CATERPILLAR®

Development of Enabling Technologies for High Efficiency, Low Emissions Homogeneous Charge Compression Ignition (HCCI) Engines

Program Manager: Scott Fiveland

DOE Contract: **DE-FC26-05NT42412**

DEDOE Technology Manager: Roland Gravel

NETL Project Manager: Carl Maronde

Project ID: ace_38_fiveland

DOE Merit Review

Washington, D.C.

May 18^{th}, 2009

Note: This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Collaborations

University of Wisconsin
Engine Research Center

Lund University

AEC MOU

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

Oak Ridge National Laboratory

- In-cylinder heat transfer
- Exhaust Availability
- Leverage advanced materials CRADA

Sandia National Laboratories

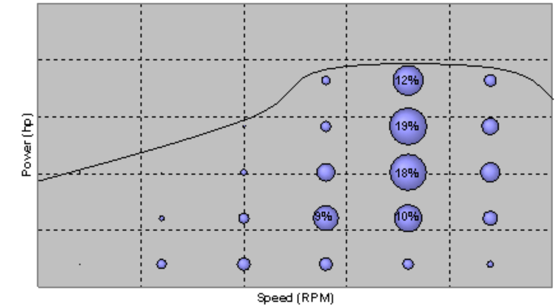
- Optical diagnostics
- Fuel spray and combustion
- Fuels effects

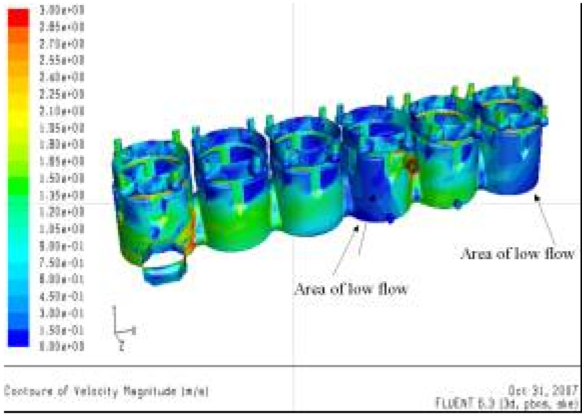
ExxonMobil Research and Engineering

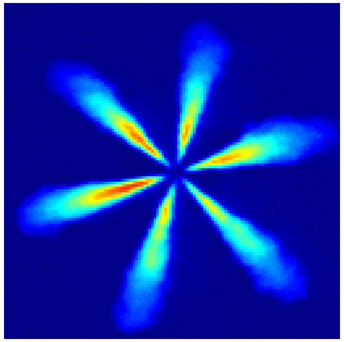
- Fuels effects
- Combustion Chemistry/modeling

Outline

- Program Overview/Purpose
- 2008/2009 Focus Areas
- Technical Approach
- 2008 Program tasks
- 2009 Planned Program Tasks







Program Overview

Timeline

- Start: 8/01/2005
- Finish: 6/30/2009

Budget

- Total Project Funding (Phase 1,2)
  - DOE - $10,309K
  - Contractor - $10,309 (Phase 1,2)
- Funding received FY08 & FY09
  - DOE ~ $2,700K[1]
  - Contractor ~ $2,700K

Partners

- Exxon-Mobil
- Sandia National Laboratory
- Oak Ridge National Laboratory

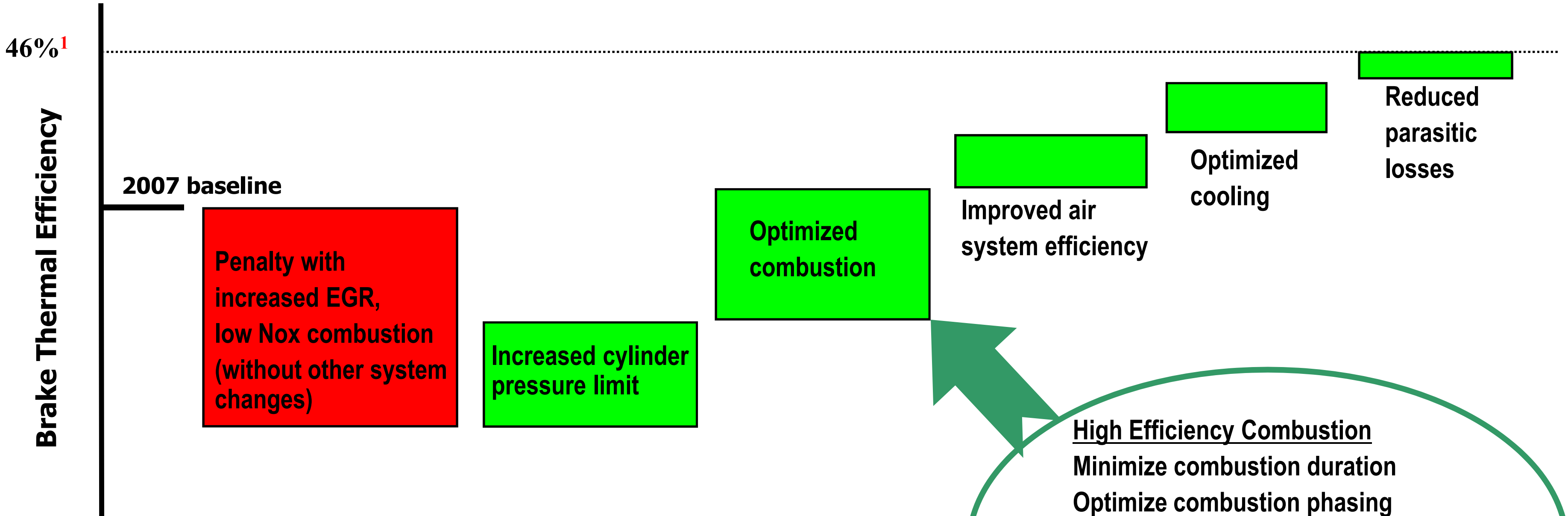
Technical Barriers

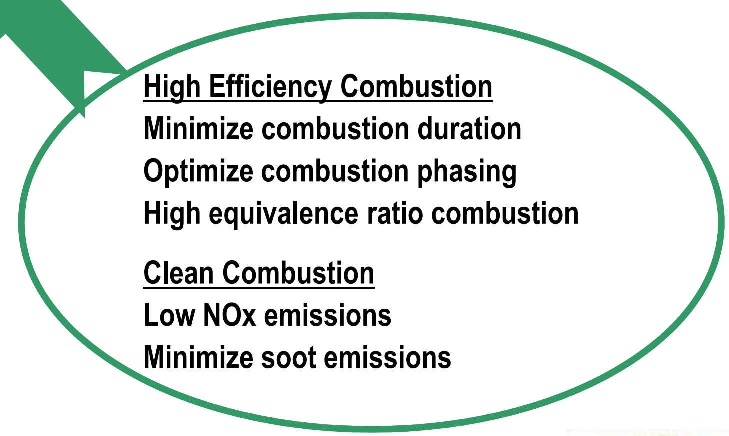
- **Mixture Preparation / Air Utilization**
  - Excessive HC,CO and soot emissions with HCCI – type combustion
  - Excessive soot at high BMEP (Ø > 0.8)
- **High heat rejection**
  - Increased EGR requirements
  - Increased in-cylinder heat transfer with HCCI
- **Power density / load capability**
  - Cylinder pressure and rise rate limits
  - High equivalence ratio at high BMEP
- **Robust combustion control**
  - Transient control of HCCI (PCCI)
  - Combustion feedback sensors
  - Combustion mode switching

[1] **As per FY2008 & 2009 plan**

Purpose of Work

- Assess production viable low temperature combustion technology building blocks to enable a low emissions and high thermal efficiency (46%[1]).





Why Low Temperature Combustion?

- Potentially short combustion durations are thermodynamically attractive
- Low NOx and PM emissions reduce or eliminate need for aftertreatment
  - →Reduced backpressure and lower cost
  - →Reduced regeneration cost

1 As Per Solicitation DOE Contract: **DE-FC26-05NT42412**

Technology Barriers

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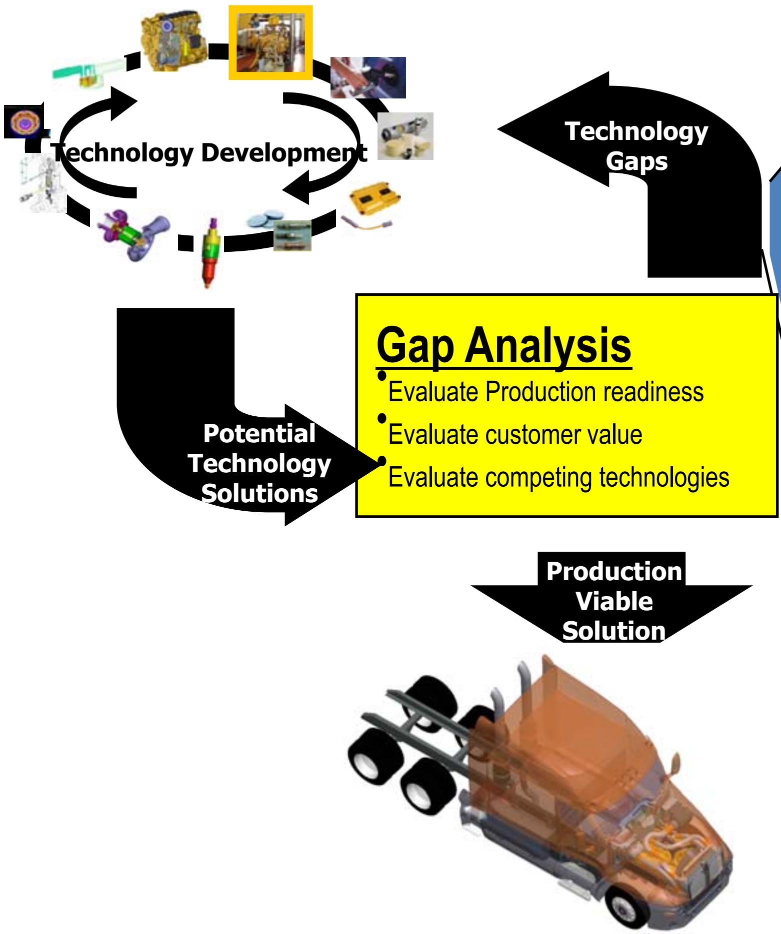

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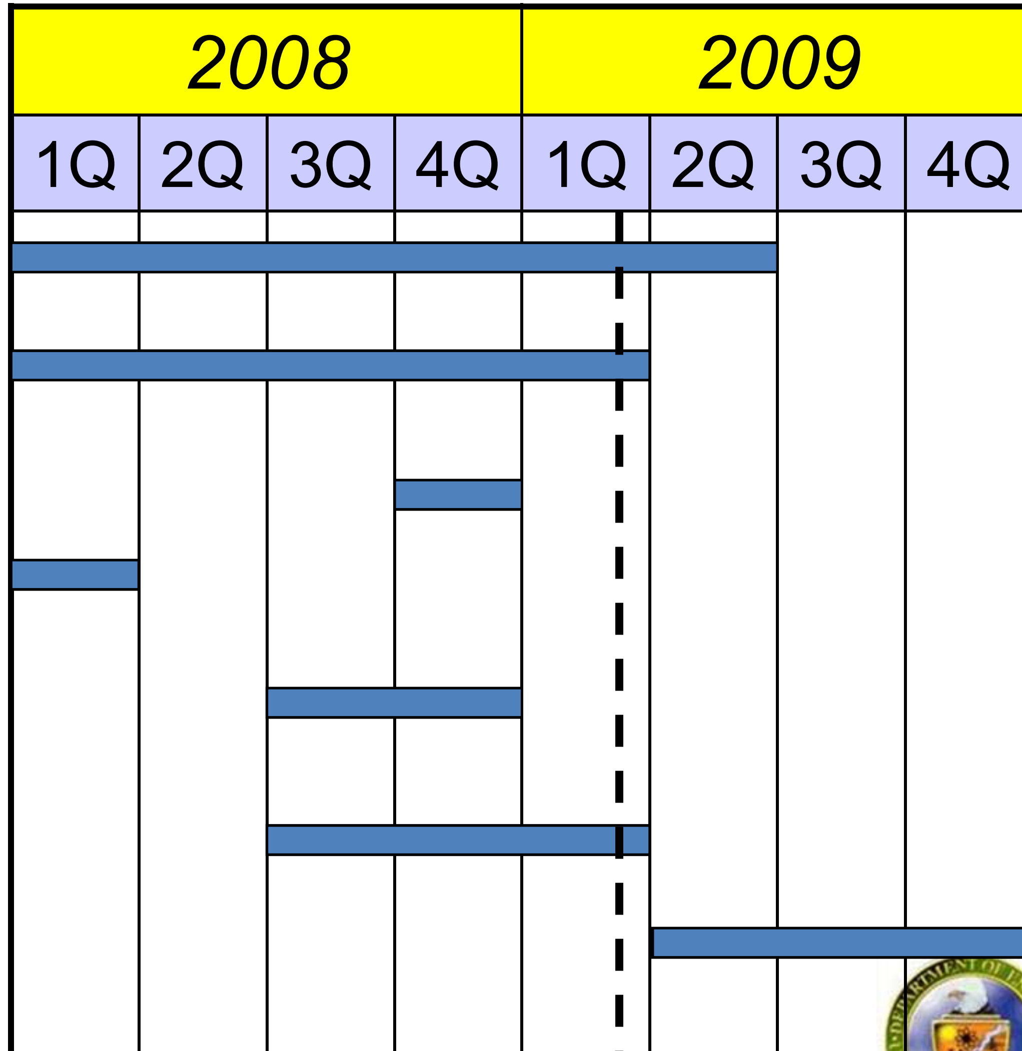
[1] As Per Solicitation DOE Contract: **DE-FC26-05NT42412**

Key Focus Areas

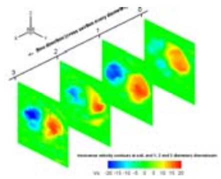
- Combustion & Power Density
  - Characterize the HCCI combustion process & technology gaps using experiments & simulation (gap identification)
  - Investigate the use of fuel blending to improve the load range
  - Visualize early injection events in order to optimize the spray injection
  - Assess lifted-flame combustion (local premixing) as an emissions building block
- Control
  - Develop algorithms to enable combustion mode switching
- Heat Rejection
  - Reduce engine heat rejection

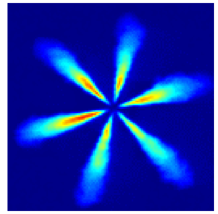
2008/2009 HECC Milestones (1 of 2)

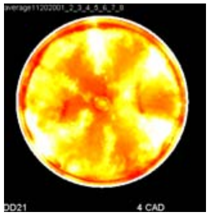
- Injector orifice geometry investigation
- Precision cooling (project suspended before completion)
- VCR bearing redesign
- C15 PCCI demonstration
- PCCI combustion modeling, spray and wall impingement model improvements (project suspended before completion)
- Sandia injector upgrade
- Lifted flame combustion development



Technical Approach







Combustion Research (ET)

Combustion Modeling CAT3D/XFD/CATMZ/FIRE (ET)

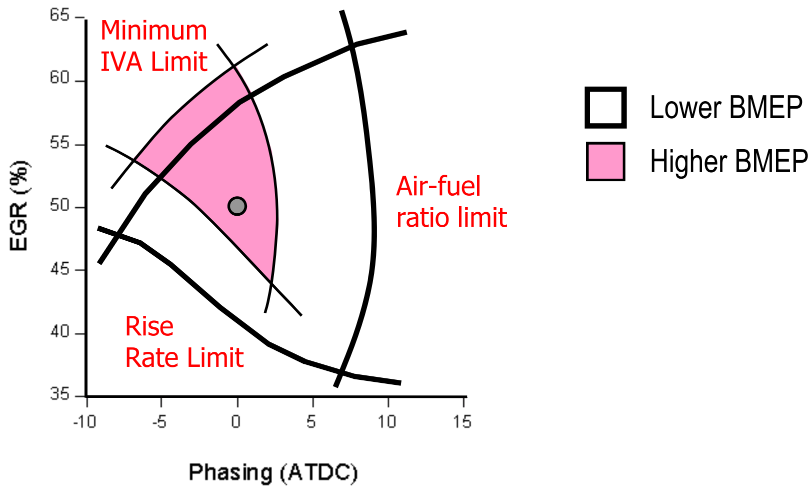
Air-System Development (ET/MEC)

Injector Development (Fuel Systems, ACP)

Combustion Development (GEDNA/LPSD Perkins/LEC/Solar)

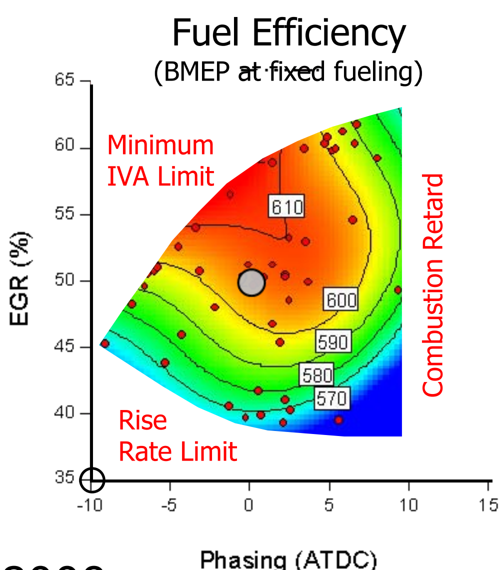
Single-Cylinder Engine Testing

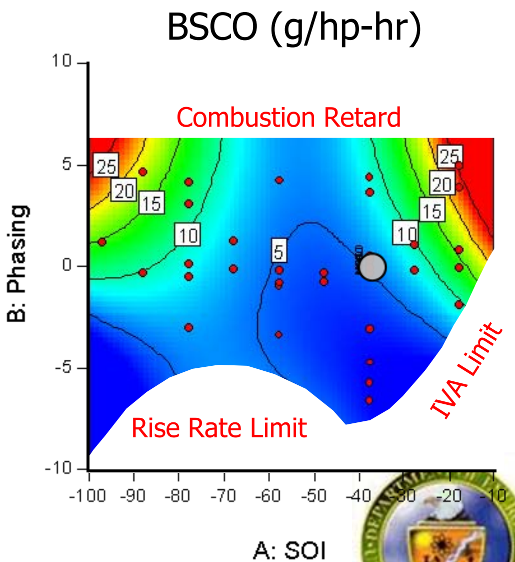
- Objective:
  - Quantify the fundamental relationships between control parameters and engine performance and emissions
  - → Input to 0-d combustion model for engine system simulation and basis for model based control
  - → Define optimal combustion mode for improved thermal efficiency



- Approach:
  - Extensive exploration of key control parameters
  - Generated response surfaces to key control parameters

- Accomplishments:
  - Established the effect of key control parameters on engine operating limits
    - EGR, IVA etc.
  - Demonstrated 4% BSFC improvement @ BMEP < 750kPa

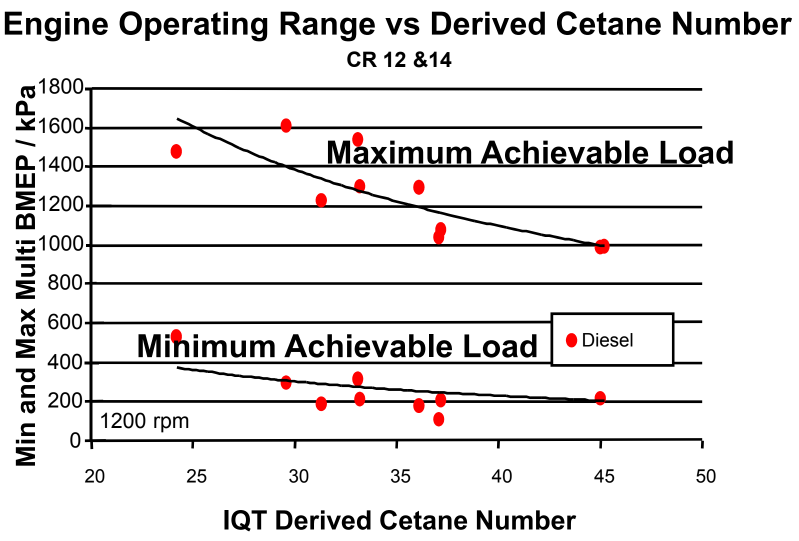


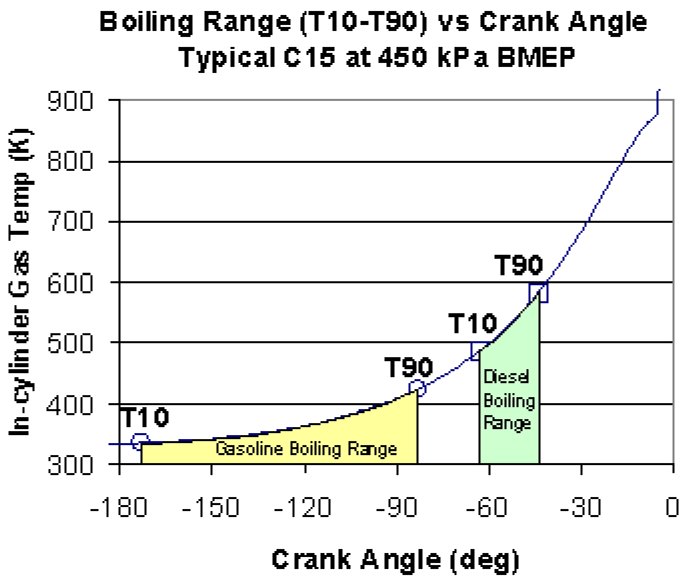


Background work, FY 2007 & Early 2008

PCCI Combustion – Fuel Blending Technologies to Increase HCCI/PCCI Power Density & Load Capability

- Fuels
  - Load range is affected by cetane number
  - High volatility fuel increases the injection window (mixing)
  - No commercially available fuel meets all requirements
  - Investigating diesel / gasoline fuel blends



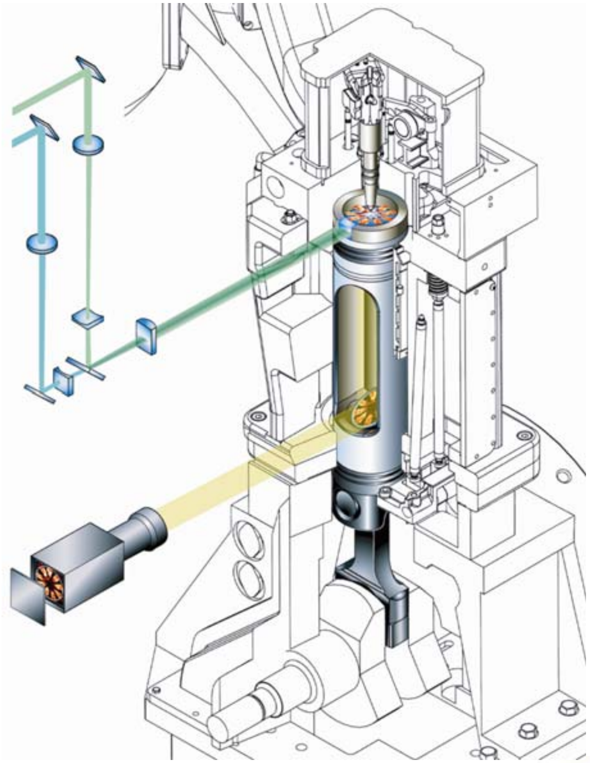


Optical Engine Testing with Sandia National Laboratories

Sandia National Laboratories

Overall Objective: Use Optical Engine to study early injection wall impingement.

- 2008/2009 Objective:
  - Upgrade to a fuel system representative of current production
  - Enable higher injection pressure capability
  - Enable multiple injection capability



- Approach:
  - Upgrade to Caterpillar Common Rail fuel injector
- Accomplishments:
  - New fuel injectors and ECM delivered to SNL
  - Cylinder head modifications complete
  - High pressure fuel supply upgrade – in-process

FY 2008

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Effect of Early Injections on Piston Impingement

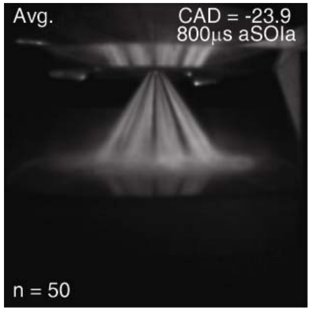
	Injection Timing [°ATDC]	Injection Pressure [MPa]	F [-]	EGR [%]	Intake Temp. [°C]	Load gIMEP [bar]	Boost [bar]
Baseline Condition	-39.5	142	0.39	50	42	4.82	1.418
Injection Timing Sweep	-69.5 to -29.5	142	0.39	46.6 to 50.2	42	4.82	1.418
Injection Pressure Sweep	-36.3 to -39.5	47, 95, 142	0.39	50	42	4.82	1.418
Equivalence Ratio and Boost Sweep	-39.5	142	0.24 to 0.58	50	42	4.82	2.060 to 1.132
EGR and Boost Sweep	-39.5	142	0.39	30 to 70	42	4.82	1.188 to 1.949
Intake Temperature and Boost Sweep	-39.5	142	0.39	50	32 to 62	4.82	1.373 to 1.508
Intake Temperature and Equivalence Ratio	-39.5	142	0.39 to 0.41	50	32 to 62	4.82	1.418
Load and Boost Sweep	-39.5	142	0.39	50	42	3.82 to 5.83	1.203 to 1.629

SANDIA Lab, C. Mueller

Sandia National Laboratories

C. Mueller

SOI = -69.5° ATDC



SOI = -29.5° ATDC

Early Injections Lead to Liquid Fuel Impinging on Piston Top

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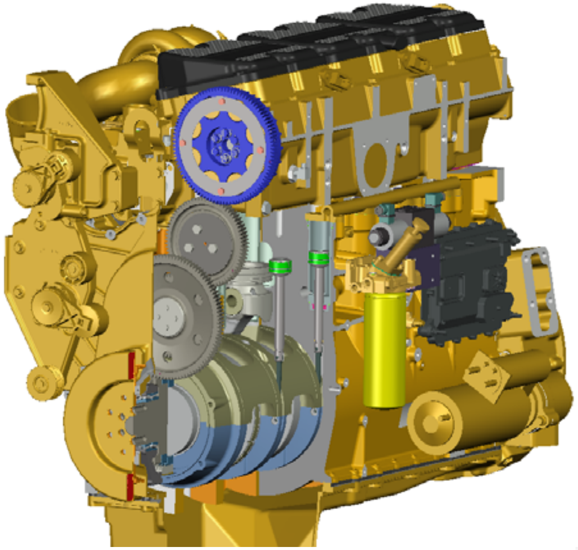
Variable Compression Ratio Engine

- Variable Compression Ratio
  - Effective means of extending load range at the expense of compression ratio
  - Optimal phasing does not outweigh expansion ratio loss to reach full load
  - May be adequate if using HCCI/PCCI only for NOx emissions control
  - Does not address diesel liquid fuel impingement

- Objective:
  - Reduce parasitic losses associated with VCR engine
  - Design a more robust eccentric crank bearing system
- Approach:
  - Redesigned crank carrier bearing system
  - Conducted FEA and rolling element analysis
- Accomplishments:
  - Analysis predicts acceptable bearing life with new design



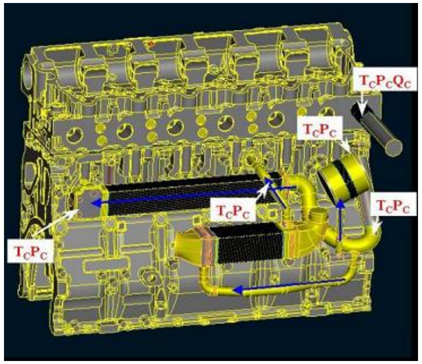
VCR - US Patent Application 2006/0112911

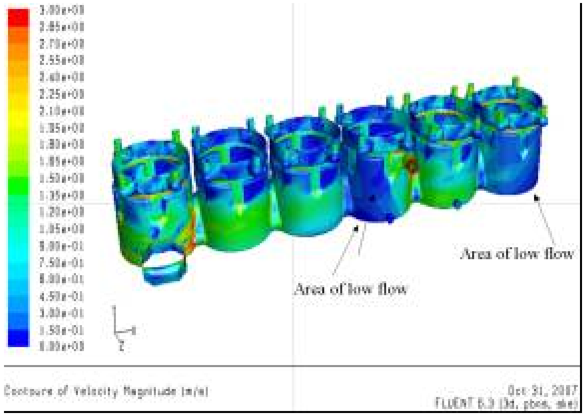
FY 2008

Precision Cooling

- Reduced heat rejection in the cylinder block
- Increased enthalpy in the exhaust gas
- Reduced thermal stress in the engine block

- Objective:
  - Develop a method to analyze precision cooling
  - Apply method to predict baseline and evaluate alternative configurations
- Approach:
  - Combination of 1D simulation & CFD
  - Application of FEA
- Accomplishments:
  - Baseline analysis completed & correlated with experiments (pressure drop)
  - Thermal data correlation → 1st pass (currently on hold)





FY 2008

2009 HECC Milestones (2 of 2)

Lifted flame combustion development

Literature review: transient control of PCCI

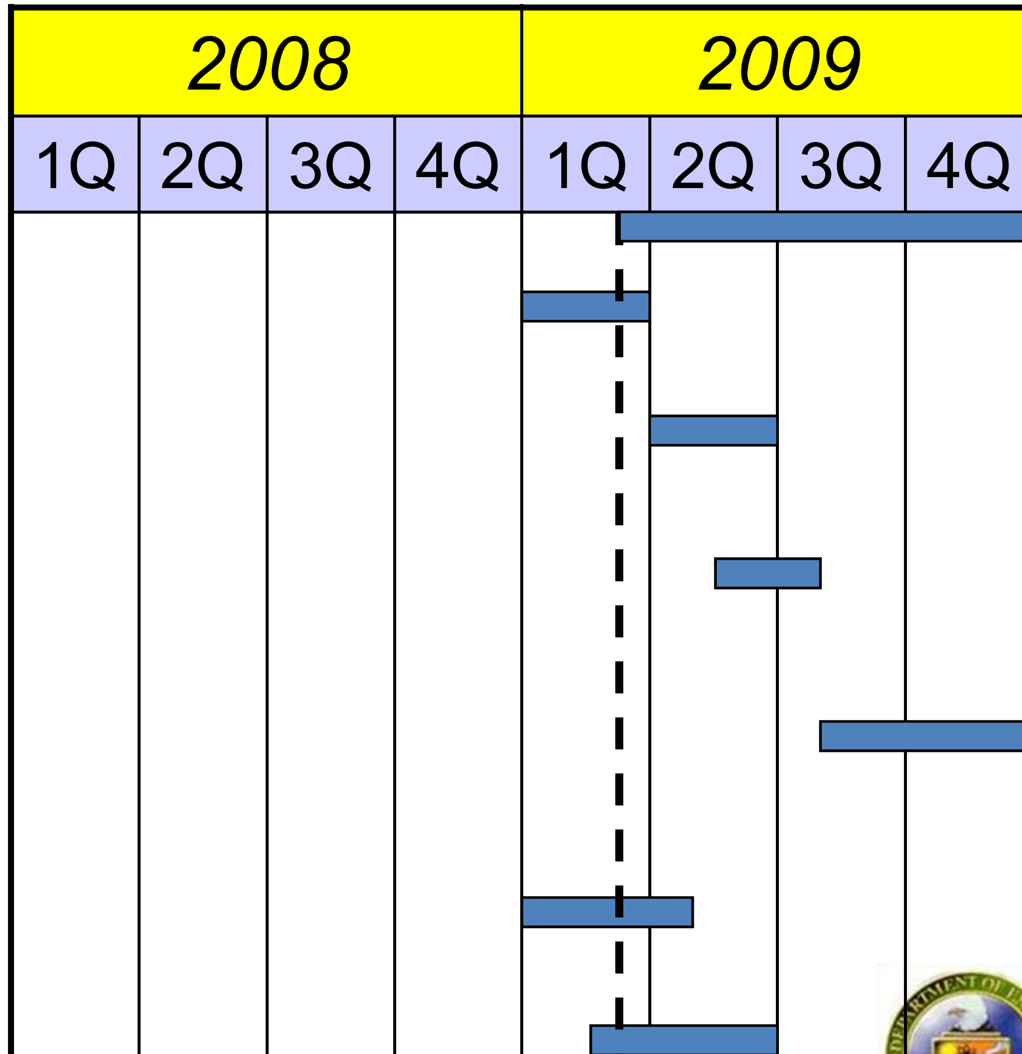
Steady state engine tests for transient control model development

Transient control strategies development & hardware procurement

Multi-cylinder engine testing for demonstration of transient control

Wells to wheels analysis for heavy duty applications

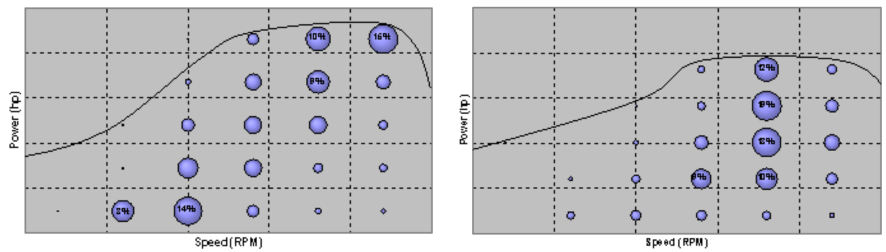
On-Engine testing of fuel blends



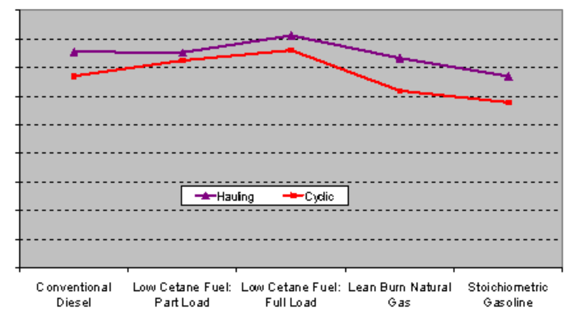
Tank-to-Wheels Analysis

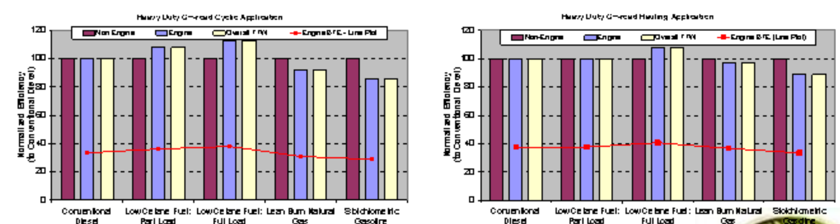
- Objective:
  - Energy audit comparing SI, CI and HCCI/PCCI combustion processes for heavy duty applications
  - Quantify benefits of alternate combustion regimes as enabled by alternative fuels for heavy duty applications
- Approach:
  - Detailed system wide and individual component wide analysis of energy flow
  - Engine system simulation combined with field data to evaluate effect of different heavy duty application work-cycles on the powertrain efficiency
- Accomplishments:
  - Completed energy audit on two different off-road heavy duty applications
  - Completed comparison of the impact of alternate combustion regimes on efficiency in heavy duty applications
  - Identified opportunities for applying alternate combustion regimes to improve efficiency of heavy duty applications

Application Histograms



Tank-to-Wheel Efficiency



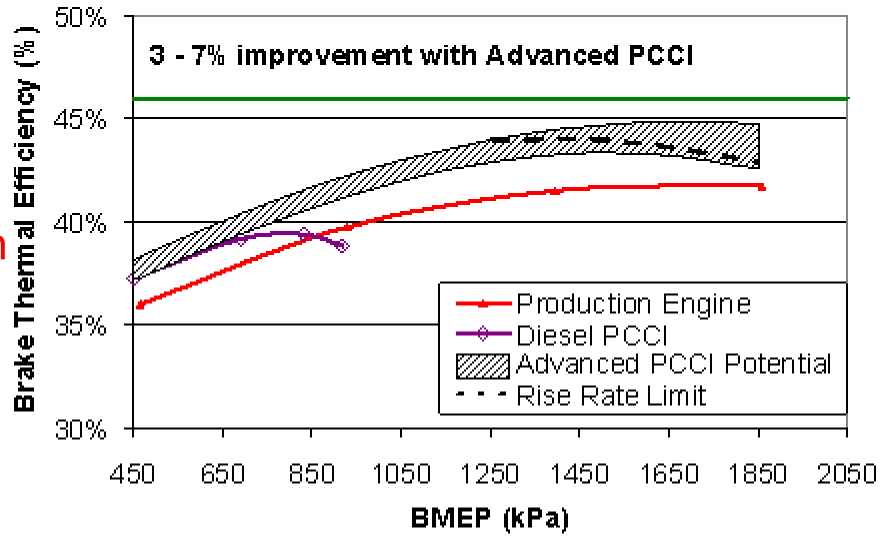


FY 2009

Gasoline / Diesel Fuel Blend Testing

- Objective:
  - Assess ability of 'modified' fuel properties to increase load range
  - Improve thermal efficiency by increasing the load range of PCCI combustion
  - Reduce soot emissions in diffusion combustion regime

C15 Engine Simulation Results



- Approach:
  - Test multiple gasoline / diesel fuel blends with a range of derived cetane number on single-cylinder test engine.
  - Characterize impact on combusting spray using optical techniques in high-temperature spray vessel

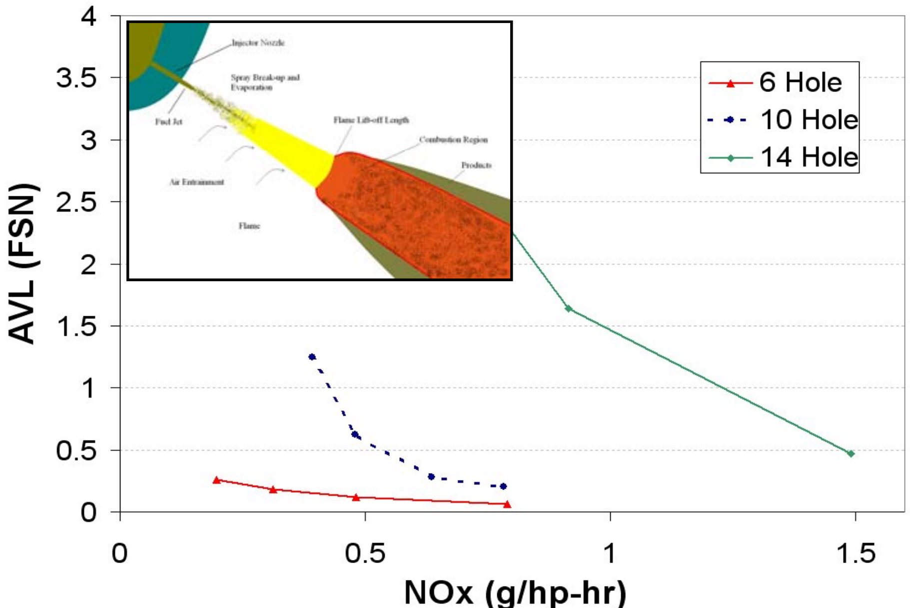
- Accomplishment:
  - Testing currently in-progress (March – April)
  - Results currently being processed

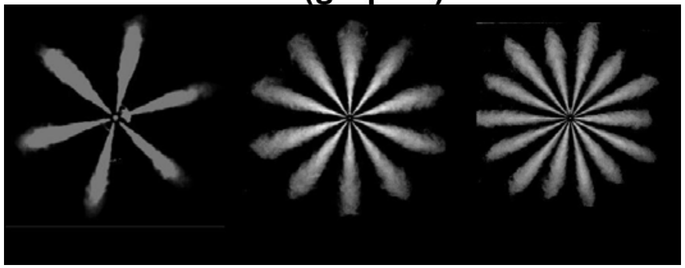
FY 2009

"Lifted Flame" Combustion

- 2008 - demonstrated order of magnitude soot reduction with 6-hole nozzle, but nozzle lacked flow capacity for a 15 L engine
- Soot emissions increased with increased number of holes
- **Objective:**
  - Understand soot emissions increase with increasing number of holes
  - Maximize the low soot benefit of "lifted flame" combustion through optimization of injector nozzle and combustion chamber geometry
- **Approach:**
  - Investigate plume – to- plume interaction of a combusting multi-plume spray using high-temperature spray vessel (Jun – Aug)
  - Optimize injector nozzle and combustion chamber through combination of combustion simulation and single cylinder engine testing. (Sept – Dec.)

Effect of Increasing Number of Plumes on Emissions Performance





6 Hole 10 Hole 14 Hole

FY 2009

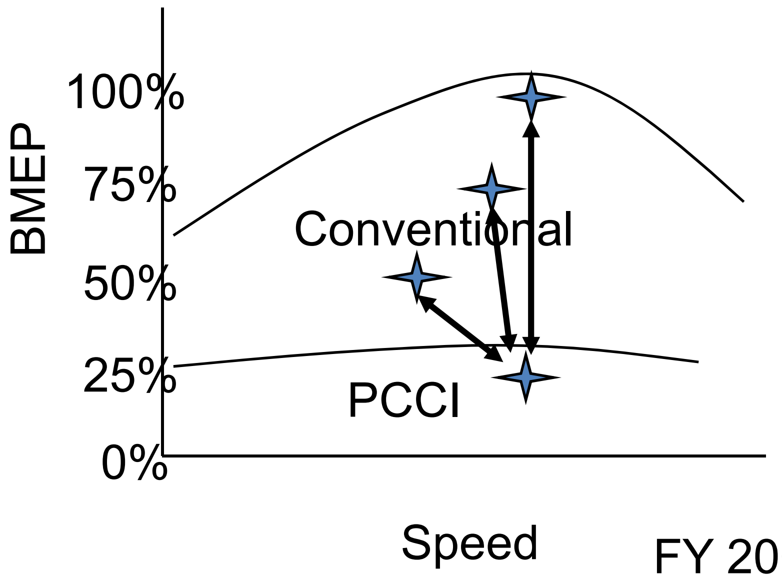
Combustion Mode Transition

Expectations

- No perceivable torque blip
- Minimal emissions spike (limit to current transient spikes)
- Minimal changes in high load performance (?)
- Minimal cost and complexity impact (?)

Challenges

- Adding / removing EGR quickly (if resolved can support the Tier 4 Interim challenge during the transients as well)
- Robustness of PCCI combustion (hardware variability effects?)
- Significant timing change (torque blips?)
- Open loop control of PCCI combustion



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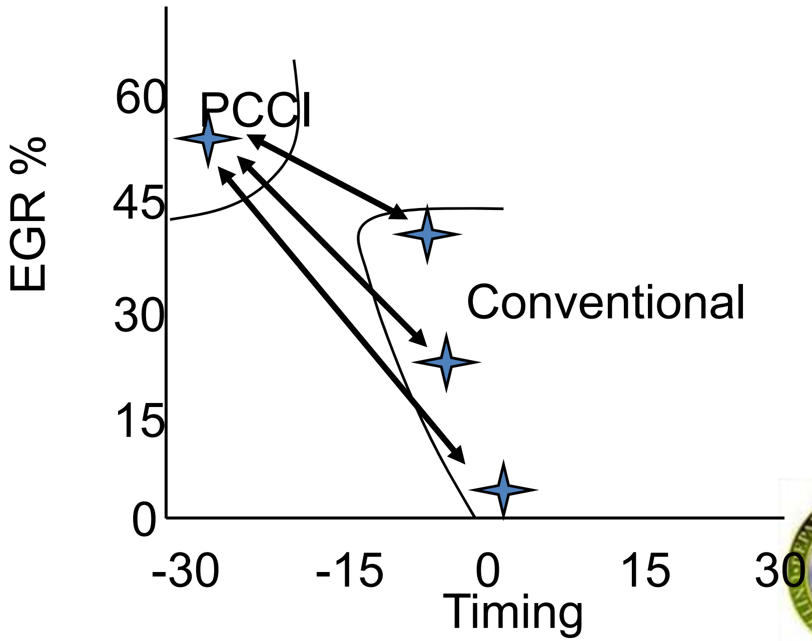
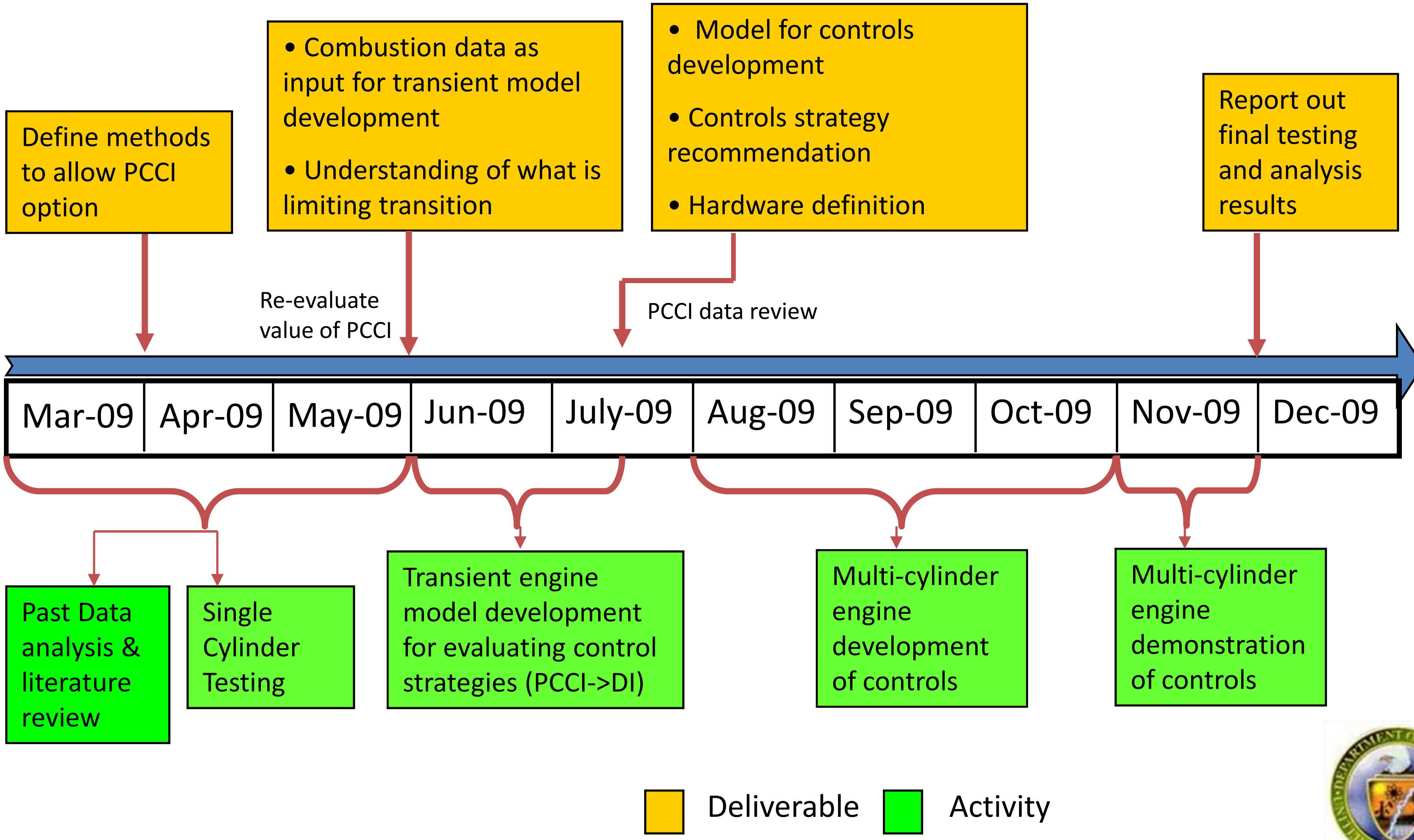


2009 Combustion Mode Transition-Deliverables



Summary

- Performance - HCCI/PCCI (low temperature combustion) potentially offers increased thermal efficiency with reduced requirements for DPF regeneration. Demonstrated 4% BSFC improvement below 750 kPa BMEP. Low load fuel economy benefit will be application dependent
- Control - Inability to adequately control combustion phasing and liquid fuel impingement limits the load range and thermal efficiency benefit of diesel HCCI/PCCI
- Fuel Chemistry - Fuel blending (gasoline & diesel) is one method to increase load
- Combustion - Lifted flame combustion is a potential low-soot diffusion combustion technology that is compatible with HCCI/PCCI. Demonstrated order of magnitude soot reduction. Plume-to-Plume interaction is a challenge