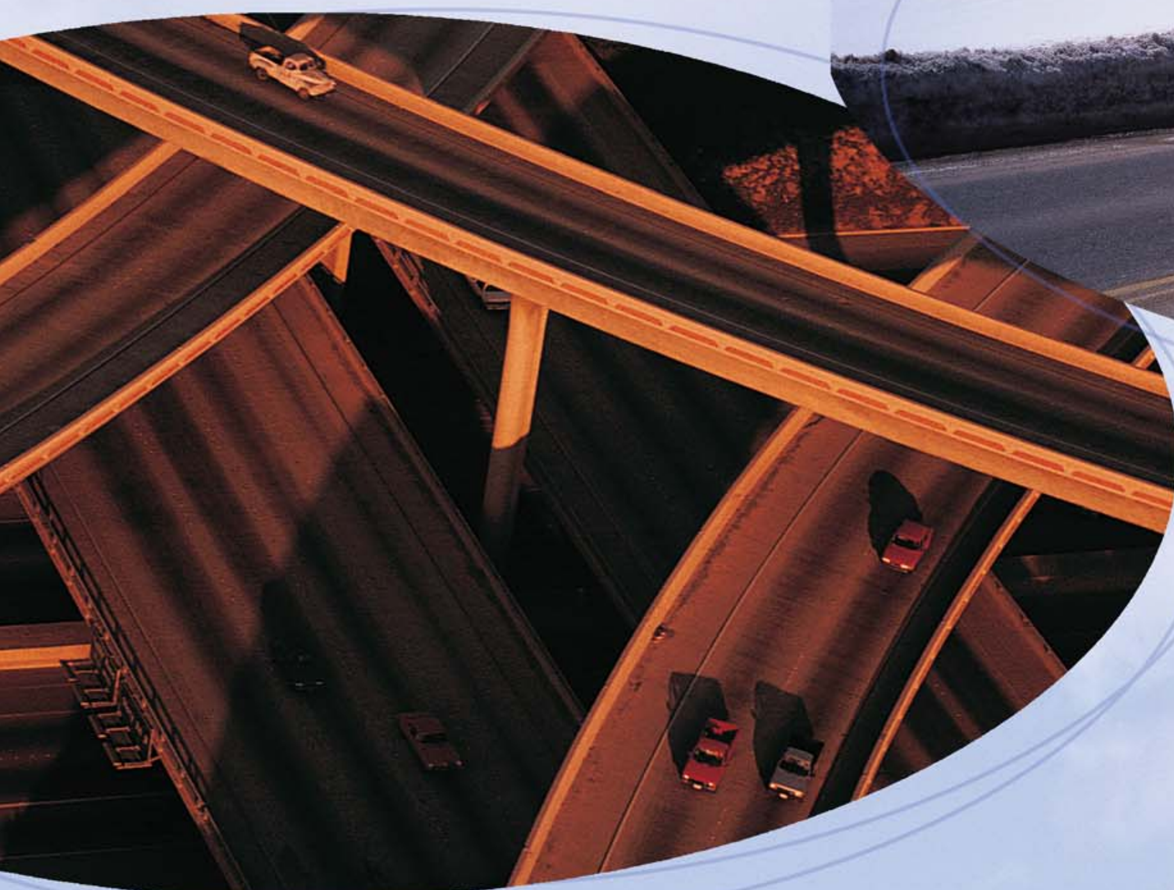
United States
Environmental Protection
Agency

Clean Automotive Technology Program

Developing Cleaner and More Efficient Vehicles and Engines for Tomorrow

2006 Progress Report



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Introduction

Background

Transportation and mobility are central to the American economy and way of life. While the world's desire for personal mobility and commercial transportation has evolved, so have the geopolitical and environmental landscapes. Global demand for oil is at an all-time high, driving up the price of gasoline and diesel fuel, and the environmental consequences of mobile source emissions have become more and more apparent. More than 100 million Americans live in counties that do not attain federal clean air standards for ozone (O_3), sulfur dioxide (SO_2), particulate matter (PM), or other air pollutants, mostly because of emissions from the transportation sector.[1] Transportation sources are also responsible for emitting prodigious amounts of carbon dioxide (CO_2), a greenhouse gas that is accelerating global climate change. In fact, transportation was the second largest source of CO_2 in the United States in 2004, accounting for approximately 30 percent of national CO_2 emissions.[2]

In response, the U.S. Environmental Protection Agency's (EPA's) Office of Transportation and Air Quality (OTAQ) is spearheading a range of programs to reduce mobile source emissions. Among them, the Clean Automotive Technology Program is especially equipped to meet the environmental and fuel supply challenges of tomorrow. The Clean Automotive Technology Program leverages American industrial and academic ingenuity in automotive engineering to develop cost-effective advances for cleaner, more fuel-efficient engine and vehicle designs. The program's end products—prototypes that spur changes in automotive design and manufacturing—help America's fleet improve fuel efficiency and reduce CO_2 emissions while maintaining the superior vehicle performance that American drivers have come to expect.

1 *Toward a Cleaner Future*, Office of Transportation and Air Quality Progress Report 2005, EPA 420-R-05-011, November 2005.

2 *Inventory of U.S. Greenhouse Gas Emissions and Sinks*: 1990–2004, EPA 430-R-06-002, April 2006.

What Is the Clean Automotive Technology Program?

The goal of the Clean Automotive Technology Program is to research, evaluate, and develop advanced technologies that help vehicles increase fuel efficiency, reduce regulated emissions such as nitrogen oxides (NO_X) and PM, and cut greenhouse gas emissions. With technological breakthroughs and engineering innovations, the program produces clean, efficient vehicle and engine prototypes and encourages manufacturers to incorporate these cost-effective designs into cars and trucks developed for the marketplace.

The Clean Automotive Technology Program focuses on both drivetrain and engine design. EPA's research on drivetrain design focuses on hydraulic hybrid technology to achieve significant increases in fuel efficiency. EPA's recent research on engine design focuses on clean diesel combustion technology, homogeneous charge compression ignition, and free piston engines, all of which promise to reduce air pollutants.

The National Vehicle and Fuel Emissions Laboratory: Home to the Clean Automotive Technology Program

EPA established the National Vehicle and Fuel Emissions Laboratory in 1971 in Ann Arbor, Michigan—near the birthplace of the automobile industry and home to some of the world's most advanced vehicle manufacturing, testing, and research facilities. Since its founding, the lab has been at the forefront of developing clean automotive technology and designing programs to reduce and prevent air pollution. It is now recognized as a leader in advanced emission testing services and automotive technology to reduce conventional pollutants and greenhouse gas emissions. This 185,000-square foot facility houses 400 experts in a variety of technical and public policy fields, including auto mechanics, engineering, chemistry, economics, natural resources management, and law.

Working with Partners

EPA works cooperatively with industry and university partners throughout the United States to bring advanced automotive technologies from EPA's laboratory to market. Public-private partnerships with industry and university research facilities benefit all parties:

- Automotive manufacturers benefit from cost-effective use and leverage of government resources to research and evaluate environmentally friendly technologies. They also help accelerate development of new technologies with commercial value and gain a competitive edge in a highly competitive global market.
- Universities benefit by being involved in cutting-edge research and supplementing students' education with training in advanced automotive technologies at EPA's world-class labs and testing facilities.
- EPA benefits from the shared expertise of its partners and through sharing the high upfront costs of technology development.
- Most importantly, the public benefits when clean, efficient technologies are incorporated quickly into vehicles, resulting in more fuel-efficient vehicles and cleaner air.

EPA's industry partnerships are formalized through Cooperative Research and Development Agreements (CRADAs). In signing a CRADA, EPA's partners commit to supporting the development of advanced technologies by assisting in one or more of the following activities:

- Sharing development costs
- Providing components and parts
- Performing research and development
- Evaluating technology
- Sharing information and expertise
- Facilitating commercialization

As of 2006, six different companies were working with EPA to promote the development and commercialization of advanced technologies. In addition, four university partners had collaborated actively with EPA—performing tests on clean engine components at EPA's Ann Arbor, Michigan, laboratory or at their own testing facilities and sharing a variety of resources.

EPA Technology Transfer Industry Partners

ORGANIZATION	CLEAN ENGINES	HYDRAULIC DRIVETRAINS
Eaton Corporation — Fluid Power		✓
Ford Motor Company	✓	
International Truck and Engine Corp.	✓	✓
Parker-Hannafin Corporation		✓
UPS		✓
U.S. Army National Automotive Center		✓

EPA Technology Transfer University Partners

ORGANIZATION	CLEAN ENGINES	HYDRAULIC DRIVETRAINS
Michigan State University	✓	✓
University of Michigan		✓
University of Toledo		✓
University of Wisconsin		✓

Summary of Recent Key Accomplishments

Innovations and breakthroughs from the Clean Automotive Technology Program are the result of decades of work pioneered by scientists, engineers, and manufacturers that have collectively invested significant capital and time in pursuit of improved systems. Technical advances such as these require hundreds of tests and thousands of hours to advance to the state of commercial viability.

For 2004 through 2006, the program's most significant accomplishments include the following:

- As of October 2006, filed for five new patent applications, adding to the 18 applications already pending and 42 patents issued. These patents will enable clean technologies to be more quickly adopted into vehicles destined for sale and use in the United States.

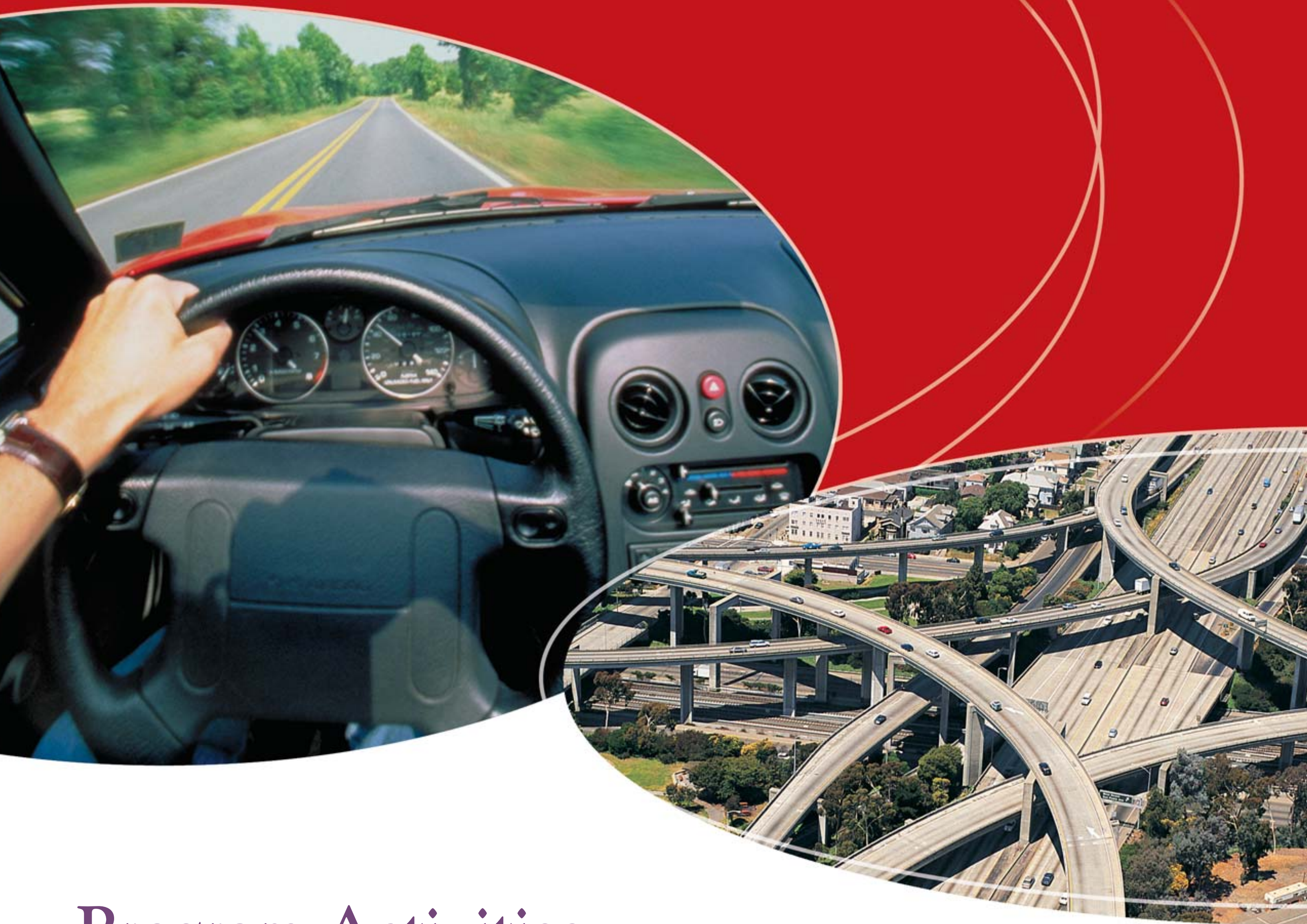
- Working on six CRADAs with industry partners and four cooperative agreements with institutions of higher education.

EPA Inventions

The Clean Automotive Technology Program applies for patents on a regular basis to secure rights to its innovations and enable them to be shared with commercial partners. These patents encompass a range of hydraulic components, hydraulic hybrid vehicle configurations and control methods, clean diesel combustion technologies, homogeneous charge compression ignition, and other advanced alternative engines. A total of 29 advanced technology patents have already been issued to EPA.

- Demonstrated prototypes at 15 major conferences, competitions, and other forums around the nation. As a result, EPA estimates that several thousand influential industry stakeholders learned directly about the program's emerging technologies.

- Developing breakthroughs to create clean diesel combustion engines that meet NO_x levels established by Tier 2 standards.



Program Activities

Advancing Promising Technologies

EPA's clean automotive technology research is focused on hydraulic hybrid vehicles and clean engines. Incorporating hydraulic hybrid technology and cleaner engines into an SUV or delivery truck could cut CO_2 emissions by more than 40 percent and increase fuel economy by more than 70 percent above current models. If EPA's prototypes were incorporated into today's fleet of cars and light trucks, the air quality and oil consumption improvements and greenhouse gas emissions reductions would be impressive.

Hydraulic Hybrid Vehicles

Hydraulic hybrid drivetrains are a priority for EPA because they yield higher fuel efficiency, lower emissions, reduced operating costs, and better acceleration performance than traditional drivetrains. EPA has developed two types of hydraulic hybrid vehicles—mild hydraulic hybrids and full hydraulic hybrids.

How Hydraulic Hybrids Work

Hydraulic hybrid technology uses a hydraulic energy storage and propulsion system in the vehicle. A major benefit of a hydraulic hybrid vehicle is fuel economy improvement due to the vehicle's ability to capture energy normally lost in vehicle braking. The hydraulic system can capture and store more than 80 percent of the energy normally wasted in vehicle braking and use this energy to help propel the vehicle during the next vehicle acceleration. The hydraulic system also enables the engine to operate more efficiently when the engine is needed.

Because the business of medium- and some heavy-duty vehicles—such as urban delivery trucks, shuttle buses, and waste disposal vehicles—involves stop-and-go driving, hydraulic hybrid technology could provide significant benefits to these types of vehicles, saving money in fuel costs and reducing emissions.

In urban stop-and-go driving, as much as one-half of all of the energy available at the vehicle wheels is lost in braking.

Mild hydraulic hybrids draw from two sources of power to operate the vehicle—the gasoline or diesel engine and the hydraulic components. Because both power sources work together, a typical diesel-powered or gasoline-powered vehicle can be fitted with hydraulic components as a secondary energy storage system to help it run more efficiently.

The central hydraulic components in any hydraulic hybrid drivetrain are two hydraulic accumulator vessels (a high-pressure tank capable of storing hydraulic fluid that compresses inert nitrogen gas and a low-pressure accumulator) and one or more hydraulic pump/motor units. When the vehicle brakes, the hydraulic pump/motor uses the kinetic energy of the braking to move hydraulic fluid from a low-pressure accumulator into a high-pressure accumulator, increasing the pressure of nitrogen gas in the high-pressure accumulator.

EPA/UPS Demonstration Truck Delivers Results

In June 2006, EPA and UPS introduced the world's first full hydraulic hybrid delivery truck to a crowd of auto industry representatives, environmentalists, and reporters in Washington, D.C. Laboratory tests show that this EPA-patented technology can increase fuel efficiency by 60 to 70 percent in urban driving conditions and reduce CO_2 by 40 percent compared to conventional UPS diesel delivery trucks. EPA estimates the upfront costs for the hybrid components (when produced in volume) for a typical delivery vehicle could be recouped in fewer than three years, and net savings over a vehicle's lifespan could exceed $50,000.* EPA and UPS showcased the truck throughout the Northeast and Southwest to demonstrate its performance.

* Assuming diesel fuel price of $2.75 per gallon.

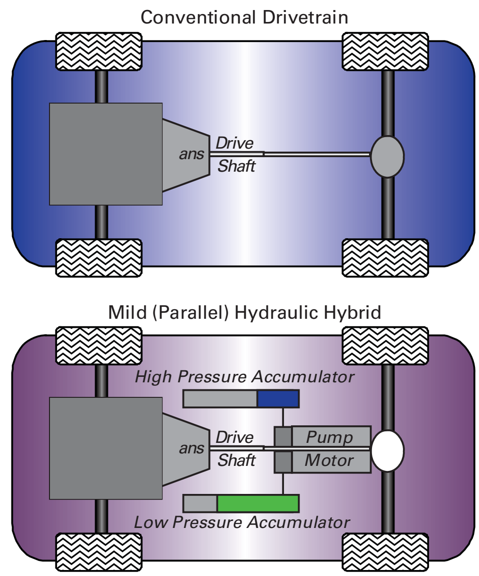
EPA's Mild Hydraulic Hybrid Truck in a Medium Duty Delivery Truck Chassis

During the next vehicle acceleration, the hydraulic pump/motor unit uses the high-pressure hydraulic fluid to generate torque, sending the fluid back to the low-pressure accumulator, which is transferred to the driveshaft. Because the vehicle is being propelled by the hydraulic fluid transfer rather than fuel combustion, this method of acceleration reduces emissions.

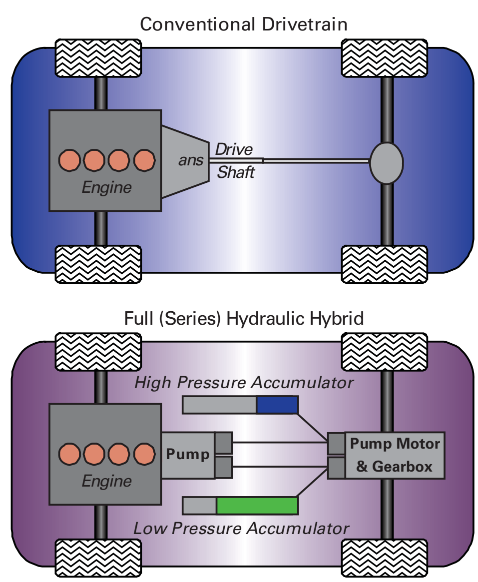
During the past few years, EPA has focused its hydraulic hybrid technology research on creating a *full* hydraulic hybrid drivetrain, which operates even more efficiently by replacing the transmission and enabling operation of the vehicle's engine near its peak efficiency. In fact, EPA unveiled the world's first full hydraulic hybrid SUV at the 2004 Society of Automotive Engineers (SAE) World Congress in Detroit, Michigan. This vehicle had outstanding performance in the laboratory. Dynamometer tests showed that the full hydraulic hybrid SUV offered an estimated 35 to 55 percent fuel economy improvement over a comparable, commercially available SUV and a 25 to 35 percent reduction in CO_2 emissions due to the hydraulic technology.

While this hydraulic hybrid technology is projected to increase the cost of a large SUV by about $600, consumers

Conventional vs. Mild Hydraulic Hybrid Drivetrain



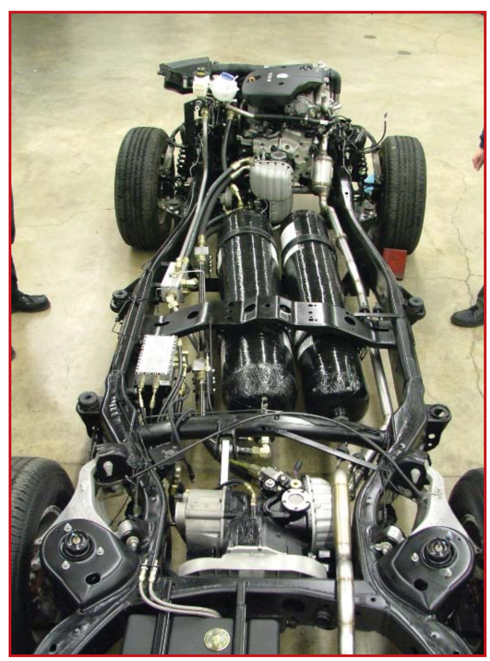
Conventional vs. Full Hydraulic Hybrid Drivetrain



Full Hydraulic Hybrid SUV

could expect to recoup this cost in fewer than three years through fuel savings and maintenance savings due to reduced brake wear.

In 2005, EPA developed a full hydraulic hybrid package delivery truck with UPS (see page 7 for an update on this project). The delivery truck expanded on previous demonstrations and evaluations of the technology through a partnership arrangement with UPS, Eaton Corporation (hydraulic supplier), International Truck and Engine Corporation (urban truck and engine manufacturer), and the U.S. Army's National Automotive Center. In laboratory tests, EPA achieved a 60 to 70 percent improvement in fuel economy and a 38 to 41 percent reduction in CO_2 emissions for the demonstration truck.



Chassis View

Clean Diesel Combustion Engines

EPA's engine research focuses on developing engines that are simultaneously clean, efficient, and cost effective and that have a high potential to produce real-world benefits. Current research in the Clean Automotive Technology Program has focused primarily on clean diesel combustion (CDC) engines, which can help vehicles meet EPA's Tier 2 vehicle emissions standards cost-effectively.

EPA focuses research efforts on CDC technology because it reduces the costs of complying with emissions standards. In addition, it significantly reduces NO_X emissions below what is currently achievable without the need for exhaust treatment systems, and it can be applied to either light-duty or heavy-duty diesel engines.

Tier 2 and Clean Engine Development

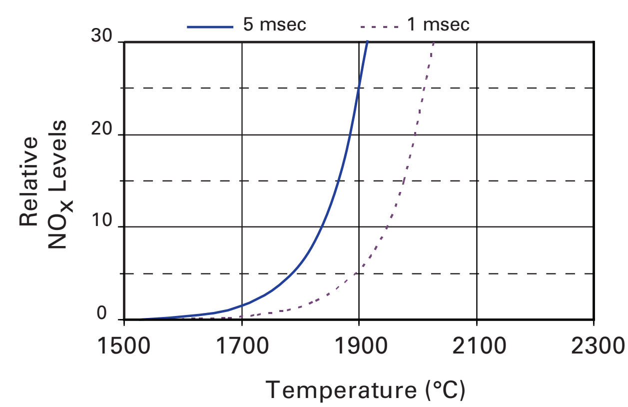
EPA's Tier 2 vehicle emissions standards require new cars, SUVs, pickup trucks, and vans to meet NO_X, carbon monoxide, PM, and non-methane hydrocarbon emissions standards, which will make vehicles 77 to 95 percent cleaner than 2003 models.

Comparably, large trucks must meet the new 2007/2010 heavy-duty (HD) standard of less than 0.2 grams per brake-horsepower hour (g/BHP-hr) NO_X. EPA's 2007 HD standard requires that 50 percent of heavy-duty engines sold achieve NO_X emissions of 0.2 g/BHP-hr. The 2010 HD standard requires 100 percent of heavy-duty engines to achieve the same emissions level.

How CDC Technology Works

CDC technology keeps NO_X emissions from forming when the diesel fuel is burned in the engine. Through a series of engine improvements—to increase the performance of the diesel fuel injection system, reoptimize and refine air management/turbocharging systems, and improve the combustion system—CDC technology maintains consistent diesel engine combustion while maintaining peak temperatures below 1700° Celsius (°C) or about 25 percent lower temperature than conventional diesel engines. NO_X pollution is formed in an engine only at temperatures exceeding approximately 1700°C. Conventional diesel engine combustion typically reaches temperatures of 2300°C and higher. At these high temperatures in the engine's combustion chamber, the nitrogen and oxygen in air combine to form NO_X.

NO_x Formation During Diesel Combustion



EPA's Clean Diesel Combustion Minivan

CDC Partnerships

EPA is working closely with industry partners to develop and prove the promise of CDC technology. For example, in 2004, EPA and the International Truck and Engine Corporation announced a partnership to further develop EPA's CDC technology for cars, SUVs, and light pickup trucks. The International Truck and Engine Corporation has begun researching and evaluating CDC effectiveness in its new SUV-sized V-6 diesel engine.

In 2005, EPA and Ford Motor Company developed a Ford Galaxy minivan demonstration vehicle to showcase CDC technology. The diesel minivan gets 30 to 40 percent better mileage than a gasoline minivan, while meeting EPA's Tier 2 emission standards for NO_X of 0.07 grams per mile. The test vehicle showed that CDC technology can maintain high diesel efficiency and performance while achieving dramatic emissions reductions.

Building on Successes

In 2005, EPA and Ford Motor Company agreed to continue research efforts on the development of CDC technology. This work will build on previous joint research with the Ford Galaxy minivan, refining and testing the potential for the commercial application of CDC technology that meets the stringent Tier 2 emission standards and is more fuel-efficient than gasoline.

Building on its hydraulic hybrid drivetrain partnership with UPS, Eaton Corporation, International Truck and Engine Corporation, and the U.S. Army's National Automotive Center, EPA is continuing its UPS delivery truck demonstrations to a second phase. The plans for the latter phase of this project entail combining the hydraulic hybrid vehicle research with EPA's innovative CDC engine demonstrations into one package delivery truck. With the addition of the CDC engine, the demonstration truck is expected to meet EPA's 2010 NO_X standard for heavy duty-trucks without the need for any diesel exhaust treatment systems.

Pursuing the Next Generation of Clean Engines

EPA has recently begun focusing on two clean engine technologies: clean homogeneous charge compression ignition (HCCI) and free piston engine (FPE) technologies. Both HCCI and FPE have shown tremendous promise in EPA's laboratories and are ready for field demonstrations. EPA is currently looking for industry partners to help develop these exciting new technologies.

HCCI—Diesel Fuel Efficiency with Gasoline Emissions

HCCI technology has shown tremendous promise in laboratory testing. Because engine peak temperatures are cooler in an HCCI engine than in spark-ignited and diesel engines, HCCI significantly reduces NO_X emissions. In addition, premixed combustion in HCCI engines reduces PM emissions to low levels. Because of these features, an HCCI engine could perform with the fuel economy of a diesel engine, but with significantly lower emissions.

An HCCI engine can operate using many fuels as long as the fuel can be vaporized and mixed with air before ignition. EPA tested the HCCI engine concept with a four-cylinder gasoline-fueled engine that includes the EPA patented HCCI technology. Initial tests show multiple benefits of HCCI:

- Diesel-like fuel efficiency with gasoline.
- No exhaust treatment systems needed to achieve low NO_X emissions.
- HCCI possible for full operating range of the engine.

Under the Clean Automotive Technology Program, EPA has been working with Michigan State University to expand the operating range and performance of HCCI. Further, EPA is evaluating HCCI for use in hybrid vehicles.

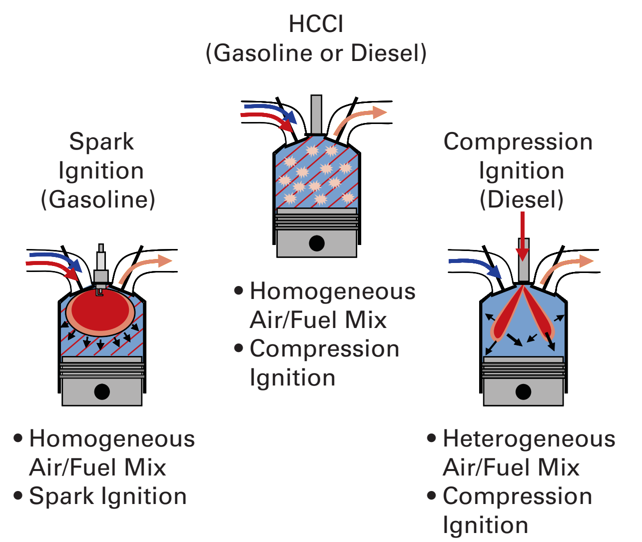
How HCCI Engines Work

A HCCI engine combines the principles of a traditional gasoline-powered engine with those of a traditional diesel-fueled engine. In an HCCI engine, fuel is homogeneously premixed with air (as in a spark-ignited gasoline engine) with a high proportion of air to fuel. As with diesel engine combustion, HCCI combustion is initiated by compression igniting the homogeneous fuel charge. Gasoline has primarily been used for initial demonstrations by EPA.

The technical challenges of HCCI engines involve controlling the combustion process and expanding the mode of operation to a larger proportion of an engine's load and speed range.

Homogeneous Charge Compression Ignition

Combines Best Attributes of Gasoline and Diesel Engines



FPE—A Simpler, More Efficient Engine

FPEs offer higher fuel efficiency, lower emissions, and lower initial and maintenance costs than a traditional combustion engines. In addition, EPA has developed FPEs that can combust a variety of petroleum or renewable fuels and deliver hydraulic energy. FPE benefits include:

- **Higher fuel efficiency.** The fuel efficiency of an FPE is higher than that of a traditional combustion engine because there are lower friction losses (due to fewer parts and the pistons not having side forces exerted on them from a crankshaft).
- **Lower emissions.** An FPE yields lower NO_X emissions because the products of combustion remain at high temperatures for shorter periods of time than in traditional engines, limiting the opportunity for NO_X to form.
- **Lower initial cost.** Due to the simplicity of FPE design, the manufacturing cost of an engine is anticipated to be much lower than the system it would replace.
- **Lower maintenance costs.** Maintenance costs for an FPE are lower due to simpler design and fewer parts.

EPA has designed two FPEs—a two-stroke engine and a four-stroke engine. EPA's engine testing indicates that four-stroke efficiency exceeds that of the best available diesel engine/hydraulic pump combination. In addition, EPA has developed a novel and robust control system for the FPE that could be incorporated into a vehicle drivetrain.

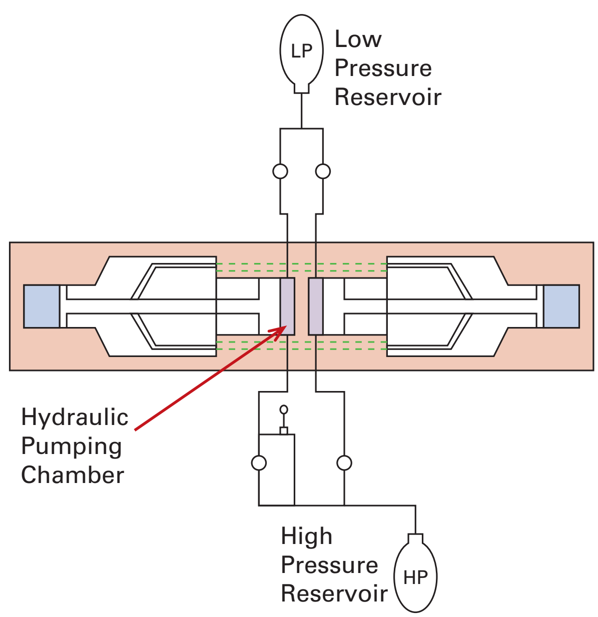
How FPEs Work

An FPE is a combustion engine in which the piston movement is not limited by any mechanical linkage. There is no crankshaft or flywheel. FPEs typically deliver their energy in pneumatic, hydraulic, or electric form.

The EPA FPEs are an integrated combination of an internal combustion engine and a hydraulic pumping system. The core of the engine is a combustion piston directly linked to a hydraulic pumping chamber. The piston assembly is not connected to any other mechanism and is free to move within the limitations of the cylinders. In this way, the energy of the combustion process is almost directly converted into hydraulic energy.

EPA Free-Piston Engine

- Internal combustion engine with no output shaft: direct conversion to hydraulic power
- Dual-piston, opposed cylinder design
- Centrally located hydraulic pumping chamber



Looking Ahead

EPA has ambitious plans to continue developing advanced vehicle technologies to help reduce the impact of vehicles on the environment by increasing fuel efficiency while reducing greenhouse gases and regulated emissions.

EPA's goals for the Clean Automotive Technology Program include:

- Accomplishing further technical advances in drivetrain and clean engine technologies, including meeting EPA's 2010 heavy duty NO_X standard with more than 30 percent fuel economy improvements.
- Continuing to work diligently with industry partners to bring promising developing technologies to market, with the goal of guiding hydraulic hybrid drivetrain and clean diesel combustion engine technology to commercial production by 2010.
- Involving new industry and university partners in groundbreaking new clean engine research including HCCI and FPE technologies.

With constraints on the supply of fossil fuels and increases projected for fuel prices into the foreseeable future, the work of the Clean Automotive Technology Program is as important as ever. EPA looks forward to continuing its efforts to advance innovative new technologies side-by-side with industry and university partners, leveraging resources towards making transportation as clean and fuel-efficient as possible.

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