Automotive HCCI Engine Research

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DOE Office of Vehicle Technologies

Project ID: ACE006

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Overview

Timeline

- Project provides fundamental research supporting DOE/industry advanced engine development projects.
- Project directions and continuation are evaluated annually.

Barriers identified in VT Multi-Year Program Plan

- Inadequate fundamental knowledge of engine combustion:
  - Fuel injection, evaporation, and mixing;
  - Heat transfer and thermal stratification;
  - Ignition, low-temperature combustion, and emissions formation.
- Target goals for Advanced Combustion R&D (2015):
  - 25% Gasoline fuel economy improvement;
  - Achieve Tier II, Bin 2 emissions with < 1% thermal eff. penalty.

Budget

- Project funded by DOE/VT
- FY09 funding: $580k
- FY10 funding: $620k

Partners

- Project lead: Richard Steeper; Post-doc: Russ Fitzgerald
- University/National Lab:
  - Lawrence Livermore National Lab and University of Wisconsin:
    - KIVA model of automotive HCCI optical engine.
  - Stanford University:
    - 5-year diagnostic development program (completed this year).
- Industry:
  - GM & Ford (extensive technical interactions);
  - 15 Industry partners in DOE's Advanced Engine Combustion Working Group.

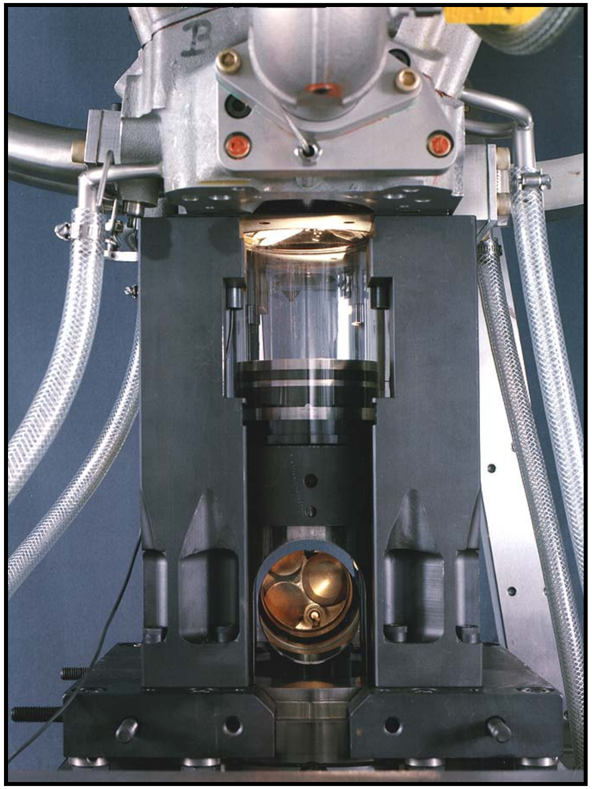
Relevance: Objectives and Milestones

- Overall objective:
  - Expand our fundamental understanding of low-temperature combustion (LTC) processes to remove barriers to the implementation of clean and fuel-efficient automotive HCCI engines.

- Near-term objectives:
  - Quantify thermal and chemical effects of the negative valve overlap (NVO) fueling strategy used to control and extend HCCI combustion.
    - Milestone: Perform experiments comparing thermal effects of NVO fueling with intake air heating.
    - Milestone: Perform seeding experiments to determine role of specific NVO product species.
  - Characterize the extent of NVO reactions during NVO-fueled operation:
    - Milestone: Optimize our laser-absorption diagnostic to measure [CO] in fired engine.
  - Advance the capabilities of our computer models of automotive HCCI combustion.
    - Milestone: Predict reactive products of NVO fueling using Chemkin 0-D engine model.
    - Milestone: Simulate fired NVO operation of our engine using KIVA model.

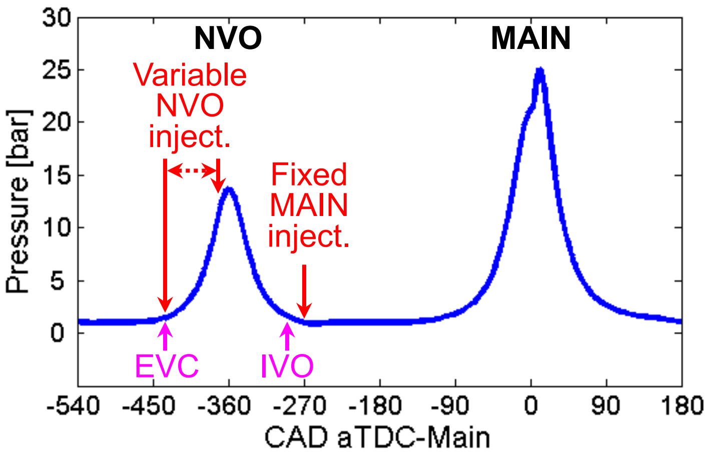
Approach

- Perform experiments in an optical engine equipped and configured for automotive HCCI combustion strategies.
- Develop and apply diagnostics to acquire in-cylinder measurements of fundamental physical processes.
- Apply suite of computer models to guide and interpret engine experiments.
- Leverage knowledge gained through technical exchange with DOE Vehicle Technologies program participants.



Technical Accomplishments – FY10

- Our current primary focus is NVO operation as a promising strategy for HCCI combustion control under low-load conditions.
  - NVO operation enables dilution/thermal control through residual gas retention;
  - In addition, fuel can be injected during NVO providing further control of main combustion.



Terminology:
EVC, IVO: Exhaust valve closing, intake valve opening
CAD aTDC-Main: Crank angle degrees after top dead center of main combustion

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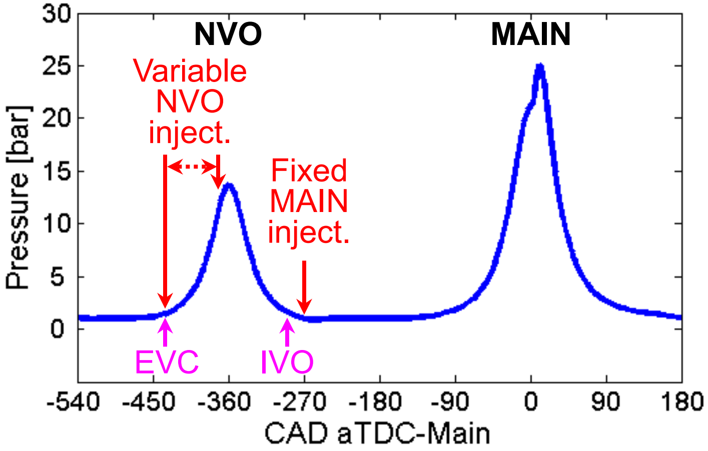
- Accomplishments of our NVO research this year are described in this section:
  - NVO engine experiments (details at right);
  - Diagnostics for in-cylinder measurements;
  - Model development.
- Begin by looking at NVO-fueling experiments…



Typical operating conditions

Engine	Automotive, 1 cyl., optical
Valve overlap	-150 CAD
Resid. gas fraction	~50%
Geom. compr. ratio	11.5
Speed	1200 rpm
Fuel	Iso-octane

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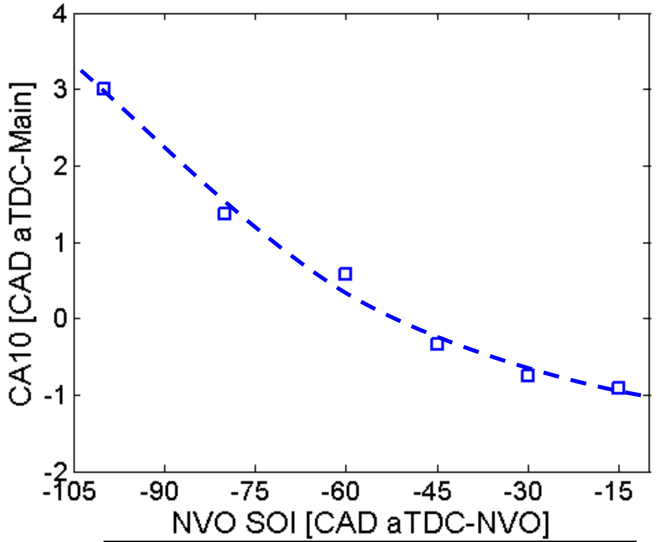
NVO fueling assists control of main combustion

- Our experiments have characterized the effects of both the amount and timing of NVO fuel injection on combustion phasing.*
- The relationship between NVO fueling and main phasing is complex, e.g., effects of NVO SOI on:
  - 10% burn point of main combustion (CA10);



Low load: 150 kPa
NVO fuel mass: ~10% of main fuel

* 2010 SAE Paper No. 2010-01-0164
SOI: Start of injection

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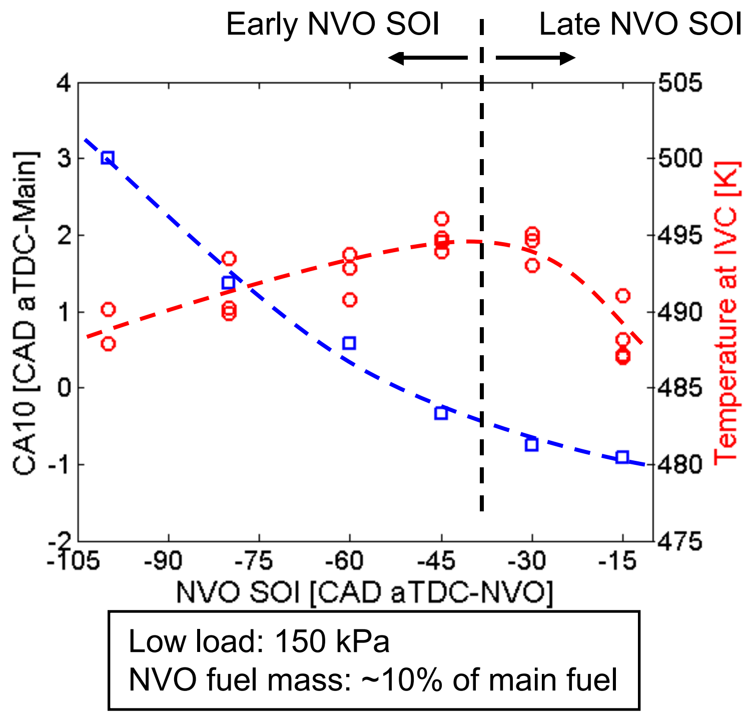
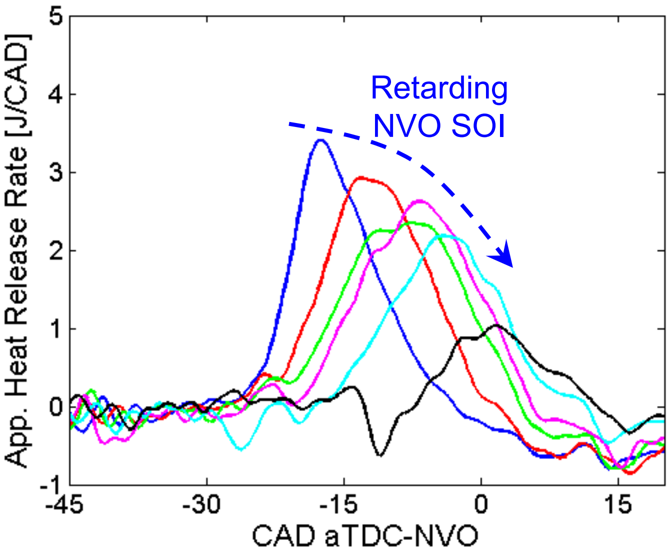
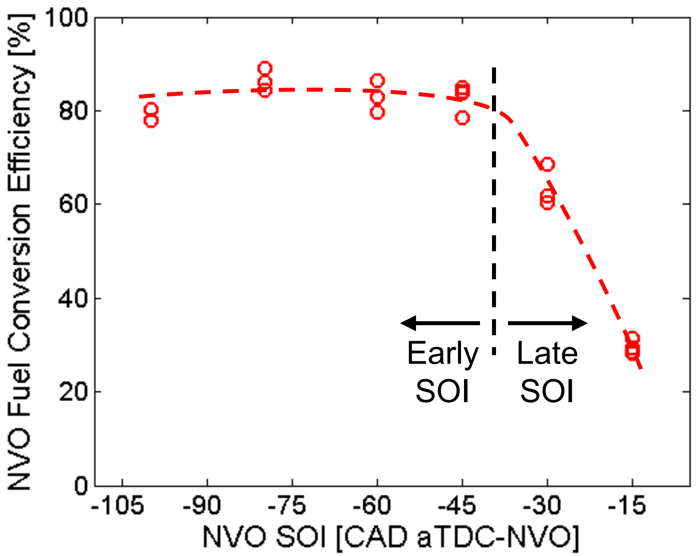
- The relationship between NVO fueling and main phasing is complex, e.g., effects of NVO SOI on:
  - 10% burn point of main combustion (CA10);
  - Temperatures at intake valve closing (IVC).
  - We have identified a clear distinction between early and late NVO SOI that is seen throughout our results.
- A convenient approach for analyzing our results is to begin with the NVO period and proceed through the cycle to main ignition…



Examination of HR during NVO period

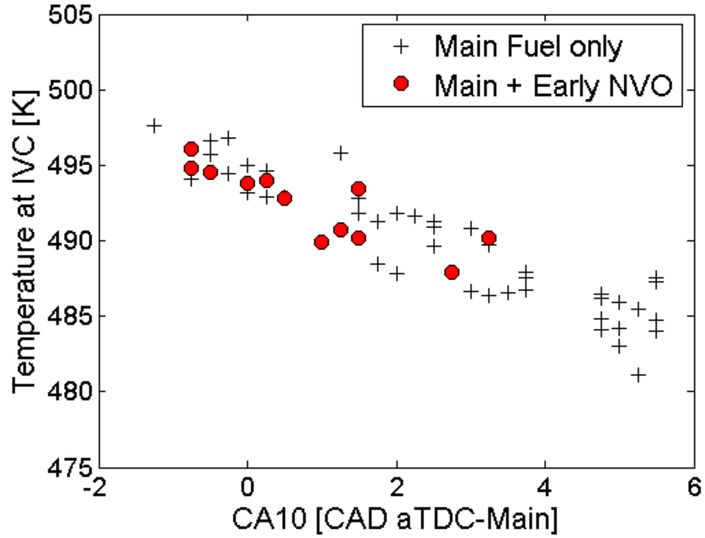
- We have characterized several NVO processes:
  - Residual trapping via computed temperatures;
  - Fuel injection via spray imaging;
  - Combustion and reformation via:
    - Optical measurements of composition (more later);
    - Heat-release calculations.
- NVO heat-release analysis provides insight:
  - Phasing and duration of NVO HR progress monotonically with NVO SOI;
  - But we find that NVO combustion efficiency falls off dramatically for late NVO injection.
- Piston wetting is an obvious factor:
  - We observe fuel films, pool fires, and rich combustion associated with late NVO injections;
  - These provide a plausible explanation of the late vs. early SOI behavior.
- Next experiments shift focus from the NVO period to the end of intake stroke…

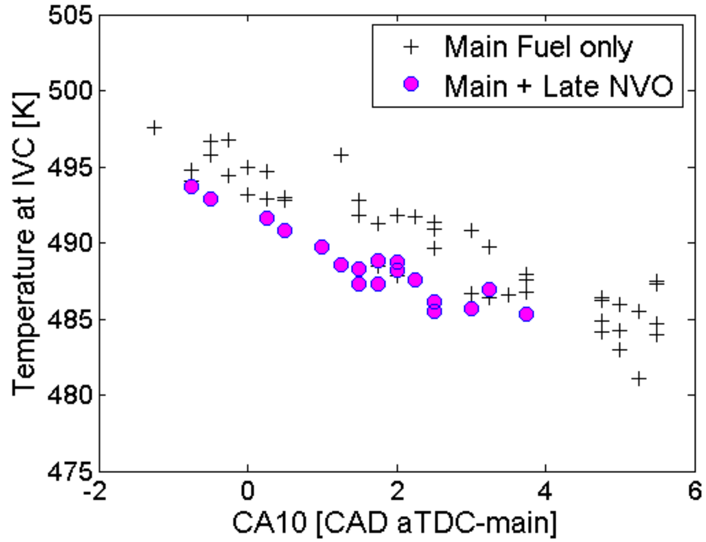




Examination of temperatures at IVC

- Useful insights come from comparing NVO-fueled (split injection) with main-fueling-only operation:
  - Does NVO fueling have the same effect as intake air heating on main combustion phasing?
  - If so, then we would say that its effect is primarily thermal, and not chemical.
- To aid comparison of these experiments, we developed a rigorous cycle-temperature model.*
- Sample graphs show calculated temperatures at IVC as a function of recorded CA10.
  - Early NVO fueling (top): for a given CA10, temperatures for the two cases are the same. → Thermal effect.
  - Late NVO fueling (bottom): The same CA10 is achieved with a lower T_{IVC}.
  - This is <u>important evidence of a possible chemical effect</u>.
- Further evidence of this chemical effect is seen if we look at the main compression stroke…



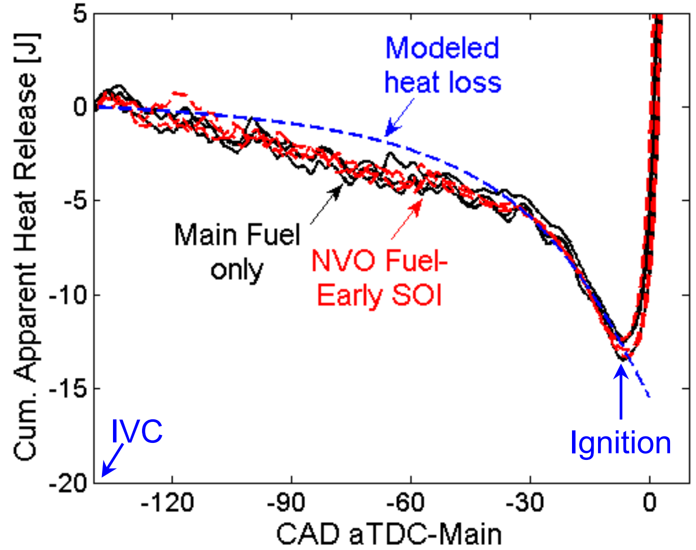


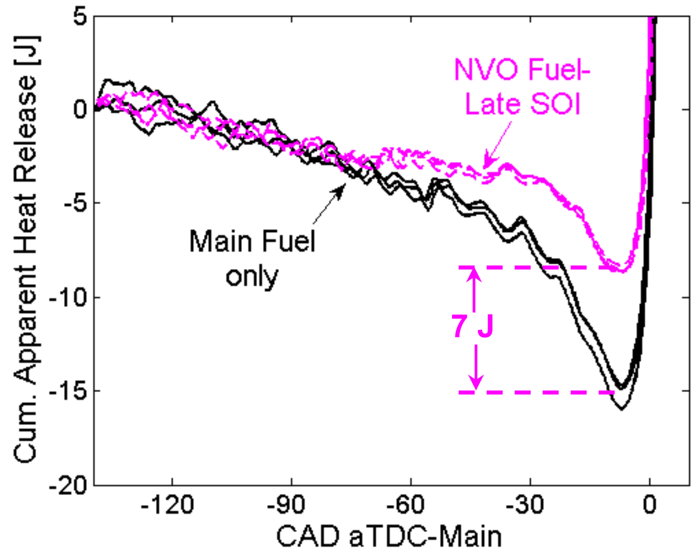
*2010 SAE Paper No. 2010-01-0343

Examination of HR during compression stroke

- Selected NVO- and main-fueled cases with the same main combustion phasing are compared:
  - Cumulative AHR is plotted from IVC through ignition.
- Early NVO plot (top): The traces are superimposed indicating an identical thermal history.
  - All traces generally follow predicted cylinder heat loss.
  - Again, we see only thermal effects for early NVO fueling.
- Late NVO plot (bottom): The late-NVO-fueling trace deviates substantially from the main-fuel case.
  - Exothermic reactions starting near -60 CAD release 7 J.
  - ➡ These anomalous results provide clear evidence of an important chemical effect of late NVO fueling.

- For further assessment of chemical effects we turned to chemical kinetic models…

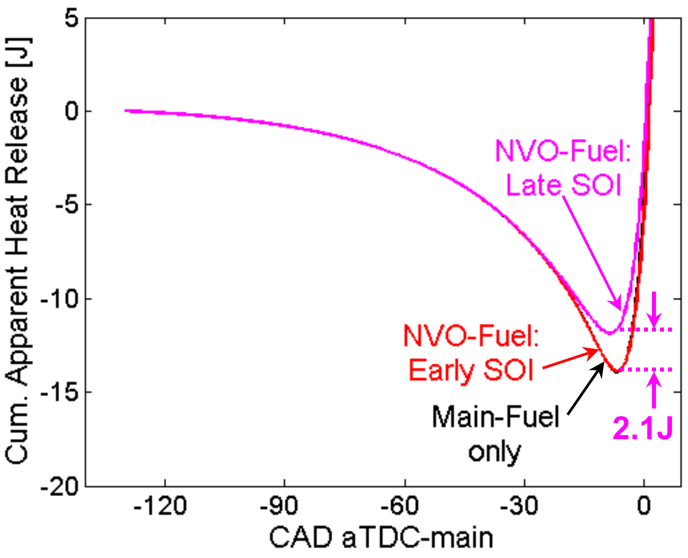




CHEMKIN simulations provide support

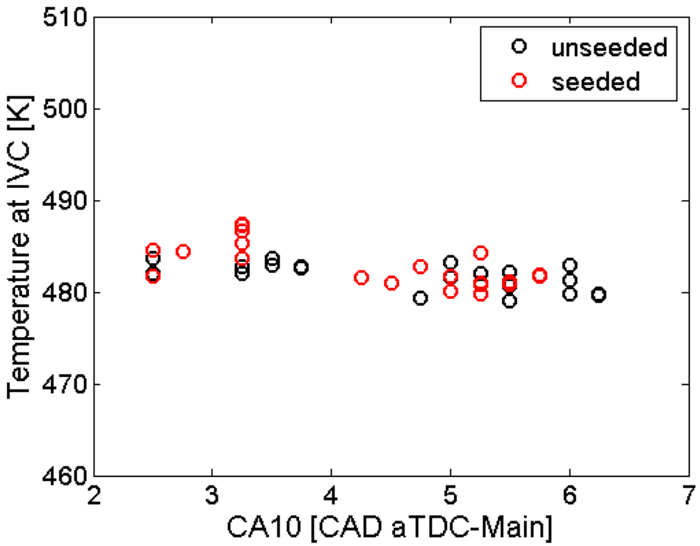
- We modeled the same experiments using a Chemkin 0-D engine simulator, along with:
  - Detailed iso-octane/n-heptane kinetics mechanisms;
  - Initial and boundary conditions from the experiments.
- Model results support our engine data:
  - Main-fuel-only and NVO early-SOI fueling traces are indistinguishable.
  - But NVO late-SOI fueling leads to predicted early exothermic reactions, albeit less significant (2 J vs. 7 J).
- The simulation also identified potentially important reactive species carried over from NVO:
  - Candidates include ethylene, acetylene, and formaldehyde.

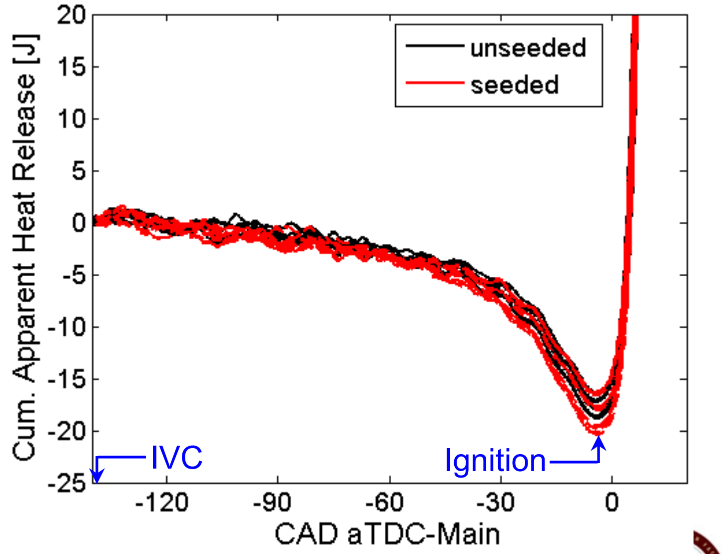
- To test specific candidate species, we began a series of seeding experiments this year…



Seeding experiments

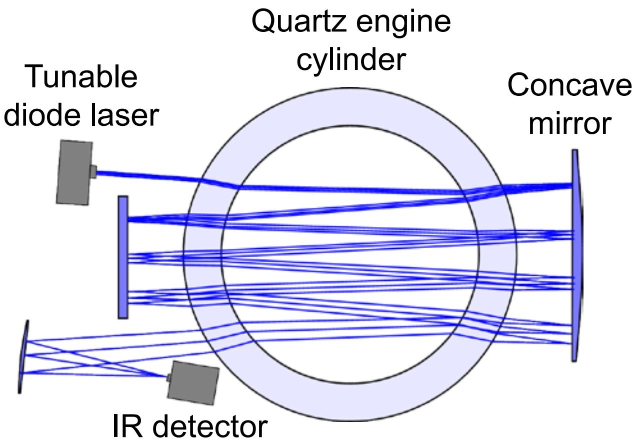
- These experiments test for chemical effects by seeding select species into the intake charge.
  - Candidates are reformed or partially reacted products of NVO reactions, identified by modeling.
  - Tests are main-fuel-only; no fuel is injected during NVO.
  - Seeded results are compared with unseeded.
- Sample experimental results shown for 2500 ppm CO:
  - For a given main combustion phasing, temperatures at IVC are the same for seeded and unseeded tests.
  - Also, no difference in HR is observed during compression.
  - We conclude that CO is not responsible for our anomalous early heat release.
- All seeding tests conducted so far have had similarly negative results, but we have other candidates to test.
- To capture further details of NVO chemistry we have developed a new diagnostic…

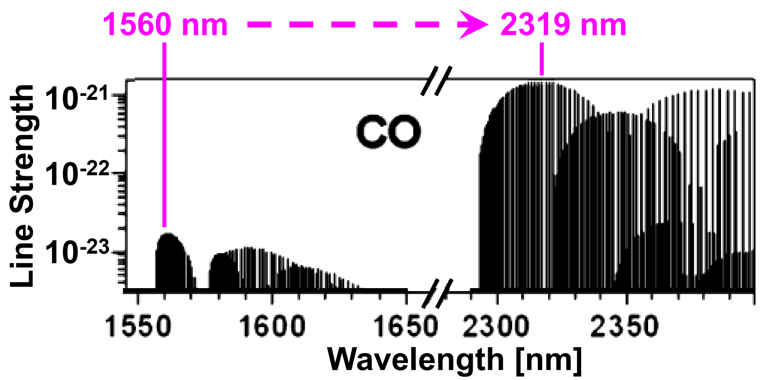




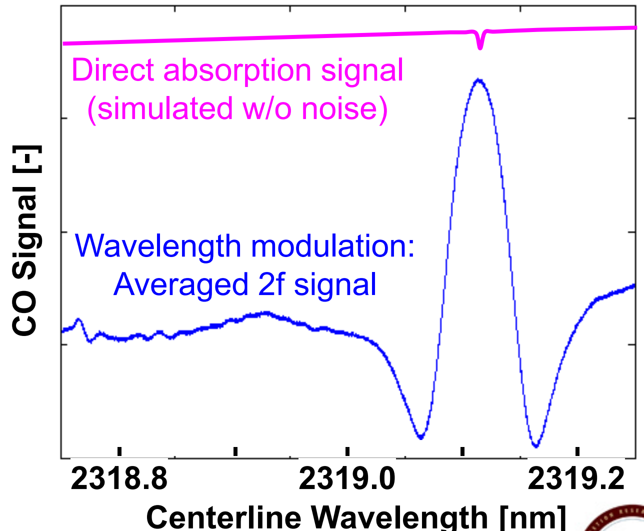
Tunable diode laser absorption spectroscopy

- We have developed a laser absorption diagnostic for measuring in-cylinder concentrations:
  - Multiple pass geometry provides spatial average;
  - Fast detector permits time-resolved measurements.
  - Tunable diode laser (TDL) allows selectivity and signal-to-noise enhancement.
- Current-year accomplishments for CO detection:
  - Upgraded TDL from 1560 to 2319 nm for big signal boost;
  - Implemented wavelength-modulation signal processing;
  - Successfully performed in-cylinder measurements…



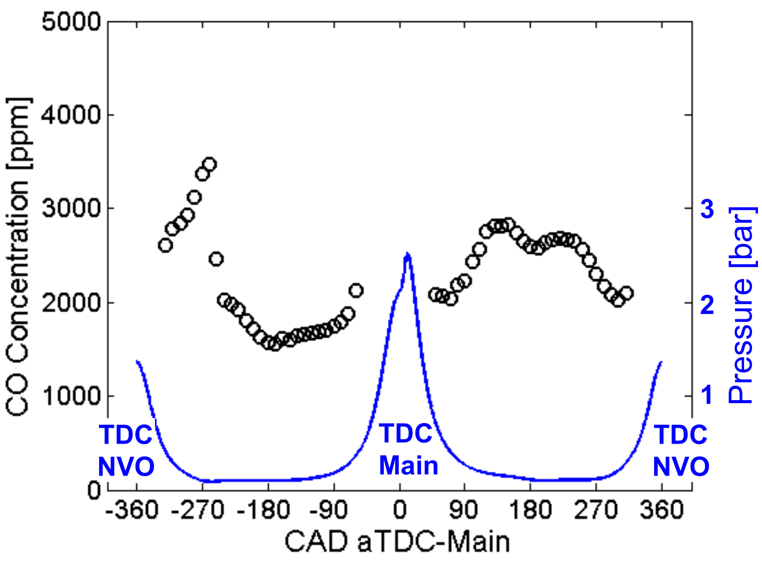


Ebert et al., *Proc. Comb. Inst.* 30:1611-1618 (2005).



Cycle-resolved measurements of CO

- Sample CO data from NVO-fueled, fired operation:
  - 1-ms time resolution through most of cycle;
  - Gaps in data due to piston obscuration, high pressure.
- Data trends are complex but repeatable:
  - CO produced during NVO and main combustion;
  - CO mixing out during intake stroke;
  - Steady concentration during exhaust -- matches emissions bench within 100 ppm.



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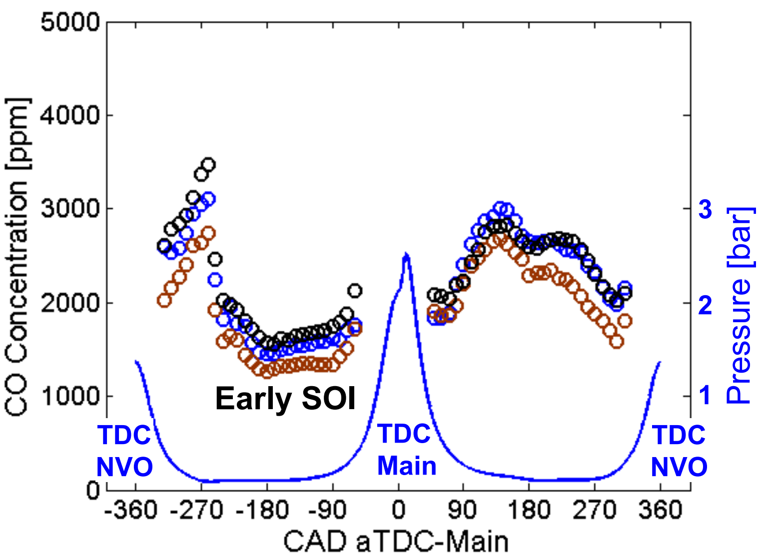

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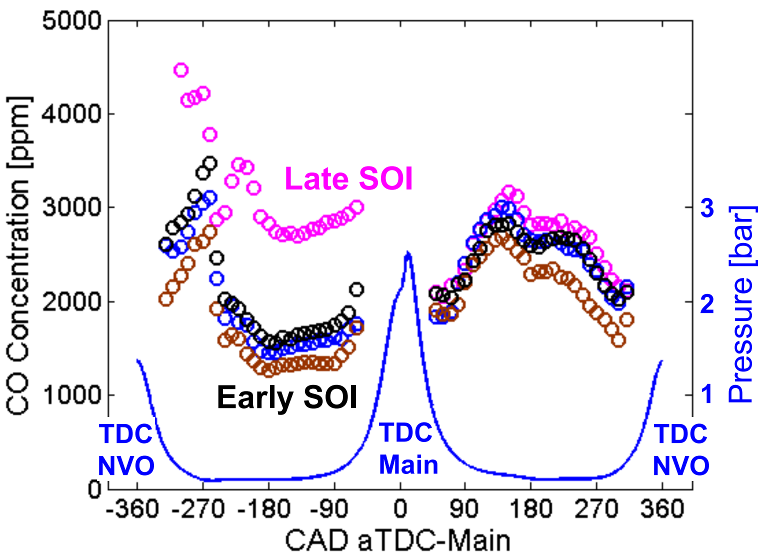
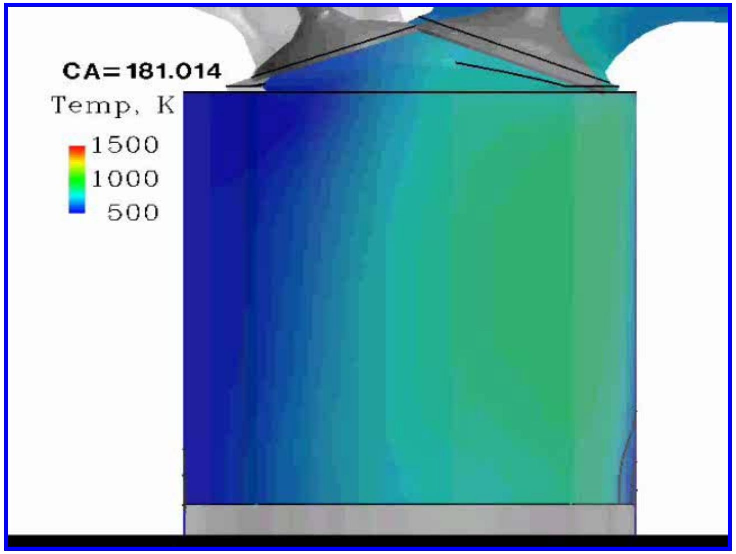
- Initial trials performed for NVO SOI sweep:
  - Trends are similar for all early-SOI NVO fueling cases;
  - Also, late-SOI fueling cases are distinct;
  - Measurements support our earlier observations.



- Future steps:
  - Record [CO] for a full range of NVO-fueling conditions;
  - Apply CO data to validate our KIVA model.
  - Extend diagnostic to other species.

Modeling accomplishments

- Multi-year collaboration with UW and LLNL has produced a CFD/kinetics model of our engine:
  - Validation using fired data is in progress;
  - Includes NVO fueling and combustion/reforming;
  - Guides our understanding of NVO strategy.
- We have continued our development and application of several other modeling tools:
  - Cycle-temperature analysis tool;
  - Chemkin 0-D piston/cylinder simulator;
  - GT Power 1-D full engine model.



Animated KIVA results

Collaborations

- University partners:
  - University of Wisconsin and Lawrence Livermore National Lab: Development and application of a KIVA/Multi-zone kinetics model of the automotive HCCI optical engine continued this year.
  - Stanford University: Our 5-year diagnostic-development project was successfully completed this year.
- Automotive OEM partners:
  - GM Research is actively engaged in our automotive HCCI research program: interactions include bimonthly teleconferences, exchange of results, and hardware support.
  - Ford Research has defined topics of mutual interest that are the basis of new collaborations.
- DOE Working Group partners:
  - Research results are shared with DOE's Advanced Engine Combustion and University HCCI Working Groups in semi-annual meetings.

Future Work

- Engine experiments:
  - Pursue optical engine experiments designed to reveal underlying chemistry/physics of NVO operation.
- TDL absorption diagnostic:
  - Characterize the effects of NVO parameters on cycle CO production and consumption.
  - Extend diagnostic to detect additional species such as H_2O, CO_2, C_2H_2.
- KIVA model:
  - Validate model using measured in-cylinder CO concentrations.
  - Identify reactive products of NVO fueling for testing via seeding experiments.
  - Apply model predictions to interpret engine experiments.
- Upgrade engine facility:
  - Plan modifications based on the installation of similar engine hardware in the new Lean-Burn DI Spark-Ignition Fuels Lab (Sjöberg).
  - Improve optical access, upgrade components, and extend operating conditions to enhance relevance of our research to current engine development.

Summary

- The Automotive HCCI Engine project contributes to the development of low-temperature combustion strategies that can help achieve DOE emissions and efficiency goals.
- The project approach combines:
  - Optical engine experiments,
  - Diagnostic development,
  - Engine and combustion modeling.
- Current work focuses on the NVO combustion strategy. Accomplishments include:
  - New insights into thermal and chemical effects of NVO fueling,
  - New diagnostic capability for time-resolved, in-cylinder measurements of composition.
  - Advancement of HCCI engine modeling tools.
- Multiple collaborations leverage the impact of our research:
  - DOE's Advanced Engine Combustion group reviews research results and contributes feedback;
  - GM and Ford provide continual technical and material support;
  - University of Wisconsin, and LLNL participate in automotive HCCI engine modeling.