High Efficiency Clean Combustion in Multi-Cylinder Light-duty Engines

Presented by Robert Wagner

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U.S. Department of Energy

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Overview

Activity evolves to address DOE challenges and is currently focused on milestones associated with Vehicle Technologies emissions objectives.

Timeline
- Consistent with VT MYPP
- Activity scope changes to address DOE needs

Budget
- FY 2008 $400k
- FY 2009 $400k
- FY 2010 $300k (in progress)

Barriers
- Efficiency/emissions
- Combustion control
- VT performance milestones

Partners / Interactions
- University of Wisconsin (dual-fuel combustion)
- UW-Sandia (PM modeling, common engine geometry)
- Delphi Automotive Systems (PFI injectors)
- Industry technical teams, DOE working groups, and one-on-one interactions.
- ORNL fuels, emissions, and health impacts activities.
Objective is to develop and assess the potential of advanced combustion concepts on multi-cylinder engines for highest 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 (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>

Addresses challenges related to implementation of high efficiency combustion concepts on multi-cylinder engines.

- High dilution levels
- Heat rejection
- Boosting
- Thermal management
- Adaptive controls
Milestones

- FY 2010 Q3 – In progress (coordinated with Fuel Technologies Program)

- FY 2010 Q4 – In progress
  Characterize sensitivity of advanced combustion operation to engine thermal conditions and impact on efficiency, emissions, and stability.
Approach

Modeling + Experiments + Analysis + Collaboration

- **Modeling**
  - Combustion modeling for guiding experiments (with University of Wisconsin).
  - Dynamic models for understanding dispersion phenomena and developing *real time* controls and feedback metrics.
  - Engine-system models for evaluating efficiency opportunities/losses.
  - Vehicle system models for estimating real-world fuel economy potential.

- **Experiments**
  - Multi-cylinder to address implementation issues related to cylinder-to-cylinder balancing, dilution, heat rejection, turbo-machinery, …

- **Analysis**
  - Thermodynamic analysis to understand fuel usage distribution.
  - Gaseous and PM emissions analysis to understand combustion process, aftertreatment matching, and for model validation.

- **Collaboration**
  - University of Wisconsin on dual-fuel modeling and single-cylinder experiments.
  - Delphi Automotive Systems on PFI fuel injectors.
  - ORNL fuels, emissions, and health impacts activities.
Engine experiments make use of two GM 1.9-L engines

- **Three controllers in use**
  - dSpace MABX with Ricardo VEMPS.
  - National Instruments based system developed by Drivven.
  - “Open” ECU supplied by GM.

- **Hardware modifications and/or additions**
  - Expanded temperature control of coolant, lubricant, EGR, fuel.
  - Port-Fuel-Injection (PFI) gasoline fuel system.
  - Low pressure EGR system.
  - BorgWarner 2-stage turbocharger system (*in progress*).

- **Instrumentation**
  - Temperatures and pressures necessary for 2nd Law analysis.
  - In-cylinder pressure all four cylinders.
  - Extensive exhaust characterization and special diagnostics.

- **Advanced technology integration**
  - Emission control devices.
  - Waste heat recovery systems.
  - Alternative fuel and dilution systems.

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<table>
<thead>
<tr>
<th>Number of Cylinders</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore, mm</td>
<td>82.0</td>
</tr>
<tr>
<td>Stroke, mm</td>
<td>90.4</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>17.5</td>
</tr>
<tr>
<td>Rated Power, kW</td>
<td>110</td>
</tr>
<tr>
<td>Rated Torque, Nm</td>
<td>315</td>
</tr>
</tbody>
</table>

2-stage turbocharger (graphic used with permission of BorgWarner)
Focus on engine conditions consistent with light-duty drive cycles and with those used in related activities at ORNL and elsewhere

- 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 Summary

- **Demonstrated dual-fuel combustion concept on multi-cylinder engine.**
  - Collaborated with University of Wisconsin to bridge modeling to multi-cylinder experiments.
  - Characterized implementation challenges and potential for high efficiency and low emissions.
  - Explored influence of intake mixture temperature, boost pressure, swirl, and combustion phasing.
  - Next steps include other engine speed-load combinations, speciation of gaseous and PM emissions, and ethanol blends.

- **Explored load expansion and sensitivity of PCCI operation to thermal boundary conditions.**
  - Load expansion of HECC operation.
  - Low pressure / high pressure EGR balancing for maximizing BTE with lowest possible emissions.

- **Substantial modifications for better control in support of high efficiency advanced combustion research.**
  - **High Speed Controls** – National Instruments based system with “next cycle” control capability.
  - **Port-Fuel-Injection Gasoline System** – Added to light-duty diesel engine with integrated controller conducive to algorithm development.
  - **Expanded Dilution** – Integrated LP EGR system.
  - **Efficient Turbo-Machinery** – 2-Stage BorgWarner turbocharger system (in progress).
  - **Thermal Boundary Control** – Increased temperature authority and control of intake, EGR, lubrication, and coolant systems.
Dual-fuel operation is under investigation in collaboration with UW

- Dual-fuel approach shown at UW to have high indicated thermal efficiency with very low emissions.
  - Modeling ~49% Net ITE.
  - Single-cylinder experiments ~45% Net ITE.

- Multi-cylinder implementation has additional challenges.

- UW support to ORNL includes:
  - Modeling of GM 1.9-L engine to provide guidance on gasoline / diesel balancing, diesel pilot parameters, and intake charge conditioning.
  - Dual-fuel start-up procedure.

See Kokjohn et al. (SAE 2009-01-2647) and Hanson et al. (SAE 2010-01-0864) for more details on dual-fuel concept.
Engine modifications included addition of PFI gasoline fuel system

- Intake charge conditions based on UW modeling within range of current hardware configuration.
  - Port fuel gasoline injection with single in-cylinder diesel injection.
  - No EGR.
  - Intake pressure 1.3 bar.
  - Intake temperature 40 °C.

- **DRIVVEN control system.**
  - Full control of both diesel and gasoline injection timing, cylinder-to-cylinder balancing, swirl valve, variable geometry turbo, etc.
  - Standard “next-cycle” control capabilities.
  - Future experiments will make use of “next-cycle” control and adaptive nonlinear controls experience to address potential stability and balancing issues.
More details on modifications to GM 1.9-L MCE

Modified intake showing PFI injectors. Cylinder 1 is offset due to high pressure pump interference.

System installed on engine with common gasoline fuel rail.

Delphi Multec-3 extended tip injectors with narrow spray angle.
Initial experiments focused on speed-load condition consistent with LD drive-cycle modal point (2300 rpm, 4.2 bar BMEP)

Key Points
- Approximates 2300 rpm, 4.2 bar BMEP condition.
- PFI gasoline.
- Single event diesel injection.
- No EGR.

Parameter space investigated in these experiments.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Modeling (UW)</th>
<th>Experiment (ORNL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net IMEP [bar]</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Speed [rev/min]</td>
<td>2300</td>
<td>2300</td>
</tr>
<tr>
<td>Total Fuel Mass [g/s]</td>
<td>1.16 g/s</td>
<td>1.22 g/s</td>
</tr>
<tr>
<td>Estimated Inj. Pressure [bar]</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Percent premixed gasoline [% mass]</td>
<td>65 to 85</td>
<td>65 to 85</td>
</tr>
<tr>
<td>Diesel injection timing [° ATDC]</td>
<td>-20 to -60</td>
<td>-30 to -70</td>
</tr>
<tr>
<td>Intake Surge Tank Pressure [bar]</td>
<td>1.3</td>
<td>1.1 to 1.3</td>
</tr>
<tr>
<td>Intake Surge Tank Temperature [° C]</td>
<td>40</td>
<td>38 to 45</td>
</tr>
<tr>
<td>Swirl Level [% DC]</td>
<td>OEM</td>
<td>40 to 100 (max)</td>
</tr>
<tr>
<td>Relative Humidity (%)</td>
<td>14</td>
<td>58</td>
</tr>
<tr>
<td>Diesel Fuel</td>
<td>ULSD</td>
<td>ULSD</td>
</tr>
<tr>
<td>Gasoline (Octane (R+M)/2)</td>
<td>91.60</td>
<td>91.95</td>
</tr>
</tbody>
</table>
Modeling information from University of Wisconsin provided guidance on establishing efficient dual-fuel operation

- **80 to 85% of total fuel premixed gasoline**
  - Increased gasoline percentage phases combustion later and lowers peak PRR.

- **Injection timing earlier than -30° ATDC**

- **Advancing the injection timing**
  - Lowers the diesel fuel equivalence ratio and extends the ignition delay.
  - Increases reactivity of the squish region and lowers UHC levels.

### Table: Diesel SOI [° ATDC]

<table>
<thead>
<tr>
<th>% Gasoline</th>
<th>Diesel SOI [° ATDC]</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>-20</td>
</tr>
<tr>
<td>65</td>
<td>184</td>
</tr>
<tr>
<td>70</td>
<td>181</td>
</tr>
<tr>
<td>75</td>
<td>179</td>
</tr>
<tr>
<td>80</td>
<td>175</td>
</tr>
<tr>
<td>85</td>
<td>176</td>
</tr>
</tbody>
</table>

- **NOx limit = 1 g/kgf**
- **PRR limit = 10 bar°**

Source: Prof. Rolf Reitz, Sage Kokjohn, University of Wisconsin, personal communication 12/30/2009.
Reference condition

2300 rpm, 5.5 bar IMEP

### Operating Parameters
- Boost (bar): 1.18
- Intake Temp (C): 90
- VSA DC (%): 42.6
- EGR (% Vol): 15

### Performance & Emissions
- BTE (%): 32.1
- ITE net (%): 39.4
- NOx (ppm): 94
- CO (ppm): 423
- HC (ppm): 296
- FSN: 1.78
- Exhaust T (C): 412

Heat Release Rate (J/°deg)

NMEP (kPa)

MFB50 (%)
Example of dual-fuel and conventional combustion

- 2300 rpm, 5.5 bar IMEP
- General observations as compared to conventional combustion.

<table>
<thead>
<tr>
<th>↑ BTE</th>
<th>↓ NOx</th>
<th>↓ PM</th>
<th>↑ CO, HC</th>
<th>↑ P Rise Rate</th>
<th>↓ Exhaust T</th>
</tr>
</thead>
</table>

**Gasoline/Diesel Dual-Fuel Combustion**

**Conventional Combustion**
Diesel SOI used to control combustion phasing

- Experiments trend well with modeling.
  » Similar agreement seen for other parameters.
- HR double peak observed for SOI -30
  » Not predicted by model.
  » Observed in single-cylinder experiments at UW.

### Experiment

<table>
<thead>
<tr>
<th>Condition</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Total Fuel Mass [g/s]</td>
<td>1.16</td>
<td>1.22</td>
</tr>
<tr>
<td>Percent Gasoline (%)</td>
<td>80</td>
<td>81</td>
</tr>
<tr>
<td>Diesel SOI (° ATDC)</td>
<td>-20 to -60</td>
<td>-30 to -60</td>
</tr>
<tr>
<td>Diesel Inject P (bar)</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Intake Pressure (bar)</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Intake T (° C)</td>
<td>40</td>
<td>42</td>
</tr>
<tr>
<td>Swirl (DC %)</td>
<td>Stock</td>
<td>70</td>
</tr>
</tbody>
</table>
Combustion phasing effects on HC/CO and NOx emissions

- Particulate emissions were very low for all cases.
- BTE is highest (32%) for SOI = 60 °BTDC.

UW Model Results

Increasing BTE

81% Gasoline, Swirl DC= 70%

80% Premixed Gasoline

85% Gasoline

65% Gasoline

70% Gasoline

75% Gasoline

80% Gasoline

85% Gasoline
Overall experimental trends in ISFC similar to model predictions

- Experimental parameter space is extensive and not fully explored or optimized.
- Higher ISFC (lower ITE) for experiments.
  - Cylinder-to-cylinder differences in inducted mass, heat rejection, etc.
  - Cylinder-to-cylinder balancing important.

Indicated specific fuel consumption (g/kW-hr)

<table>
<thead>
<tr>
<th>% Gasoline</th>
<th>Diesel SOI [°ATDC]</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-20</td>
<td>-30</td>
</tr>
<tr>
<td>65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>202</td>
<td>200</td>
</tr>
<tr>
<td>85</td>
<td>204</td>
<td>201</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>% Gasoline</th>
<th>Diesel SOI [°ATDC]</th>
<th>UW Model Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-20</td>
<td>-30</td>
</tr>
<tr>
<td>65</td>
<td>184</td>
<td>184</td>
</tr>
<tr>
<td>70</td>
<td>181</td>
<td>179</td>
</tr>
<tr>
<td>75</td>
<td>170</td>
<td>177</td>
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<tr>
<td>80</td>
<td>175</td>
<td>177</td>
</tr>
<tr>
<td>85</td>
<td>176</td>
<td>181</td>
</tr>
</tbody>
</table>
General Observations

- Experimental observations mirrored model predictions.
- Dramatic reductions in PM and NOx with increasing BTE.
- Cylinder-to-cylinder balancing important for high efficiency.
- Swirl level has optimum level depending on gasoline-to-diesel ratio and has strong impact on BTE.
- Pressure rise rate sensitive to intake mixture temperature.
- Boost pressure also has strong impact on BTE. Higher not always better.

<table>
<thead>
<tr>
<th></th>
<th>Diesel</th>
<th>Dual-Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline (%)</td>
<td>0</td>
<td>81</td>
</tr>
<tr>
<td>Boost (bar)</td>
<td>1.18</td>
<td>1.30</td>
</tr>
<tr>
<td>Swirl DC (%)</td>
<td>32.1</td>
<td>32.2</td>
</tr>
<tr>
<td>BTE (%)</td>
<td>32.1</td>
<td>32.2</td>
</tr>
<tr>
<td>NOx (ppm)</td>
<td>94</td>
<td>5.4</td>
</tr>
<tr>
<td>FSN</td>
<td>1.78</td>
<td>0.02</td>
</tr>
<tr>
<td>CO (ppm)</td>
<td>423</td>
<td>1988</td>
</tr>
<tr>
<td>HC (ppm)</td>
<td>296</td>
<td>2669</td>
</tr>
<tr>
<td>Exhaust T (°C)</td>
<td>412</td>
<td>247</td>
</tr>
</tbody>
</table>

Summary of “best case” results seen to date on multi-cylinder engine.
Collaborations and Interactions

• University of Wisconsin
  » Dual-fuel combustion modeling and sharing of experimental data and observations.
  » PM speciation data in support of UW particulate modeling (in progress).
  » Common engine geometry.

• Delphi Automotive Systems
  » Specification and supply of several PFI injector designs.

• General Motors
  » Support of GM 1.9-L engines and open controllers.

• BorgWarner
  » Guidance on operation and modeling of 2-stage turbo-machinery as well as design of low-pressure EGR system.

• Industry Tech Teams, DOE AEC/HCCI Working Groups, and one-on-one interactions.
  » ORNL is member of Advanced Engine Combustion Working Group which is administered by Sandia National Laboratories.

• Other ORNL-DOE Activities
  » Fuels, emissions, health impacts, and vehicle systems modeling projects.
Next Steps FY 2010

- **On track** to meet milestones end of Q3 and Q4.
- **Continue dual-fuel combustion experiments and analysis on MCE.**
  - Thermodynamic analysis to better understand efficiency and loss mechanisms.
  - Additional experiments at additional speed-load conditions.
  - Refined parameter sweeps (e.g., boost, swirl, thermal boundaries, etc) to better understand efficiency-emissions trade-offs.
  - Automated cylinder balancing with multiple engine parameters.
  - Integration of oxidation catalyst (leveraged activity).
  - Detailed gaseous and PM emissions characterization including speciation (leveraged activity). Information will be shared with UW for model validation.
- **Complete cell modifications to enable improved control of intake mixture composition, temperature, and pressure.**

*Advanced combustion focused GM 1.9-L engine*

*BorgWarner R2S for GM 1.9-L engine*
Future FY 2011

• Continue role to develop and assess potential of high efficiency concepts on multi-cylinder engines.
  » Numerous concepts showing high efficiency potential in idealized single-cylinder engine.
  » Multi-cylinder engine has additional challenges which must be addressed.
  » Controls for improved robustness.

• Leverage with fundamental expertise and on-going activities to better understand fuel economy potential and systems integration challenges.
  » Emissions characterization.
  » Health effects issues.
  » Aftertreatment.
  » Fuel effects.
  » Vehicle systems modeling and drive-cycle simulations.
Summary

On track to meet FY 2010 milestones.

- **Relevance**
  » Develop and assess potential of advanced combustion concepts on multi-cylinder engines for highest efficiency and lowest possible emissions.

- **Approach**
  » Modeling + Experiments + Analysis + Collaboration

- **Technical Accomplishments**
  » Demonstrated dual-fuel combustion concept on MCE.
  » Explored load expansion and sensitivity of PCCI operation to thermal boundary conditions (not shown).
  » Substantial modifications to engine-system to better support multi-cylinder combustion research.

- **Collaborations**
  » University of Wisconsin on dual-fuel combustion.
  » BorgWarner on 2-stage turbo-machinery and low-pressure EGR.
  » Regular communication to DOE, industry, and others through technical meetings and one-on-one interactions.

- **Future**
  » Continue role to explore and enable advanced concepts on multi-cylinder engines. Controls is an important component of current and future implementations.
  » Speciation of gaseous and PM emissions in support of UW-Sandia modeling efforts.