Optimizing Low Temperature Diesel Combustion

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“This presentation does not contain any proprietary or confidential information”
US EPA mandates require emissions of PM and NOx from heavy-duty diesel engine exhaust to be reduced by 90% between 1998 and 2010 – meet emissions targets without compromising fuel efficiency

**Goals:** Develop methods to further optimize and control LTC engines in-cylinder, with emphasis on diesel-fueled engines

**Barriers:** Control of fuel/air mixing and wall-wetting is difficult due to low volatility of diesel fuel. Combustion phasing determined by chemical kinetics

**Approach:** Use high fidelity computing and high-resolution engine experiments synergistically to create and apply advanced tools needed for low emissions engine combustion design

Engine technologies to be considered include operation on LTC-D with transition to advanced Compression Ignition Direct Injection (CIDI) combustion at higher loads and starting conditions ("mixed-mode" operation)

**Outcomes:** Efficient, low-emissions combustion concepts proposed, evaluated and understood
Task 1: Fundamental understanding of LTC-D and advanced model development

1.1a Develop combustion models - Reitz
1.1b Optical engine measurement - Sanders
1.2a LES turbulence Models - Rutland
1.2b Mixing Measurements - Ghandhi

Task 2: Experimental Investigation of combustion control concepts

2.1 VVT/VGS for combustion control HD engine - Reitz
2.2 Injection and fuel effects LD engine - Foster

Task 3: Application of models for Optimization of combustion & emissions

3.1 GA Optimized piston geometry - Reitz
3.2 Optimized spray characteristics - Reitz
3.3 Improving mixing using LES - Rutland

Task 4: Impact of heat transfer and spray impingement on LTC-D combustion

4.1 Thermal analysis with CFD + metal heat conduction - Reitz
4.2 Temperature & heat flux measurements - Ghandhi

Task 5: Transient engine control with mixed-mode combustion

5.1 Multi-cylinder LD engine control with mixed-mode combustion – Foster/Farrell
5.2 Engine system analysis with mixed-mode regime transitions - Rutland
Question 1: Relevance to DOE - Strong tie to emissions, link to efficiency?
Response: Use of diesel gives improved efficiency (plus alternative fuels).

Question 2: Approach - i.) PLIF less resolved than LES?
Response: PLIF resolution exceeds LES: provides accurate model input.
ii.) Hardware needed for mixed-mode operation plus after-treatment costly.
Response: Optimized in-cylinder combustion minimizes after-treatment needs & offers improved fuel efficiency and after-treatment system durability.
iii.) GA matches injector to piston geometry? Response: Yes
Response to Reviewer Comments - SMMR 6/07

Question 3: Technical Accomplishments/Progress to DOE goals
Two injector system is costly – can incorporate into one injector?
Response: Demonstrate efficacy of VIP/VGS (e.g., multiple injections)

Question 5: Approach/relevance of proposed future research
i.) Reduced chemical kinetics validation? Response: Project 1.1b’s data
ii.) Account for combustion noise? Response: Optimized multiple injections
iii.) Use of merit functions in optimization? Response: Use MOGA methodology

Strengths/Recommendations:
Identify DERC role.
Response: 20% match fund

Weaknesses: Clarify technologies to be used with after-treatment.
Response:
- focus on minimized need for after-treatment
- increase LTC load range.
HCCI/LTC attractive due to low NOx and soot emissions. However, ignition and combustion is controlled by complex chemical kinetics and turbulence interactions.

**Approach:** Develop accurate reduced chemistry mechanisms for auto-ignition. Combine chemistry with advanced combustion CFD model (KIVA-CHEMKIN-G).

**Accomplishments:** PRF-Bio mechanism developed (< 55 species) and validated with engine data. Volumetric and flame propagation combustion models integrated using Damköhler number time scale switch criterion. Improved NOx model with HCN.

**Plans for Next Year:** Validate reduced mechanisms with engine data, with in-cylinder species measurements from Task 1.1b.
Comparison of measured and simulated in-cylinder species composition histories will help optimize low-temperature combustion processes.

**Approach**: Using advanced laser sensors and novel applications of traditional optical instruments, catalog in-cylinder gas properties under varied engine operating conditions.

**Accomplishments**: H₂O vapor sensing near 1350 nm has been developed. Temperature precision is < 5 K at 100 kHz (better at lower data rates). In-cylinder FTIR demonstrated, many species including H₂O, CO₂, CO, NO, C₂H₂, and CH₂O are now accessible.

**Plans for Next Year**: Interact with Task 1.1a by collecting in-cylinder species data to compare with simulation results.
High-efficiency low-emission combustion requires precise control of mixing.

**Approach:** Develop high fidelity, computationally efficient models of mixing through integrated comparison with high resolution in-cylinder experiments.

**Modeling Accomplishments:** LES scalar dissipation model integrated in flamelet model with detailed chemistry. Dissipation used to differentiate flamelet burning and homogeneous combustion modes.

**Technical Barriers:** Limited LES grid resolution → accurate models.

**Plans for Next Year:** Detailed comparison of dissipation model results with experimental data.

**Experimental Accomplishments:** Fluorescence saturation measurements performed with 3-pentanone. Mixing measurements during the intake and compression stroke performed.

**Plans for Next Year:** Complete characterization of intake flows, develop database of diesel and gas jets. Investigate dissipation spectra to resolve differences in experimental and modeled resolution levels.
Task 2: Experimental investigation of LTC-D combustion control concepts: 2.1 VVT-VGS in HD engine

Early injection provides sufficient time for fuel/air mixing for HCCI, but can have excessive wall wetting and too early ignition with diesel fuel

**Approach:** Use late IVC VVA to control Comp. Ratio, plus variable geometry/injection pressure sprays. Assess Adaptive Injection Strategy - 2 Stage Combustion (TSC) with low/high injection pressures.

**Accomplishments:** 2010 emissions levels demonstrated with TSC at 11 Bar IMEP. 2-injector system has low emissions HCCI, with soot/BSFC controlled by late injection.

**Plans for Next Year:** Assess IVC timing/EGR/Boost effects with TSC

<table>
<thead>
<tr>
<th>Model Results - GA Optimum 1757rpm, 57% Load</th>
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<tbody>
<tr>
<td>IVC (° CA)</td>
</tr>
<tr>
<td>-----------</td>
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<tr>
<td>-95</td>
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</table>

<table>
<thead>
<tr>
<th>BSFC 214 g/kW-h</th>
<th>NOx</th>
<th>Soot</th>
<th>CO</th>
<th>HC</th>
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<tbody>
<tr>
<td>Optimum</td>
<td>0.181</td>
<td>0.033</td>
<td>12.88</td>
<td>2.04</td>
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</table>
Task 2: Experimental investigation of LTC-D combustion control concepts: 2.2 injection and fuel effects on mixing

Investigate potential of achieving LTC-D operation with different nozzle geometries and with a range of fuels

**Approach:** Use advanced injection systems with different nozzle configurations, on research GM 1.9L diesel engine with fuel property variations from FACE matrix (from BP)

**Accomplishments:** Chose an optimal nozzle. Tested fuels ECD-1, US-ULSD 1 & 2, and Blends E, H, C, and C+. At this load (5.5 bar) significant improvement of CO, HC, and ISFC from increasing cetane number and volatility,

**Plans for Next Year:** Complete tests on remainder of fuels, evaluate impact of specific FACE matrix parameters.
Task 3: Application of detailed models for Optimization of LTC-D: 3.1 Optimization of HD engine piston bowl geometry

Simultaneously optimize piston shape and spray for low emissions and fuel economy

**Approach:** Apply multi-objective optimization genetic algorithm (MOGA) with KIVA-CTC code. Validate results with KIVA-Chemkin.

**Accomplishments:** Highly efficient MOGA (NSGA II) formulated – SAE 2008-01-0949

Real-time method for determining convergence. Optimum piston design and spray parameters found for both high- and low-load operation.

**Plans for next year:** Validate optimized piston experimentally on Caterpillar 3401 HD engine.
- Implement data mining methods to reduce computational resource requirements.
- Further improve MOGA, and reduce CPU time of KIVA-Chemkin simulation to directly couple MOGA with detailed chemistry.
Task 3: Application of detailed models for Optimization of LTC-D: 3.2 optimal spray characteristics

Develop optimal injection and combustion methodologies for low emissions operation

Approach: 2-Spray angle, group-hole nozzle explored - Combine bowl spray with squish spray for improved mixing for near-homogeneous HCCI-like combustion/improved access to oxygen

Accomplishments: Grid-independent spray model developed for standard and group-hole nozzles – SAE 2008-01-0970

2-Spray angle gives improved fuel preparation

Plans for next year: Use Genetic Algorithm to optimize spray parameters over range of speed/loads.

Group-hole nozzle sprays

Improved spray model

Standard KIVA
Improving understanding of early injection and variable valve actuation on LTC efficiency and emissions

**Approach:** Develop and use advanced LES turbulence, mixing, and combustion models in validated engine CFD

**Accomplishments:**
- Grid resolution studies of sprays
- Implemented and tested LES flamelet combustion model
- Successfully simulated changes in emissions due to IVC changes

**Plans for Next Year:** Continue validation with experimental data and extend studies to higher load conditions and advanced injection

<table>
<thead>
<tr>
<th></th>
<th>NOx ratio</th>
<th>SOOT ratio</th>
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<tr>
<td>Exp.</td>
<td>0.4</td>
<td>2.0</td>
</tr>
<tr>
<td>LES</td>
<td>0.9</td>
<td>1.8</td>
</tr>
<tr>
<td>RANS</td>
<td>2.1</td>
<td>1.1</td>
</tr>
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Emission: ratios of late IVC (275 CA) to stock IVC (217 CA)
Task 4: Impact of heat transfer and spray impingement on LTC-D: 4.1 & 4.2 Thermal Analysis Modeling & Experiments

Thermal management critical for LTC control, especially for transient operation. Project explores heat transfer effects on ignition timing, emissions, and heat release

**Approach:** 1.) Use Sandia HD engine for model development 2.) Design and implement mechanical linkage or telemetry system for Caterpillar HD diesel engine to measure (piston) heat flux and temperature

**Accomplishments:** Sandia engine temperature field characterized. Position of heat flux sensors on Cat piston and head selected with KIVA-HCC simulations. Mechanical linkage system under test.

**Plans for Next Year:** Engine tests with instrumented piston. Investigate heat transfer mechanisms. Compare data with simulations. Modify operating conditions to isolate heat-transfer effects.
Evaluate steady state and transient LTC operation to understand requirements for combustion phasing control

**Approach:** Use coordinated engine experiments and system simulations to study LTC load and mode transients

**Accomplishments:** Initiated testing program on transient multi-cylinder engine. Implemented and tested multi-cylinder system simulation with advanced combustion models; simulated potential operating conditions for DPF regeneration experiments; explored EGR and combustion phasing interactions.

**Plans for Next Year:** Use system model to study combustion control for near stoichiometric operation and high EGR. Investigate transient LTC-D and emissions

High Speed NO Measurement, 5 bar to 2.5 bar, 2000 RPM
5 Tasks integrated to develop methods to optimize and control LTC-D for fuel efficiency and low emissions

**Approach:** Use novel diagnostics, fuel-types, injection concepts, optimized piston geometry with advanced CFD models and coordinated engine experiments

**Accomplishments:**
- In-cylinder FTIR species diagnostic developed
- Grid-independent spray model developed
- LES applied to identify low emissions operation
- Low emissions demonstrated with IVC control and Adaptive Injection System
- Improvement of CO, HC, and ISFC with increased cetane number and volatility in PCCI
- System model and transient dyno operational for load change/ mode transition exploration

**Plans for Next Year:** Explore methods to reduce emissions and increase fuel efficiency
- Further demonstrate LTC on HD and LD engines
- Optimize injection strategies, matched with piston
- Demonstrate and test transient control strategies
Tech. Transfer & Collaborations/Interactions

DOE LTC Consortium project DE-FC26-06NT42628

British Petroleum
General Motors CRL

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Diesel Emissions Reduction Consortium (DERC) 24 member companies

Caterpillar Inc.;
CDadapco;
Chevron;
Corning Incorporated;
Cummins, Inc. Fleetguard Inc.;
DaimlerChrysler AG;
Delphi Corporation;
Detroit Diesel Corporation;
FEV Engine Technology;
Ford Motor Company;
GE Global Research;
GM R&D and Planning and Powertrain;

Hyundai Motor Company;
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Volvo Powertrain
Publications, Presentations, Patents

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Patents


Selected Publications

Publications (Cont.)

- “Comprehensive Characterization of Particulate Emissions from Advanced Diesel Combustion” Dave Foster, CLEERS Workshop, May 2007, Dearborn, MI