Overview

- **Timeline**
  - Project start date: Oct. 2009
  - Project end date: Sept. 2010
  - 50% complete

- **Barriers**
  - Fundamental knowledge of engine combustion
  - Emission control
  - Hybrid technology

- **Budget**
  - Total project funding: $300k
  - DOE funding: $300k
  - New project, no FY09 funding
  - FY10 funding: $300k

- **Collaborations/Interactions**
  - DOE-ORNL emissions, after-treatment and health effects projects
  - **General Motors** (Loan of Euro spec Lean GDI BMW vehicle)
  - Idaho National Laboratory (testing support)
  - Argonne National Laboratory (integration of engine data into PSAT, Autonomie)
Objectives / Relevance

- Benchmark performance and emissions of engine featuring new technologies:
  - Engine combustion (Lean direct injection)
  - Emission control (LNT for gasoline engine)
  - Engine technology (Stop-start, smart alternator)

- Improve knowledge and understanding of those new technologies:
  - Quantify benefits and drawbacks
  - Advise on future work related to those technologies

- Make information publicly available for vehicle simulations of advanced powertrains and after-treatment systems
Milestones

- **Milestone #1 - July 31, 2010:**
  - Acquire and characterize modern lean GDI vehicle on chassis dynamometer

- **Milestone #2 - September 30, 2010:**
  - Finalize performance/emissions maps and make available with simulation example to Vehicle Systems team
Approach

- Acquire a modern lean GDI vehicle with lean NO\textsubscript{x} emission controls system from Europe (vehicle has to be representative of the most advanced technologies on the market)

- Instrument vehicle and perform chassis dynamometer experiments to characterize performance, emissions, and after-treatment system for
  - US drive cycles: UDDS, HFET, and US06
  - Steady-state experiments to establish performance/emissions maps for future vehicle simulations.

- Investigate modern production micro-hybrid performance attributes, such as engine start-stop and smart alternator control

- Make use of vehicle chassis dynamometer data to develop, substantiate, and exercise vehicle simulation with conventional and advanced powertrains
Accomplishments – Vehicle Procurement

- **MY2008 BMW 1-series 120i (E81)**

- **Vehicle on loan from GM**
  - Received early February 2010
  - Benchmarking until end of April

- **Engine specs (N43B20)**
  - 2.0l 4-cylinder
  - Lean burn combustion
  - 200 bar direct injection
  - 130 kW (170 hp) at 6,700 rpm,
  - 210 Nm (155 ft-lb) at 4,250 rpm
  - 12:1 compression ratio
  - Dual VVT
  - EGR
Accomplishments – Engine and After-treatment Instrumentation

- Exhaust system instrumentation at 4 locations:
  - NOₓ, HC, CO, CO₂, O₂ gas analyzers
  - FTIR for nitrogen oxide speciation, ammonia and hydrocarbon speciation
  - Spatially resolved capillary inlet mass spectrometer for temporal H₂ and O₂ measurements (for LNT regeneration characterization)
  - Particulate matter measurements.

- Vehicle and engine instrumentation
  - OBD link
  - Analog channels (AFR, temperature and pressure)
Accomplishments – Hybrid Features Instrumentation

• Instrumentation
  – Power analyzer procurement: Hioki 3390
    • High voltage and current Instrumentation
    • Hioki analyzers used by other national laboratories
  – Integration with chassis roll main data logger

• Start-stop
  – Engine is stopped when the vehicle is stopped and when certain criteria are met
  – Starter current monitoring (Hioki)
  – Engine operating condition (OBD link)

• Intelligent alternator
  – Battery is never fully charged so that it can accept energy. During accelerations, the alternator is not excited to reduce the load on the engine. During coast downs, the alternator recharges the battery utilizing kinetic energy from the powertrain
  – Alternator current and load current monitoring (Hioki)
  – Engine operating condition (OBD link)
Accomplishments – Drive Cycle Testing

- **US drive cycles:**
  - FTP
  - HFET
  - US06

- Three iterations to guarantee repeatability

- **Characterization:**
  - Emissions
    - Engine out
    - Tailpipe
    - LNT reductant chemistry
  - Fuel economy
  - Engine operation
Accomplishments – Steady State Testing

- Complete speed and load engine mapping
- Three iterations to guarantee repeatability
- Characterization:
  - Emissions
  - Fuel economy
  - Engine operation

![BMW E81 LGDI torque curve](image)

<table>
<thead>
<tr>
<th>RPM</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
<th>3000</th>
<th>3500</th>
<th>4000</th>
<th>4500</th>
<th>5000</th>
<th>5500</th>
<th>6000</th>
<th>6500</th>
<th>7000</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>950</td>
<td>1020</td>
<td>1106</td>
<td>1097</td>
<td>1129</td>
<td>1132</td>
<td>1158</td>
<td>1153</td>
<td>1088</td>
<td>925</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>855</td>
<td>918</td>
<td>996</td>
<td>987</td>
<td>1016</td>
<td>1019</td>
<td>1042</td>
<td>1038</td>
<td>979</td>
<td>832</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>760</td>
<td>816</td>
<td>885</td>
<td>878</td>
<td>903</td>
<td>906</td>
<td>926</td>
<td>923</td>
<td>870</td>
<td>740</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>665</td>
<td>714</td>
<td>774</td>
<td>768</td>
<td>790</td>
<td>793</td>
<td>810</td>
<td>807</td>
<td>762</td>
<td>647</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>570</td>
<td>612</td>
<td>664</td>
<td>658</td>
<td>677</td>
<td>679</td>
<td>695</td>
<td>692</td>
<td>653</td>
<td>555</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>475</td>
<td>510</td>
<td>553</td>
<td>548</td>
<td>565</td>
<td>566</td>
<td>579</td>
<td>577</td>
<td>544</td>
<td>462</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>380</td>
<td>408</td>
<td>443</td>
<td>439</td>
<td>452</td>
<td>453</td>
<td>463</td>
<td>461</td>
<td>435</td>
<td>370</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>285</td>
<td>306</td>
<td>332</td>
<td>329</td>
<td>339</td>
<td>340</td>
<td>347</td>
<td>346</td>
<td>326</td>
<td>277</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>190</td>
<td>204</td>
<td>221</td>
<td>219</td>
<td>226</td>
<td>226</td>
<td>232</td>
<td>231</td>
<td>218</td>
<td>185</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>95</td>
<td>102</td>
<td>111</td>
<td>110</td>
<td>113</td>
<td>113</td>
<td>116</td>
<td>115</td>
<td>109</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RPM</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
<th>3000</th>
<th>3500</th>
<th>4000</th>
<th>4500</th>
<th>5000</th>
<th>5500</th>
<th>6000</th>
<th>6500</th>
<th>7000</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>950</td>
<td>1020</td>
<td>1106</td>
<td>1097</td>
<td>1129</td>
<td>1132</td>
<td>1158</td>
<td>1153</td>
<td>1088</td>
<td>925</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>855</td>
<td>918</td>
<td>996</td>
<td>987</td>
<td>1016</td>
<td>1019</td>
<td>1042</td>
<td>1038</td>
<td>979</td>
<td>832</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>760</td>
<td>816</td>
<td>885</td>
<td>878</td>
<td>903</td>
<td>906</td>
<td>926</td>
<td>923</td>
<td>870</td>
<td>740</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>665</td>
<td>714</td>
<td>774</td>
<td>768</td>
<td>790</td>
<td>793</td>
<td>810</td>
<td>807</td>
<td>762</td>
<td>647</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>570</td>
<td>612</td>
<td>664</td>
<td>658</td>
<td>677</td>
<td>679</td>
<td>695</td>
<td>692</td>
<td>653</td>
<td>555</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>475</td>
<td>510</td>
<td>553</td>
<td>548</td>
<td>565</td>
<td>566</td>
<td>579</td>
<td>577</td>
<td>544</td>
<td>462</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>380</td>
<td>408</td>
<td>443</td>
<td>439</td>
<td>452</td>
<td>453</td>
<td>463</td>
<td>461</td>
<td>435</td>
<td>370</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>285</td>
<td>306</td>
<td>332</td>
<td>329</td>
<td>339</td>
<td>340</td>
<td>347</td>
<td>346</td>
<td>326</td>
<td>277</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>190</td>
<td>204</td>
<td>221</td>
<td>219</td>
<td>226</td>
<td>226</td>
<td>232</td>
<td>231</td>
<td>218</td>
<td>185</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>95</td>
<td>102</td>
<td>111</td>
<td>110</td>
<td>113</td>
<td>113</td>
<td>116</td>
<td>115</td>
<td>109</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Accomplishments – Fuel Economy Preliminary Results

- Three different operating conditions were tested:
  - Stoichiometric
  - Lean
  - Lean with Stop-start

![2008 BMW 1 Series Fuel Economy Chart]

*Range bars indicate maximum and minimum of multiple tests*
Accomplishments – Engine Emissions Preliminary Results

- Emissions were greatly affected by the first mapping exercise
  - High speed and load conditions presumed to have helped clean the LNT
  - Extra low sulfur fuel (<2ppm) used from test 8B12
  - LNT might have been contaminated with earlier higher sulfur level fuel (UTG96, ~26-27ppm sulfur at ORNL and unknown fuel at GM)

- Similar trends on NOx, CO and PM
Accomplishments – LNT Characterization (On-going)

- Operation of LNT characterized by measurement of exhaust species with FTIR, SpaciMS, and bench analyzers
- Reductant species observed at inlet to LNT include $\text{H}_2$, CO, and $\text{NH}_3$
  - $\text{H}_2$:$\text{CO}$ is much higher than previously observed in diesel engine studies
  - $\text{NH}_3$ is present due to formation by upstream Three-Way Catalyst
- More analysis in “Lean Gasoline Emission Control” (ACE031) project presentation
  - Final results to be shared with CLEERS community
Accomplishments – Start-Stop Characterization (On-going)

- Present when:
  - Vehicle stopped
  - Clutch not engaged
  - Neutral gear
  - Warm engine
  - Suitable battery charge
  - Other secondary conditions

- Fuel economy and emissions effect characterization
Accomplishments – Intelligent Alternator Characterization (On-going)

- **Principle:**
  - Battery is never fully charged so that it can absorb energy
  - During accelerations, the alternator is not excited to reduce the load on the engine
  - During coast downs, the alternator recharges the battery

- **Observations**
  - Increased alternator load during some coast downs
  - Rare alternator load reduction during accelerations
  - Excellent load adaptation: alternator load matches electrical loads out of battery
Collaboration

- VSATT- Data is available for use by Vehicle Systems Analysis technical team and others in simulating advanced powertrains (project VSS008 will use data collected here)

- Lean NO$_x$ aftertreatment data will be used in support of the CLEERS modeling activity

- ORNL Advanced Combustion Engines programs
  - Use of the steady-state engine maps and controller information measured during the chassis experiments to commission an engine setup with a micro-processor based control system.
  - Use engine dynamometer setup to explore expanded lean operation and produce more advanced engine maps which will be used for future advanced powertrain simulations.

- Idaho National Laboratory: advanced powertrain/vehicle testing support
Future Work – FY10

- Complete data collection
- Publish project findings
- Process data into useable format for simulation environment (PSAT/Autonomie)
Proposed Future Work

- Use experimental data to evaluate the potential of lean GDI engine operation and after-treatment systems with advanced (hybrid) powertrains

- Combine vehicle benchmark data with engine dynamometer experiments to develop and validate emissions control models for use with lean GDI advanced powertrain vehicle simulations

- Focus on ethanol blends and potential opportunities presented by ethanol for lean combustion and emission control
Summary

• Relevance
  – Benchmark performance and emissions of advanced lean GDI vehicle
  – Technology not sold in the US
  – Understand barriers to widespread use of this technology in US market

• Approach
  – Vehicle on loan from GM
  – Comprehensive instrumentation and Vehicle testing
  – Characterization over transient cycles and steady conditions
  – Data processing

• Technical Accomplishments
  – Vehicle acquired
  – Instrumentation completed
  – Characterization carried out in 8 weeks

• Future work
  – Publish benchmarking data
  – Format data for simulation purposes
  – Use data for other projects (advanced hybrid powertrain simulation, engine dynamometer experiment, ethanol lean burn …)
Acknowledgements and Contacts

DOE Program Manager:

- Lee Slezak, Office of Vehicle Technologies

ORNL Advanced Vehicle Systems Program Manager:

- David E. Smith

ORNL Investigators:

- Robert Wagner, Paul Chambon, Shean Huff, Kevin Norman, John Thomas, Larry Moore, Ron Lentz, Brian West, Bill Partridge, Jae-Soon Choi, Vitaly Prikhodko, John Storey, Teresa Barone, Jim Parks, Jeff Chambers