Low-Temperature Automotive Diesel Combustion

Light-Duty Combustion Experiments

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Light-Duty Combustion Modeling

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Program Manager: Gurpreet Singh, DOE EERE-OVT

Project ID#: **ACE002**

Overview

Timeline

- Project has supported DOE/industry advanced engine development projects since 1997
- Direction and continuation evaluated annually

Budget

DOE funded on a year-by-year basis

- SNL $680k (FY09), $725k (FY10)
- UW $230k (FY09), $230k (FY10)

Barriers addressed

- Powertrain cost
- Inadequate fundamental knowledge and predictive simulation capability
- Emission control
- Specific barriers

Partners

- 15 industry partners in the Advanced Engine Combustion MOU
- Collaboration with GM-funded CRL at UW (Prof. Foster)
- Additional post-doc funded by GM

Goals & technical targets impacted (2015)

Part load BTE	**Emissions:** Tier 2, Bin2
Fuel econ. improvement: 40%	**Aftertreatment Eff. Penalty:** < 1%

Objectives

Long-term:

- Improve our fundamental understanding of in-cylinder processes, develop a predictive modeling capability, and refine measurement techniques, data employed for model validation, and modeling practice

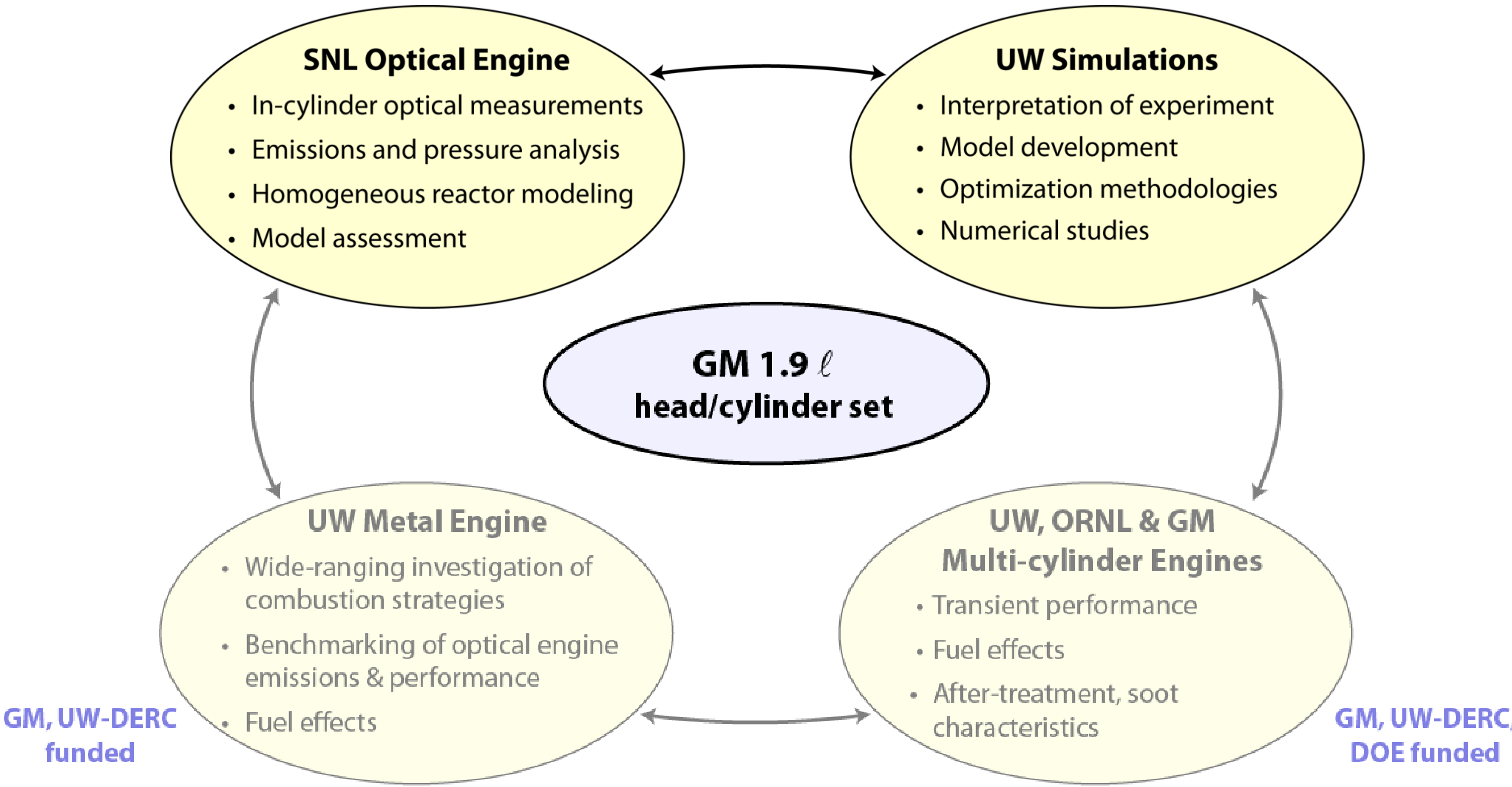
This fiscal year:

- Establish how the sources of combustion inefficiency (CO and UHC emissions) vary with combustion system parameters; resolve discrepancies between model and experiment

These objectives are met through:

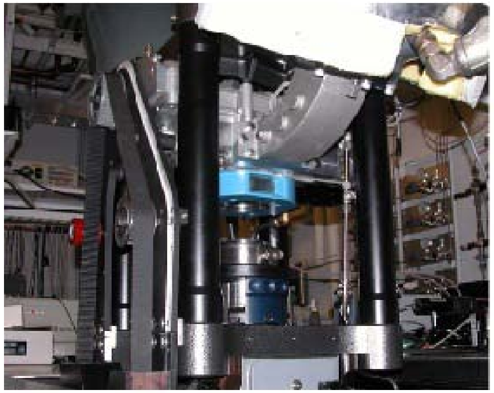
- Development and application of experimental techniques to obtain full-field scalar (UHC, CO) measurements to assess model accuracy and practice
- Comparison of model predictions (multi-dimensional and homogeneous) with experimental data
- Feedback and improvement of both the modeling and the experiments

Our approach coordinates and leverages the strengths of several institutions and $$ sources

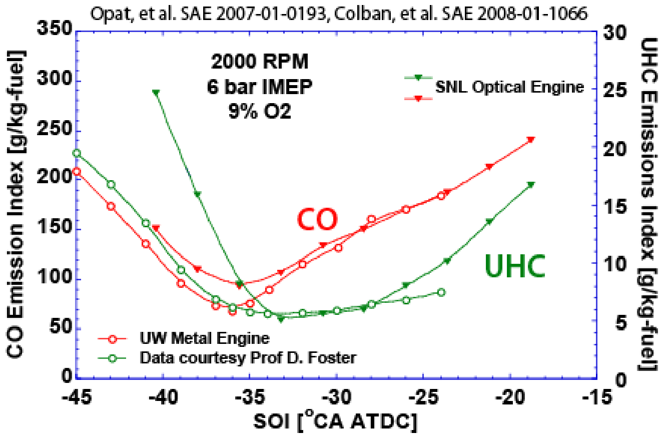


- Multi-institution effort focused on a single hardware platform
- Significant leverage of DOE funds by support from other sources

Optical engine and selected operating conditions

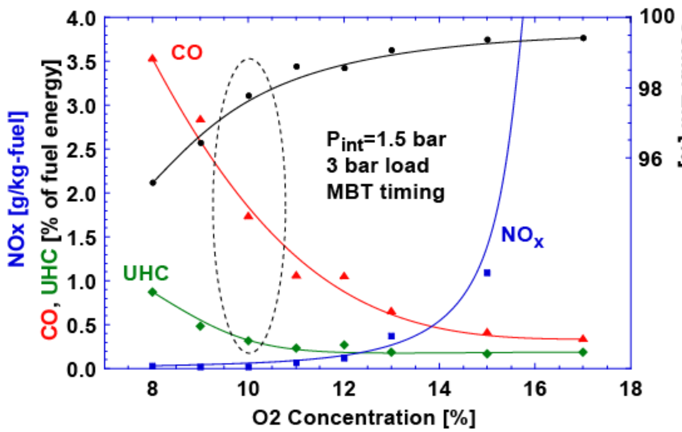


The optical engine matches a metal test engine at UW



The combustion ***and the emissions*** of the metal engine are well reproduced

The optical piston retains the same bowl and piston geometry as the metal engine (including valve-pockets)



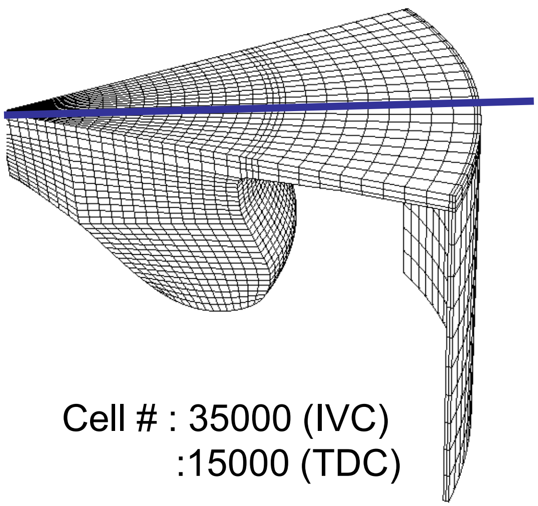
We focus on two high-dilution, PCI-like operating conditions: one dominated by finite rate kinetics and the other by limited mixing

Numerical simulations – background

KIVA release 2 coupled with Chemkin chemistry solver:

Ignition/combustion model	Chemkin chemistry solver
Mechanism	ERC-PRF mechanisms (~40 species, 140 reactions)
NO_x mechanism	Reduced GRI mechanism (4 species, 9 reactions)
Soot model	2-step phenomenological model
Turbulence model	RNG k-ε model
Atomization/breakup model	KH-RT model

Computational grid at TDC

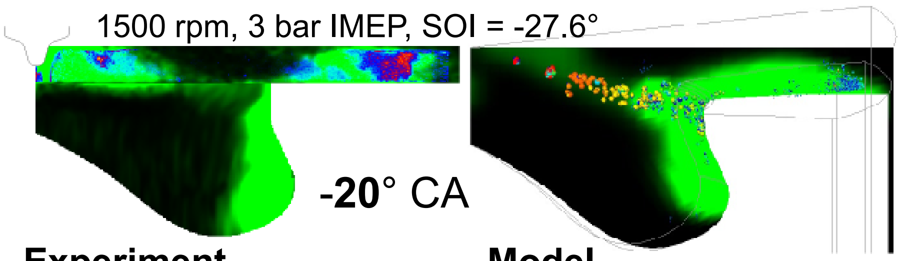


Cell # : 35000 (IVC)
:15000 (TDC)

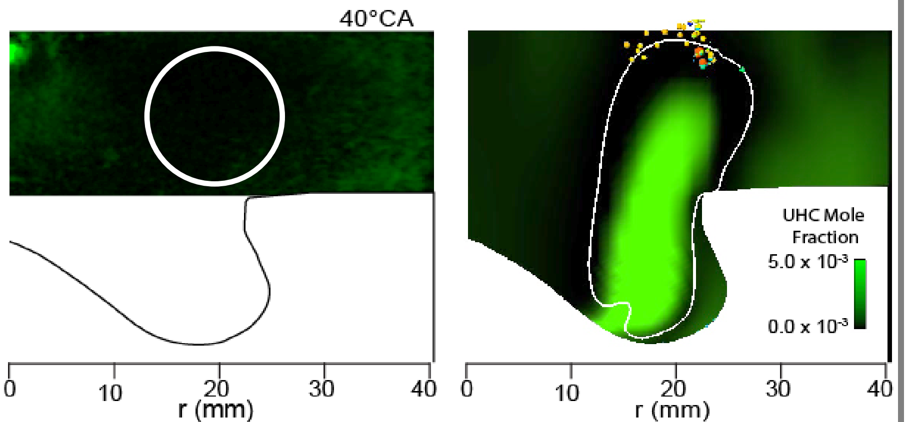
ERC grid-size and time-step independent models
(ref. SAE 2008-01-0970)

Liquid/Gas phase momentum coupling	Gas-jet model
Collision/Coalescence model	Radius-of-influence collision model
Time-step calculation	Mean collision time step model
Parcel number control	Re-group model

Recap of technical accomplishments in FY08-09



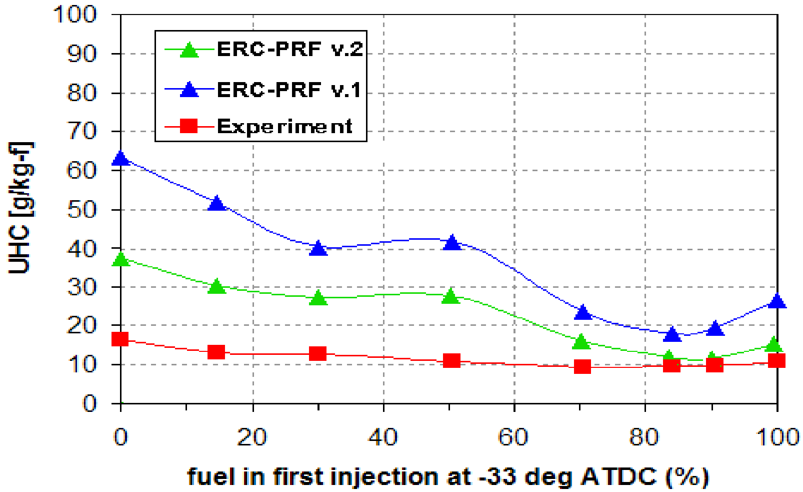
Comparison of both liquid and vapor fuel distributions with model predictions demonstrated reasonable agreement…



50-cycle averaged PLIF image

Simulation UHC distribution

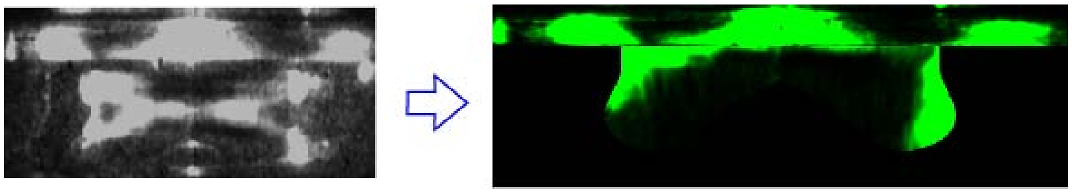
…but the model predicts that a plume of under-mixed (fuel-rich) mixture leaving the bowl, not seen experimentally, is the dominant source of UHC and CO emissions

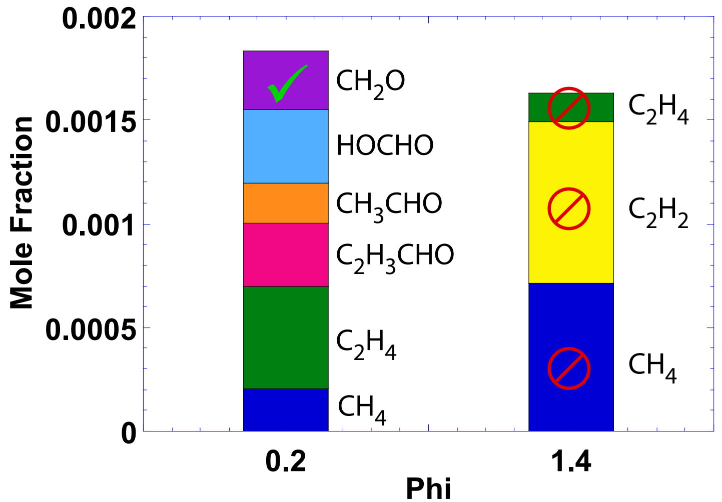


Improvements to the reduced kinetic mechanism help considerably, but do not resolve the discrepancy

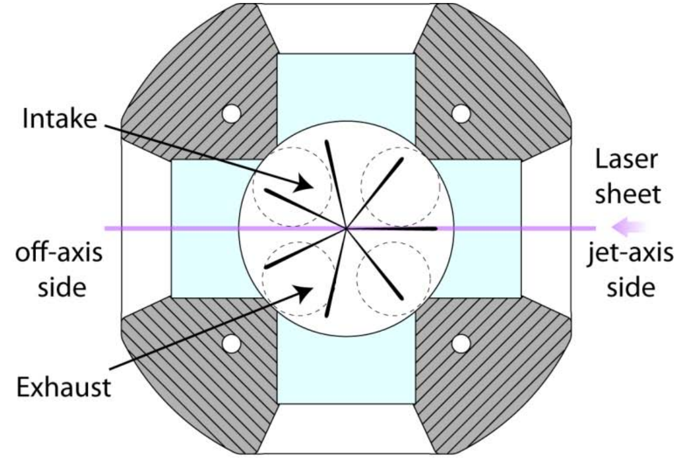
We have continued to apply the 355 nm PLIF diagnostic to a wide suite of conditions

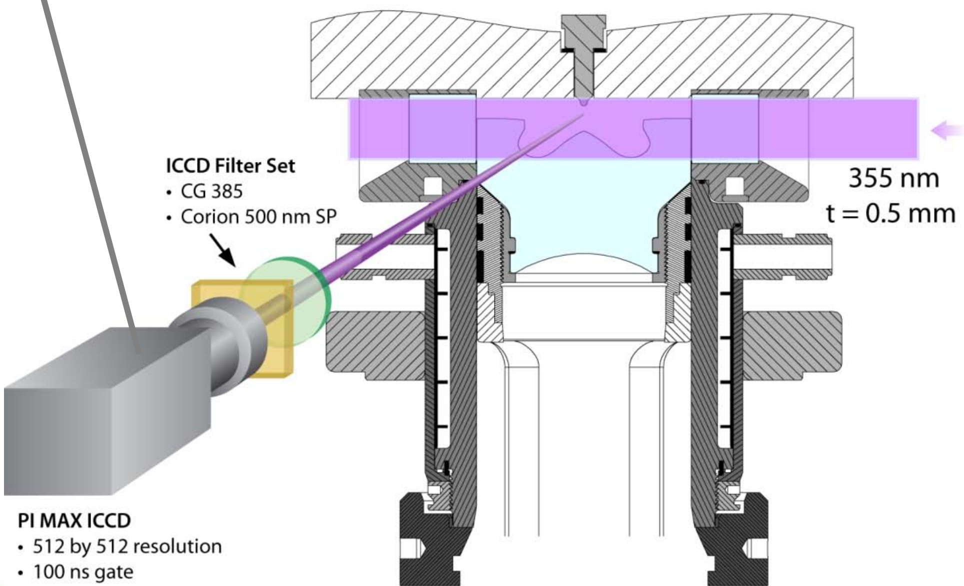
355 nm PLIF images capture CH_2O and PAH (parent fuel and products of $\phi > 2$ combustion)





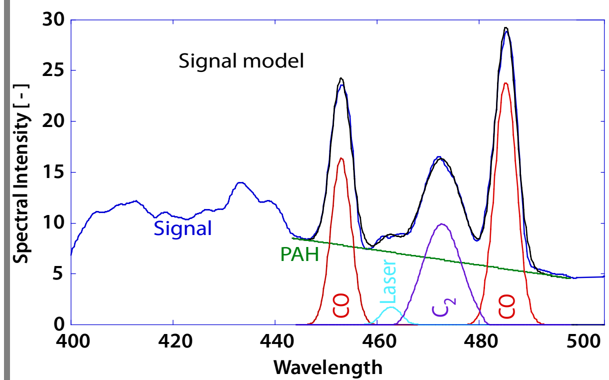
Rich mixture UHCs are not detected with 355 nm PLIF. C2H2 can be detected at 230 nm (Chem. Phys. Lett. 349:43-50)



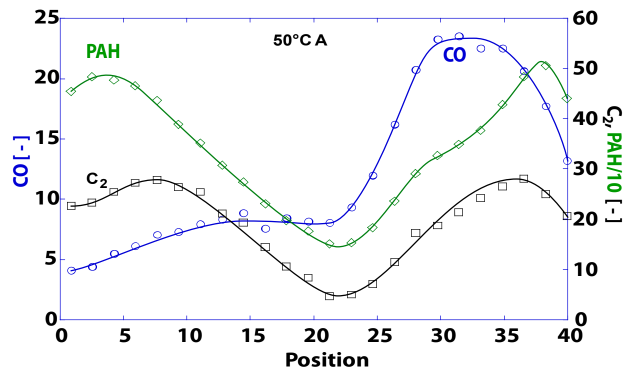


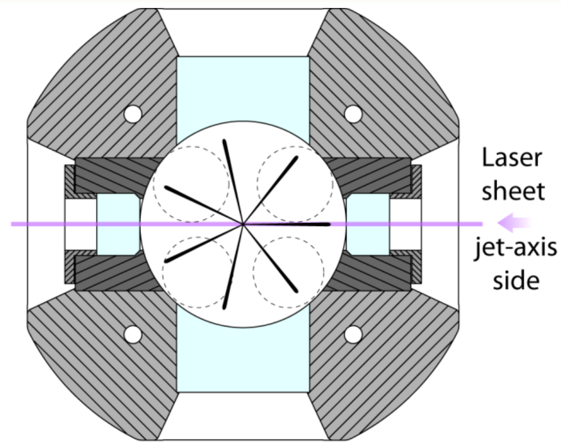
…and have improved our deep-UV diagnostic to obtain mean CO, C_2, and PAH fields

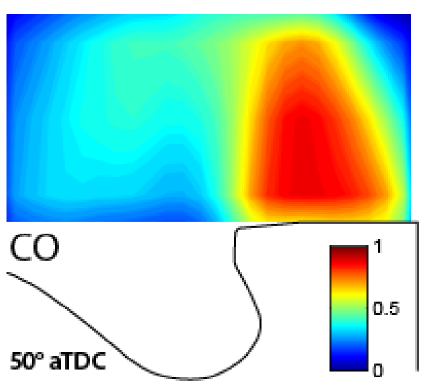
Spectrally-resolved data are obtained along a line...



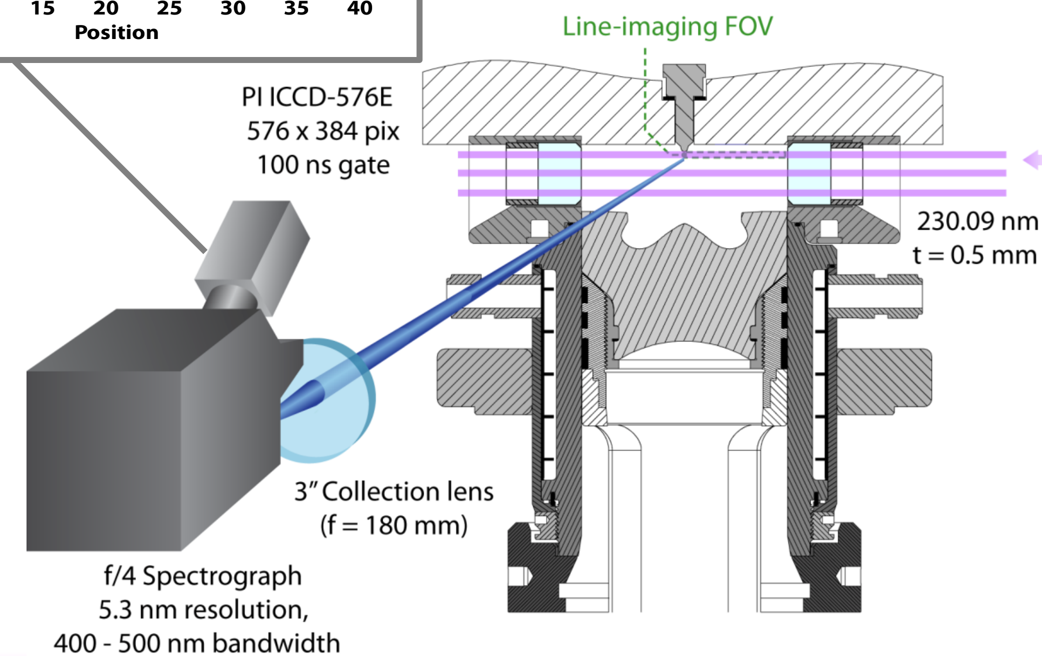
…providing radial profiles of CO, C_2, and PAH







Smoothing splines are fit to profiles measured at multiple heights, yielding a 3-d image



Highlights of technical accomplishments in this reporting period

SNL:

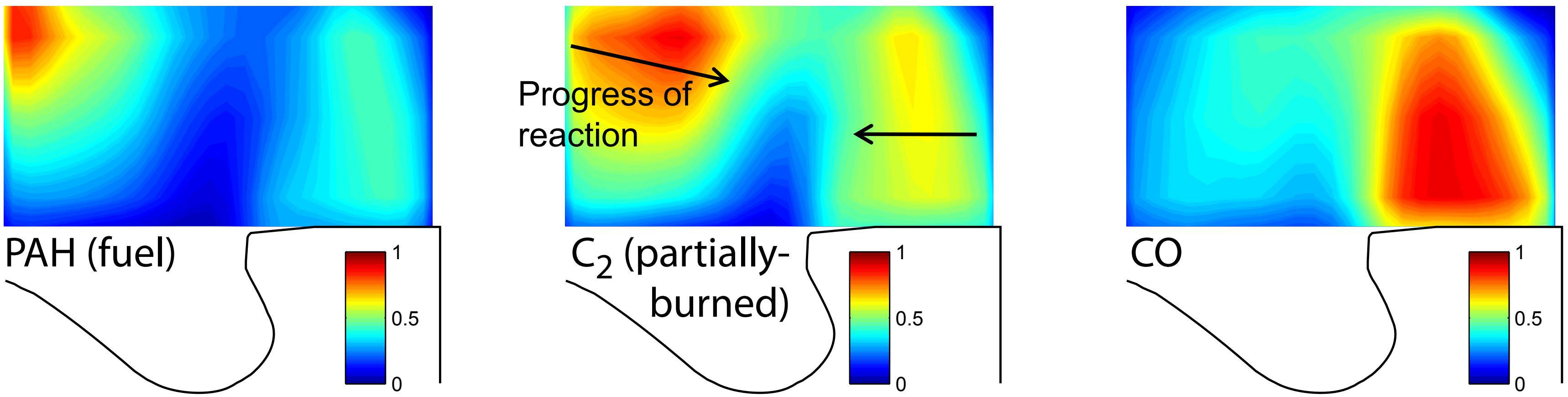
- Developed improved deep-UV LIF technique to image 2-d mean distributions of C_2, PAH, and CO
- Applied complementary 355 nm PLIF and deep-UV LIF to a broad range of operating conditions and fuels:
  - Early-injection (SOI, load, O_2, squish height and targeting sweeps)
  - Late-injection (impact of excessive retard)
  - Euro 5, pilot-injected "cold start" calibration
  - Biofuels matrix (tests conducted with 9 different fuels/blends)

  Developed a "library" of experimental data to compare with simulations
- Performed detailed chemistry, homogeneous reactor simulations to clarify fundamental differences between early- and late-injection LTC (PCI v. MK)

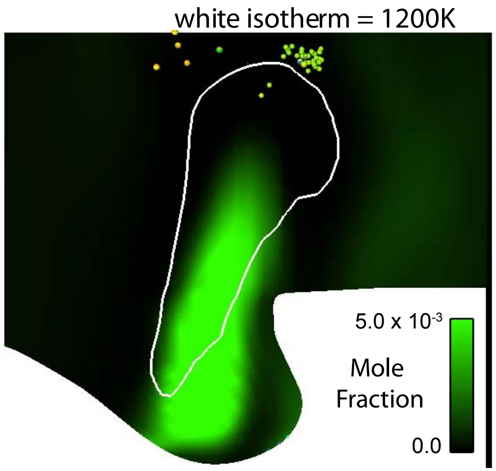
UW:

- Performed simulations of LTC combustion examining a broad range of variables that impact the UHC and CO in the fuel-rich plume leaving the bowl
- Developed variable pressure injection system and tested in UNIBUS and split-heat-release combustion schemes
- Developed alternative reduced PAH chemistry mechanisms and examined sensitivity of soot predictions to PAH chemistry

A plume of mixture is clearly observed leaving the bowl during expansion…but it is "clean" mixture



Measured CO and UHC @ 50°CA

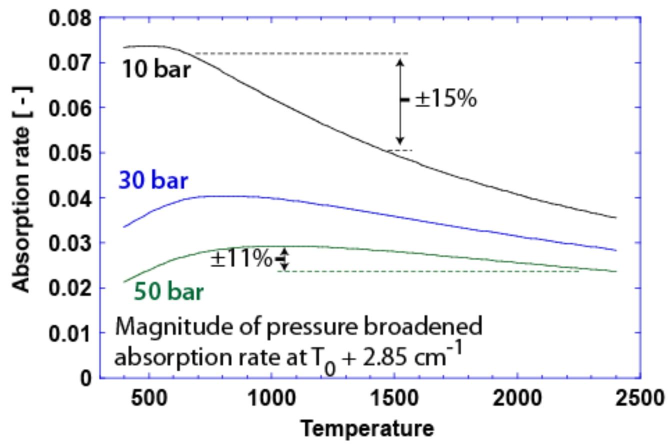


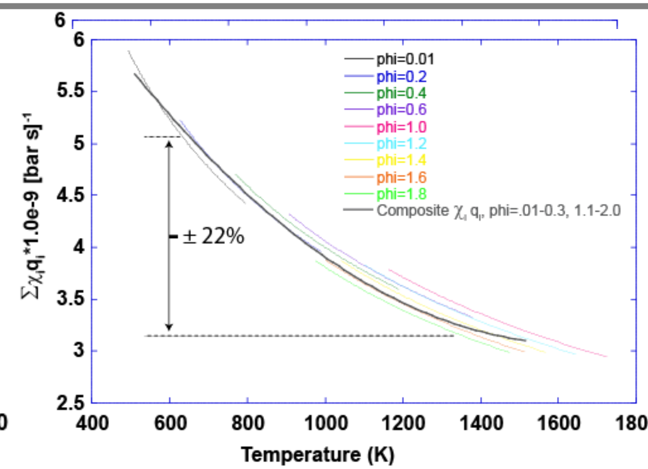
Modeled UHC
(CO is similar)

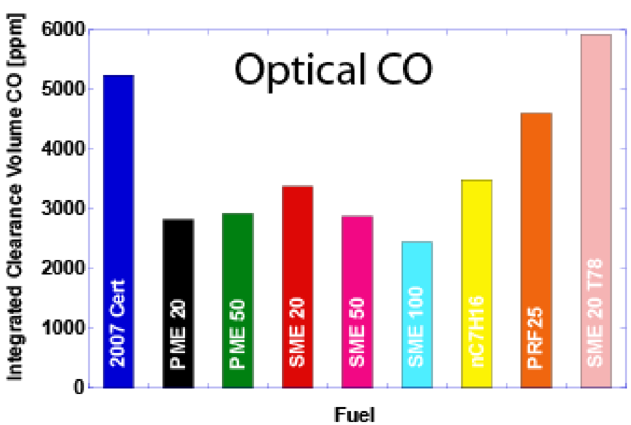
- At this operating condition, there is no rich-mixture plume of UHC or CO is observed leaving the bowl. The discrepancy is in the modeling
- At 50° CA, 83% of the cylinder volume is within the clearance volume. The dominant sources of UHC and CO are likely captured
- The mean flow structure, and the presence of CO/UHC in the squish volume, are well predicted

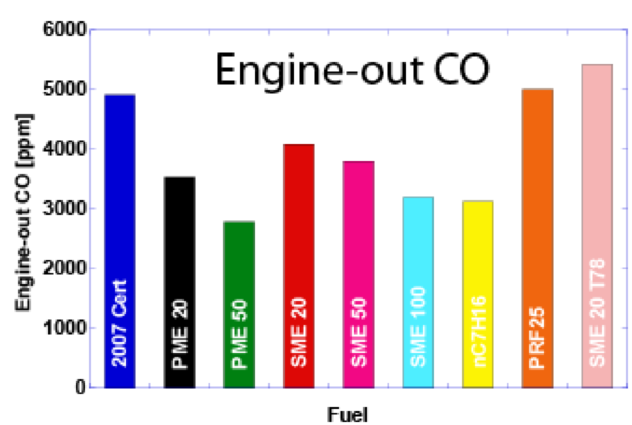
The CO LIF results are semi-quantitative – lending credence to the measured spatial distributions

We apply temperature and pressure corrections to the CO absorption and quenching rates









Despite remaining uncertainties, the magnitude and trends of the spatially-integrated optical data match engine-out emissions well

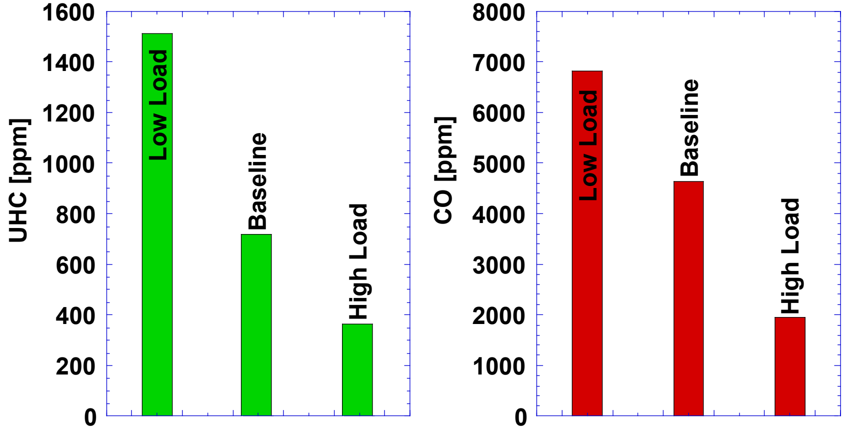
The "progress of reaction" is also clearly visible in the load sweep results

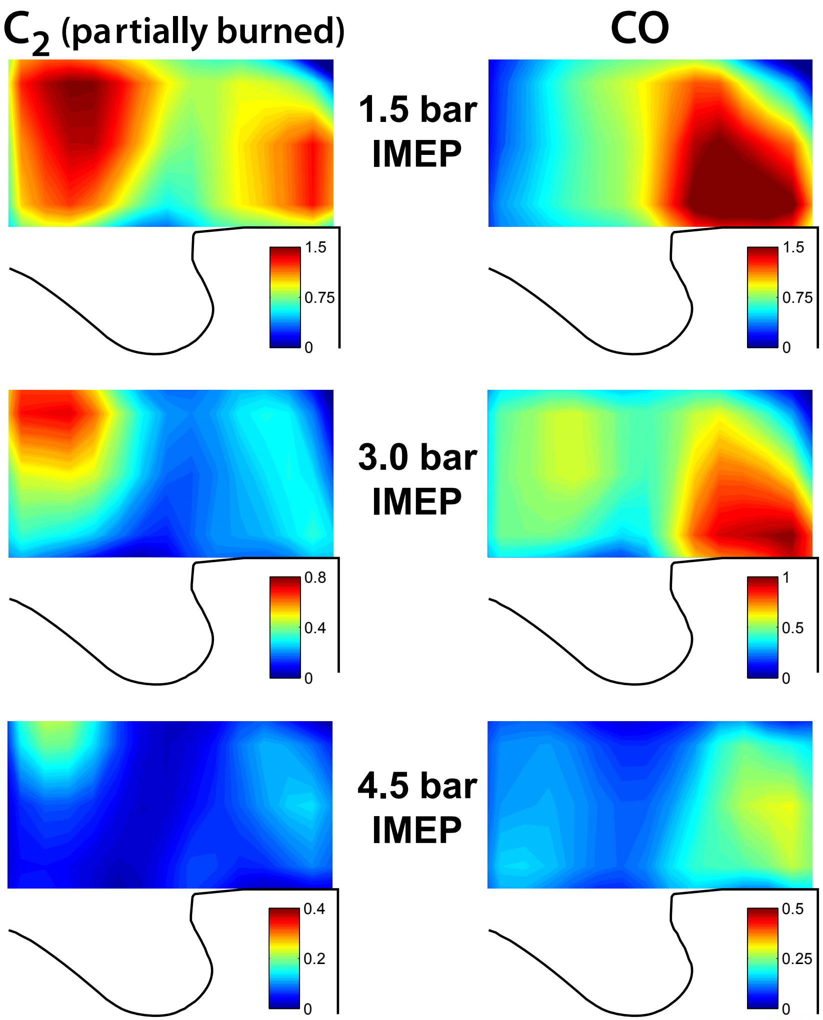
Partially-burned UHC near the injector and in the squish volume decreases with increasing load...

...as do engine-out UHC emissions

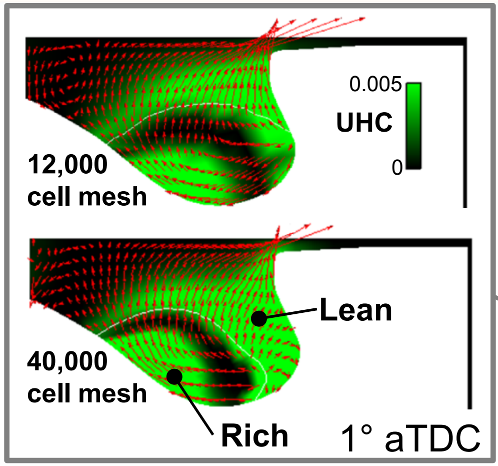
Increased load also promotes oxidation of squish volume CO…

…but CO near the injector first increases as UHC oxidation improves, then is oxidized at the highest load



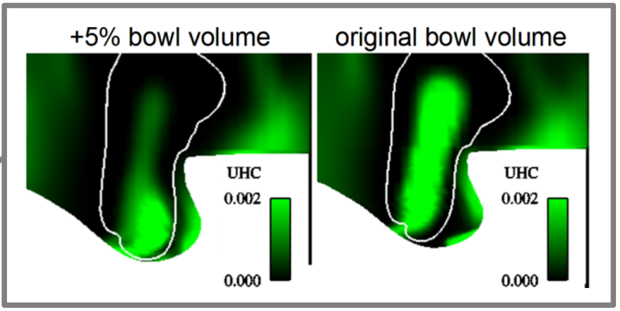


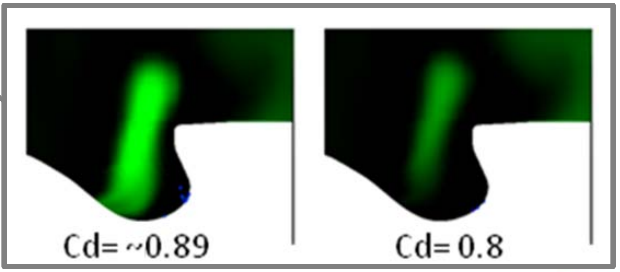
The impact of model parameters and initial conditions on the rich plume have been systematically examined



- The simulations have been performed with several alternative kinetic mechanisms, with no substantial improvement
- Intake temperature reduction increased squish volume UHC, but does not substantially impact the bowl plume
- Likewise, grid resolution does not change the resulting mixture distribution

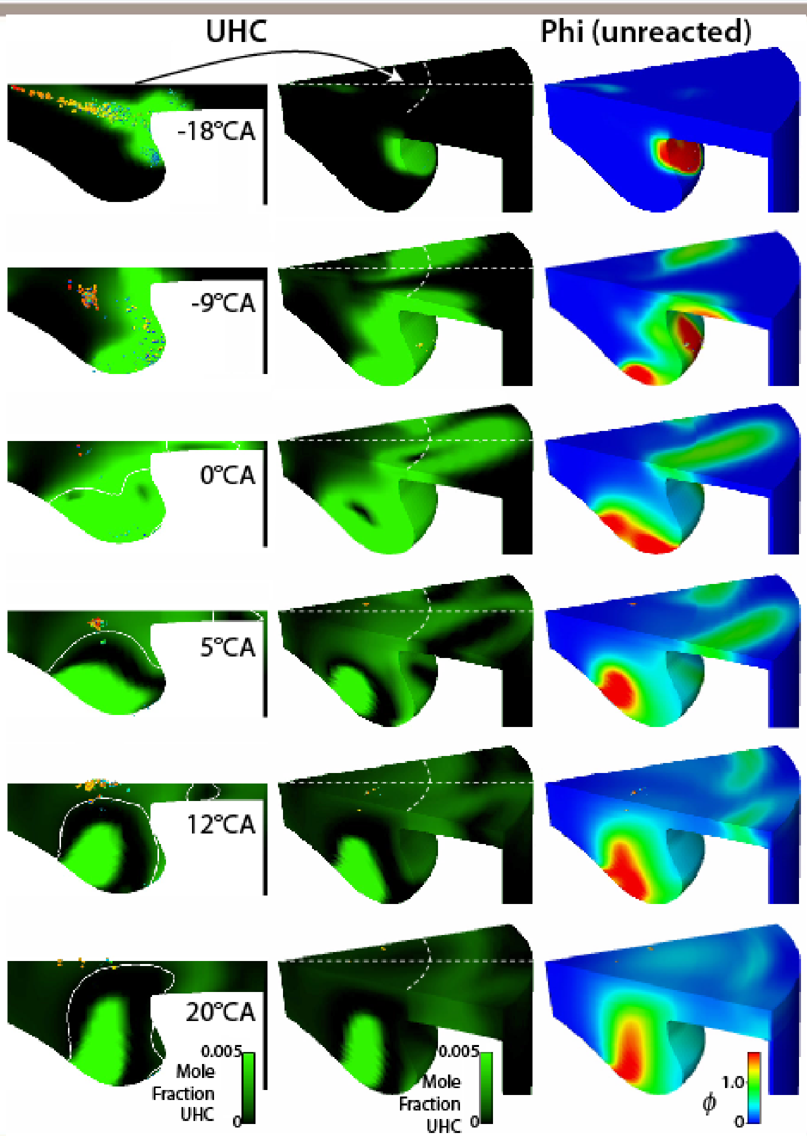
- O_2 concentration perturbations (10% – 11%) do not eliminate the plume
- Geometry changes (increased bowl volume) help — more air is available for mixing
- Increased jet momentum (through lowered Cd) also helps





The simulation of mixing processes, not kinetics or computational issues, is likely responsible for the bowl plume discrepancy

Modeling results help us understand the origin of the UHC & CO found within the squish volume



With SOI ≈-23°, fuel vapor is injected into the squish volume

The squish flow does not force the fuel back into the bowl, although no squish volume fuel remains in the jet-axis plane

Near peak HTHR, UHC in near stoichiometric mixture is fully oxidized

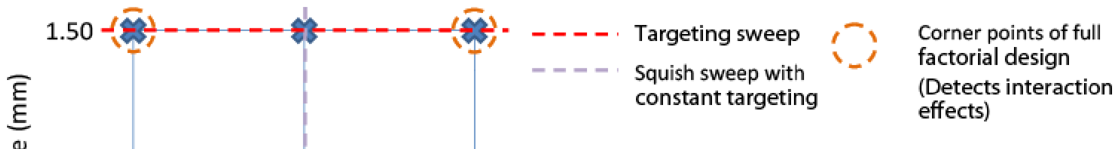
A large amount of lean mixture UHC, from between two fuel jets and the tail of each individual jet, is positioned near the bowl rim

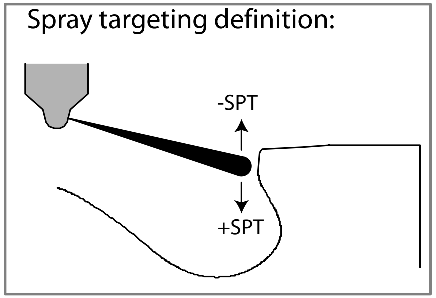
The reverse squish flow and gas expansion in the bowl forces this mixture into the squish volume

Lean mixture from near the bowl rim is the dominant source of squish volume UHC, plus a remnant of fuel injected into the squish volume

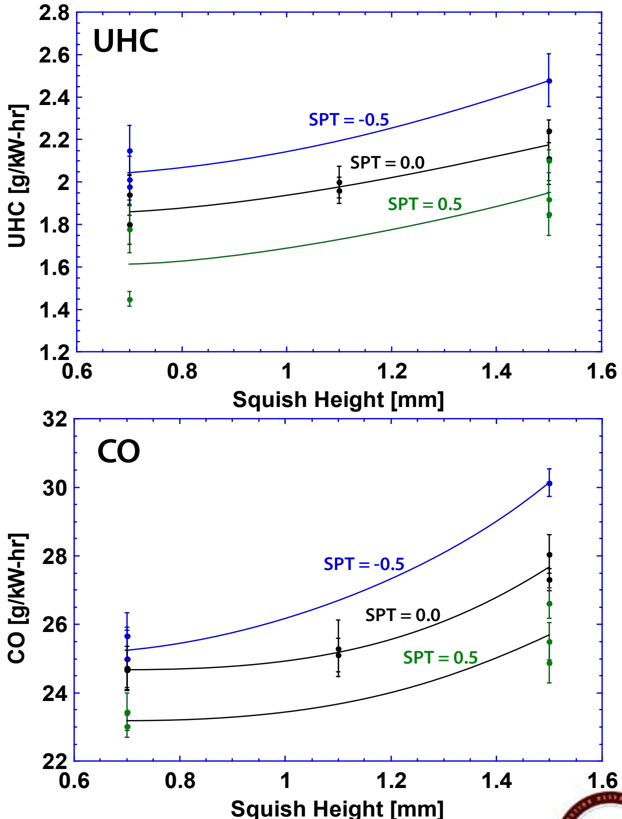
How do valve pockets change this picture?

The impact of squish height and targeting on UHC & CO emissions is consistent with this understanding





CO and UHC emissions are minimized with smaller squish heights and spray targeting deeper within the bowl



- Response surface design with seven test points and one replicate (i.e., the entire test matrix was measured twice)
- For each squish height, the injector tip protrusion was adjusted to maintain a fixed relative spray targeting
- Each variable, squish height and spray targeting, was varied by as much as the engine design permitted

Collaborations and coordination with other institutions

Within Vehicle Technologies program:

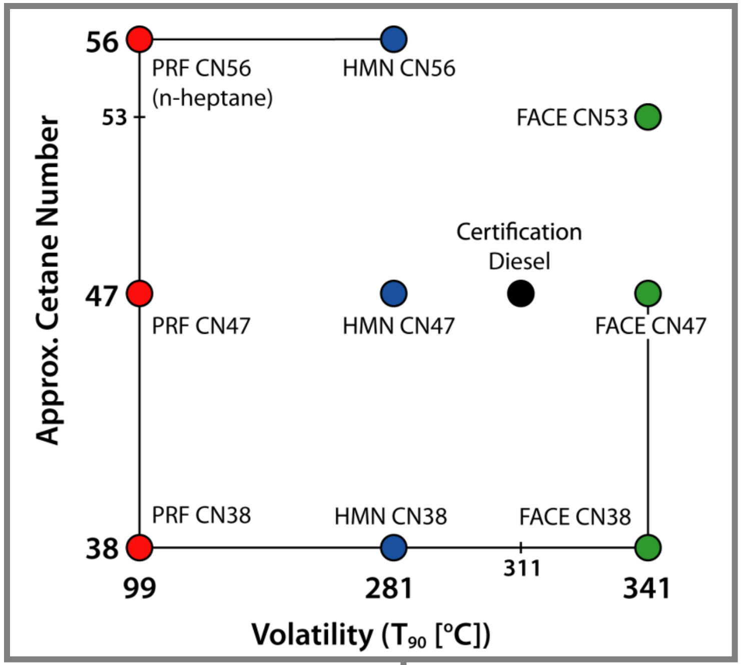
- Formal collaboration between SNL-UW-ORNL
- Participation in Advanced Engine Combustion group, including presentations and discussion with 20 industrial/national laboratory partners:

Ex-Vehicle Technologies program:

- Strong ties with GM:
  - GM-funded post-doctoral researcher
  - Monthly teleconferences
- Strong ties with Lund University engine research
  - Exchange students perform research at Sandia
  - Lecture series and participation in LU research by SNL staff

Future work – SNL

- Investigate impact of mixing processes on rich bowl plume by conducting imaging studies for various injection pressures, swirl ratios, and injector hole sizes
- Extend UHC imaging work and make flow measurements to evaluate asymmetries in the squish volume caused by discrete fuel jets, piston top valve pockets, and head valve recesses.
- Evaluate the impact of close-coupled post-injections on in-cylinder CO/UHC distributions
- Examine impact of fuel effects on UHC/CO emissions by investigating an orthogonal matrix of fuel ignition properties and volatility



- Quantify C_2H_2 detection limits using 230 nm LIF (semi-quantitative C_2H_2 is important for soot model validation)

Future work – UW

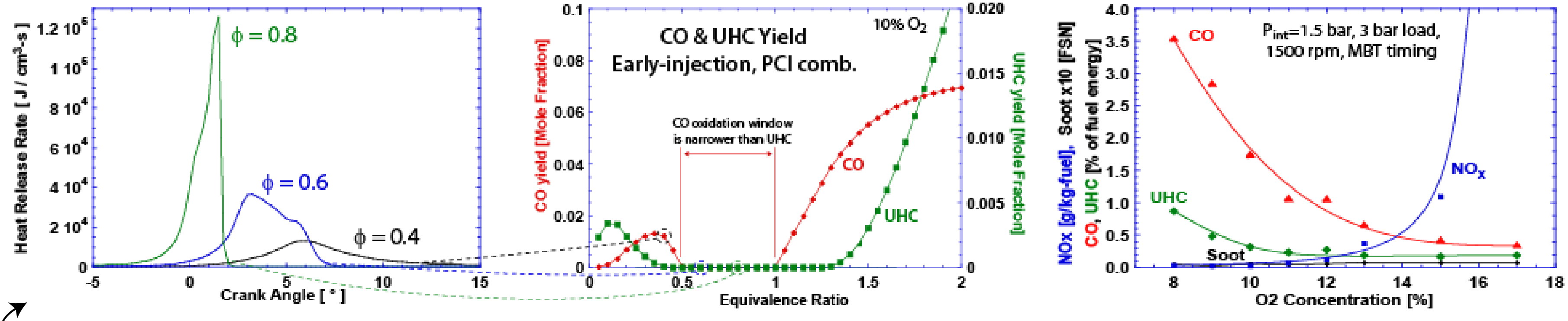
- Continue to investigate discrepancies between measured and simulated in-bowl UHC and CO distributions. Focus on mixing performance and compare against experimental data for flow swirl, injection pressure, and injector hole size sweeps
- Investigate impact of the detailed geometry of piston top valve pockets and head valve recesses on flow and species distributions within the squish volume
- Continue to test and improve reduced chemical kinetic mechanisms and extend mechanisms to alternative fuels
- Investigate soot model sensitivity to PAH chemistry through comparison of results with two reduced PAH mechanisms to soot mass emissions and particle size data obtained at SNL, UW, and ORNL
- Further characterize potential benefits of variable pressure fuel injection and of dual fuel combustion systems in light-duty engines

Summary

- Experiments investigating in-cylinder UHC and CO distributions in LTC operating regimes have identified the fundamental sources of engine-out emissions. The experiments have been conducted over a broad range of parameters, providing a library of data against which model results can be compared
- Detailed comparison of experimental UHC and CO distributions throughout the combustion event have shown many areas of close agreement, but also areas where model improvement is required — in particular the fuel-air mixing processes within the bowl
- On-going work will continue to evaluate discrepancies and improve model predictions, and will extend these studies to examine the impact of asymmetries — especially valve pockets

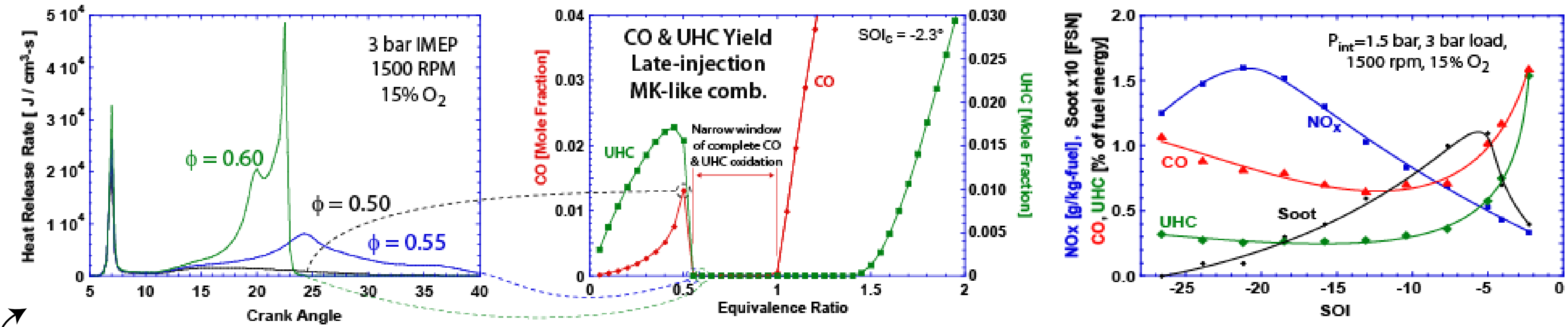
Advances are being made in our fundamental understanding, quantitative experimental techniques, and predictive modeling capabilities — but additional work is required

The combustion kinetics are fundamentally different between early- and late-injection LTC strategies (SNL)



With early-injection, lean mixtures fail to complete the latter stages of HTHR...

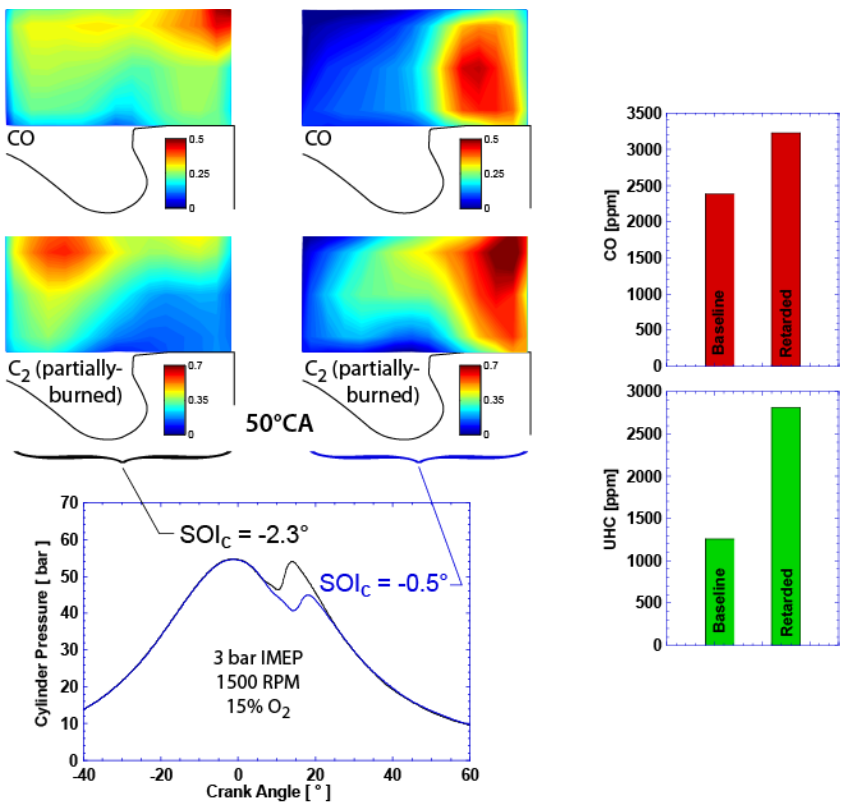
...leading to a more rapid increase in CO emissions than UHC



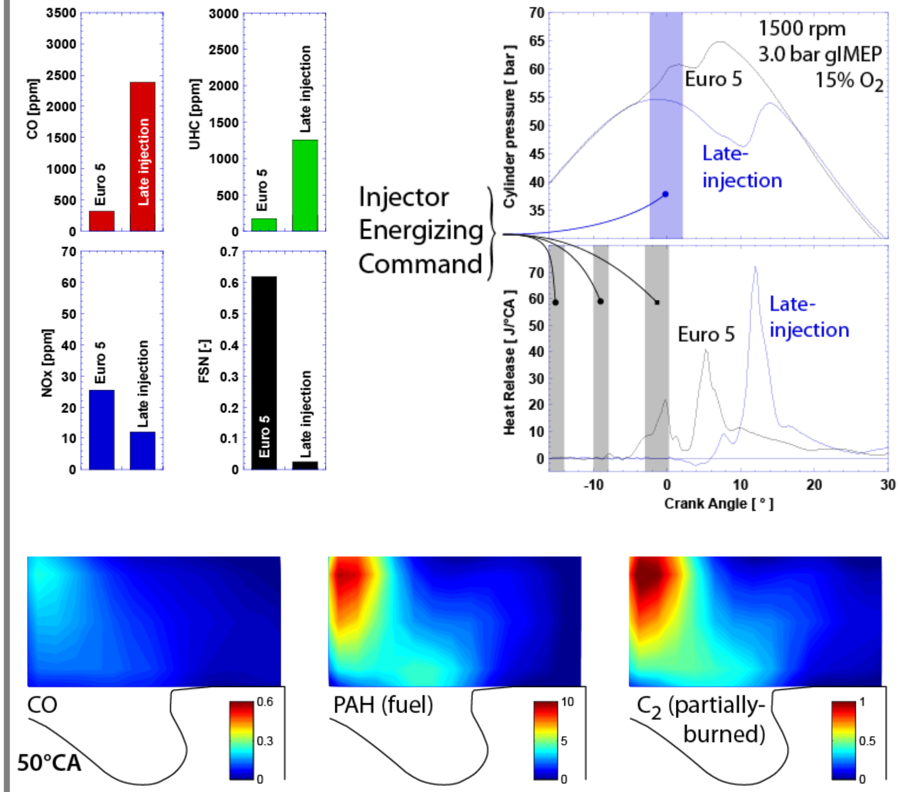
With late-injection, lean mixtures fail to transition to HTHR and little CO is formed…

...thus UHC increases more rapidly than CO with excessive timing retard

Additional, major conclusions from SNL imaging work



- With excessive timing retard, the CO and UHC emissions from MK-like LTC move to the squish volume

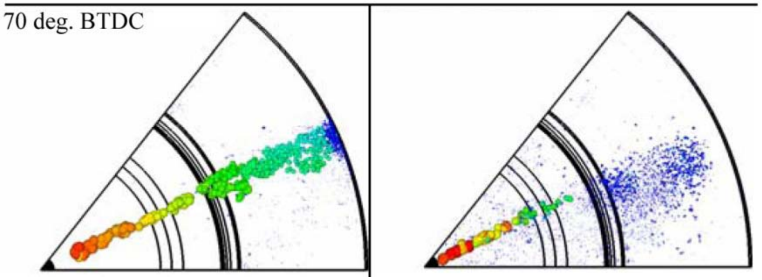


- With a Euro 5 cold-start calibration, the dominant UHC/CO sources are found near the injector

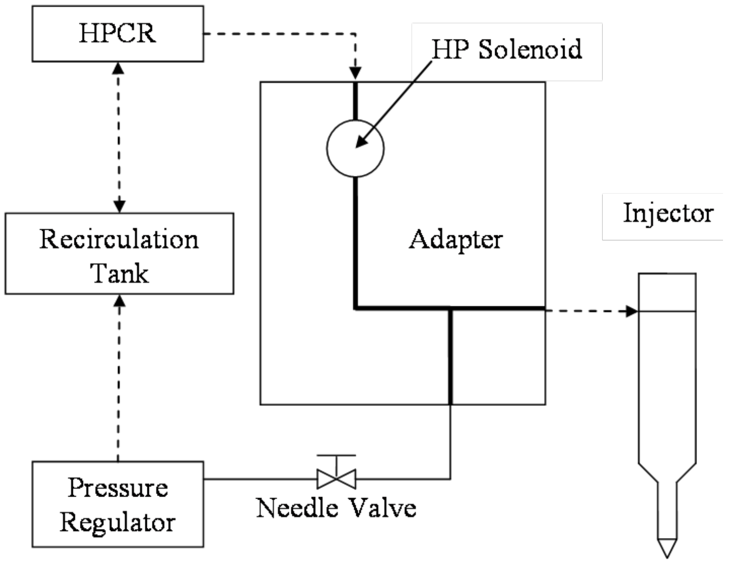
UW has also developed a variable pressure injection system for light-duty applications

- Low pressure injections early in the cycle can reduce liner impingement
- The variable pressure injection system switches between low- and high-injection pressures in a single engine cycle

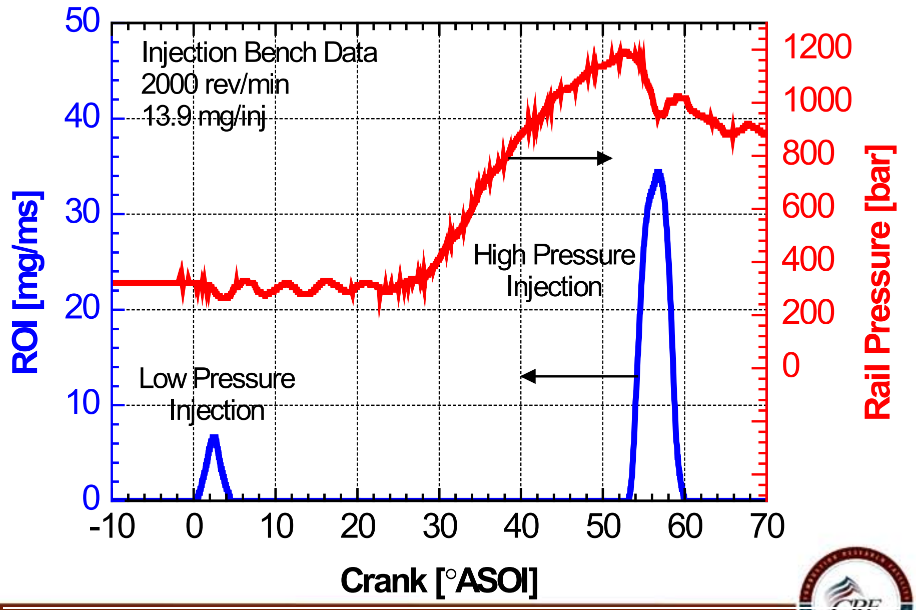
High Pressure 860 bar | **Low Pressure 100 bar**



Kokjohn et al. SAE 2009-01-0127



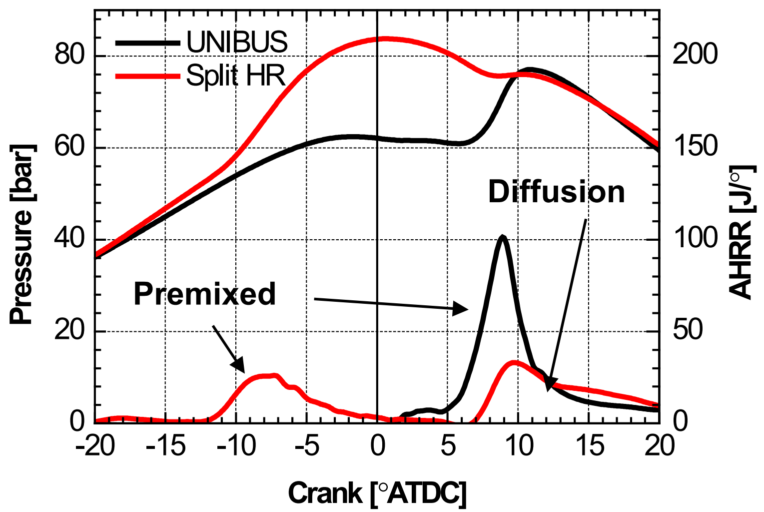
Swor et al. SAE 2010-01-0340



Two dual-injection combustion strategies have been investigated with promising results

UNIBUS-type and split HTHR combustion strategies explored at 5.5 bar IMEP and 2000 rev/min

- Low-pressure (300 bar) injection near 50° BTDC
- High-pressure (1200 bar) injection near TDC
- Sweeps of injection pressure, SOI's, EGR, and swirl



Optimum Results

	UNIBUS	Split HR
NOx (g/kW-hr)	0.1	0.25
Soot (g/kW-hr)	0.05	0.05
gISFC (g/kW-hr)	**183**	195
Peak PRR (bar/deg)	6	**3**
Fuel in Pulse 1 (%)	20	50
EGR (%)	55	44

Split HTHR was effective at controlling the peak PRR

- Lower levels of EGR required for low peak PRR
- Penalty in fuel consumption

UNIBUS-like strategy yielded high efficiency

- 55% EGR was required to control peak PRR

Swor et al. SAE 2010-01-0340