Overview

Activity direction evolves with the DOE needs and is currently focused on milestones associated with Vehicle Technologies emissions objectives.

Duration
- Consistent with VT MYPP
- Activity scope changes with DOE needs

Barriers
- Efficiency/combustion
- Emission control
- Engine management

Budget
- FY 2006 $350k (milestone met)
- FY 2007 $350k (milestone met)
- FY 2008 $400k (milestone met)
- FY 2009 $400k (in progress)
- FY 2010 $400k (anticipated)

Interactions / Collaborations
- Industry technical teams
- DOE working groups
- One-on-one interactions with industry
- Common engine geometry between Sandia, UW, and ORNL.
**Objective** is to further development, implementation and integration of advanced combustion for optimal efficiency and lowest possible emissions

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Peak Brake Thermal Efficiency (HC Fuel)</td>
<td>41%</td>
<td>42%</td>
<td>43%</td>
<td>44%</td>
<td>45%</td>
</tr>
<tr>
<td>Part–Load Brake Thermal Efficiency</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(2 bar BMEP @ 1500 rpm)</td>
<td>27%</td>
<td>27%</td>
<td>27%</td>
<td>29%</td>
<td>31%</td>
</tr>
<tr>
<td>Emissions</td>
<td>Tier 2 Bin 5</td>
<td>Tier 2 Bin 5</td>
<td>Tier 2 Bin 5</td>
<td>Tier 2 Bin 5</td>
<td>Tier 2 Bin 5</td>
</tr>
<tr>
<td>Thermal efficiency penalty due to emission control devices</td>
<td>&lt; 2%</td>
<td>&lt; 2%</td>
<td>&lt; 2%</td>
<td>&lt; 1%</td>
<td>&lt; 1%</td>
</tr>
</tbody>
</table>

**FY 2008 Milestone ➔ complete**

Explore HECC operation and EGR/air mixture temperature effects to better understand implementation of low temperature combustion processes on multi-cylinder engines (September 30, 2008).

**FY 2009 Milestone ➔ in progress**

Characterize cylinder/cyclic dispersion of HECC operation for modal conditions which are consistent with LD diesel operation (September 30, 2009).
Important to consider interactions/compatibility of combustion strategy with other efficiency enabling technologies

Active research on-going in many of these areas in support of DOE and Vehicle Technologies objectives

Engine & System Supervisory Control

Fuel Technology

Advanced (HECC) Combustion

Engine

Thermal Recovery

Aftertreatment & Regeneration

Power Electronics and Controls

Electric Machinery

Physical/Chemical Characterization

Novel Diagnostics and Sensors

Component and System Modeling

Thermodynamics

Nonlinear Dynamics

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Comprehensive **approach** necessary for successful implementation of **robust** HECC operation

**Thermodynamics**
Identification of efficiency opportunities and synergies with thermal energy recovery.

**Combustion Stability**
Characterization and control of cyclic/cylinder dispersion for more robust HECC operation.

**Combustion Noise**
Phenomenological models and combustion characterization methods.

**Exhaust Speciation**
Improved understanding of particulate and gaseous emissions and matching with emission controls.

**Intake Charge Preparation**
LP+HP EGR systems for manipulating intake charge conditions.

**Flexible Engine Control**
Unconstrained control and integration of custom algorithms.

**Modeling**
Guidance for experiments as well as interpretation of experimental data.

**ORNL toolbox** for multi-cylinder combustion research
Simulation + Experiment + Collaboration

**Simulation** to characterize and evaluate HECC operation from engine to vehicle level.

- Combustion modeling (In-house multi-zone models)
  » Guide experiments and interpret experimental data.

- Engine-system modeling (GT-Power & WAVE)
  » Evaluate combustion management strategies, design/evaluate auxiliary systems such as low-pressure EGR, etc.

- Vehicle System modeling (PSAT & GT-Drive)
  » Evaluate integration of technologies (e.g., HECC, thermal energy recovery, aftertreatment, etc.) and operational strategies across simulated drive cycles.

**Experiments** for development and demonstration of methods in multi-cylinder environment.

<table>
<thead>
<tr>
<th>Engine Model</th>
<th>Year</th>
<th>Number Cylinders</th>
<th>Bore, mm</th>
<th>Stroke, mm</th>
<th>Compression Ratio</th>
<th>Rated Power, kW</th>
<th>Rated Torque, Nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM 1.9-L</td>
<td>2005, 2007</td>
<td>4</td>
<td>82.0</td>
<td>90.4</td>
<td>17.5</td>
<td>110</td>
<td>315</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MB 1.7-L</td>
<td>1999</td>
<td>4</td>
<td>80.0</td>
<td>84.0</td>
<td>19.0</td>
<td>66</td>
<td>180</td>
</tr>
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</tbody>
</table>
More details on multi-cylinder engine platform

MB 1.7-L Engine (1999)

- Bosch Gen 1 fuel system
- Modifications include VGT, HP & LP EGR, throttle, etc.
- Flexible micro-processor based controls
- WAVE model

Transition to more modern engine platform complete


- Bosch Gen 2 fuel system
- OEM version includes VGT, EGR cooler, throttle, etc.
- Geometry common to ORNL, UW, and SNL (optical)
- Open ECU and flexible micro-processor based controls
- GT Power model
Engine conditions consistent with LD drive cycles and consistent with those used in related activities at ORNL

- Used to estimate drive-cycle emissions and efficiency for technology comparisons.
- Considered representative speed-load points for light-duty diesel engines.
- Method does not account for cold-start, transient phenomena, aftertreatment regeneration, etc.

<table>
<thead>
<tr>
<th>Point</th>
<th>Speed / Load</th>
<th>Weight Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1500 rpm / 1.0 bar</td>
<td>400</td>
<td>Catalyst transition temperature</td>
</tr>
<tr>
<td>-</td>
<td>1500 rpm / 2.0 bar</td>
<td>NA</td>
<td>VT milestone condition (not included in FTP estimate)</td>
</tr>
<tr>
<td>2</td>
<td>1500 rpm / 2.6 bar</td>
<td>600</td>
<td>Low speed cruise</td>
</tr>
<tr>
<td>3</td>
<td>2000 rpm / 2.0 bar</td>
<td>200</td>
<td>Low speed cruise with slight acceleration</td>
</tr>
<tr>
<td>4</td>
<td>2300 rpm / 4.2 bar</td>
<td>200</td>
<td>Moderate acceleration</td>
</tr>
<tr>
<td>5</td>
<td>2600 rpm / 8.8 bar</td>
<td>75</td>
<td>Hard acceleration</td>
</tr>
</tbody>
</table>

For more information on modal conditions see SAE 1999-01-3475, 2001-01-0151, 2002-01-2884, 2006-01-3311 (ORNL)
Technical Accomplishments/Progress (since February 2008)

- Established and compared HECC methods for optimal efficiency, emissions, and combustion noise (MB and GM engines).
- Explored load expansion and thermal influences with additional emphasis on higher load operation more consistent with engine downsizing (GM engine).
- Performed drive-cycle simulations based on experimental HECC maps to characterize potential of conventional and advanced powertrains.
- Evaluated fuel properties effects on HECC operation (Fuels Technologies activity)
- In progress characterizing cylinder/cyclic dispersion sensitivity to HECC method and EGR/air maldistribution (not shown).

FY 2009 experiments scheduled for Spring 2009 (now) and are on-going.
Premixed Charge Compression Ignition (PCCI) combustion is primary path for this activity

- Most compatible with current and near-term engine technologies.
- Purpose is to reduce in-cylinder emissions formation with minimal impact on brake thermal efficiency.
- Driven by high intake charge dilution and high fuel injection pressures to increase premixed combustion.
- Sensitive to thermal boundary conditions and transients.
- Many acronyms but collectively referred to as High Efficiency Clean Combustion (HECC).
Several PCCI approaches explored on the MB and GM engines from an efficiency and systems integration perspective

- Advanced combustion approaches use similar intake charge dilution and fuel injection pressure *for each engine*.
- Mass of fuel delivery is the same for all strategies *for each engine*.
- Experiments performed for FTP modal conditions described earlier.
MB efficiency and emissions comparison for several strategies under road load conditions

- Early PCCI appears most effective for HECC operation.
- Combustion noise higher for HECC (88-90 dB range)
- Similar trends observed for moderate acceleration conditions.

Data source: MB Engine, 1500 rpm, 2.6 bar BMEP
Similar trends for GM engine but with much lower PM emissions

- Similar trends observed for moderate acceleration conditions.
- Note significant difference in scales as compared to MB data on previous slide.
- CO/HC emissions also much higher for these experiments.

Data source: **GM Engine**, 1500 rpm, 2.6 bar BMEP
Advanced combustion is trade-off between NOx, PM, and BTE

- Explored for several strategies on both engines for FTP modal conditions.
  - For comparison shown, high BTE is accompanied by higher PM.
  - As an example, BTE of 29% with reasonable NOx and PM has also been demonstrated on GM for 1500 rpm, 2.0 bar BMEP.

- Influenced by thermal conditions such as encountered during cold-start and transients.
  - Thermal effects of intake mixture, EGR, coolant, and lubrication currently under investigation.

- Controllable to better match aftertreatment, thermal energy recovery, or other technologies.
  - “Characterization of LNTs for LD diesel engines”
  - “Emissions controls for multimode LD diesel engines”
  - “Vehicle Technologies efficiency engine milestones”

Data source: 1500 rpm, 2.6 bar BMEP (road load)
Thermal conditions affect ability to achieve good efficiency with low emissions

- Lower intake air-EGR mixture temperatures enable expanded HECC operation.
- Most significant impact was on PM formation.
- Lower intake temperature was necessary to achieve HECC at 3.8 bar BMEP, 1500 rpm.

\[ \Delta T \approx 8-10 \, ^\circ C \]

\text{higher intake temperature} \quad \text{lower intake temperature}
Analysis/modeling provides guidance on pathways and thermal effects on emissions formation

- Experimental heat release profiles with phenomenological model are used to construct the combustion path across the 3-D map of soot and NOx as a function of $\phi$-T-O$_2$.
- 3D Soot-NOx map demonstrates: (a) soot zone is shrunken at low oxygen concentration; (b) high dilution has potential to avoid the rich soot zone.

OEM (red)  
High dilution (green)  
HECC (pink)  

Analysis/model validated with KIVA and performance and engine-out emissions data.
Mixed-mode HECC operation investigated over drive cycles with experimental maps and PSAT

- Uses mixed-mode simulation with HECC operation when appropriate as dictated by speed-load requirement.
- Vehicle configuration based on MB 1.7-L diesel engine and Honda Civic chassis.
- Simulations include cold- and warm-start with (shown) and without aftertreatment.

Vehicle in HECC mode 91% of UDDS.
Drive cycle simulations show benefits of mixed-mode HECC operation on NOx and soot emissions and challenges associated with HC/CO

- Simulations also complete with NOx and PM aftertreatment models.
  - Different regeneration strategies and combustion modes.
  - Evaluation with advanced powertrains such as HEV and PHEV.
  - See VSS06, Daw, “PHEV Engine and Emissions Models” for more information.

- Models in development with GT-Drive to evaluate bottoming cycle potential on light-duty drive cycles.

<table>
<thead>
<tr>
<th>FTP CYCLE</th>
<th>HECC and conventional</th>
<th>Conventional only</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx, g/mi</td>
<td>UDDS: 0.348, US06: 1.076, ECE: 0.248</td>
<td>UDDS: 0.897, US06: 1.325, ECE: 1.072</td>
</tr>
<tr>
<td>Soot, g/mi</td>
<td>UDDS: 0.038, US06: 0.089, ECE: 0.028</td>
<td>UDDS: 0.065, US06: 0.096, ECE: 0.079</td>
</tr>
<tr>
<td>HC, g/mi</td>
<td>UDDS: 0.668, US06: 0.304, ECE: 1.033</td>
<td>UDDS: 0.418, US06: 0.295, ECE: 0.639</td>
</tr>
<tr>
<td>HECC time, %</td>
<td>90.9</td>
<td>na</td>
</tr>
<tr>
<td></td>
<td>57.6</td>
<td>na</td>
</tr>
<tr>
<td></td>
<td>96.2</td>
<td>na</td>
</tr>
</tbody>
</table>
Path Forward

- Continued integration with other advanced technologies and fuels research in support of 2010 and beyond Vehicle Technologies objectives.
- Continued load expansion efforts to improve use with engine downsizing.
- Continued exploration of sensitivity to engine thermal conditions for improved integration with other advanced technologies.

*Transient and systems integration issues are becoming more and more important AND are focus points of the next phase of ORNL advanced combustion research.*
Summary or take away points

• **Objective / Approach**
  » To further development, implementation and integration of advanced combustion for optimal efficiency AND lowest possible emissions
  » Comprehensive approach including modeling, analysis, and experiment.

• **Technology Path & Demonstration**
  » Development and demonstration of advanced combustion strategies with combined emphasis on efficiency, emissions, and integration with other technologies including aftertreatment.
  » Load expansion for improved in-cylinder emissions reduction across conventional speed-load maps with additional emphasis on higher load operation more consistent with engine downsizing.
  » Drive-cycle simulations based on experimental advanced combustion maps are being used to characterize potential of HECC operation for conventional and advanced powertrains.

• **Technology Transfer**
  » Aspects of this activity are regularly communicated either directly or indirectly to DOE, industry, and others through government working groups, technical meetings, and one-on-one interactions.

• **Longer Term**
  » *Transient* issues are becoming more and more important. *Need* for more emphasis on the development, integration, and evaluation of advanced transportation technologies to better understand synergies and/or operational issues for optimal efficiency AND lowest emissions.