation industry's gross output of $784 billion.[5]

Diesel engines are much more efficient than gasoline engines; today they convert 45% of the fuel's chemical energy into mechanical work, compared to only 30% for gasoline engines.[6] Diesel engines' superior fuel efficiency was an important driver of their initial, widespread adoption in the U.S. following the construction of the interstate highway system. Over the ensuing decades, combustion research at national labs, computer modeling tools, and public-private research collaborations produced tremendous technological advances, allowing manufacturers to greatly increase the efficiency of diesel engines[7] while lowering nitrogen oxide (NOx) and particulate matter pollution from new engines by 99%.[8] Today's highly efficient, low-emission diesel engines are the result of years of research by both the government and the private sector, often working together to advance knowledge of combustion and overcome design challenges, ultimately producing a technology that is fundamental to our modern transportation system.

Figure 2: **The Four-Stroke Internal Combustion Diesel Engine**



How Diesel Engines Work

The past few decades have brought vast improvements in diesel engine efficiency and reductions in engine emissions. To examine how technological breakthroughs have led to the development of cleaner and more efficient diesel-powered vehicles, it is helpful to take a moment to understand the basic mechanics behind the internal combustion engine. Most diesel engines today run on essentially the same four-stroke internal combustion process that German engineer Rudolf Diesel developed in the 19th century.[9] Inside a diesel engine are cylinders, each of which has a fuel injector, an air intake valve, an exhaust valve, and a piston that moves up and down. The combustion cycle has four stages, each denoted by a piston stroke. During the first piston stroke, the piston moves down, allowing air to be drawn into the cylinder through the intake valve. During the second stroke, the piston moves back up, compressing (and thereby heating) the air in the cylinder. At the beginning of the third stroke, diesel fuel is injected under high pressure into the cylinder. The fuel is ignited by the compressed and heated air, creating hot exhaust gases that expand and rapidly drive the piston downward. This allows the pistons to move the crankshaft, which converts their downward linear motion into rotary motion that turns the wheels. In the fourth stroke, the piston moves back up, pushing spent gases out of the cylinder through the exhaust valve and allowing the cycle to begin again. Figure 2 shows the different steps of the four-stroke diesel combustion cycle.[10]

Development of the Technology

The diesel engine was developed by German engineer Rudolf Diesel in 1896, in an attempt to improve upon the inefficient steam engines common in his day.[11] In contrast to modern diesel engines, early models were heavy and bulky. Prior to the 1920s, they were primarily used in ships and submarines, large vehicles that could accommodate the engines' size and weight and which benefitted from their efficiency. It was not until 1908, when initial patents for diesel engines expired, that Rudolf Diesel began to pursue the design and development of smaller engines for light-duty vehicles.[12] As diesel engines grew smaller and stronger, new applications for them continued to be found. In 1931, the Caterpillar Diesel Tractor revolutionized agriculture by becoming the first volume production diesel tractor, as well as the first tractor powerful enough for use in large-scale agriculture and major construction projects.[13] Diesel engines were used extensively in military equipment during both World War I and World War II. During the 1950s, the U.S. government purchased diesel-powered construction equipment to build the U.S. Interstate Highway System. Once the highways were built, interstate commerce boomed as trucks running on diesel carried goods thousands of miles across the country, marking the start of a new era for the diesel industry. During the following decades, engine companies such as Caterpillar, Cummins, and Detroit Diesel built engines for private vehicles and for construction vehicles commissioned by the U.S. government.

The federal government funded basic combustion research and coordinated multidisciplinary R&D in the wake of the 1973 oil embargo.

In the early 1970s, medium and heavy trucks had an average fuel economy of roughly 5.7 miles per gallon. Due to low fuel prices, manufacturers had little incentive to improve fuel performance, resulting in flat or declining fuel efficiencies throughout the 1970s (Figure 3).[14, 15, 16] Improving vehicles' fuel economy only became a national priority after the 1973 oil embargo, when the government became interested in supporting technological innovation as a means to increase U.S. energy efficiency and reduce dependence on foreign oil.

The government's participation in combustion research during this period was of critical importance to the engine industry. Engine and vehicle manufacturers were willing to invest in research to improve the efficiency of their products, as long as doing so increased value to the customer. However, technological innovation in the 1970s and the 1980s was significantly hampered by a lack of fundamental knowledge about the combustion process.[17] To significantly improve engine efficiency, engine manufacturers needed data and information on combustion, and ultimately, they needed computer software capable of simulating this process. Conducting this basic scientific research and using it to build powerful and accurate simulation tools was no easy task. It required enormous funding as well as the cooperation of engine manufacturers, universities, and national laboratories. Even if the private industry could have obtained the necessary research funding, it is unlikely that it would have been able to achieve the necessary level of cooperation between the private, public, and academic sectors.

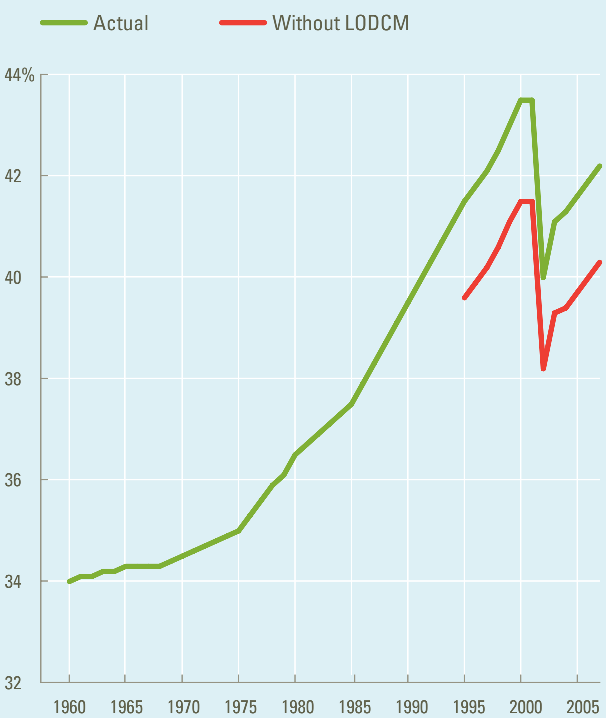
The government sought to address these needs when it founded the Combustion Research Facility (CRF) in 1981 and the Advanced Combustion Engine R&D (ACE R&D) program in 1986. These two initiatives brought together researchers at national labs, universities, engine companies, and automakers. The researchers were tasked with conducting basic research that would lead to a deeper understanding of the combustion process, then to use that information to build practical tools and applications that would enable the private industry to build cleaner and more efficient engines. Among the CRF and ACE R&D program's partners were the nine labs and universities listed in Table A1 in the appendix, as well as private companies such as General Motors, Ford, Cummins, Caterpillar, and General Electric.

Figure 3: **Fuel Economy for Medium- and Heavy-Duty Trucks, 1970-2010 (mpg)**

Government-led advanced combustion research improved fuel economy, saved U.S. consumers billions of dollars, and spurred further private sector innovation.

Research conducted through the ACE R&D and CRF programs led to a number of technological innovations and breakthroughs that dramatically increased engine efficiency and reduced emissions. According to scientists at the CRF and several U.S. diesel engine manufacturers, two research areas within the ACE R&D program—laser and optical diagnostics and combustion modeling (LODCM)—prevented a 4.5% decline in diesel engine brake thermal efficiency between 1995 and 2007 (Figure 4).[18] This improved vehicle fuel economy and saved the United States 17.6 billion gallons of diesel fuel during that period, which translates to $34.5 billion in reduced spending on fuel. Fuel savings also resulted in lower emissions, which reduced mortality and the incidence of several health conditions, generating $35.7 billion in health and environmental benefits. Between 1986 and 2007, the research budgets of the CRF and ACE R&D programs (not just the LODCM) totaled $931 million after adjustment for inflation. This means that less than a $931 million investment generated at least $70.2 billion in economic benefits for the United States.[20]

Figure 4: **Brake Thermal Efficiency of U.S. Heavy-Duty Diesel Trucks, 1960–2007.**



The red line shows hypothetical engine efficiencies in the absence of the ACE R&D sub-programs on laser and optical diagnostics and combustion modeling (LODCM). Note that the drop in efficiency from 2001–2002 was due to a legal settlement that required engine manufacturers to adhere to new NOx emissions standards 15 months earlier than expected, leaving them insufficient time to meet the standard while preserving fuel efficiency. As a point of reference, Brian Mormino, Director for Energy Policy and Environmental Compliance Audit at Cummins Inc., notes that in 2013, manufacturers are demonstrating engines with brake thermal efficiencies above 50%.[19]

Research supported by ACE R&D and the CRF also created a wealth of knowledge that indirectly spurred further technological innovation. An analysis of diesel engine-related patents filed 1976-2009 found that, on average, DOE patents were more frequently cited than patents held by the 10 leading vehicle and engine companies, save one.[21] (Only Nissan's patents were cited more often than those of DOE.) This highlights the extraordinary role that federally-funded combustion research has played in creating the knowledge that enabled private sector innovation and breakthroughs in advanced combustion engine technology.

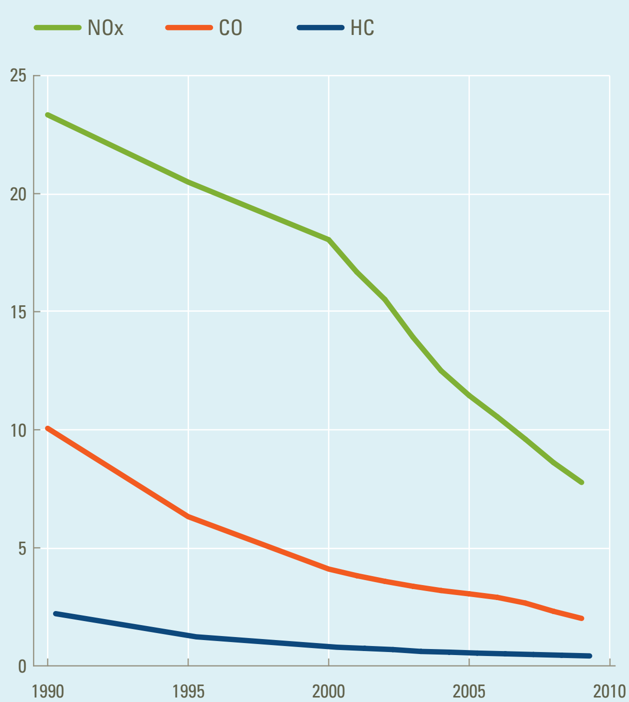
The federal government developed simulation tools that enabled engine manufacturers to build cleaner engines at lower cost.

One of the Department of Energy's major contributions to diesel engine research and innovation was the development of tools that simulate the combustion process. These tools have been used by engine manufacturers to build cleaner and more efficient engines that generate fuel savings and preserve public health. Two important combustion simulation tools that the government has developed are the KIVA codes and data and tools from the Cross-Cut Lean Exhaust Emissions Reduction Simulation (CLEERS) project. The KIVA codes were developed by Los Alamos National Laboratories (LANL) in 1982, and they were released to the public in 1985 when computers became fast enough to run the software.[22] The KIVA software simulated the fluid dynamics of engine internal combustion processes and was widely used by engine manufactures and automakers such as Caterpillar, Cummins, General Motors, Ford, and Chrysler. For example, the engine manufacturer Cummins used a later version of the KIVA software to reduce development time and cost by 10–15% for its 2007 ISB 6.7-L diesel engine. This simulation software helped them meet the 2010 EPA pollutant emission standards three years before they were phased in.[23]

Research supported by ACE R&D and the CRF also created a wealth of knowledge that indirectly spurred further technological innovation.

Following the success of the KIVA simulation software, the Department of Energy launched the Cross-Cut Lean Exhaust Emissions Reduction Simulation (CLEERS) initiative with the goal of supporting the development of cleaner diesel engines.[24] Historically, diesel engines have produced high levels of nitrogen oxides (NO and NO_2, or NOx), particulate matter (PM), and hydrocarbons (HC), all of which constitute a serious health and environmental threat. As such, these pollutants have been regulated by increasingly stringent emissions standards set by the Environmental Protection Agency (EPA) as shown in Table A2 in the appendix.[25] Launched in 2001, CLEERS provided engine manufacturers with simulation tools and databases needed to develop lean-burn technologies.[26] Lean-burn engines use excess oxygen in order to ensure more complete combustion, making them cleaner and more efficient than traditional engines. In addition, automakers have used CLEERS to develop more efficient and less costly after-treatment technologies.

Figure 5: **Pollutant Emissions from Diesel-Powered Heavy Trucks (g/mile).**



For instance, GM developed new catalyst materials using CLEERS data, and Ford demonstrated the use of urea and selective catalytic reduction systems to control emissions.[27] In combination with the EPA standards, the CLEERS initiative has given both direction and tools to the private sector to innovate quickly and successfully. This has resulted in dramatic emissions reductions: in 2009, U.S. heavy trucks emitted 81% less HC, 80% less CO, and 67% less NOx per mile than they did in 1990 (Figure 5).[28, 29, 30]

The government has established public-private partnerships to coordinate advanced diesel combustion research and accelerate efficiency gains.

In addition to creating powerful simulation tools that enabled private companies to develop increasingly clean and efficient engines, DOE also played an important role in bringing together the public, private, and academic sectors to collaborate on basic research and technological innovation goals.

Starting in the 1990s, the U.S. government initiated a number of partnerships between government agencies and the private sector, including automakers, engine manufacturers, energy companies, and electric utilities. The four main programs were the Partnership for a New Generation of Vehicles (PNGV) in 1993, the 21st Century Truck Partnership in 2000, the FreedomCAR and Fuel Partnership in 2002, and US Drive in 2011. These partnerships worked to conduct research and development that would improve vehicle efficiency, reduce harmful emissions, and reduce U.S. dependence on foreign oil. Notably, the Department of Defense has played a key role in the 21st Century Truck Partnership, which has sought to promote U.S. energy security both by improving fuel economy of heavy duty vehicles and by developing more reliable and efficient army equipment. Table 1 summarizes the composition and goals of the four main vehicle technology R&D partnerships.[31, 32, 33, 34]

The four major programs above were not the only mechanisms by which government partnered with the private sector, enabling advances in diesel engine technology. For instance, engine manufacturer Cummins highlights the benefits of government collaboration in reducing the emissions of conventional pollutants

Table 1: **Public-Private Partnerships for Vehicle Technology R&D**

Year	Partnership	Members	Goals	Progress
1993	Partnership for a New Generation of Vehicles (PNGV)	7 federal agencies; United States Council for Automotive Research (USCAR), which includes DaimlerChrysler, Ford, General Motors	Develop affordable, fuel-efficient, low-emission vehicles that meet all customer needs	Reduced vehicle weight Advances in aluminum, magnesium, and polymer components Created low-friction carbon coating
2000	21st Century Truck Partnership	DOE; U.S. Department of Defense; U.S. Department of Transportation; U.S. Environmental Protection Agency; 16 engine manufacturers and automakers	Improve truck fuel efficiency while lowering operating costs and reducing emissions Focus on both commercial trucks and military equipment	Reduced wind drag Homogenous charge compression ignition (HCCI) for commercial engines Emissions reductions Critical enabler for ultra-low sulfur diesel fuel
2002	FreedomCAR and Fuel Partnership	DOE; USCAR; five energy providers; 2 electric utilities	Improve vehicle fuel economy to reduce dependence on foreign oil and achieve energy security	Durable fuel cell membranes Better understanding of catalysts Improved modeling & analysis tools Onboard hydrogen storage tech
2011	US Drive: Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability	DOE; USCAR; Tesla Motors; 5 energy industry members; 3 electric utilities	Develop clean and efficient vehicles through R&D in various technical areas including advanced combustion, emissions control, materials development, and fuel formulation	Has begun supporting projects in 12 focus areas (6 vehicle areas, 3 fuel areas, 3 crosscutting technology areas) Still early for commercial results

Through technological innovation achieved by collaboration between the DOE, national labs, universities, and the private sector, engine manufacturers have been able to implement a variety of state-of-the art technologies that ensure diesel engines are running cleanly and efficiently.

from diesel engines. In 2001, the EPA introduced stringent exhaust standards requiring 99% reductions in particulate matter and NOx by the year 2010. Through a Cooperative Research and Development Agreement (CRADA) between Cummins, the Department of Energy, catalyst manufacturer Johnson Matthey, and Pacific Northwest National Laboratory (PNNL), Cummins was able to achieve the required emissions reductions by 2007, three years early. (The pollutant reductions shown in Figure 5 reflect the average performance of the U.S. heavy truck fleet, which lags far behind the state-of-the-art due to the long service lives of heavy trucks.) Cummins asserts that the participation and discoveries of the national laboratory "proved key" to understanding catalytic systems, enabling them to develop a highly advanced diesel engine and exhaust aftertreatment system that met EPA standards.[35]

Current Status

The diesel internal combustion engine has come a long way from Rudolf Diesel's prototype in 1896. Through technological innovation achieved by collaboration between the DOE, national labs, universities, and the private sector, engine manufacturers have been able to implement a variety of state-of-the art technologies that ensure diesel engines are running cleanly and efficiently. Several widely used advanced technologies are described in Table 2.[36]

To ensure that the U.S. transportation industry can continue to reap the benefits of diesel engines, while minimizing their contribution to pollution, the DOE continues to promote research and technological innovation in advanced diesel combustion. In its 2009 Annual Progress

Table 2: **Advanced Diesel Engine Technologies that Improve Fuel Economy and Reduce Emissions**

Technology	Description and Benefits
Advanced Fuel Injection (Common Rail Systems and Electronic Unit Injectors)	During the 1980s, fuel injection methods that deliver fuel at higher pressures were developed. In the 1990s, fuel injection started to be managed electronically for more precise control of the combustion process. These advances reduced soot formation and engine emissions.
Turbocharging	Turbocharging uses what would have been wasted energy in exhaust gases to power turbines that pressurize air in the engine's cylinder, allowing the engine to produce more power. This increase in power enables automakers to use smaller and lighter engines, increasing mileage while reducing emissions.
Exhaust Gas Recirculation (EGR)	During exhaust gas recirculation, exhaust gases are pushed into cylinder along with intake air. This dilutes the air/fuel mixture in the cylinder, thereby reducing the temperature achieved during combustion, which in turn reduces NOx formation.
Homogeneous Charge Compression-Ignition (HCCI)	HCCI is an advanced fuel injection technology. It differs from traditional fuel injection in that fuel and intake air are first mixed, and then injected into the engine simultaneously. This results in lower-temperature combustion that occurs more uniformly throughout the cylinder, reducing NOx and PM formation. Research is currently focusing on reducing the cost and improving the performance of HCCI.
Diesel Particulate Filters (DPF)	As a result of EPA standards requiring reduction in PM emissions from diesel-powered vehicles, diesel particulate filters are used in many passenger and commercial diesel engines to physically filter exhaust gases.
Catalysts (Selective Catalytic Reduction and Lean NOx Catalysts)	For the past decade, catalysts have been used in diesel engines to reduce NOx emissions. Catalysts use chemical compounds to transform NOx into nitrogen gas. DOE research has focused on improving the durability and performance of catalysts.

Report for the ACE R&D Subprogram, DOE announced research goals related to reducing engine emissions, improving efficiency, and converting engine waste heat to electricity.[37] Specific technical goals for 2015 include increasing engine efficiency for diesel powered passenger vehicles to 45% and increasing engine efficiency for commercial vehicles to 50%.[38] To achieve these goals, the DOE and its public and private sector partners will have to develop new technologies as well as improve the performance and lower the cost of existing technologies such as thermoelectric generators, turbo-machinery, flexible valve systems, and advanced combustion systems. The report also emphasizes the importance of further reducing diesel engine emissions, which have historically been a barrier to market acceptance for diesel powered vehicles, especially in the light-duty vehicle sector. Developing cleaner engines that can achieve greater market penetration could generate significant fuel savings and energy security benefits.

Lessons

The history of U.S. government involvement in advanced diesel combustion research has not only left a legacy of remarkable technological innovation, but also provided important insight regarding the role of the private sector in supporting research and development. By supporting advanced diesel combustion research, the government performed two important functions that the private industry would not have been able to perform alone.

First, the government supported basic research and the development of complex simulation tools based on that research. By nature, basic research is often a necessary first step towards technological innovation, but it is not guaranteed to generate short-run profits and, as a result, is under supplied by private industry. Since the 1970s, the government has coordinated and supported a comprehensive research effort to increase understanding of the combustion process and emissions. This effort was multidisciplinary and could not be completed by a single research group. Instead, it was conducted by scientists working in various areas of physics, chemistry and engineering at universities and labs across the country.

Second, in addition to orchestrating a collaborative basic research effort, the government ensured that this research was put to use by leading the development of the KIVA codes and the CLEERS database that made a wealth of new information easily accessible to private industry. Both of these endeavors were costly and risky—for instance, the KIVA codes were developed years before adequate computing power was available for their implementation. To coordinate the development of these simulation tools, the government relied on its extensive network of connections with researchers and facilities, as well as the advice and insights from private industry.

It is evident that both the creation of knowledge about the combustion process and the practical application of that knowledge required massive collaborative efforts within and between the public sector, the private sector, and academia. This spirit of collaboration was carried on in the vehicle technologies partnerships that formed between the government and the private sector over the past two decades.

Overall, by coordinating and supporting advanced diesel combustion research, the government helped to develop clean and efficient engines that power the American truck industry while also promoting national goals such as protecting public health and promoting energy security. Notably, the government's investment in advanced diesel combustion R&D paid off, generating a remarkable return on investment of over $70 billion in economic benefits from less than $1 billion invested from 1986 through 2007. The history of advanced diesel engines shows that government support of energy R&D is not wasteful and can generate a positive return on investment for the country while simultaneously achieving health, environmental, and national security benefits.

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Appendix

Table A1: Research Goals of National Labs and Universities Partnering with the CRF

Partner	Area of Research
Lawrence Livermore National Laboratory (LLNL)	combustion chemistry
Lawrence Berkeley National Laboratory (LBNL)	homogeneous charge engines and processes
Los Alamos National Laboratory (LANL)	large-scale computer models
Purdue University	heat and mass transfer
Princeton University	direct fuel injection engines
University of Wisconsin	experimental engineering processes
Massachusetts Institute of Technology (MIT)	flame propagation
Pennsylvania State University	fluid mechanics in engines
Imperial College (London)	fluid mechanics in engines

Table A2: EPA Emission Regulations for Heavy-Duty Highway Vehicles

Model Year	NOx (g/bhp-hr)	PM (g/bhp-hr)	HC (g/bhp-hr)
1988–1989	10.7	0.60	1.3
1990	6.0	0.60	1.3
1991–1993	5.0	0.25	1.3
1994–1997	5.0	0.10	1.3
1998–2003	4.0	0.10	1.3
2004–2006	2.0	0.10	0.5
2007–2010	0.2	0.01	0.14
Percent Reduction by 2010	**98%**	**98%**	**89%**

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