Advanced Combustion and Emission Control (ACEC) Activities

February 8, 2005

FreedomCAR Advanced Combustion and Emission Control (ACEC) Goals

• Reduce petroleum dependence by removing critical technical barriers to the mass commercialization of high-efficiency, emissions-compliant internal combustion engine (ICE) powertrains

• Primary directions
  − ICE efficiency improvements for cars and light-duty trucks through low-temperature combustion and minimization of thermal and parasitic losses
  − Emission control development integrated with combustion strategies for emissions compliance and minimization of efficiency penalty
  − Increased efficiency and power density for hydrogen ICE
  − Coordination with fuels R&D to enable clean, high-efficiency engines using both hydrocarbon-based fuel (petroleum and non-petroleum) and H₂

• 2010 technical goals
  − Best engine brake thermal efficiency 45%
  − Powertrain cost $30/kW
  − NOx & PM emissions Tier II Bin5
## ACEC Goals and Status

Goals reflect strategy to move from gasoline PFI to diesel/gasoline/H₂ DI

<table>
<thead>
<tr>
<th>Goals for HC Fuel</th>
<th>2004 Status</th>
<th>Goals by Fiscal Year</th>
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<tbody>
<tr>
<td></td>
<td>PFI</td>
<td>DI</td>
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<tr>
<td>ICE peak brake thermal efficiency</td>
<td>%</td>
<td>30</td>
</tr>
<tr>
<td>ICE Powertrain cost (1)</td>
<td>$/kW</td>
<td>20</td>
</tr>
<tr>
<td>Projected vehicle emissions</td>
<td>Tier 2</td>
<td>&lt; Bin 10</td>
</tr>
<tr>
<td>Emission control fuel economy penalty (2)</td>
<td>%</td>
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<tr>
<td>Emissions Durability</td>
<td>k miles</td>
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<td>DI</td>
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<tr>
<td>H₂ ICE peak brake thermal efficiency</td>
<td>%</td>
<td>38</td>
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<tr>
<td>H₂ ICE Powertrain cost (1)</td>
<td>$/kW</td>
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<td>45</td>
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<tr>
<td>Projected vehicle emissions</td>
<td>Tier 2</td>
<td>&lt; Bin 5</td>
<td>Bin 5</td>
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(1) High volume production of 500,000 per year
(2) Fuel economy penalty over combined Federal Test Procedure due to emission control relative to diesel vehicle with 2003 emissions

## US Diesel Emission Standards

Fuel Sulfur Regulation: current - 500 ppm, future - 15 ppm starting in 2006

- By 2009, same standards for all US 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

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### Diesel Tailpipe Emissions Regulations (<8500 lb)

![Diagram showing diesel tailpipe emissions regulations](chart)

### Heavy Duty Diesel Truck Emission Standards (>8500 lbs)

![Diagram showing heavy duty diesel truck emission standards](chart)
Research Strategy

PNGV Future Today Future

Combustion & Emissions

Combustion Optimization
Reduce Thermal/Mechanical Losses

LTC at Light Load

HC Fuels

Low Temp Combustion

2003

2006

2007

2010

2015

Emissions For LTC

$30/kW

$30/kW

Combustion Optimization

2010

Bin 5 Emissions 45% Peak Efficiency

2003

Bin 5 Performance for Fresh Catalysts

2003

LTC at Light Load

2007

Expanded Load Range

2010

2015

Durable Bin 5 System

$30/kW

$30/kW

H₂ ICE

Improved Efficiency

Direct Injection

Combustion Optimization

2004

2005

Sulfur Trap Feasibility

PM Measurement Systems

2004

2005

2007

Combustion Control Sensors

2003

Bin 5 Performance for Fresh Catalysts

2003

LTC at Light Load

2007

Expanded Load Range

2010

2015

Durable Bin 5 System

$30/kW

$30/kW

Combustion Understanding

Modeling, kinetics, fundamentals

Enablers

2004

2005

2007

Combustion Control Sensors

Combustion

• 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
  – LTC to reduce engine-out emissions which reduce requirements for aftertreatment system
  – Expand LTC to cover more of the driving schedule
  – Improve engine efficiency
  – Study interaction of fuel properties on LTC to determine synergies
  – Improve understanding of combustion fundamentals and thermodynamic processes
  – Synergy with hybrids
Combustion Research is Focused on Developing the Knowledge-Base Needed to Implement LTC.

Adiabatic flame temperature in air

CO to CO₂ conversion stops

Low-Temperature Combustion
- low NOx and particulate emissions
- offers diesel-like efficiency
- load range?
- combustion timing?
- heat release rate?
- transient control?
- robust combustion system?
- fuel?

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

SI combustion (stoichiometric)
- controlled heat release (flame propagation)
- controlled combustion timing
- wide load range
- three-way catalyst
- throttling losses
- lower efficiency (relative to diesel)

• Importance & Status
  - New methods for LTC with diesel-like, mixing-controlled heat release were discovered - one approach uses no EGR.
  - Since combustion is mixing-controlled, unpredictable heat-release rates in premixed systems are avoided.

• Next steps
  - Determine the boundaries & robustness of mixing-controlled LTC
  - Investigate the feasibility of using in an engine.
In-Cylinder Flow Structures Promotes Air-Fuel Mixing in Late-Injection Diesel LTC (SNL and UW).

- **Importance**
  - Late-injection LTC often sacrifices fuel economy for low emissions.
  - Previously, kinetics largely thought to dominate the entire combustion process.

- **Status**
  - Variable swirl alters the in-cylinder air motion and can produce counter-rotating vortices
    - At optimal conditions, fuel and air meet at interface with high mixing and combustion phasing is improved
    - Best fuel economy and lowest soot found between swirl ratios, $R_s$, of 2.5 and 3.5.

- **Next steps**
  - Investigate early injection strategies and the potential of flow-structure enhanced mixing to extend the speed/load range.

Achieving and Transitioning to Efficient Low Temperature Combustion (ORNL)

- **Accomplishment**
  - Achieved LTC with reduction of engine-out NOx (90%) and soot (50%) at 20% load.
  - Equal engine efficiencies during LTC and normal combustion.
  - The transition between modes was several seconds. This was faster than other studies but not sufficient for a production vehicle. The ability to achieve the LTC condition depended on the transition path.

- **Importance**
  - The combustion process is not degraded and HC emissions are not excessive.

- **Next Steps**
  - Demonstrate load expansion with low-pressure EGR and partially premixed charge preparation.
  - Demonstrate effects of transition path for expanding LTC operation range.
University Consortia Developing LTC Optimization and Control Methods (UW, PSU, UM, UCB, MIT, Stanford)

- **Importance**
  - Engine control strategies a key to utilizing LTC
  - Computer simulation used for engine design and evaluation of proposed control strategies

- **Status**
  - Gasoline HCCI transient behavior and mode changing demonstrated in engine experiments.
  - Ignition, combustion and heat transfer submodels developed and incorporated into GT-power.
  - Diesel LTC under load transients controlled with injection and intake valve timing control.
  - Calculated fuel-spray patterns with variable-spray angle produce minimal diesel fuel on wall and potential for increased combustion efficiency

- **Next steps**
  - Demonstrate strategies on laboratory engines
  - Extend simulation to full transient vehicle environment

Combustion Modeling and Chemical Kinetics are Keys to Understanding the Detailed Combustion Processes

The computational fluid dynamics codes and kinetic data developed by National Labs are relevant to and used by the industry as a whole

Temperature Distribution in a Multi-Component Evaporating Fuel Spray Calculated by KIVA-4 (LANL)

Ignition Performance Predicted with Multi-Component Kinetic for Gasoline (LLNL)

1200 rpm, 100kPa, T(BDC): Experimental=409K, Model=407-408K
**X-Ray Measurements Reveal Structure of Diesel Spray Core (ANL)**

**Importance**
- X-ray absorption used for the first quantitative measurements of the fuel-mass near the spray nozzle as functions of time and position.
- Mass and momentum data improves the accuracy of spray models, enhancing their ability to reproduce and ultimately predict the structure of the spray under different combustion regimes.

**Next Steps**
- Extend scope to measurements under actual engine conditions.
- Collaborate with spray modelers to improve the accuracy and predictive power of spray simulations using unique near-nozzle data.
- Use improved modeling to guide fuel-system development for lower emissions and higher efficiency.

**Value**
- These measurements were made with a unique facility and personnel at ANL.

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**Co-Development of Fuels and Advanced Combustion Engines is Essential to Ensure Availability of Fuels Optimized for New Combustion Regimes**

**HCCI Combustion Phasing Affected by Fuel Properties**

**Work Currently Underway**
- Characterize sensitivity of advanced combustion regimes to variations in fuel properties.

**Future Plans**
- Through parametric analysis and modeling, identify relevance of fuel properties at a molecular level to advanced combustion regimes.
- Identify bulk fuel properties (e.g., an analog to cetane) that characterize fuels optimal for advanced combustion regime operation.
H₂ ICE Research

- **Objective**
  - Develop high-efficiency, low-emission H₂ SI engines which bridge toward the future H₂ economy

- **Barriers**
  - Low power density for ultra-low emission operation
  - Unknown combustion stability, pre-ignition and knock characteristics
  - Lack of understanding of direct-injection mixing processes
  - NOx emissions at higher power density

- **Strategy**
  - Achieve power density comparable to gasoline PFI with direct injection, pressure boosting, intercooling
  - Achieve bin 5 or lower emissions with a combination of lean and stoichiometric combustion
  - Develop the fundamental knowledge-base and simulation tools
  - Other technical areas develop infrastructure and on-board storage

Emission Control Enables High-Efficiency, Lean-Burn Engines

- **NOx aftertreatment approaches**
  - LNT: lean NOx trap, also called NOx adsorber
  - Urea SCR: selective catalytic reduction with urea (ammonia)
  - HC SCR: selective catalytic reduction with hydrocarbons
  - Plasma: electrical energy creates ions to react with exhaust gases

- **Barriers**
  - LNT: fuel economy penalty, degradation by sulfur and high temp
  - Urea-SCR: infrastructure, enforcement
  - PM filter: fuel economy penalty from back pressure and effective regeneration strategies

- **Strategy**
  - LNT: improve conversion at lower temperatures, determine degradation mechanisms due to poisons and ways to reverse effect
  - Urea: system control to prevent breakthrough & unregulated emissions
  - PM filter: new regeneration methods
  - Modeling: improved fundamental understanding and simulations
Typical Emission Control System

- Separate devices shown for HC, NOx and PM control
- Components depend on strategy:
  - With SCR, urea is added
  - With LNT, HC is added in exhaust or by engine
- HC or external source necessary to heat PM filter for regeneration

Typical Performance Curves of Slightly Aged Catalysts (Ford)

- Widest temperature range for Urea SCR
- Narrower temperature range for LNT which does not cover both FTP & US06
- Plasma and HC SCR have lower NOx conversion
- HC SCR conversion too low, but might improve with new materials
Simulated FTP NOx Conversion vs Fuel-Economy Penalty Assuming 2.5L Engine (Ford)

- Lowest FE penalty for urea SCR, higher FE penalties for other strategies
- Energy requirement for urea manufacture approximately 0.2%
- FE penalty for LNT at 80% conversion exceeds technical target (<5%)

System Testing with Fresh Catalysts Shows Progress to Bin 5
Passive systems, which represent current production, do not achieve Bin 5
Active systems studied in this program (LNT, urea SCR) are required for Bin 5
Results are for fresh catalysts whose performance deteriorates with use

Emissions reduced with combustion improvements
Bin 5-8 emission achieved for cars & trucks with active NOx systems, but durability is not proven
**NOx Adsorber Aged for 1000 Hours (DOE APBF-DEC)**

- NOx adsorber for 1.9L engine aged using D15 fuel with 15-ppm sulfur
- Nine desulfations at 150hr, 300hr, then every 100hrs
- Test planned for an additional 1200hrs (120k mi equivalent)
- Test sequence designed for catalyst aging and not emission certification
- Conversion target equivalent to 0.07 g/mi NOx

- Initial conversion met NOx target, but became inconsistent during aging
  - Some desulfations restore NOx conversion (even @ 1000hr), but others do not
- Remaining issues:
  - NOx conversion during aging frequently less than target
  - Process to desulfate, mitigation of fuel penalty, other regulated emissions (NMHC)
  - Data guide other studies on mechanisms of catalyst deactivation (sulfur poisoning, thermal deactivation) and desulfation
  - LNT aging studies are value added for OEM evaluation of this technology

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**Fast-Throughput Methods Used to Discover New, NOx Reducing Catalytic Materials (GM)**

- Importance: Selective Catalytic Reduction (SCR) of NOx using HC has the potential to:
  - Simplify the emissions control strategy
  - Minimize fuel economy penalty
  - Avoid Infrastructure & dispensing issues
- Discovery of this new material is key to developing a HC SCR strategy for NOx reduction
- Status: Bench Reactor tests show that high temperature activity could be sufficient, but low temperature activity needs to be improved.

- Next Steps: Use the high throughput program to search the very large 3-5 component materials space to discover additional new materials that have good low temperature activity and higher high temperature activity. Move from Bench Reactor to engine exhaust testing.
- Example of work with high risk/high potential reward
Diesel Particulate Trap Regenerated by Microwave Spot Heating (GM)

**Current Approach: Regeneration by Exhaust Heating**
- DPF peak temperature and soot burn rate is controlled by limiting exhaust O2.
- Requires excess fuel in combustion chamber or in exhaust.
- Regeneration cycle is dependent on engine operating mode.
- Potential for uncontrolled temperature increase.

**Soot Regeneration using Microwave Spot Heating**
- Soot burning is initiated by localized microwave heating of less than 5% of DPF volume.
- Regeneration is less dependent on engine operation mode and is controlled by the lower substrate and exhaust gas temperature.
- Initiate soot regeneration at lower exhaust gas and DPF substrate temperatures (more typical of diesel 200-250°C).
- Use un-catalyzed, Cordierite substrate.
- Minimizes fuel efficiency loss.

**Next Steps**
- Continue laboratory studies using vehicle-loaded DPF substrates.
- Transition to vehicle testing and system integration.

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Response Maps for LNT Developed by CLEERS* Activity

**Importance**
- Kinetic maps summarize the response of new LNT materials to a standard test protocol.
- The map data is used to calculate LNT performance for exhaust systems.
- Industry-wide consensus on LNT device maps simplifies supplier testing and enables more rapid LNT development.

**Next steps**
- Demonstrate and refine measurement protocol and then transfer the protocol to the aftertreatment suppliers.
- Apply LNT experience to DPF and SCR.

*CLEERS is a collaboration between global OEM’s, DOE, EPA, National Laboratories, Universities & TACOM to share non-competitive data and information.
Enabling Technologies

Objective:

• Develop sensors and measurement methods necessary for implementation of control strategies

Barriers:

• New combustion and emission control systems require new sensors for system control and on-board diagnostic requirements

Strategy:

• Sensors for NOx and particulates
• Particulate measurement during transients to improve engine control
• Sensors to control combustion

Particulate Sensor shows Potential for Engine Control (Honeywell, Univ of Minnesota)

• Importance
  – Goal is to develop a PM sensor that is suitable for closed-loop control of a diesel engine and/or an on-board diagnostic monitor
  – The sensor requirements are low cost, robust to harsh environments and manufacturable in high volumes.

• Status
  – Prototype sensors were fabricated and tested for more than 100 hours in the exhaust of different engines without degradation
  – Sensor output correlates with traditional measurements and shows required temporal resolution

• Next steps
  – Continue testing, develop signal processing algorithms, correlate output to individual cylinders
Real-Time PM Diagnostic Development (SNL)

- **Importance**
  - Improved, real-time diagnostics are needed to investigate PM emissions during transient operation and to meet the upcoming not-to-exceed regulations
  - Improved PM measurement sensitivity is needed for 2007 and beyond

- **Status**
  - Project enabled commercialization of laser-induced incandescence (LII) instrument by Atrium Technologies, Inc.
  - Real-time volatile fraction measurement feasibility has been demonstrated

- **Next steps**
  - Develop volatile fraction diagnostic to enable possible commercialization
  - Develop real-time diagnostic for particulate size

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**Cost**

**Objective:**
- $30/kW for engine, transmission and emission systems

**Barriers:**
- Diesel engine costs are high relative to gasoline engines due to added content
- Cost optimization occurs during commercialization by an OEM

**Strategy:**
- First, determine technical feasibility of powertrain and aftertreatment system
- Then, improve the effectiveness of the system to reduce the cost using strategies such as LTC
Challenges and Needs

• **Open Issues**
  – Improvement of engine efficiency
  – Robust emission system
  – $30/kW cost goal

• **Research Direction**
  – More involvement of industry through vertically integrated teams (auto, energy, suppliers) and new focused solicitations
  – Continue work to improve understanding at national labs and universities
  – Focus on new combustion regimes