Low Temperature Combustion and Diesel Emission Reduction Research

by

Rolf D. Reitz, Manuel A. Gonzalez, D.,
Dave Foster, Jaal Ghandhi, Chris Rutland, and Scott Sanders

Engine Research Center UW-Madison

August 24, 2006

Acknowledgements

DOE LTC Consortium project DE-FC26-06NT42628

Industry Partners

British Petroleum, Caterpillar

Diesel Emission Reduction Consortium (DERC)

GM-ERC Collaborative Research Laboratory (CRL)

Optimizing Low Temperature Diesel Combustion

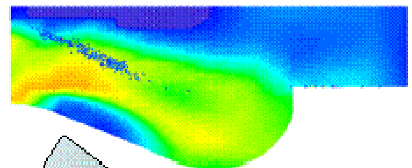
January 2006 to December 2008

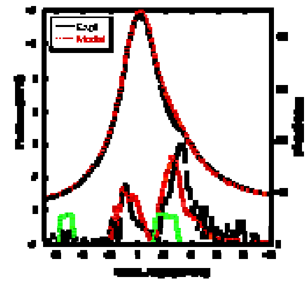
- Overall goal — develop methods to further optimize and control LTC engines, with emphasis on diesel-fueled engines
- Engine technologies to be considered include operation on LTC-D with transition to conventional Compression Ignition Direct Injection (CIDI) combustion at higher loads and starting conditions ("mixed-mode" operation)
- Approach – develop and apply high fidelity computing and high-resolution engine experiments synergistically to create and apply advanced tools needed for low emissions engine design

Optimizing Low Temperature Diesel Combustion

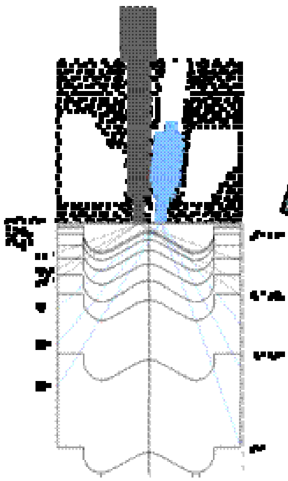
January 2006 to December 2008

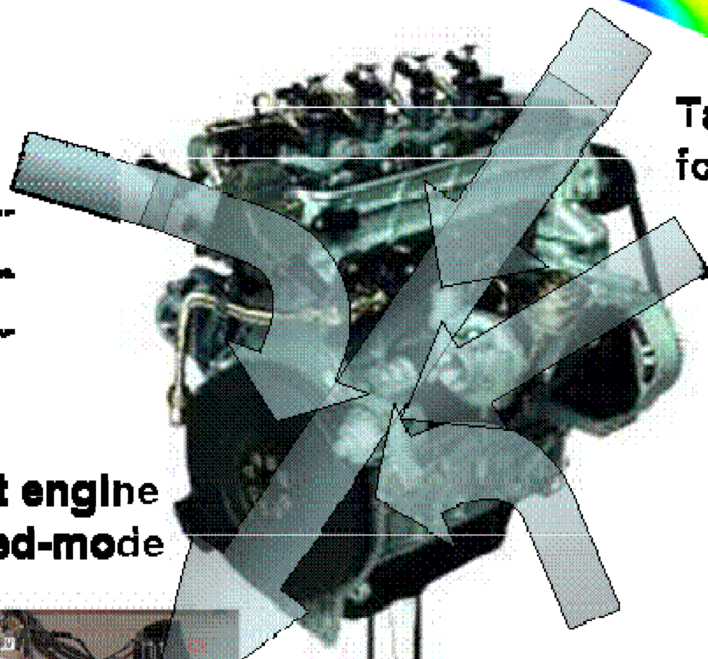
Task 1: Fundamental understanding of LTC-D and advanced model development



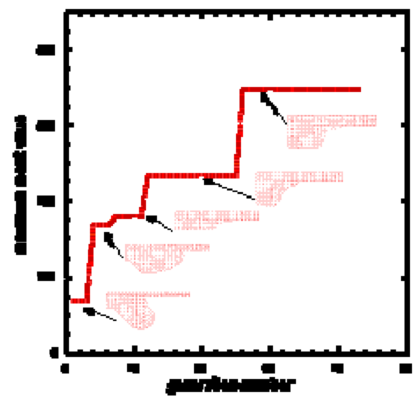


Task 2: Experimental investigation of combustion control concepts

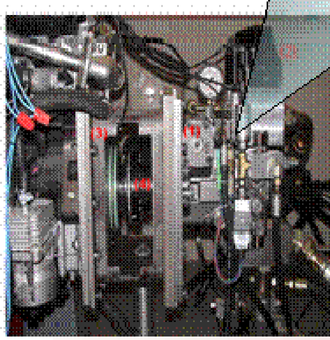


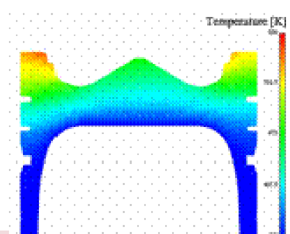


Task 3: Application of models for Optimization of combustion & emissions



Task 5: Transient engine control with mixed-mode combustion

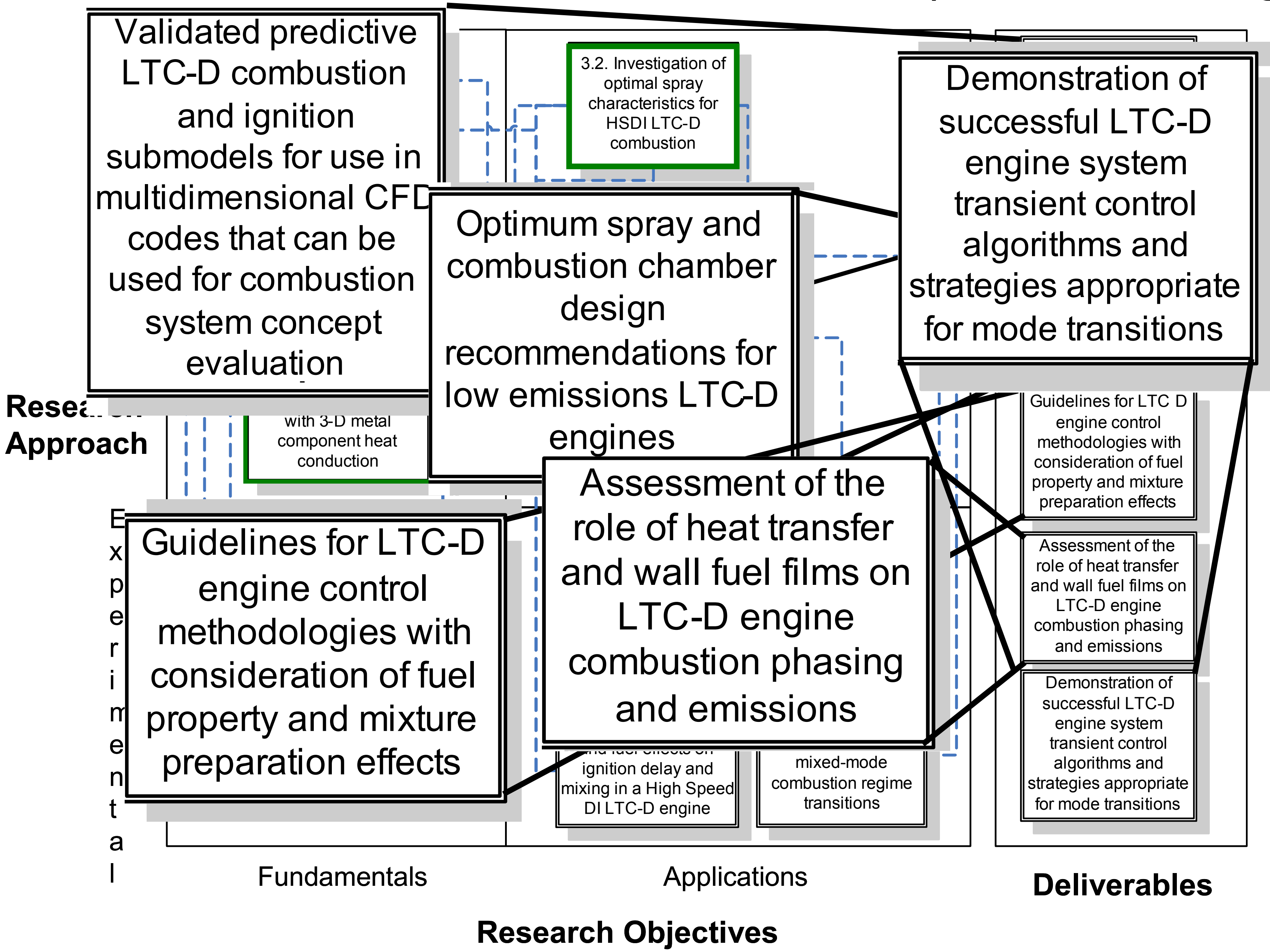




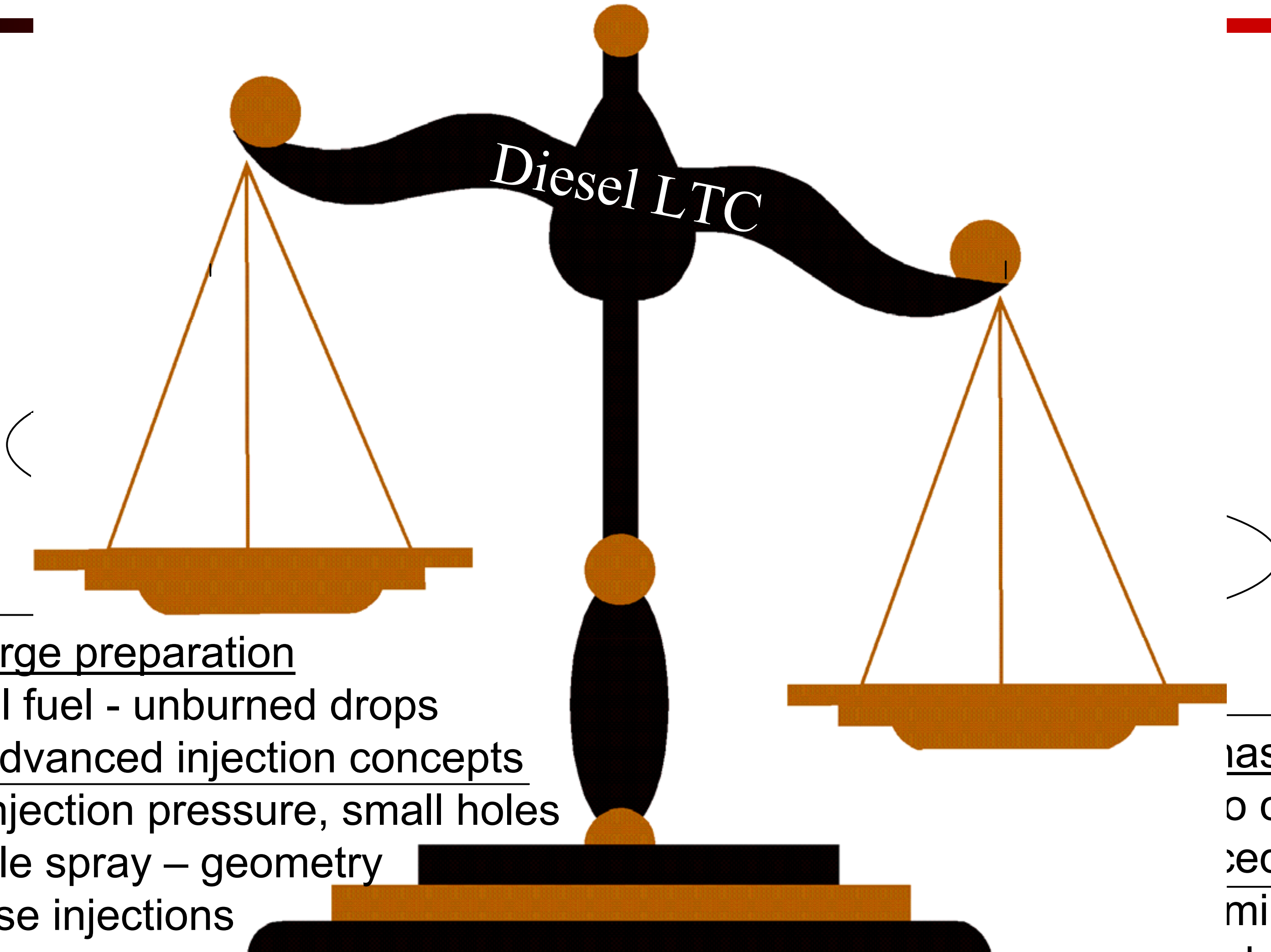
Task 4: Impact of heat transfer and spray impingement on LTC-D combustion

Ford DIATA engine http://www.fev.com/

Optimizing Low Temperature Diesel Combustion (LTC-D) / Sub-tasks linkages



Optimizing Low Temperature Diesel Combustion - Issues



Charge preparation

Prevent wall fuel - unburned drops

Enablers: Advanced injection concepts

Ultra-high injection pressure, small holes

Narrow angle spray – geometry

Multiple pulse injections

Variable Geometry Sprays

Fuel vaporization enhancement – FT fuels

asing

o control

ced controls

ming

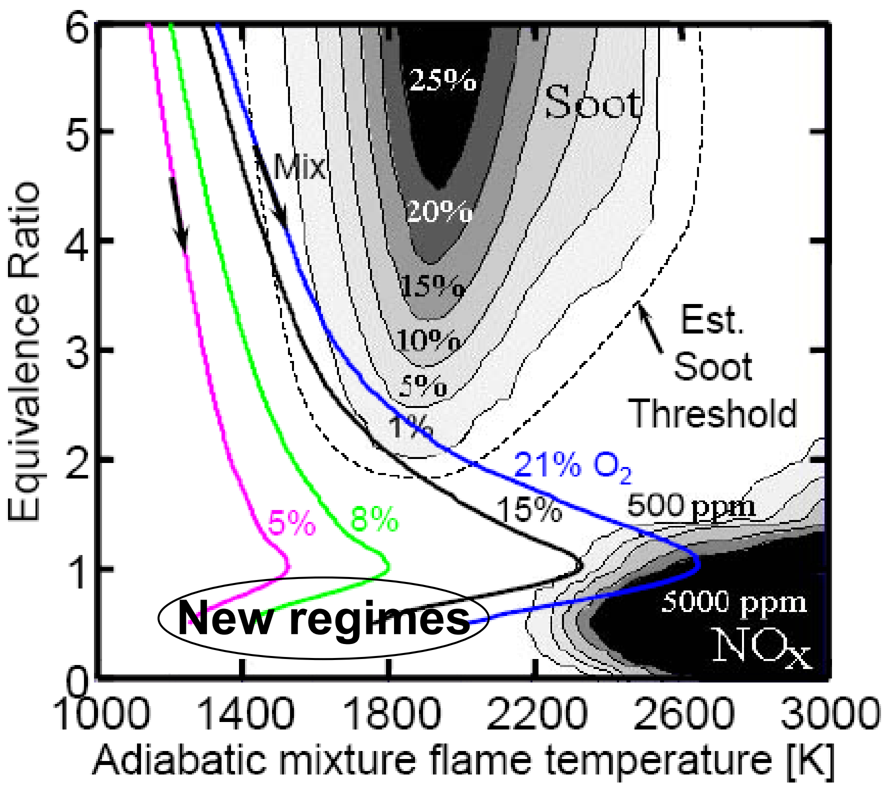
Two-stage turbo-charging

Cooling/EGR

Two stage combustion

Fuel CN reduction

Low Temperature Diesel Combustion Emissions



Kitamura et. al 2002 Int. J. Engine Research

Akihama et. al 2001 SAE 2001-01-0655

Calculated adiabatic mixture temperature at a given ϕ:
T_{fuel}: 373 K
T_a: 1000 K

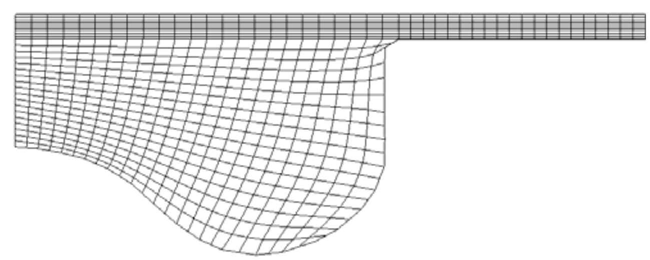
CO, HC, Soot and NOx

LTC-D design guidelines

Assume homogeneous charge
KIVA-CHEMKIN ERC n-heptane
Park & Reitz CST (Submitted)

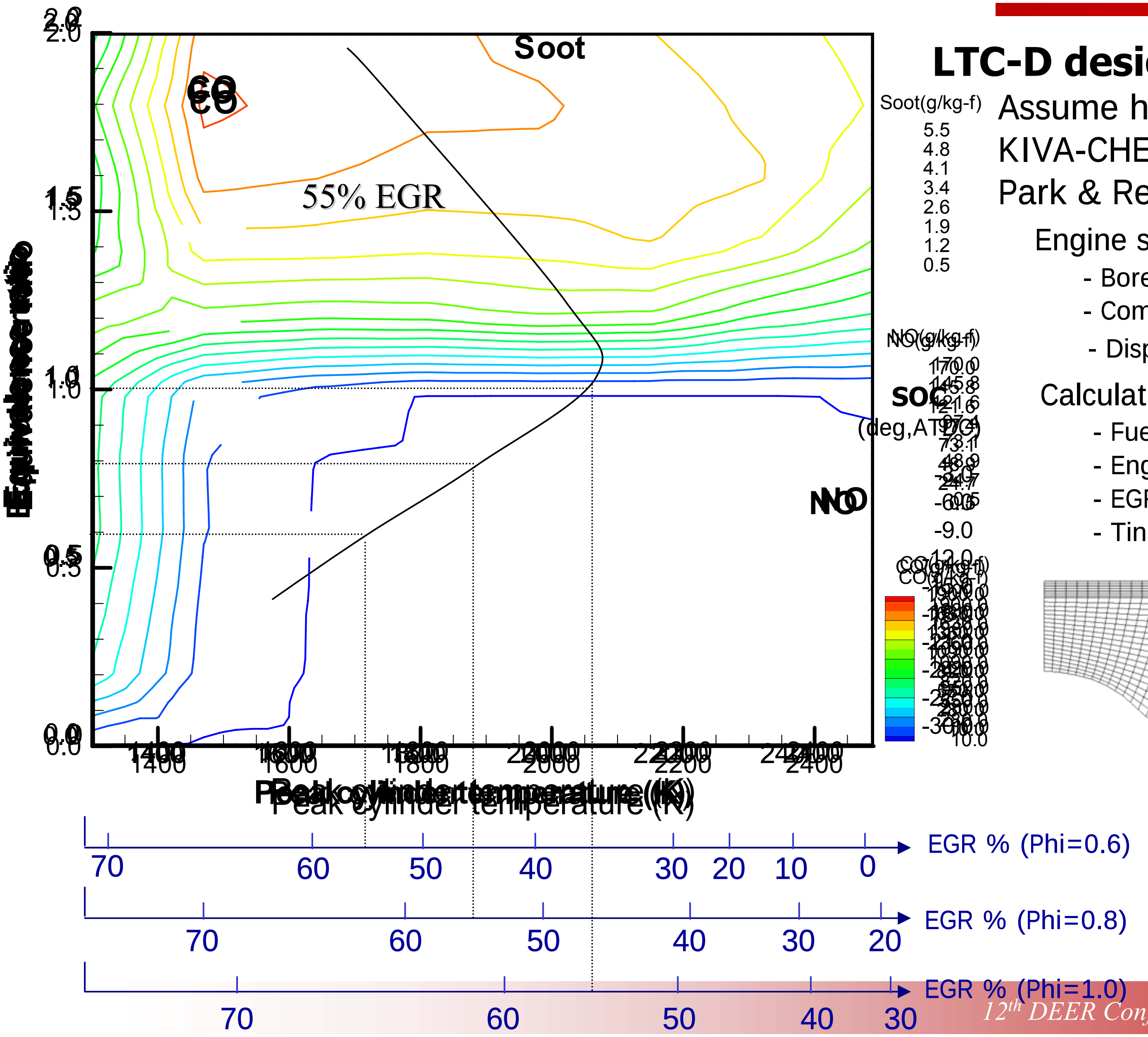
Engine specifications
- Bore x stroke : 82.0 x 90.4 mm
- Compression ratio : 16.0:1
- Displacement : 477cm^3

Calculation conditions
- Fuel amount : 20.0 mg
- Engine speed : 2,000 rpm
- EGR : 0-70%
- Tin : 320-440K



Task 1: Understanding of LTC-D & advanced model development

1.1a LTC-D and premixed combustion models



LTC-D design guidelines

Assume homogeneous charge

KIVA-CHEMKIN ERC n-heptane

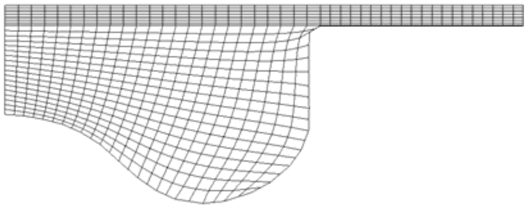
Park & Reitz CST (Submitted)

Engine specifications

- Bore x stroke : 82.0 x 90.4 mm
- Compression ratio : 16.0:1
- Displacement : 477cm^3

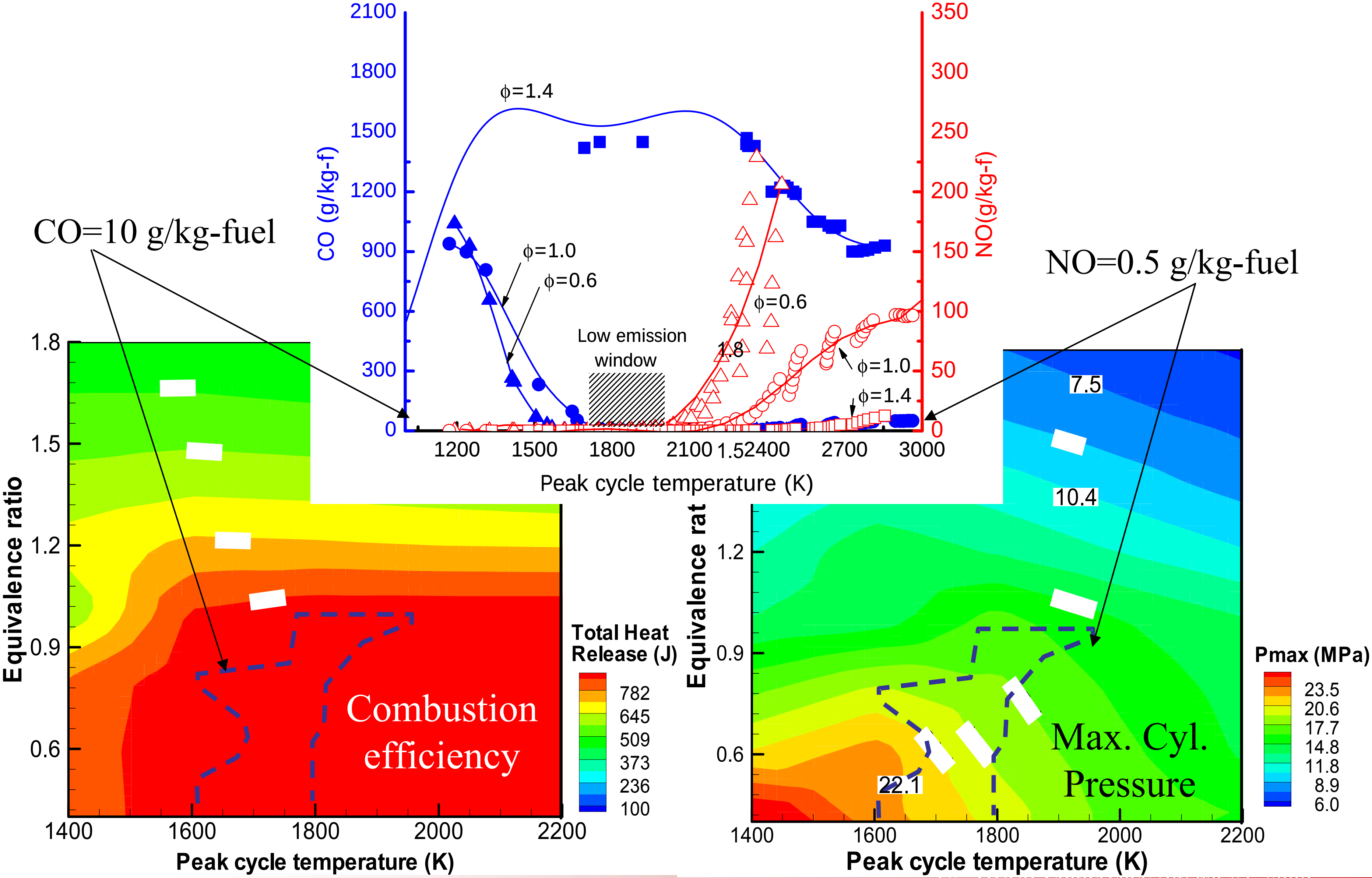
Calculation conditions

- Fuel amount : 20.0 mg
- Engine speed : 2,000 rpm
- EGR : 0-70%
- Tin : 320-440K



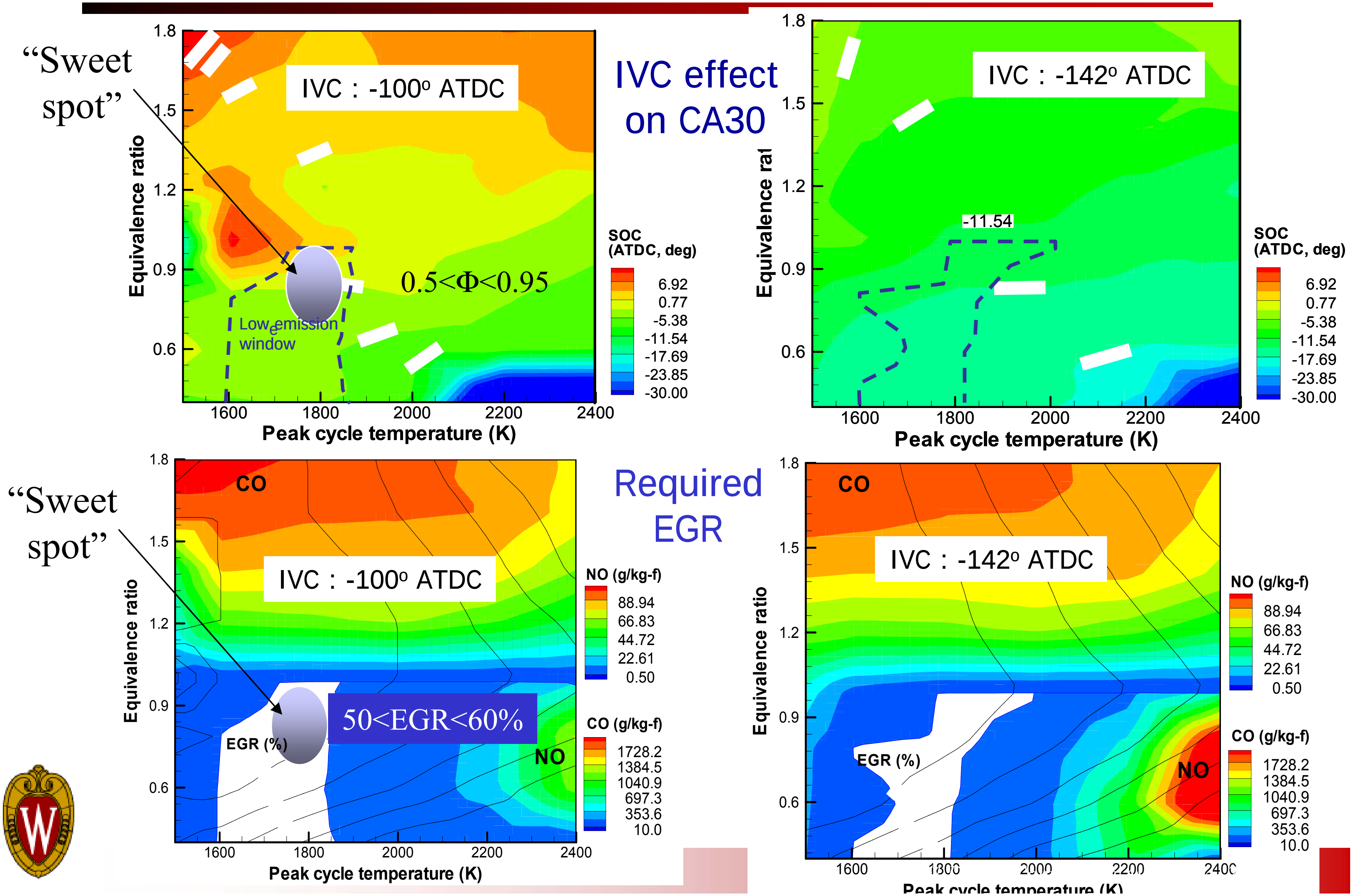
Task 1: Understanding of LTC-D & advanced model development

1.1a LTC-D and premixed combustion models



Task 1: Understanding of LTC-D & advanced model development

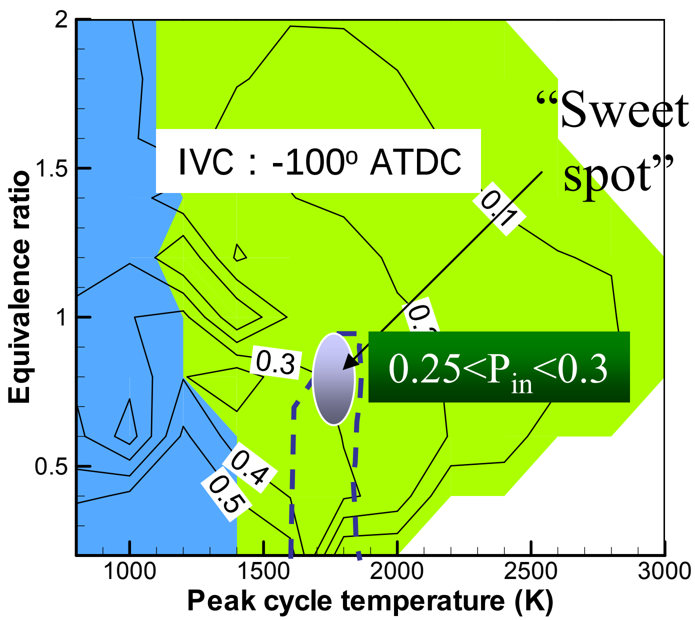
1.1a LTC-D and premixed combustion models

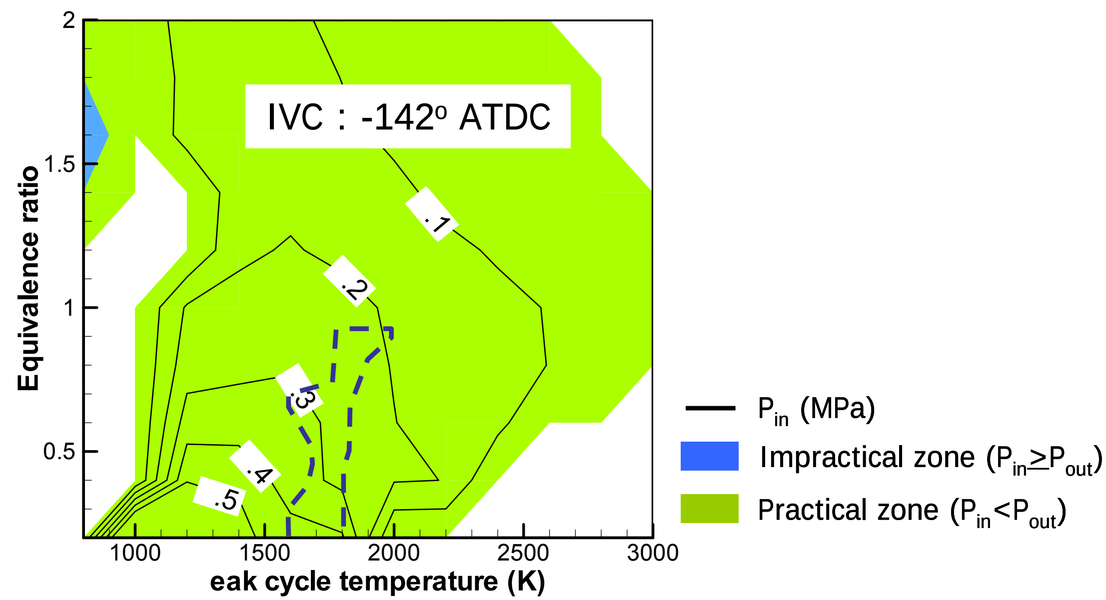


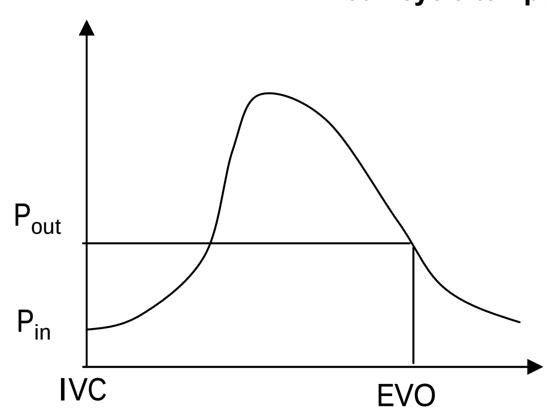
Task 1: Understanding of LTC-D & advanced model development

1.1a LTC-D and premixed combustion models

Required boost



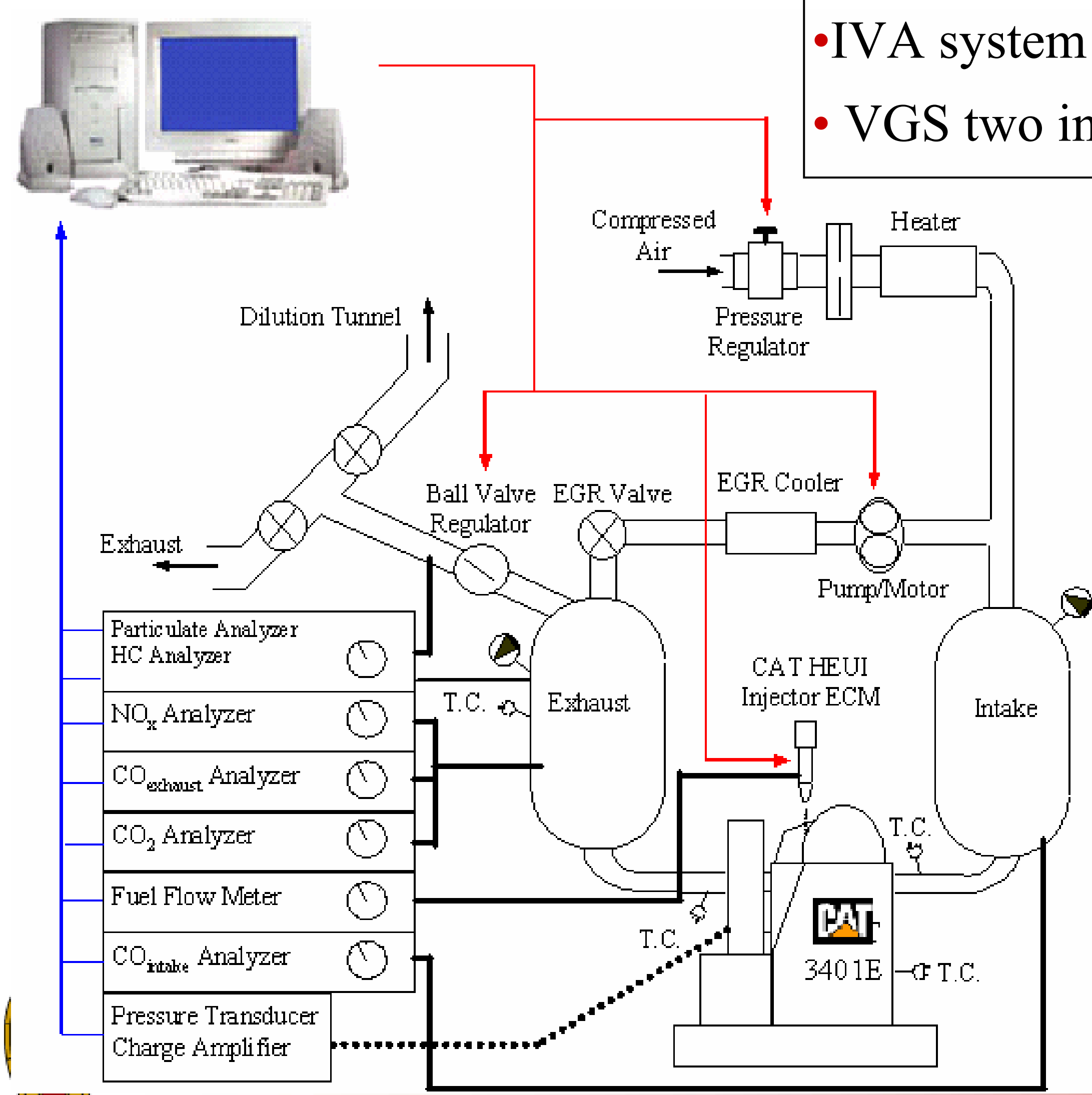




Task 2: Experimental investigation of LTC-D combustion control

2.1 Use of Variable Valve Timing and Variable Geometry Sprays

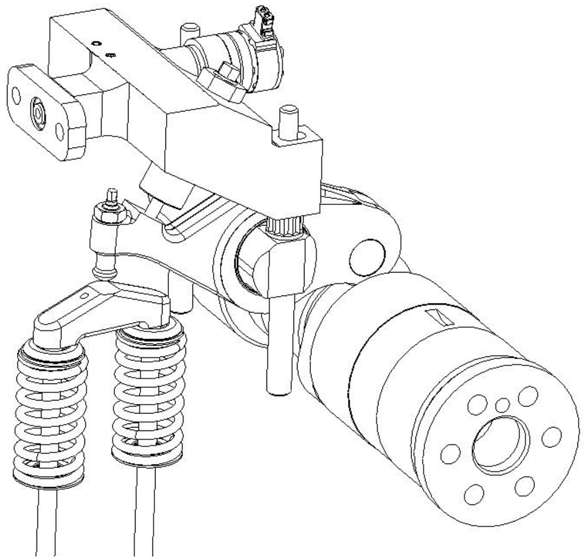
- Multiple injections, PCCI – Hardy
- IVA system – Nevin, Gonzalez, Sun
- VGS two injector system – Weninger, Gonzalez



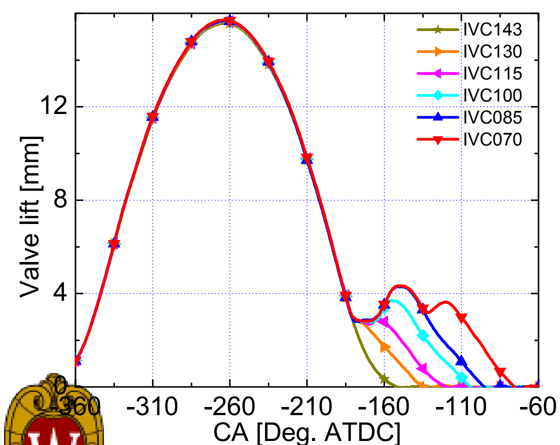
Engine	Caterpillar 3401 SCOTE (Single Cylinder Oil Test Engine) - single cylinder - direct injection - 4 valve
Bore x Stroke	137.2 mm x 165.1 mm
Compression Ratio	16.1 : 1
Displacement	2.44 liters
Combustion Chamber	Quiescent
Piston	Mexican Hat with Sharp Edge Crater
Injection System	Cat HEUI 300B

Task 2: Experimental investigation of LTC-D combustion control

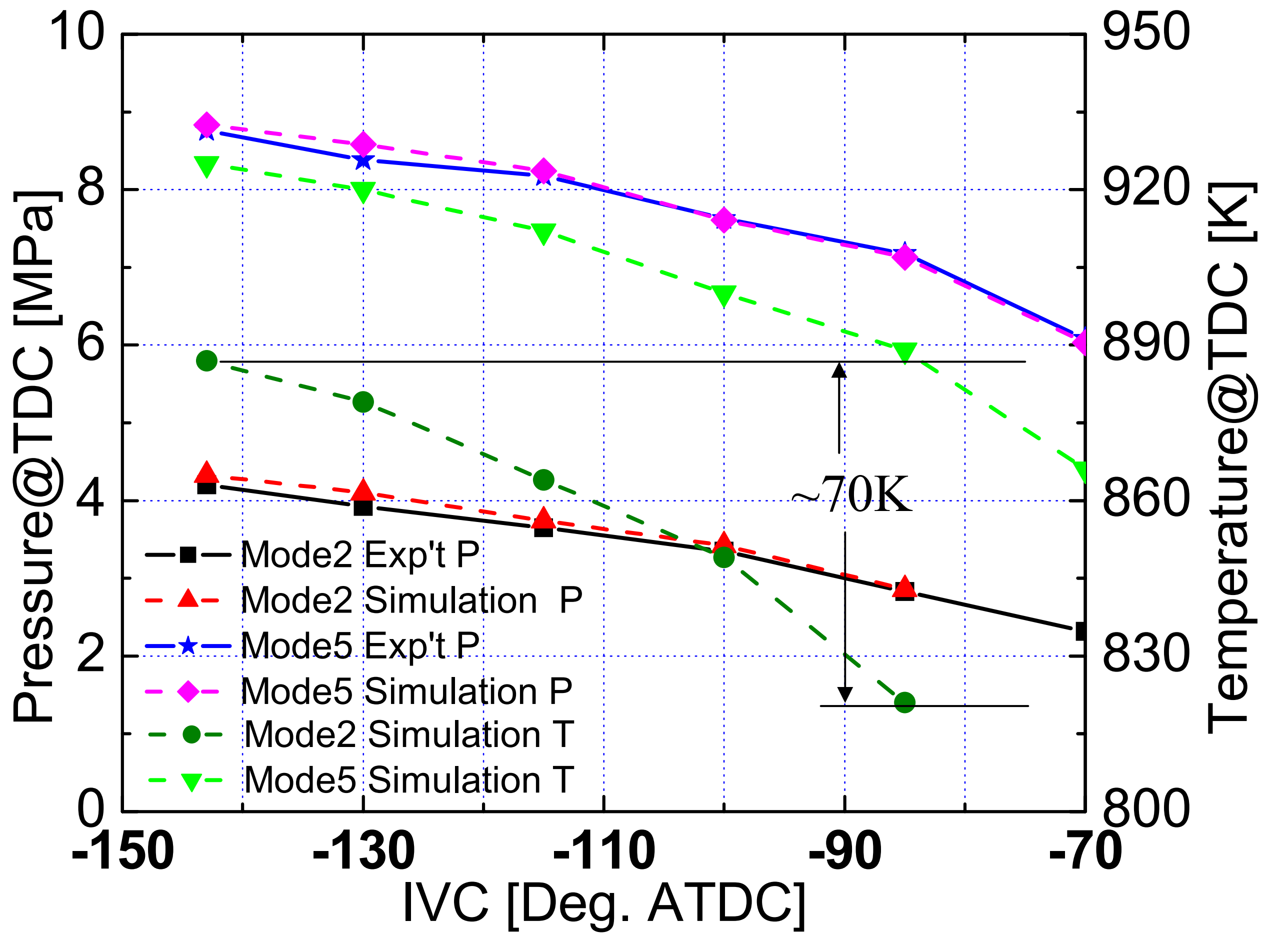
2.1 Use of Variable Valve Timing and Variable Geometry Sprays



Mode5 valve lift curve



Motored engine – GT-Power and KIVA



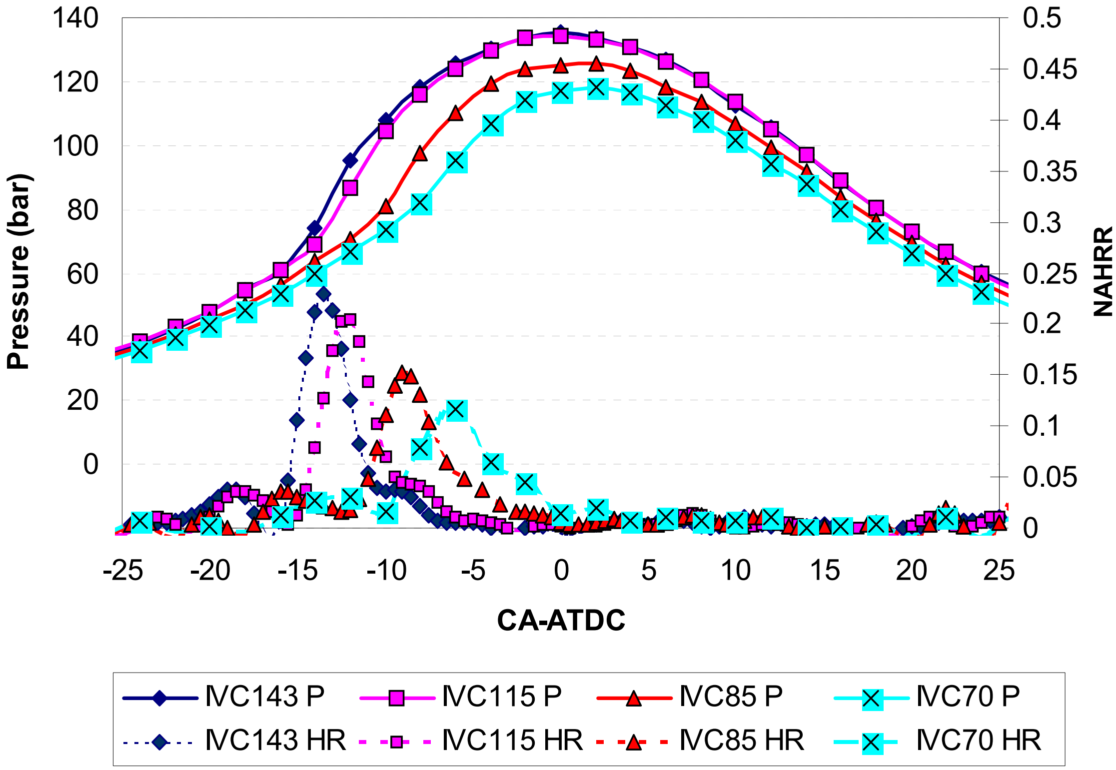
Mode2: 821rev/min, no boost

Mode5: 1737rev/min, 184kPa boost

Task 2: Experimental investigation of LTC-D combustion control

2.1 Use of Variable Valve Timing and Variable Geometry Sprays

Early injection – 0% EGR – light load - constant A/F ratio



Factor	Value
Speed (rev/min)	1737
Fuel Flow (kg/hr)	3.55 (30% Load)
Air Flow (kg/min)	4.47
Intake Temperature (K)	305
SOI (CA-BTDC)	55
Φ	0.2
EGR Rate %	0

IVC (CA-ATDC)	Intake Pressure (kPa)
-143	184.1
-130	193.7
-115	200.0
-100	210.3
-85	227.5
-70	244.1

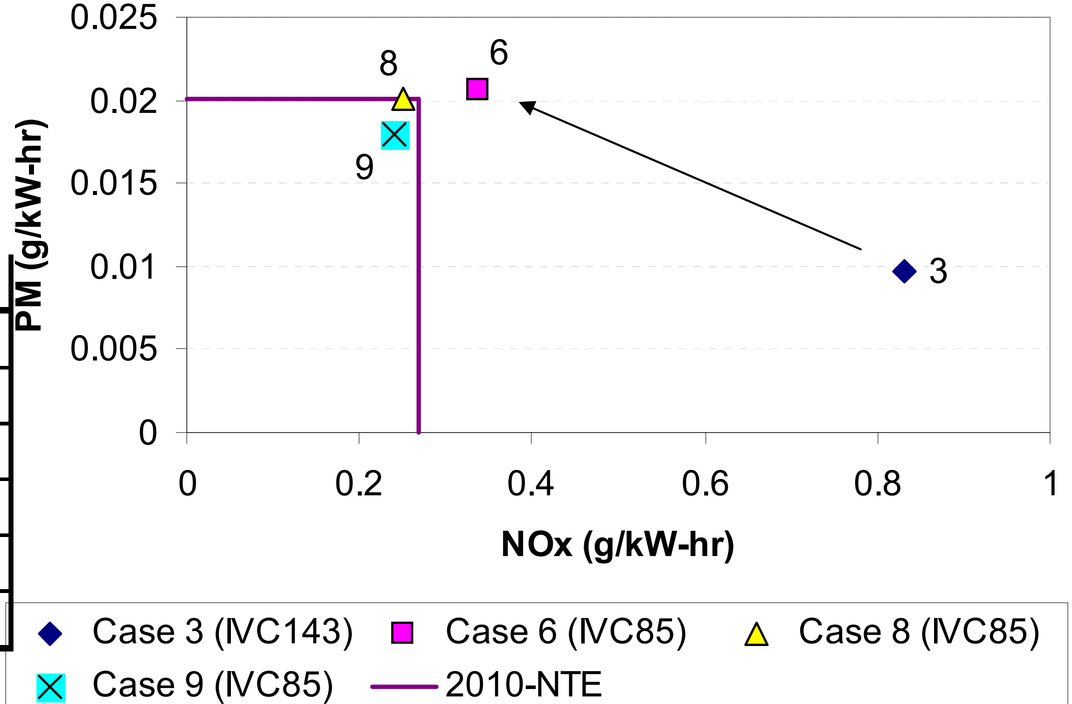
Nevin, R. MS Thesis 2006

Task 2: Experimental investigation of LTC-D combustion control

2.1 Use of Variable Valve Timing and Variable Geometry Sprays

Low load
Early Injection
40% EGR

Factor	Value
Speed (rev/min)	1737
Fuel Flow (kg/hr)	3.0 (25% Load)
EGR %	40
SOI (CA-BTDC)	55
IVC Timings (CA-BTDC)	143, 85 (Solenoic
Intake Temperature (K)	305



Run	3	6	8	9
Intake Pressure (kPa)	184.09	184.09	179.2637	172.3689
Intake Flowrate (kg/min)	2.52	2.03	1.96	1.86
IVC (CA-ATDC)	-143	-85	-85	-85
NOx (g/kW-hr)	0.8323	0.3387	0.2516	0.2392
HC (g/kW-hr)	0.932	1.4232	1.7734	1.6085
PM (g/kW-hr)	0.0103	0.0206	0.0201	0.018
CO (g/kW-hr)	32.3173	27.8242	26.5183	23.051
BSFC (g/kW-hr)	429.19	492.67	491.91	431.14
Equivalence Ratio Φ	0.265	0.2886	0.298	0.3391

Summary and Conclusions

Task 1: Fundamental understanding of LTC-D and advanced model development

1.1 Formulation of combustion models and reaction mechanisms

1.1a LTC-D and premixed combustion models – Reitz

Idealized HCCI emission characteristics reveal a low emission window (lower than 10 g/kg-f CO, 0.5 g/kg-g NO and almost soot-less)

"Sweet spot" operation IVC=100° ATDC- $0.6<\Phi<0.95$, $50<EGR<60\%$, $0.25<P_{in}<0.3$

1.1b Experimental verification measurements of species composition in an optical LTC-D engine – Sanders

Fiber-optic access to metal engine tested successfully

Acquired temperature, H2O mole fraction histories for 17 engine operating conditions

1.2 Formulation of turbulence and mixing models for LTC-D

1.2a Large Eddy Simulation Models for Mixing in Engine Applications – Rutland

LES explains cyclic variability due to intake flow and fuel vaporization unsteadiness

1.2b Fine-scale Mixing Measurements of Gas and Spray Jets in Engines – Ghandhi

Optical system designed to achieve high resolution scalar dissipation rate measurements

Summary and Conclusions

Task 2: Experimental investigation of LTC-D combustion control concepts

2.1 Use of Variable Valve Timing and Variable Geometry Sprays for mixing and combustion control in a Heavy Duty LTC-D engine – Reitz

Successful implementation of VVA system – combustion phasing control (~ 10 CA deg)

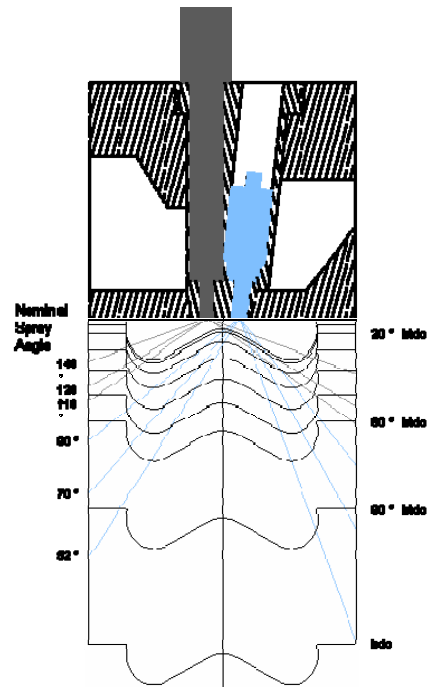
Two injector variable geometry spray concept ready for testing

2.2 Exploring injection and fuel effects on mixing and combustion regimes in a High Speed DI LTC-D engine – Foster

New single cylinder Diesel HCCI/LTC laboratory commissioned

Initiated exploration of LTC conditions with high EGR rate (> 55%)

Demonstrated emissions results consistent with expected trends

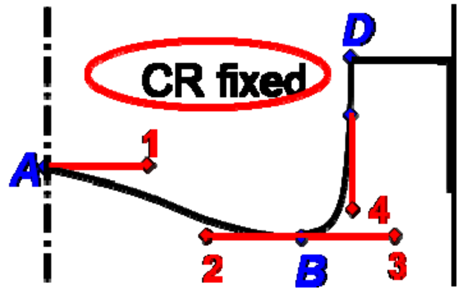


Summary and Conclusions

Task 3: Application of detailed models for Optimization of LTC-D combustion and emissions

3.1 Optimization of HD engine piston bowl geometry using GA-CFD with detailed chemistry and experimental validation – Reitz

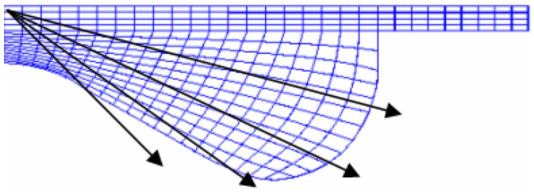
High load bowl geometry optimization in progress



3.2 Investigation of optimal spray characteristics for HSDI LTC-D combustion – Reitz

Low and high injection pressure sprays, and multi-hole nozzle arrangements are being explored for optimal charge preparation

Methodology established for evaluating spray configurations



3.3 Investigation of improved mixing strategies using early injection and LES – Rutland

CHEMKIN speed up technique 'DOLFA' implemented into KIVA-3V ERC and applied to achieve a 3~4 X speed up in full engine combustion simulations.

Grid sensitivity study performed using LES.

LES resolves finer geometric details in engine than RANS with increased resolution

Summary and Conclusions

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

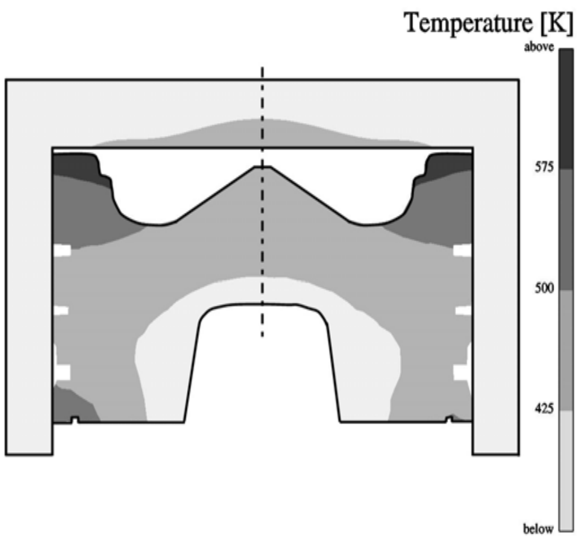
4.1 Thermal analysis of LTC-D engines using detailed CFD coupled with 3-D metal component heat conduction – Reitz

Wall heat transfer under LTC conditions being studied.

Effect of wall impingement model on film formation is being assessed for low and high pressure sprays with early injection

4.2 Experimental measurements of piston temperature and heat flux for LTC-D combustion analysis – Ghandhi

A linkage system is being designed to acquired piston temperature and heat flux daa in Caterpillar SCOTE



Summary and Conclusions

Task 5: Transient engine control with mixed-mode combustion

5.1 Multi-cylinder HSDI engine control strategies with mixed-mode combustion regime transitions – Foster

Transient engine test cell has been installed with:

1.9L Common Rail Direct Injection HSDI diesel engine

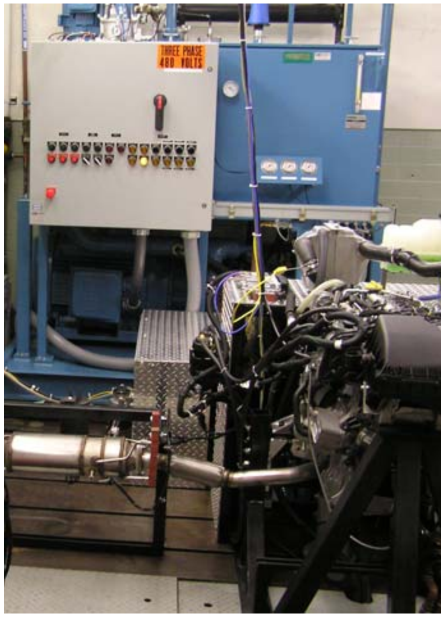
close coupled DOC and a DOC-DPF exhaust aftertreatment system.

Low inertia dynamometer system with a bandwidth of 20 Hz.

Dynamometer control and data acquisition system

Fast NOx and HC analyzers, response time (< 4ms).

Heated emission bench, Smoke meter, Combustion noise.



5.2 Engine system analysis and optimization with mixed-mode combustion regime transitions - Rutland

Engine system level simulation tool enhanced by validating emission models with experimental data from LTC-Diesel engine

Effect of different actuators on emissions evaluated during transients

GT-Power model of 1.9L four-cylinder HSDI turbocharged engine replicating experimental facility of Task 5.1 has been built

Acknowledgements

DOE LTC Consortium project DE-FC26-06NT42628

British Petroleum

Caterpillar Inc.

DOE Sandia Labs

General Motors CRL

Diesel Emissions Reduction Consortium (DERC) 24 member companies:

AVL Powertrain	BorgWarner	Caterpillar
CD-Adapco	Corning	Cummins
Delphi Corporation	Detroit Diesel	Donaldson Co.
FEV Engine Tech.	Fleetguard	Fluent
Ford Motor Co.	General Motors	Hyundai Motor Co.
ITEC	John Deere	MotoTron
Nippon Soken	Nissan	Paccar
Thomas Magnete USA	Toyota Tech. Center	Volvo Powertrain

ERC Students, Staff and Faculty