ADVANCES IN HIGH-EFFICIENCY GASOLINE COMPRESSION IGNITION

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Argonne National Laboratory

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FY16 DOE VT Program Annual Merit Review
Advanced Combustion Engine R&D/Combustion Research
1:45 – 2:15 PM, Wednesday, June 8, 2016

Project ID# ACE11

This presentation does not contain any proprietary, confidential or otherwise restricted information
OVERVIEW

Timeline

- Started May 2008
- Reviewed as part of FY17 VTO Lab Call

Budget

- Total project funding
  - DOE share 100%
  - Contractor share 0%
- Funding received in
  - FY15 $550k
  - FY16 $500k

Barriers

- From MYPP
  - Mechanism to control LTC Timing
    - Addressed in FY14-15
  - LTC high load and high speed operation
    - Covered in FY12-13
  - LTC control during change of speed and load
    - Addressed in FY16 and beyond

Partners

- GM R&D
  - Engine maps, piston crowns and other hardware, cylinder head modifications, technical support
- University of California – Berkeley
  - E10 LTHR/auto-ignition correlation
- ORNL
  - Different combustion approaches based upon reactivity of fuel
  - ORNL to use higher reactivity gasolines
OBJECTIVES/RELEVANCE: MULTI-CYLINDER, HIGH EFFICIENCY GASOLINE COMPRESSION IGNITION

Long-Term Objective
Understand the physical and chemistry characteristics of Gasoline Compression Ignition (GCI) in a multi-cylinder engine to aid industry in developing a practical high efficiency, low emission combustion system

HCCI
PFS
Mixing Limited GCI
Majority Premixed GCI
Majority Stratified GCI

Graphics courtesy ORNL (Curran & Dempsey)
OBJECTIVES/RELEVANCE: MULTI-CYLINDER, HIGH EFFICIENCY GASOLINE COMPRESSION IGNITION

Long-Term Objective
Understand the physical and chemistry characteristics of Gasoline Compression Ignition (GCI) in a multi-cylinder engine to aid industry in developing a practical high efficiency, low emission combustion system

Current Specific Objectives:
1. Evaluate effect of Low Pressure EGR upon auto-ignition and engine performance characteristics
2. Quantitatively study effect of injection strategy upon auto-ignition to develop approach for transient operation and reduced fuel sensitivity
3. Perform factorial experiments to quantify the effect of important input parameters upon engine performance, noise and emissions
## MILESTONES

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Target Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determine nozzle inclusion angle effects upon high load combustion noise and PM/NO&lt;sub&gt;x&lt;/sub&gt; (120 deg works well @ high load)</td>
<td>Jun 2015 (Completed)</td>
</tr>
<tr>
<td>Determine injection strategy requirements to enable transient operation (Time-based injections work well)</td>
<td>Sept 2015 (Completed)</td>
</tr>
<tr>
<td>Install Low Pressure EGR Loop</td>
<td>Dec 2015 (Completed)</td>
</tr>
<tr>
<td>Quantify boost sensitivity of E10 (Less than E0 but only marginally less sensitive)</td>
<td>Mar 2016 (Completed)</td>
</tr>
<tr>
<td>Develop strategy for GCI operation for entire speed/load range on E10 (Integrate LP-EGR, Boost and injection strategy)</td>
<td>June 2016 (Ongoing)</td>
</tr>
<tr>
<td>Characterize PM from GCI using E10</td>
<td>Sept 2016 (Ongoing)</td>
</tr>
</tbody>
</table>
Approach/Strategy: Use Injection Strategy, LP-EGR, Simulation & Multi-Cyl Operation to Understand Ignition and Operating Boundaries

- Run experiments and utilize validated CFD modeling to understand factors involved in GCI auto-ignition
  - Injection strategy (# of injections, timing, dwell, fuel allocation, injection pressure)
  - LP-EGR at high loads—maintain high ignition reliability while lowering combustion noise and NOx
  - Use validated modeling to assist in choosing optimum conditions
    - Feedback data to Global Sensitivity Study/Uncertainty Quantification on HPC (Som & Kodavasal)

EGR sweep: combustion phasing delay with LP-EGR

Minimum fueling strategy altered to more accurately control variables

CFD Simulations showing spread of pressure traces with perturbed inputs provided by experiment (IVC conditions, fueling rate etc.)
TECHNICAL ACCOMPLISHMENTS & PROGRESS
LP EGR SETUP & TESTING CONDITION

**Test condition:**
- EGR% sweep at constant load (BMEP ~ 3 bar at 2000 RPM)
- EGR% adjusted by separate valves (most effective exhaust valve)
- Triple injection (SOI of each: 100-70-25 deg. bTDC)
- Supercharger (ON) for P intake = 0.6 bar
  - Allows for precise control of intake pressure!

**LP EGR Adjustment by means**

<table>
<thead>
<tr>
<th>Exhaust Valve</th>
<th>Throttle valve on overall exhaust discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Valve</td>
<td>Throttle on fresh intake air upstream of turbo, to drive LP-EGR</td>
</tr>
<tr>
<td>LP EGR Valve</td>
<td>Throttle valve between post DPF exhaust and turbocharger intake</td>
</tr>
</tbody>
</table>

**Diagram:**

- Smoke meter
- Lambda sensor
- DPF
- AMA2000

**Graph:**

- Inj 1
- Inj 2
- Inj 3
- \( P_{\text{inj}} = 400 \text{ bar} \)
- \( \text{CA [deg. aTDC]} \)
- \( 0.5 \text{ ms} \)
- \( 0.6 \text{ ms} \)
LP-EGR: EFFECTIVE AT MANAGING COMBUSTION PHASING, NOISE AND EMISSIONS, EXHAUST T

- Ignition and combustion phasing are retarded at higher EGR
- Can retard more with later 3rd injection
- Increased P_inj can mitigate PM increase

GM 1.9 L 17.8:1 (CR)
Engine speed 2000 rpm/3 bar BMEP
Injection pressure 400 bar
Injector-Bosch 7 hole 120 deg umbrella angle
Fuel E10

- EGR helped lowering noise level (USCAR upper limit of 90 dBA in red)
- NOx also reduced significantly with additional EGR
- Additional work needed to reduce COV increase
LP-EGR IMPROVES PERFORMANCE AT HIGHER LOADS AS WELL

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>29.41</td>
<td>53.64</td>
<td>309.5</td>
<td>4.32</td>
<td>346.13</td>
<td>90.13</td>
<td>0.45</td>
<td>0.91</td>
<td>2.10</td>
<td>0.030</td>
</tr>
<tr>
<td>29.84</td>
<td>45.56</td>
<td>316.9</td>
<td>4.91</td>
<td>312.04</td>
<td>93.90</td>
<td>0.42</td>
<td>1.16</td>
<td>3.20</td>
<td>0.017</td>
</tr>
<tr>
<td>29.43</td>
<td>47.11</td>
<td>327.5</td>
<td>5.16</td>
<td>317.10</td>
<td>91.58</td>
<td>0.33</td>
<td>0.57</td>
<td>1.34</td>
<td>0.020</td>
</tr>
<tr>
<td>30.50</td>
<td>47.58</td>
<td>419.9</td>
<td>8.27</td>
<td>280.25</td>
<td>93.88</td>
<td>0.04</td>
<td>0.37</td>
<td>1.27</td>
<td>0.027</td>
</tr>
<tr>
<td>30.48</td>
<td>47.91</td>
<td>412.2</td>
<td>8.33</td>
<td>278.78</td>
<td>91.01</td>
<td>0.05</td>
<td>0.37</td>
<td>1.44</td>
<td>0.024</td>
</tr>
</tbody>
</table>

GM 1.9 L 17.8:1 (CR)

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>2000 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection pressure</td>
<td>400 bar</td>
</tr>
<tr>
<td>Injector-Bosch</td>
<td>7 hole 120 deg cone angle</td>
</tr>
<tr>
<td>Fuel</td>
<td>E10</td>
</tr>
</tbody>
</table>

- Emissions (NOx, HC, CO) and FSN are reduced significantly with LP-EGR
- Exhaust temperature remains high with EGR
  - Improved temperature expected with higher exhaust T
- Supercharger needed to maintain boost stability
  - Lower BSFC than intended
  - LP-EGR modifications to allow use of turbo only
Study at UCB (Vuilleumier) shows that LTHR has significant effect on gasoline HCCI ignition.

His conclusions indicate:

- A fuel’s Octane Index is a good indicator of its GCI Low-Load Performance.
- LTHR Onset Pressure in an HCCI engine correlates very well with GCI Low-Load Performance.
- *Increased intake pressure increases low-temperature heat release, enabling lower loads in a GCI engine.*
INJECTION STRATEGY: E10 MINIMUM FUELING – SOI SWEEP

- **Minimum Fueling** approach: least fuel requirement for stable combustion (COV_{IMEP} < 3%)
- Combustion mode (HCCI vs. GCI) characterized by SOIs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM 1.9 L</td>
<td>17.8:1 (CR)</td>
</tr>
<tr>
<td>Engine speed</td>
<td>1000 rpm</td>
</tr>
<tr>
<td>Injection pressure</td>
<td>400 bar</td>
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<tr>
<td>Injector-Bosch</td>
<td>7 hole 120 deg. cone angle</td>
</tr>
<tr>
<td>Fuel</td>
<td>E10</td>
</tr>
</tbody>
</table>

- **A-period** Location of ignition (CA10), and combustion phasing (CA50) seems stay constant
- **B-period** More fuel (smaller lambda) is needed to have stable combustion, but CA10/CA50 also seems constant
- **C-period** IMEP shows a drop near -60 deg. aTDC due to possible fuel entering squish region

- Both SOI and Lambda show to have effect on CA10/CA50, but lambda is more effective
- There seems to be a condition with constant lambda to fix CA10/CA50
E10 CONSTANT LAMBDA – SOI SWEEP

- Minimum fuel provides fuel requirement (least fuel) for combustion stability, but does not give same mixture to study SOI effect explicitly on ignition and combustion → constant lambda approach
- Fuel rate was adjusted to keep same lambda through all SOIs
- λ calculated from emission bench

- Almost similar ignition location in “quasi HCCI” (also similar CA50/CA90)
- Existing region where earliest ignition occurs (near -30 deg. aTDC) – reduction in fuel in squish region
- Near TDC, short residence time for ignition
- IMEP increases slightly near TDC (less fuel in squish)
- It was harder to control noise level with late injection

\[ \text{COV}_{\text{IMEP}} < 3\%, \text{ max } = 5\% \]
LOW SPEED/LOAD E10 CONSTANT LAMBDA – SOI SWEEP: EMISSION

Early injection:
- Low level of NOx in highly homogeneous mixture (quasi HCCI region)
- Incomplete combustion (high HC)
- Low combustion temperature → high CO
- Smoke number (FSN) was very low (<0.1) due to lean condition at all SOIs

Late injection (GCI mode):
- Insufficient time for air/fuel mixing
- High NOx due ~ high combustion temperature; richer zones for ignition
- Less HC and CO (aggressive reaction leads to more complete combustion)

<table>
<thead>
<tr>
<th>GM 1.9 L</th>
<th>17.8:1 (CR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine speed</td>
<td>1000 rpm</td>
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<tr>
<td>Injection pressure</td>
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<tr>
<td>Injector-Bosch</td>
<td>7 hole 120 deg cone angle</td>
</tr>
<tr>
<td>Fuel</td>
<td>E10</td>
</tr>
</tbody>
</table>
PARAMETRIC STUDY: HIGHER ENGINE SPEED CONDITION (2000 RPM)

<table>
<thead>
<tr>
<th>Engine Speed Level</th>
<th>2000 rpm</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Boost</td>
<td>Low</td>
<td>High</td>
<td>0.45</td>
</tr>
<tr>
<td>Injection pressure [bar]</td>
<td>400</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>SOI [deg. BTDC]</td>
<td>70/20</td>
<td>70/40</td>
<td></td>
</tr>
<tr>
<td>Lambda</td>
<td>2.7</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Constant Lambda</td>
<td>3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection pressure [bar]</td>
<td>400</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>SOI [deg. BTDC]</td>
<td>70/20</td>
<td>70/40</td>
<td></td>
</tr>
<tr>
<td>Boost [bar]</td>
<td>0.35</td>
<td>0.55</td>
<td></td>
</tr>
</tbody>
</table>

- **P**: Injection Pressure
- **S**: Start of injection
- **L**: Lambda
- **B**: Boost

**Sample AHRR of long vs short dwell:**
\[ P_{\text{inj}}=600 \text{ bar}, P_{\text{Intk}}=0.55 \text{ bar}, \lambda = 3.1 \]

**Double injection:**
- Same duration for pilot & main
- Fixed pilot
- Helpful for meeting COV, noise levels
FACTORIAL STUDY - **CONSTANT BOOST** TESTS SHOW INFLUENCE OF COMBUSTION MODE ON EMISSIONS, LAMBDA ON COMBUSTION PHASING

<table>
<thead>
<tr>
<th>B [bar]</th>
<th>0.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>P [bar]</td>
<td>400 600</td>
</tr>
<tr>
<td>S [deg. bTDC]</td>
<td>15 141</td>
</tr>
<tr>
<td>L</td>
<td>3.6 4.5</td>
</tr>
</tbody>
</table>

**1000 RPM**

**λ** has strong impact on ignition

**2000 RPM**

Lower performance with leaner mixture

Lower emissions with shorter dwell

<table>
<thead>
<tr>
<th>P Injection Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>S Start of injection</td>
</tr>
<tr>
<td>L Lambda</td>
</tr>
<tr>
<td>B Boost</td>
</tr>
</tbody>
</table>

![Graphs showing the influence of combustion mode on emissions and lambda on combustion phasing.](image)
FACTORIAL STUDY - CONSTANT LAMBDA TESTS SHOWS SIGNIFICANT BOOST EFFECT ON COMBUSTION PHASING, NOISE AND EMISSIONS

<table>
<thead>
<tr>
<th>L</th>
<th>4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>P [bar]</td>
<td>400 600</td>
</tr>
<tr>
<td>S [deg. bTDC]</td>
<td>15 141</td>
</tr>
<tr>
<td>B [bar]</td>
<td>0.15 0.3</td>
</tr>
</tbody>
</table>

1000 RPM

Advanced ignition at higher boost

<table>
<thead>
<tr>
<th>P Injection Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>S Start of injection</td>
</tr>
<tr>
<td>L Lambda</td>
</tr>
<tr>
<td>B Boost</td>
</tr>
</tbody>
</table>

2000 RPM

Overmixed at high P_inj (high HC, CO)

Reduced COV, BSFC, Increased Noise at higher boost
RESPONSES TO FY15 REVIEWER COMMENTS

- **Reviewer Comment**
  - Efficiency/noise tradeoff?
  - How to address low exhaust temperatures at low load?
  - Perhaps too much attention paid to imaging, not enough to injection strategy for LD installation?
  - Additional PM characterization?

- **Response**
  - Specifically addressed this year in trying to keep noise below 90 dBA
  - LP-EGR, along with late injection timing, appear to have the leverage to increase exhaust temperature at low load
  - Less focus on endoscopic imaging, more focus on injection strategy and implications for transient operation; understanding different modes of operation for different speeds/loads
  - Collaboration with HeeJe Seong (TEM sampling) and additional SMPS/EEPS measurements. FSN mostly for operational interest
COLLABORATIONS

- Engine maps, piston crowns and other hardware, cylinder head modifications, technical support
- E10 LTHR influence upon auto-ignition
- Fuel influence on LTHR
- Collaboration with Scott Curran
- High reactivity fuels @ ORNL
- Low reactivity fuels @ ANL
- Comparison of mixture stratification levels

In addition, this project is involved in the AEC Working Group
- Co-Optima project is also related to this work
REMAINING BARRIERS AND CHALLENGES

- Reliable and repeatable ignition and combustion phasing
  - Characterize injection strategy as optimal for transient behavior
  - Characterize injection strategy to minimize slight fuel property variations
    - Octane number in particular, along with EtOH content

- Improve air handling to make LP-EGR more effective
  - Better characterize injection/boost/EGR interactions

- Examine CR as influence for Combustion Noise/BSFC tradeoff

- Study influence of these parameters upon PM to insure future EPA compliance
PROJECT FUTURE WORK

- Continue to explore/understand effect of injection strategy upon GCI operation
  - E10 is sensitive to both boost and EGR
- Explore more conditions with LP-EGR
  - Provide more boost at low speeds/loads with EGR
- Examine influence of CR upon combustion noise
  - Alter IVC relative to exhaust cam
  - Use lower CR piston crowns (we have 16, 15 and 14:1)
- Continue to develop strategy for transient operation with injection, boost and EGR
- Continue to track and account for USCAR guidelines combustion noise
  - Target <90 dB for high load, <85 dB for low load
- Continue to characterize GCI particulate emissions
  - TEM sampling and analysis
SUMMARY

Understand the physical and chemistry characteristics of Gasoline Compression Ignition (GCI) in a multi-cylinder engine to aid industry in developing a practical high efficiency, low emission combustion system

1. LP-EGR has a significant effect upon combustion noise, combustion phasing, exhaust temperature and engine-out emissions.

2. Injection strategy is also influential to engine operating outputs
   - DoE analysis quantified effects of input variables
   - Boost and EGR were also found to have large influence

3. PM output is very low for GCI; almost all conditions below 0.1 FSN.
   - Detailed PM study is forthcoming; collaboration with HeeJe Seong
THANK YOU FOR YOUR ATTENTION!

QUESTIONS?
TECHNICAL BACK UP SLIDES
ENGINE SPECIFICATIONS AND TESTED FUELS PROPERTIES
E10 WAS USED FOR IDLE AND LOW LOAD EXPLORATION

### Engine Specifications

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression ratio</td>
<td>17.8:1</td>
</tr>
<tr>
<td>Bore (mm)</td>
<td>82</td>
</tr>
<tr>
<td>Stroke (mm)</td>
<td>90.4</td>
</tr>
<tr>
<td>Connecting rod length (mm)</td>
<td>145.4</td>
</tr>
<tr>
<td>Number of valves</td>
<td>4</td>
</tr>
<tr>
<td>EGR System</td>
<td>High Pressure EGR</td>
</tr>
<tr>
<td></td>
<td>Mixing far upstream for homogeneity</td>
</tr>
<tr>
<td>Injector</td>
<td>7 holes, 0.141-mm diameter</td>
</tr>
<tr>
<td>Umbrella Angle</td>
<td>148° and 120°</td>
</tr>
<tr>
<td>Injection Rail Pressure</td>
<td>500 bar and 250 bar</td>
</tr>
<tr>
<td>Boosting</td>
<td>Variable Geometry Turbocharger (VGT) And/or Eaton Supecharger</td>
</tr>
</tbody>
</table>

### Properties of the Tested Fuel

<table>
<thead>
<tr>
<th>Property</th>
<th>E10 gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>AKI Rating</td>
<td>87.2</td>
</tr>
<tr>
<td>RON</td>
<td>90.7</td>
</tr>
<tr>
<td>MON</td>
<td>83.7</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>7</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>.7342</td>
</tr>
<tr>
<td>Lower heating value (MJ/kg)</td>
<td>42.0</td>
</tr>
<tr>
<td>Initial boiling point (°C)</td>
<td>103.5</td>
</tr>
<tr>
<td>T10 (°C)</td>
<td>132.3</td>
</tr>
<tr>
<td>T90 (°C)</td>
<td>320.7</td>
</tr>
</tbody>
</table>
How was GCI idle achieved on 87 AKI gasoline?

<table>
<thead>
<tr>
<th>Engine Speed (RPM)</th>
<th>CN (dB)</th>
<th>BSFC (g/kW-h)</th>
<th>NOx (g/kW-h)</th>
<th>HC (g/kW-h)</th>
<th>CO (g/kW-h)</th>
<th>Comb. Eff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>750</td>
<td>68.8 (-12%)</td>
<td></td>
<td></td>
<td>1.367 (+406%)</td>
<td>2.153 (+142%)</td>
<td>87 (-10%)</td>
</tr>
<tr>
<td>1000</td>
<td>88.5 (+3%)</td>
<td>303 (+6%)</td>
<td>0.8 (-49%)</td>
<td>3.5 (+189%)</td>
<td>2.9 (-51%)</td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td>92 (+7%)</td>
<td>330 (+9%)</td>
<td>0.8 (-49%)</td>
<td>3.5 (+189%)</td>
<td>2.9 (-51%)</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>94 (+9%)</td>
<td>208 (+4%)</td>
<td>1 (-90%)</td>
<td>0.25 (+32%)</td>
<td>1.9 (+141%)</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td>90 (+0.7%)</td>
<td>227 (-2%)</td>
<td>0.4 (-92%)</td>
<td>0.4 (-92%)</td>
<td>1.1 (-24%)</td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>93 (+6%)</td>
<td>229 (+2%)</td>
<td>0.5 (-82%)</td>
<td>0.5 (-82%)</td>
<td>1.6 (+62%)</td>
<td></td>
</tr>
</tbody>
</table>

*Idle compared to diesel at 1000
EXPANSION OF LOWER LOAD LIMIT WITH 87 AKI GASOLINE

Methodology

- Minimum fueling SOI sweeps
  - 3% CoV of IMEP limit for each cylinder individually
- Single injection per cycle
- 850 RPM engine speed (previous studies also done at 1500 RPM)
- 250 or 500 bar injection pressure
- 148° and 120° injector nozzle
- Combustion noise target <90 dB
- Maximized boost (1.05 bar)
- 45 °C intake air temperature
  - No external intake heating
- No EGR

Based on SAE 2015-01-0832
SOOT RADIATION DIFFERENCES BETWEEN GASOLINE AND DIESEL

- 2-color optical technique is very effective at measuring soot production.
- Graph in lower right (GCI) is with the same scale as graph in upper right (Diesel).
- Optical diagnostics can be effective at identifying boundary conditions for GCI.