Late Intake Valve Closing and Exhaust Rebreathing in a V8 Diesel Engine for High Efficiency Clean Combustion

High-Efficiency Clean Combustion Engine Designs for Compression Ignition Engines

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Outline

- Objectives
- Technical Approach & Hardware
- Discussion of Variable Compression Ratio - Late Intake Valve Closing & Two Stage Turbo Charging
- Discussion of Internal EGR - Exhaust Rebreathing
- Estimated overall driving cycle impacts
- Summary
- Acknowledgements
Objectives

● Investigate the use of variable valve actuation (VVA) as a means to improve the efficiency of a light duty diesel engine approaching and exceeding Tier 2 Bin 5 NOx emission levels

  ➤ Multi-cylinder engine testing using a “simple mechanism” VVA system – steady state engine-out emission targets combined with aftertreatment technology for beyond Tier 2 Bin 5 tailpipe targets and enhanced fuel economy
    — Late Intake Valve Closing (LIVC) Study
    — Exhaust Rebreating Study

● Barriers addressed

  ➤ To operate at Low Temperature Combustion (LTC) conditions using “VVA simple mechanisms” for control of effective compression ratio and internal EGR (IEGR)
  ➤ Expand the useful range of the Early Premixed Charge Compression Ignition (PCCI) LTC mode in order to reduce fuel consumption
  ➤ To reduce engine out emissions
  ➤ To minimize the fuel energy required to raise exhaust gas temperature for catalyst efficiency and regeneration
## VVA Strategies

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Valve profiles</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Late Intake Valve Closing</strong></td>
<td><img src="image1" alt="Graph" /></td>
<td>• Too limiting for engine breathing reducing volumetric efficiency and torque</td>
</tr>
<tr>
<td>(both valves)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| **Late Intake Valve Closing** | ![Graph](image2) | • Effective compression ratio control  
• Reduces volumetric efficiency  
• LIVC with extended duration, same expansion ratio with reduced compression ratio (improved efficiency) |
| (one valve)                   |                |                                                                                                                                               |
| **Intake Re-breathing**       | ![Graph](image3) | • Higher heat losses than exhaust re-breathing  
• More difficult to open than exhaust valve                                                                                                                                 |
| (Intake valve re-opening during exhaust stroke) |            |                                                                                                                                               |
| **Exhaust Re-breathing**      | ![Graph](image4) | • Only one exhaust valve lift profile need to be changed  
• Multiple profiles possible and combined with intake - exhaust pressure control  
• Easier to be opened than intake valve  
• Less heat losses than intake re-breathing                                                                 |
**Technical Approach - Hardware**

**Multi Cylinder Engine – VVA Study**
- Late Intake Valve Closing (phasing of one valve per cylinder)
- Exhaust Rebreathing (re-opening of one valve per cylinder) with single and two stage turbocharging

<table>
<thead>
<tr>
<th>Configuration/Displacement</th>
<th>V8 4.5 liters</th>
</tr>
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<tbody>
<tr>
<td>Compression Ratio</td>
<td>16.0:1</td>
</tr>
<tr>
<td>Bore x stroke</td>
<td>88 mm x 92 mm</td>
</tr>
<tr>
<td>Valve Train</td>
<td>DOHC - 4v</td>
</tr>
<tr>
<td>Intake Configuration</td>
<td>Outboard intake with integrated cam cover intake manifold</td>
</tr>
<tr>
<td>EGR System</td>
<td>Cooled external</td>
</tr>
<tr>
<td>Exhaust System</td>
<td>In Vee exhaust with manifold integrated into head</td>
</tr>
<tr>
<td>Emissions System</td>
<td>DOC, Urea SCR and DPF</td>
</tr>
</tbody>
</table>

- Concentric Camshafts and phaser
- Two-stage turbocharging
- Secondary exhaust opening profile

Base Engine Testbed
**VVA - Late Intake Valve Closing**

LIVC phasing capability up to 90 ca degrees

Two stage system, concentric camshaft and phaser in multi-cylinder engine head

**Effective compression ratio in LIVC operating range**

\[
CR_{\text{effective}} = \frac{V_{\text{effective}}}{V_{\text{TDC}}}
\]

**Engine operating map for LIVC study**
1-D Modeling for LMK 4.5L V8 Diesel Engine

Target: 70 ca deg phasing of one intake valve matching AFR and EGR

Two stage charging selected
### Charging

- **Modeling air handling**
  - 1-D modeling base engine and VVA system
  - Charging hardware selection

#### BSFC (g/Kw-h)

- AFR matching only reached when using a High Pressure VGT not using VNT closing which have detrimental BSFC performance
- Experimental work also have shown emissions benefits with a controlled reduction in AFR

<table>
<thead>
<tr>
<th>Pressure ratio</th>
<th>Corrected Flow</th>
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<tbody>
<tr>
<td>0.465</td>
<td></td>
</tr>
<tr>
<td>0.48</td>
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<tr>
<td>0.495</td>
<td></td>
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<td>0.51</td>
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<td>0.525</td>
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<td>0.66</td>
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<tr>
<td>0.66</td>
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<td>0.675</td>
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<td>0.69</td>
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<tr>
<td>0.705</td>
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<tr>
<td>0.72</td>
<td></td>
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<tr>
<td>0.735</td>
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<td>0.75</td>
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<td>0.75</td>
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<tr>
<td>0.765</td>
<td></td>
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<tr>
<td>0.78</td>
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</tbody>
</table>
**Effective Compression Ratio on Cylinder Pressure**

- Peak cylinder pressure reduction resulted by LIVC implementation for lower effective compression ratio

- Start of injection can be advanced for constant combustion phasing to compensate for longer ignition delay

---

SCE 1600 rpm x 4.2 bar LIVC60 EINOx 0.3 g/kg-f

Early PCCI (blue color, LIVC70) and late PCCI

- Coef of Variation of combustion phasing increases with LIVC, cam phasing control stability and impact of changing flow dynamics of individual cylinders
Variation of main engine parameters at different LIVC phasing and constant NOx

- Advancing SOI for constant phasing
- AFR drops with less efficient charging
- Flow to intake manifold
- Less EGR at constant NOx

1600 rpm/4.8 bar BMEP
Normal combustion
Coolant @ 88°C, Bypass OFF
< 1.2 g/kg EINOx
Ca50 12 atdc fix
Fix 70% VNT position
Variation of main engine parameters at different LIVC phasing and constant NOx

1600 rpm/4.8 bar BMEP
Normal combustion
Coolant @ 88°C, Bypass OFF
< 1.2 g/kg EINOx
Ca50 12 atdc fix
Fix 70% VNT position

Optimum BSFC determined by Phasing, Heat transfer, Friction

Lower temperature profile for higher HCs

Higher oxygen accessibility by lower effective compression ratio and variable swirl
AFR, BSFC, HC, Smoke with LIVC Phasing

Consistent trends are observed at different keypoints.

Base and LIVC 50 ca degrees
1200 rpm/3.9 bar BMEP
Normal combustion
Coolant @ 88°C, Bypass OFF
Ca50 9 atdc fix
Fix 72% VNT position
30-42% EGR sweep
Smoke vs AFR at Low NOx with LIVC Phasing for PCCI Combustion Modes

Early PCCI encounters either high smoke or high noise if using a conventional valve lift profile.

For LIVC, a single injection strategy could achieve good overall engine performance.

By using LIVC, the combustion phasing can be advanced for better fuel economy.

The AFR can be reduced because smoke emissions are lower due to longer ignition delay.

The combustion noise is controlled within the noise limits by adjusting the injection timing.
LIVC 50 ca delay - Overall Effects

Impact FTP Cycle
- BSFC ~ -0.5%
- PM ~ -25%, > 50% at keypoints
- HC > +17%

Operating region defined by trade-offs of fuel efficiency and emissions (boundaries: HCs at light loads; loss of ignition delay advantage for mixing at higher loads and AFR drop)
Internal EGR
Exhaust rebreathing events

- Keypoints operating area selected by HC contribution to cold start FTP cycle
- High/Low Lift and duration profiles
- Valvetrain exhaust implementations opposite to intake helical and tangential ports
Internal EGR approach

- Representative IEGR profiles
- Modeling of HC and NOx contributing keypoints

Exhaust Valve Flows
650 rpm/2.2 bar

Exhaust Valve Flows
1600 rpm/6.8 bar

Fixed cams for switching profiles options
Internal EGR relative to Baseline

• Turbine In temperature can be increased along all the operating range
• Can induce light-off for the DOC catalyst
• Varies with heat transfer, AFR by substitution of External (Bypass) EGR (%)
• Internal EGR amount by model based approach

RPM/TORQUE
Internal EGR relative to Baseline

- Post DOC performance, (as HC % of reduction) is favored by less engine out emissions plus faster light-off and higher conversion by higher operating temperature.

DOC inlet and Post DOC temperature can be further increased by HC/CO additional conversion (also changes in turbine operating point efficiency).

Fix RPM/BMEP keypoints
In 200 sec warm-up phase
Coolant @ 40C, Bypass ON
NOx ≤ target
Impact of IEGR

Whole FTP Cycle

- Fuel consumption ~ +0.3%
- Tailpipe Hydrocarbons ~ -20% (-50% first 200 sec of FTP cycle)

First 200 sec in the warmup phase FTP Cycle – Estimate by weighting factors

- Test vehicle weight 7000 lbs. Exhaust Gas temperature Management at low coolant temperature
  >20 % of the fuel consumed in FTP cycle
- Smoke impact constrains for maximum applied engine bmeps
Comparing exhaust heating strategies

- Fix RPM/BMEP keypoints in 200 sec warm-up phase
- Coolant @ 40°C, Bypass ON
- NOx ≤ target

- For matching exhaust temperature, IEGR by exhaust rebreathing shows promising results for a competitive strategy to retarded timing at idle

- Sources of sensitivity to port location to be subject of detailed investigation
Vehicle TVW 7000 lbs

- Phase 1 with highest contribution to HC and NOx overall tail-pipe emission for FTP
- Increasing exhaust temperature by 40 degrees
  - Overall emission for FTP can be reduced by 25% (HC) and 17% (NOx)
  - Total HC reduction Engine-out plus higher conversion 35%
Patent application - Diesel engine with switching roller finger followers for internal EGR control

The application of switching roller finger followers on the exhaust valvetrain of multi-cylinder diesel engines for selectively producing the re-opening of exhaust valves for internal EGR control

<table>
<thead>
<tr>
<th>EGR Level</th>
<th>Exh Valve #1</th>
<th>Exh Valve #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>1</td>
<td>On</td>
<td>Off</td>
</tr>
<tr>
<td>2</td>
<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>3</td>
<td>On</td>
<td>On</td>
</tr>
</tbody>
</table>

Ways to apply the system:

- Single Exhaust valve per cylinder - allows one discrete rebreathing profile to be used, switchable
- Both exhaust valves per cylinder - single actuator, allows a higher amount of EGR to be introduced based on a single actuator
- Both exhaust valves per cylinder - dual actuator circuit, allow combinations of internal EGR rate to be achieved (zero, low and high)
- Both Exhaust valves per cylinder - dual actuator circuit, dual lift profiles, flexible control with 3 levels of internal EGR possible (additional control achieved with back pressure regulation)

1-D Simulation
Idle
Internal EGR replacing external EGR

Exhaust Valve Flow

Gas Flow (Kg/sec)

Crank Angle (Deg)
Summary

- Late Intake Valve Closing for Changing Effective Compression Ratio and Exhaust Rebreathing for Internal EGR have been investigated with promising results

- Operating envelope
  - LIVC operation at part loads for emissions and FE of hot FTP cycle, constrained by charging system capability
  - IEGR operation from idle to part loads for warm-up and emissions of cold FTP cycle. Max BMEP determined by smoke limitations

<table>
<thead>
<tr>
<th>VVA</th>
<th>Major impacts</th>
<th>Benefits / Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategies</td>
<td>FTP75 cycle fuel cons.</td>
<td>FTP75 cycle emissions.</td>
</tr>
<tr>
<td>Intake</td>
<td>Profiles</td>
<td>NOx  PM  HC  CO  Comb noise  Exhaust temp</td>
</tr>
<tr>
<td>Exhaust</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LIVC</td>
<td>1% * reduction</td>
<td>50% PM reduction</td>
</tr>
<tr>
<td>Internal EGR</td>
<td>0.3-0.5% increase **</td>
<td>~20% HC reduction</td>
</tr>
</tbody>
</table>

Higher FE potential improvement for LIVC including the benefit for increased DPF regen interval

*: Depending on charging capability
**: Compensation by warm-up strategy and aftertreatment impact

**Key:**
+ improved
o neutral
- worse

Advanced Diesel
DEER Conference 2010
Summary

- Variable valvetrain techniques have significant impacts on fuel efficiency and emissions with packaging and control challenges for implementation with different alternative valvetrain mechanisms in new engine designs.

- Late intake valve closing and exhaust rebreathing provide further optimization opportunities for fuel efficiency and emissions.

- Experimental impacts and estimations for the assessment of application are highly dependent on engine architecture and engine performance and emissions targets.