Overview of DOE’s Combustion Engine R&D Program

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Advanced Combustion Engine R&D
FreedomCAR and Vehicle Technologies (FCVT) Program
Energy Efficiency and Renewable Energy
U.S. Department of Energy

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FCVT Program Mission
To develop more energy efficient and environmentally friendly highway transportation technologies that enable America to use less petroleum.
--EERE Strategic Plan, October 2002--
Our Oil Situation

(Millions of barrels per day)

<table>
<thead>
<tr>
<th>Country</th>
<th>Production (Mbd)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>1.79 (9.5%)</td>
<td></td>
</tr>
<tr>
<td>US Domestic</td>
<td>7.36</td>
<td></td>
</tr>
<tr>
<td>Venezuela</td>
<td>1.51 (8.0%)</td>
<td></td>
</tr>
<tr>
<td>Mexico</td>
<td>1.36 (7.2%)</td>
<td></td>
</tr>
<tr>
<td>Nigeria</td>
<td>0.95 (5.0%)</td>
<td></td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>1.62 (8.5%)</td>
<td></td>
</tr>
<tr>
<td>Iraq</td>
<td>0.55 (2.9%)</td>
<td></td>
</tr>
<tr>
<td>Other OPEC</td>
<td>0.63 (3.3%)</td>
<td></td>
</tr>
<tr>
<td>Other Non-OPEC</td>
<td>2.76 (14.5%)</td>
<td></td>
</tr>
<tr>
<td>U.K.</td>
<td>0.44 (2.3%)</td>
<td></td>
</tr>
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</table>

Crude Oil & Petroleum Products
Gross Imports 61%
Domestic 39%

Data for the month of March 2005

Note: Domestic production includes crude oil, natural gas plant liquids, refinery gain, and other inputs. This is consistent with EIA, MER, Table 3.2.
Previous versions of this chart included crude oil and natural gas plant liquids only.
Collaborations are Key to Answering Transportation Challenges

FCVT pursues five 2010 technological goals in advanced combustion engines, electric propulsion systems, energy storage, hydrogen-fueled ICEs, and materials technologies.

FCVT pursues dramatically improved fuel economy with near-zero emissions through advanced combustion engines and heavy hybrid drives that can use renewable fuels.
The Federal Role

- Undertake High-Risk Mid- to Long-Term Research
- Tap Unique National Lab Expertise
- Help Create a National Consensus
Vision: the achievement of vehicles and fuels that lead to a clean and sustainable energy future

Principles:
- Freedom from petroleum dependence and pollutant emissions
- Freedom to make personal mobility choices and to obtain fuel affordably and conveniently
Potential Pathways to the Hydrogen Economy

- Fuel Cell Technology
- Hydrogen Production & Storage Technology
- Advanced Engine & Fuels Technologies
- Power Electronics & Energy Storage

Research Will Make Technology Available

- Gasoline/Diesel ICE Hybrid
- Advanced ICE Hybrid
- Transitional Liquid Fuels Advanced ICE Hybrid
- H₂ Fuel Advanced ICE Hybrid
- H₂ Fuel Fuel Cell Hybrid

Energy Security

Today

2020 and beyond
Mid-Term (*FCVT* Program)

- Continue support for other technologies to reduce oil consumption and environmental impacts.
  - Hybrid Electric
  - Clean Diesel/Advanced ICE
  - Biofuels

Long-Term (**HFCIT** Program)

- Develop technologies to enable mass production of affordable hydrogen-powered fuel cell vehicles and the hydrogen infrastructure to support them.

*FreedomCAR and Vehicle Technologies
**Hydrogen, Fuel Cells, and Infrastructure Technologies
FreedomCAR Internal Combustion Engine Goals

- By 2010, internal combustion engine powertrain system costing $30/kW, having a peak brake engine efficiency of 45% and meet emission standards; and
- Internal combustion engine powertrain system operating on hydrogen with a cost target of $45/kW by 2010 and $30/kW in 2015, having a peak brake thermal efficiency of 45% and meet emissions standards (this goal is shared with the Hydrogen, Fuel Cells, and Infrastructure Technologies Program).
Research, Development and Demonstration in Five Key Technology Areas

- Engine Systems
- Heavy-Duty Hybrid
- Parasitic Losses
- Idle Reduction
- Safety
Improve Efficiency of Engine Systems

- Improve Class 7-8 brake thermal efficiency to 50% by 2010
- Research and develop technology to achieve 55% efficient prototype by 2013
- Explore new diesel fuel specifications using renewables and non-petroleum-based fuels to displace 5% of petroleum by 2010
By 2009, same standards for all U.S. cars & light-duty trucks
- Fleet average of Bin 5, maximum emissions Bin 8
- In states with California emissions, only Bin 5 diesels

US standards are more stringent than current EU standards

HD diesels have emission challenges similar to LD

Paths to Bin 5:
- With existing engine-out emissions, must achieve 90% PM/NOx reduction
- By further reducing engine-out emissions, aftertreatment burden reduced
Focus on new processes with potential for improved efficiency and reduced emissions

- Low Temperature Combustion (LTC) strategies such as Homogeneous Charge Compression Ignition (HCCI).

Barriers

- Poor understanding of LTC fundamentals
- LTC operating range limited to low to moderate loads
- Control of combustion and heat-release rates for LTC for steady and transient conditions

Strategy

- Improve engine efficiency
- LTC to reduce engine-out emissions which reduce requirements for aftertreatment system
- Expand LTC to cover more of the driving schedule
- Study interaction of fuel properties on LTC to determine synergies
- Improve understanding of combustion fundamentals and thermodynamic processes
- Synergy with hybrids
Combustion research is conducted under an MOU with 10 companies and 5 national labs.
Adiabatic flame temperature in air

CO to CO₂ conversion diminishes

Temperature [K]

Equivalence ratio

Soot limit

Soot

NOₓ

LTC

Diesel combustion
- controlled heat release (mixing)
- controlled combustion timing
- wide load range
- high efficiency (relative to SI)
- NOₓ and PM emissions

Spark ignition (SI) combustion
- controlled heat release (flame propagation)
- controlled combustion timing
- wide load range
- three-way catalyst
- low efficiency (relative to diesel)

Combustion Research is Focused on Low-Temperature Combustion (LTC)

- offers diesel-like efficiency (high CR & no throttling)
- low NOₓ and particulate emissions
- load range?
- combustion timing?
- heat release rate?
- transient control?
- fuel?
LTC Combustion Research Projects at SNL

- HCCI Fundamentals
- HSDI
- Heavy-duty
- Automotive HCCI
- Fuels
- LTC/Diesel
Experimental Research Approach

- Laser-based optical diagnostics.
- Realistic engine conditions.
- Realistic engine geometries with optical access through:
  - *pistons*.
  - *cylinder liner*.
  - *spacer plates*.
  - *exhaust ports*. 
**Objective:** Investigate the fundamentals of HCCI combustion.

**Research:**
- Low-load combustion efficiency (fuel stratification and ignition quality)
- Combustion timing control (intake temperature, heat transfer, residuals, burn duration, and fuel composition and stratification)
- High-load operation (pressure boost and thermal stratification).

**PI:** John Dec
**Objective:**
Provide the technological base required to develop high-efficiency HSDI engines operating on LTC/diesel that meet mandated emissions regulations.

**Research:**
- Investigate early- and late-cycle injection strategies for achieving LTC under highly swirling conditions (diesel fuel).
- Extending investigations of swirl effects on standard diesel combustion to include LTC and multiple injections strategies for improving diesel combustion.

- **PI: Paul Miles**
In-cylinder flow shown to be critical to effective late-injection LTC (SNL, UW, & WS)

- Late-injection LTC often sacrifices fuel economy for low emissions.

- Status:
  - Counter-rotating vortices improve late-cycle LTC
    - fuel and air meet with high mixing.
  - A spray-swirl momentum balance controls vortex formation:
    - swirl, bowl design, speed, load, injection pressure, and spray angle
  - Best fuel economy at swirl ratios ($R_s$) between 2.5 and 3.5.

- Next step:
  - Investigate early injection strategies and the potential of flow-structure enhanced mixing to extend the speed/load range.
Objective:
Provide the fundamental understanding of LTC and advanced diesel combustion processes needed to improve performance and reduce emissions from heavy-duty engines.

Research:
• Multiple injection strategies (close-coupled pilot and post, multiple main).
• Late- and early- injection strategies in heavy-duty engines.
• PI: Mark Musculus
**Conventional Diesel Combustion:**

High Soot and NOx Formation

*Laser/imaging diagnostics in an optical heavy-duty diesel engine reveal in-cylinder combustion and pollutant-formation processes.*

The vaporized fuel-air mixture downstream of the liquid is relatively uniform and *fuel-rich* ($\phi = 2-4$)

After the *liquid fuel penetrates 25 mm*, it is vaporized by the hot, entrained gases.

Shortly after the premixed fuel burns, *soot forms* in the hot, fuel-rich region *throughout the jet cross-section*.

A thin diffusion *flame* forms on the jet periphery. NO forms near this high-temperature flame.

* Schematic representation of combusting in-cylinder diesel fuel jet
For this mode of combustion, in-cylinder processes are radically different than conventional diesel combustion.

Liquid fuel (blue) rapidly vaporizes near end of injection during cool flame heat release (green).

Under low-density of early-injection, liquid fuel (blue) penetrates 50 mm or more, even as it vaporizes.

The strongest soot luminosity (red) is usually observed in roll-up vortices near the head of the jet.

OH (green) fills the jet cross-section, indicating leaner mixtures ($\Phi<2$) than conventional diesel combustion.

* Schematic representation of combusting in-cylinder diesel fuel jet
**Objective:**
Investigate HCCI fuel-air mixing and combustion processes in an automotive size engine.

**Research:**
- Injection strategies for HCCI/SCCI combustion.
- Characterize fuel-air mixing processes for variable injection timing using various injectors.
- Relationship between injection timing, combustion and emissions.
- HCCI/spark-ignited mixed-mode operation.
- **PI: Dick Steeper**
Fuel stratification can be used to improve HCCI emissions performance

- The stratification induced by delaying injection significantly improves conversion of CO to CO₂.
- The PDF analysis is shown to be a useful tool for predicting emissions trends.

• Probability density function (PDF) plots from LIF images show the strong effect of start-of-injection (SOI) timing on the distribution of φ.
Objective:

Develop a fundamental understanding of fuel effects on LTC and diesel combustion processes in heavy-duty CI engines.

Research:

• Oxygenated fuels.
• Biodiesels fuels.
• Fischer-Tropsch fuels.
• Oil-sands derived fuels
• Ideal fuel characteristics?

PI: Chuck Mueller
Accomplishment

• Achieved 2010-compliant steady-state NO\textsubscript{x} emissions with low smoke, high efficiency, and high power density using an oxygenated fuel and high levels of EGR.

Significance/Benefit

• This is an important step along the path to identifying fuel properties that enable optimal combustion in low-temperature operating regimes.

\[
\begin{align*}
\text{21\% } O_2 \\
\phi_\Omega (H) &= 2.7 \\
\text{9\% } O_2 \\
\phi_\Omega (H) &= 2.9
\end{align*}
\]
**Objective:**
Determine the effects of injector, in-cylinder and fuel parameters on LTC / advanced diesel combustion emissions processes with emphasis on high-power density and low-emission combustion modes.

**Research:**
- Determine parameter limits (injection pressure, orifice diameter, ambient gas conditions, and fuel properties) for generating low-emission, mixing-controlled combustion conditions.
- Multiple injection strategies.
- **PI: Lyle Pickett**
**Objective:**

Investigate fundamentals and operational issues of homogeneous and partially stratified combustion by conducting detailed analysis of chemical kinetics linked with fluid mechanics.

**Research:**

- Conduct high fidelity analysis of HCCI and PCCI combustion
- Determine the effect of operating conditions (geometry, turbulence level, load, fuel, etc.) on engine performance and emissions
- Analyze direct injected engines for combustion control and increased power
- Explore alternative and low grade fuels
- **PI: Salvador Aceves. Daniel Flowers**
Temperature distribution in a multi-component evaporating fuel spray calculated by KIVA-4 (LANL)

Modeling Tools for Physical And Chemical Kinetic LTC Processes Are Being Developed

The computational fluid dynamics codes and kinetic data developed by National Labs will be key to development and optimization of LTC combustion systems.

Ignition Performance predicted with multi-component kinetic for gasoline (LLNL)

<table>
<thead>
<tr>
<th>% Composition</th>
<th>Mix 1</th>
<th>Mix 2</th>
<th>Mix 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iso-Octane</td>
<td>60</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>n-Heptane</td>
<td>8</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Toluene</td>
<td>20</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Methyl cyclohexane</td>
<td>8</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>1-Pentene</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RON (blend)</td>
<td>99.2</td>
<td>94</td>
<td>87.6</td>
</tr>
<tr>
<td>MON (blend)</td>
<td>94.5</td>
<td>84.9</td>
<td>62.8</td>
</tr>
</tbody>
</table>

1200 rpm, 100kPa, T(BDC): Experimental=409K, Model=407-408K
Transitions to, from, and within High Efficiency Clean Combustion (HECC) studied at ORNL

- **Accomplishments**
  - Transition from OEM condition to HECC with reduction of engine-out NOx (90%) and soot (50%) at 20% load
  - Equal engine efficiencies during HECC and conventional combustion
  - Seamless load transitions within the HECC regime

- **Importance**
  - Combustion is stable in HECC and during transitions
  - Improved engine-system efficiency

- **Next Steps**
  - Demonstrate load expansion with low-pressure EGR and partially premixed charge preparation
  - Continue to explore speed and load transitions, without emissions excursions
Importance and Status:
- Unique capability to accurately measure the fuel distribution near the spray nozzle using x-ray absorption.
- Provides data that is crucial for the development of accurate spray models.

Next Steps:
- Extend scope of measurements (pressure, temperature) to realistic engine conditions.
- Collaborate with spray modelers to improve the accuracy and predictive power of spray simulations.
- Use improved modeling to guide fuel-system development for lower emissions and higher efficiency.

Measurements of the spray core at two different injection pressures and three different ambient pressures of N₂

Colors show mass per unit area
Diesel Fuel Spray (1,000 Bar)
**UW, PSU, UM, UCB, MIT, Stanford**

Engine control strategies and models for optimization and are keys to utilizing LTC

**Status:**
- Gasoline HCCI transient behavior and mode changing demonstrated in engine experiments.
- Ignition, combustion and heat transfer submodels developed for GT-power.
- Diesel LTC under load transients controlled with injection and intake valve timing control.
- Models show variable-spray angle fuel jets produce minimal “wall wetting” and increased combustion efficiency.

**Next steps:**
- Demonstrate strategies on laboratory engines
- Extend simulation to full transient vehicle environment
<table>
<thead>
<tr>
<th>Awardees</th>
<th>Additional Team Members</th>
<th>Scope of Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caterpillar, Inc.</td>
<td>ExxonMobil, IAV Automotive, SNL</td>
<td>Identify and/or advance technologies to enable low temperature, high efficiency combustion solution for 2010 on-highway truck or 2014 non-road machine applications; implement HCCI combustion using enhanced engine sensors, “intelligent” engine control, variable compression ratio, and fuel composition.</td>
</tr>
<tr>
<td>Cummins, Inc.</td>
<td>International, DaimlerChrysler, British Petroleum, LLNL, ORNL</td>
<td>Develop variable valve timing and premixed charge compression ignition (PCCI) technologies, and integrate them into a production-viable engine; demonstrate engines for both passenger and commercial vehicles and compatibility with renewable fuels.</td>
</tr>
<tr>
<td>Detroit Diesel Corporation</td>
<td>Freightliner, Schneider, Shell, DaimlerChrysler, ORNL, SNL</td>
<td>Combine processes that enhance engine combustion individually into one system that enables high efficiency clean combustion; investigate fuel effects, including renewable fuels; develop system hardware and controls to improve thermal efficiency of commercial engines while meeting emissions levels of 2010 and beyond.</td>
</tr>
<tr>
<td>General Motors Corporation</td>
<td>Sturman Industries</td>
<td>Develop parallel paths to improve passenger vehicle efficiency for both spark ignition and diesel engines; focus on variable valve timing technologies for short- and long-term applications to allow implementation of homogeneous charge compression ignition operation.</td>
</tr>
</tbody>
</table>

**National Laboratory Team Members:** SNL – Sandia National Laboratory; LLNL – Lawrence Livermore National Laboratory; ORNL – Oak Ridge National Laboratory; ANL – Argonne National Laboratory
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<th>Scope of Work</th>
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</thead>
<tbody>
<tr>
<td>International Truck and Engine Company</td>
<td>Ricardo, Borg-Warner Turbo, Jacobs Vehicle Systems, Mahle, Conoco-Phillips, UC Berkeley, LLNL, ANL</td>
<td>Develop and apply HCCI combustion over as large an operating range as possible by integrating commercial or near-commercial fuel, air, and engine technologies (variable valve timing, variable compression ratio, variable nozzle turbocharging, and fuel injection equipment) with advanced controls; demonstrate in a commercial diesel engine.</td>
</tr>
<tr>
<td>John Deere Product Engineering</td>
<td>Sturman Industries, Ricardo Technologies, Purdue University</td>
<td>Develop stoichiometric compression-ignition engine with low-pressure loop cooled exhaust gas recirculation (EGR) and a diesel particulate filter followed by a three-way catalyst; combustion will be similar to conventional diesel combustion with lower peak temperatures. Modify a commercial diesel engine with high injection pressure fuel system, variable valve timing and advanced electronic controls along with aftertreatment and low pressure loop EGR system.</td>
</tr>
<tr>
<td>Mack Trucks, Inc.</td>
<td>UCLA, Sturman Industries, Advanced Energy Systems</td>
<td>Develop and demonstrate an air-power-assist (APA) engine for improving fuel efficiency by 15 percent with emissions meeting the 2010 regulations; engine would utilize braking energy to pump compressed air into an onboard tank; during acceleration engine is powered by the compressed air with or without burning diesel fuel until the compressed air is depleted; develop key technology (fully-flexible engine valve actuation system) required for the APA engine; test on a commercial diesel engine.</td>
</tr>
<tr>
<td>Awardees</td>
<td>Additional Team Members</td>
<td>Scope of Work</td>
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</tr>
<tr>
<td>Michigan State University</td>
<td>Visteon.</td>
<td>Integrate advanced technologies for high efficiency clean combustion for in-vehicle fuel economy improvement of 20% over production port-fuel-injected gasoline engines; employ a high-compression-ratio, modified Atkinson cycle using a novel low-pressure direct injection fuel system and electronically-controlled pneumatic valve actuation; enhance and enable these systems by combustion sensing ionization feed-back control for knock and combustion stability control and a forward-backward mass air flow sensor system for precise air-fuel ratio control.</td>
</tr>
<tr>
<td>Honeywell International</td>
<td>University of Minnesota Center for Diesel Research and John Deere Power Systems</td>
<td>Develop, validate, and optimize advanced fast-response particulate matter and nitrous oxides sensors suitable to support an exhaust gas recirculation control system in diesel engines; validate and operate the sensors under conditions expected in diesel engine applications.</td>
</tr>
<tr>
<td>Delphi Automotive Systems, LLC</td>
<td>Electricore, Inc.</td>
<td>Develop and validate an optimal, cost effective approach to variable valve actuation for advanced, low-temperature combustion processes in diesel engines; include development and scale-up testing of a continuously variable valvetrain system with appropriate control systems.</td>
</tr>
<tr>
<td>Envera, LLC</td>
<td>Magna-Steyr and Automotive Specialists</td>
<td>Develop fast-response actuator system for adjusting the compression ratio to improve efficiency in variable compression ratio gasoline and diesel engines; provide improved control of advanced homogeneous charge compression combustion processes; focus on demonstrating an actuator system having a fast cycle-resolved response, high reliability, low cost, and minimal parasitic power load on the engine; fabricate, install, and test an optimized actuator system in a vehicle.</td>
</tr>
</tbody>
</table>