Heavy Duty HCCI Development Activities

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Agenda

• Background
• Systems approach
• Controls Development
• Heat Flux Measurements
• Optical Engine Results
• HCCI fuel effects
• Conclusions
Engine Industry Challenges

- Improving fuel efficiency while meeting much more stringent emissions standards is a tremendous technical challenge.

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Technology Investment

Thermal Efficiency

NOx (g/hphr)

- 2003
- 2007
- 2010
- 2003

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Systems Approach to HCCI Development

- FEA
- Simulation
- Single and Multi Cylinder Testing
- Aftertreatment
- HCCI Fuels
- Air Systems
- Combustion Development
- Fuel Systems
- Controls
- In-cylinder Diagnostics
- Desired Speed/Power
- Efficiency
- Emissions
- Compression Ratio
- A/F Ratio
- Heat Rejection
- Percent CGI Pressure
- CGI Valve A/F Ratio Efficiency Emissions Desired Speed/Power
- Boost Pressure
- VGT Position Back Pressure VIVA Setting
- Cylinder Pressure Rise Rate
- Exhaust Temperature
- Caterpillar
- T&SD Technology & Solutions Division
Systems Approach to HCCI Development

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Controls Challenges

• Need robust method for detecting start of combustion (cylinder pressure sensor, ion sensor, torque fluctuation on crank, knock sensor, strain gauged head bolts, microphones, etc.)

• Transient operation, transitioning to different speed/load points

• Activities:
  – Sensor evaluation
  – RPAC installation, feedback control capability on multi
  – Preliminary controls architecture developed
  – Cylinder pressure feedback implemented
  – Basic phasing control demonstrated using intake valve actuation (IVA) to balance cylinders
  – Speed and load step tests demonstrated
VVA for Cylinder Balancing

Feedback off

Feedback on
300 RPM Transition, Constant Load

Baseline transition strategy

Optimized transition strategy
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- CGI Pressure Ratio
- Percent CGI
- Heat Rejection
- Boost Pressure
- VGT Position
- Back Pressure
- VIVA Setting
- Injection Timing
- Exhaust Temperature
- Diesels
- Gas Turbine
- Caterpillar
- Technology & Solutions Division
Heat Rejection Comparison

- Compared HCCI and conventional combustion with CGI (clean gas induction) at a part load operating condition
- For same CGI rate, NOx and BSFC, the engine block jacket water heat rejection was >50\% higher for HCCI compared to conventional combustion (other heat rejection values similar)
- Is there significantly higher in-cylinder heat transfer to block/head/piston? (due to hotter bulk gas combustion near walls, short burn duration?)
Related Research

- Tsurushima et al. premixed DME/Propane HCCI (SAE 2002-01-0108)
- Chang et al. gasoline HCCI (SAE 2004-01-2996)
Heat Flux Measurement

- **Medtherm-heat flux probe**
  - Two j-type TC, front side and back side
  - Front side has micro-second response time
  - Installed in head between exhaust valves

- **Instrumented liner**
  - 20 k-type TC radially
  - ~ 15 mm from liner top
  - Results showed no major difference in liner temps between HCCI and conventional combustion
Knock Effect on Heat Flux

HCCI operation, 1500 rpm

- 1900 BMEP, baseline CGI%
- 1860 BMEP, baseline - 5% CGI
- 1500 BMEP, baseline - 11% CGI

Crank Angle Degree

Heat Flux (MW/m²)

Cylinder pressure (MPa)
Effect of Partial Stratification

Heat flux vs combustion phasing

Heat Flux (MW/m^2)

10
9
8
7
6
5
4
3
2
1

-15 -10 -5 0 5 10 15 20
start of combustion (deg atdc)

- Trendline - Conventional
- Trendline - HCCI

1800 rpm, >1400 BMEP
1800 rpm, 1000 BMEP
1500 rpm, 1500 BMEP
1500 rpm, 1000 BMEP
1200 rpm, >1500 BMEP
1200 rpm, 1000 BMEP
Conventional Comb, 1800 rpm
Conventional Comb, 1500 rpm
Conventional Comb, 1200 rpm
premixed DME/propane HCCI
Systems Approach to HCCI Development

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- In-cylinder Diagnostics
- Controls
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- Combustion Development
- Air Systems
- Aftertreatment
- HCCI Fuels

In-cylinder Diagnostics

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Optical Engine Testing with Sandia National Lab

- Goal of Project: use optical diagnostic techniques to supply a knowledge base of in-cylinder processes under LTC operating conditions
  - To understand reasons underlying observed emissions levels
  - To gain insight into approaches to implement fuel or hardware changes that ameliorate the problems
  - To help validate simulations of in-cylinder mixing and LTC
- Partnering with Chuck Mueller and Glen Martin at Sandia on the Caterpillar/Sandia 3171 optical engine
- Optical diagnostics techniques used include natural luminosity, liquid and vapor phase spray imaging, soot imaging, PLIF
# Sandia Compression-ignition Optical Research Engine (SCORE)

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<tr>
<th>Specification</th>
<th>Value</th>
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<td>Research engine</td>
<td>1-cyl. Cat 3176</td>
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<tr>
<td>Cycle</td>
<td>4-stroke ClID</td>
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<tr>
<td>Valves per cylinder</td>
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<tr>
<td>Bore</td>
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<td>Stroke</td>
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<td>116° ATDC compr.</td>
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<td>Piston bowl diameter</td>
<td>90 mm</td>
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<td>Piston bowl depth</td>
<td>16.4 mm</td>
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<td>Squish height</td>
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<tr>
<td>Swirl ratio</td>
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<td>Displacement per cyl.</td>
<td>1.72 liters</td>
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<td>Fuel Injector</td>
<td>HEUI 450A</td>
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<td>Injector tip</td>
<td>Multi-hole nozzle</td>
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![Diagram of the engine](image-url)
Camera View Orientation for Cycle Integrated Natural Luminosity (CI NL) Movies

- Exhaust valves
- Injectors
- In-cylinder pressure transducer
- Glow plug hole
- Intake valves
- Exhaust runner
- Intake runner

Cycle 59
CI NL Movie of HCCI Combustion

Full-Cycle Soot Incandescence with Apparent Heat-Release Rate
1200 rpm, 9.1 bar IMEP
Systems Approach to HCCI Development

- FEA
- Simulation
- In-cylinder Diagnostics
- Controls
- Fuel Systems
- Combustion Development
- Air Systems
- Single and Multi Cylinder Testing
- Aftertreatment
  - HCCI Fuels

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Fuel/ Engine Systems Approach

CAT
- Hardware
- Engine Testing
- Systems Integration
- Combustion Modeling
- Fluid Dynamics

ExxonMobil
- Fuel
- Advanced Characterization
- Refining Process Technology
- Chemical Kinetics
- Systems Modeling

Optimized Systems

Benefits For:
- Consumer
- Environment
- Industry
Preliminary Fuel Effects Study

- **Study parameters:**
  - **Ignitability**
    - Cetane number: 39 - 55
    - Octane number (R+M)/2: 63 - 91
  - **Aromatic content**
    - 28 - 45%
  - **Volvatility**
    - Gasoline
    - No.1 diesel fuel
    - No.2 diesel fuel
  - **Other fuel parameters generally well matched when varying single property**

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<td>Aromatics %</td>
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<td>Aromatics %</td>
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<tr>
<td>T90, °F</td>
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**DIESEL FUELS**

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<td>Aromatics %</td>
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<tr>
<td>T90, °F</td>
<td>495</td>
<td></td>
<td>T90, °F</td>
<td>596</td>
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<td>T90, °F</td>
<td>618</td>
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**GASOLINES**

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<th>(R+M)/2</th>
<th>81</th>
<th>&gt;&gt;&gt;</th>
<th>(R+M)/2</th>
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<td>Aromatics %</td>
<td>15</td>
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<td>Aromatics %</td>
<td>26</td>
<td></td>
<td>Aromatics %</td>
<td>27</td>
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<tr>
<td>T90, °F</td>
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<td></td>
<td>T90, °F</td>
<td>309</td>
<td></td>
<td>T90, °F</td>
<td>299</td>
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Test Engine

- Single-cylinder Caterpillar 3401 engine
- Cylinder displacement: 2.44 liters
- Bore/Stroke: 137/165 mm
- Valves/cylinder: 4
- Swirl ratio: 0.4
- Hydraulically intensified fuel injection system. Multi-hole nozzle
- All emissions engine-out
- Main control variables: fuel injection timing, boost/backpressure
- Careful engine control to identify fuel effects
No Benefit for Increased Cetane in Expanding High Load Operability

- Increasing cetane # produced undesirable advance in combustion phasing
- Cylinder pressure rise rate and increase in peak cylinder pressure result in lower load capability
- Similar behavior for natural and additized cetane
Cetane Number Had Small Effect on Emissions

1800 rpm, 25% load
Aromatics Has Small Impact on Emissions

1500 rpm, 25% load
Increased Volatility Generally Reduces Emissions

- Cylinder Pressure, MPa
- Crank Angle, deg.
- Engine Load, %
- AVL Smoke Number
- NOx, ppm
- HC, ppm

- T90 = 596 F
- T90 = 495 F
Gasoline Can Also Achieve High HCCI Engine Loads

- Reduced octane rating enabled operation over a broader speed/load range

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<th>(R+M)/2 = 81.2</th>
<th>(R+M)/2 = 91.2</th>
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<tbody>
<tr>
<td></td>
<td>1200 rpm</td>
<td>1800 rpm</td>
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<tr>
<td>Maximum Load</td>
<td></td>
<td></td>
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<tr>
<td>Achieved</td>
<td>70%</td>
<td>82%</td>
<td>75%</td>
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<tr>
<td>Minimum Load</td>
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<tr>
<td>Achieved</td>
<td>25%</td>
<td>25%</td>
<td>50%</td>
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Numerous Challenges Remain For HCCI

- Cold start with lower compression ratios
- Air system development requirements
- Light load HC/CO cleanup
- Controlling combustion phasing and transient operation
- Cylinder to cylinder variability
- Structural reliability with higher cylinder pressure and rise rates
- Small hole production related issues
- Noise/vibration
New DOE Program for Continued High Efficiency Clean Combustion Development

- Program coordination
- Test/Analysis
- Truck/Machine system integration and packaging
- Combustion

- Optical diagnostics
- Fuel spray and combustion
- Fuels effects

- Closed loop control
- Transient controls
- Vehicle calibration
- Sensors
Summary

• Significant progress made on expanding operating range for HD HCCI engine
• Full load HCCI is extremely challenging
• Fuels effects can have positive/negative impacts on performance and emissions
• Much work still needed to determine production feasibility of HCCI as a 2010 emissions strategy
• Advanced technology Diesel engines should continue to have long term viability as a prime power source for on and off-highway markets