Automotive HCCI Engine Research

Richard Steeper

Sandia National Laboratories

2011 DOE Vehicle Technologies Annual Merit Review

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Program Manager: Gurpreet Singh
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.

Budget

- Project funded by DOE/VT
- FY10 funding: $620k
- FY11 funding: $680k

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.

Partners

- Project lead: Richard Steeper
- University/National Lab:
  - Lawrence Livermore National Lab and University of Wisconsin:
    - KIVA model of automotive HCCI optical engine.
  - 6 National labs and 5 universities in DOE Working Groups.
- Industry:
  - GM & Ford (extensive technical interactions);
  - 15 Industry partners in DOE Working Group.

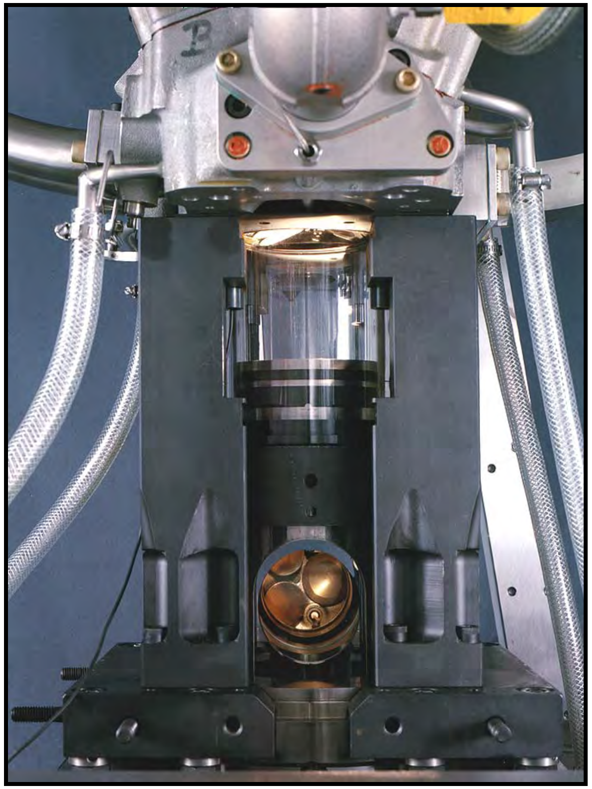
Relevance: Objectives and Milestones

- 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.

- Specific, multi-year objectives:
  - Quantify thermal and chemical effects of the negative valve overlap (NVO) fueling strategy, with the goal of increasing automotive HCCI efficiency through extension of load range.
    - Milestone: Perform engine experiments to identify chemical effects of NVO fueling on main combustion phasing.
    - Milestone: Perform seeding experiments to test reactivity of specific NVO product species.
  - Characterize chemical reactions during NVO-fueled operation:
    - Milestone: Develop and apply a laser-absorption diagnostic to make quantitative, time-resolved measurements of [CO] in fired engine.
  - Advance the capabilities of our computer models of automotive HCCI combustion.
    - Milestone: Validate KIVA simulation of NVO-fueled operation in our optical engine.
    - Milestone: Continue enhancement of GT-Power and CHEMKIN engine models.

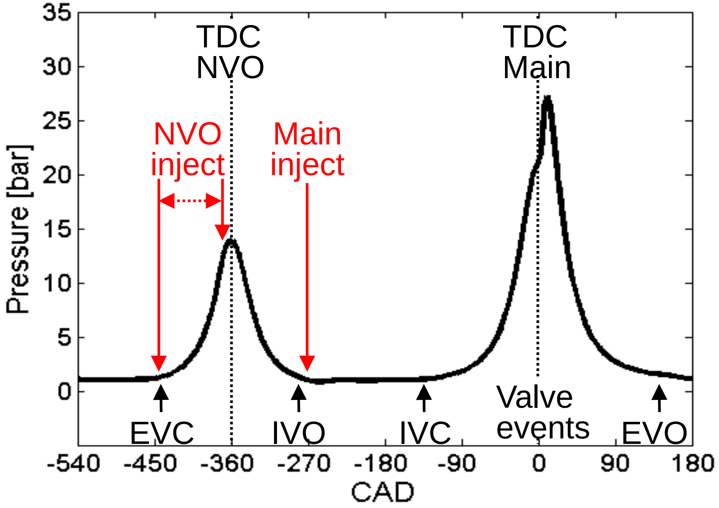
Approach

- 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 – FY11

- Based on input from automotive OEMs, we continue to focus on the NVO strategy for control of combustion during low-load HCCI operation.
  - NVO operation enables dilution/thermal control by retaining high residual gas fractions (RGF);
  - In addition, fuel can be injected during NVO (split injection) providing further authority over main combustion phasing.
  - Goal of research is to extend the range of high-efficiency HCCI operation via application of NVO fueling strategy.
- Presentation of the year's accomplishments is divided into 3 topics:
  - NVO-fueling experiments;
  - Laser-absorption diagnostic;
  - Optical engine modeling.

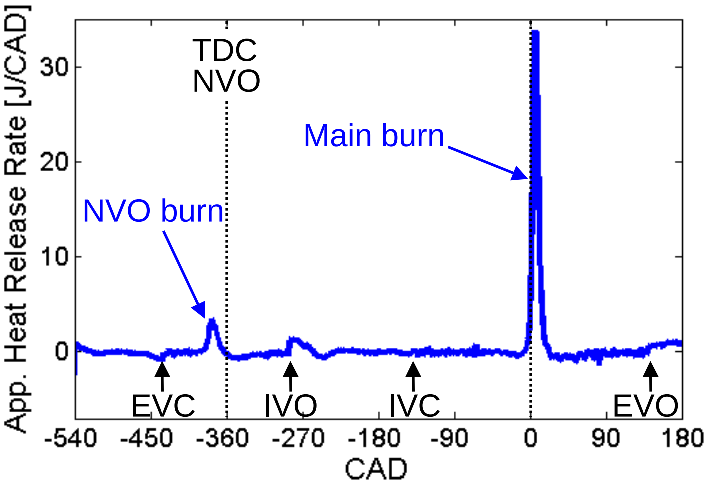


Typical NVO operating conditions

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

NVO fueling experiments

- NVO fueling can affect main combustion in two ways:
  - Thermal effects are well documented:
    - Large RGF + NVO heat release control T_{IVC};
    - Phasing of main burn is largely controlled by T_{IVC}.
  - Chemical effects are more challenging:
    - Reformed fuel from NVO could affect main ignition;
    - But measurement of such effects is difficult.



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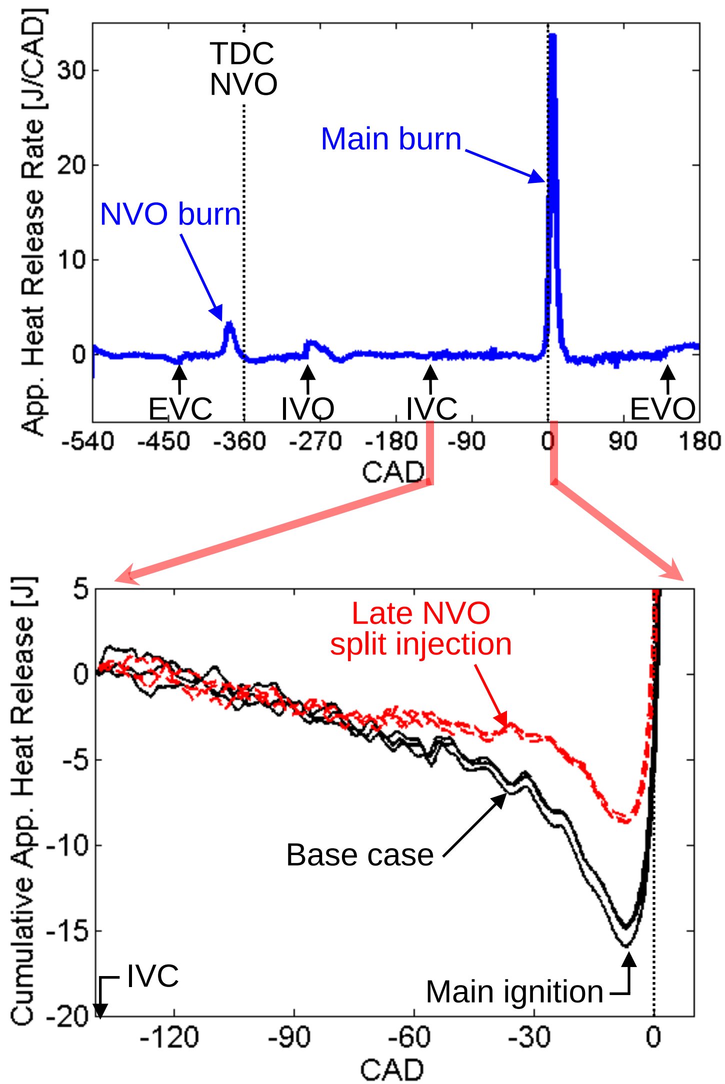
- Analysis of heat release leading up to main ignition has provided insight (data reported last year):
  - 'Base case' operation shows steady cumulative heat loss;
  - For late NVO injections, early heat release is observed in advance of main ignition;
  - Interpreted as a chemical (*carry-over*) effect of NVO fueling.



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  - For late NVO injections, early heat release is observed in advance of main ignition;
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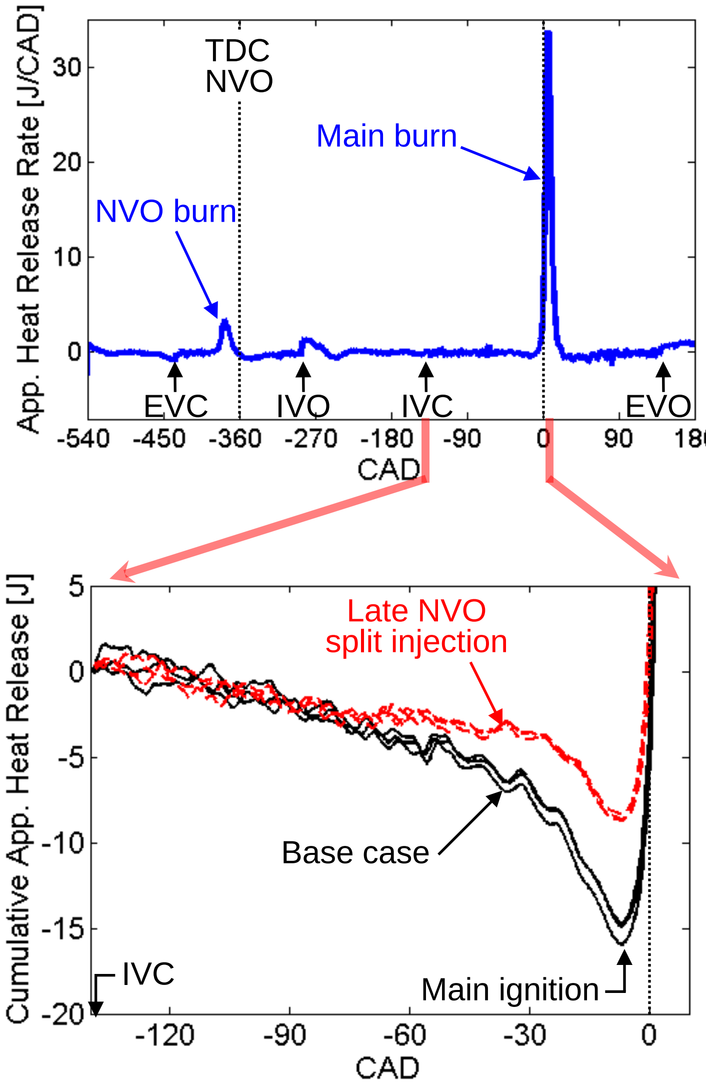
- This year, we have continued the experiments:
  - Expanded the matrix of operating conditions and database of performance data;
  - Characterized effect of optical vs. metal components;
  - Performed seeding experiments to test candidate species potentially responsible for early heat release…



Progress in seeding experiments

- Experiment setup:
  - –Engine operated with high RGF but little or no NVO fueling (depending on intake temperature);
  - –Single select species are seeded at low levels into the intake air;
  - –Candidate species are partially reacted products of NVO reactions, identified by modeling;
  - –Seeded results are compared with unseeded.

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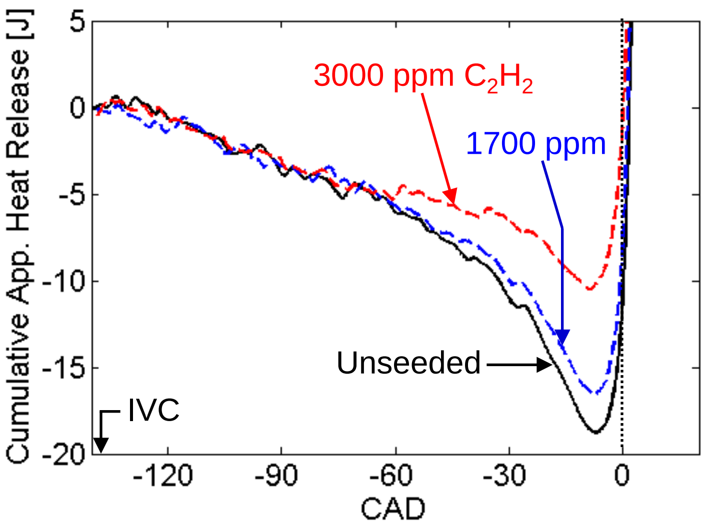
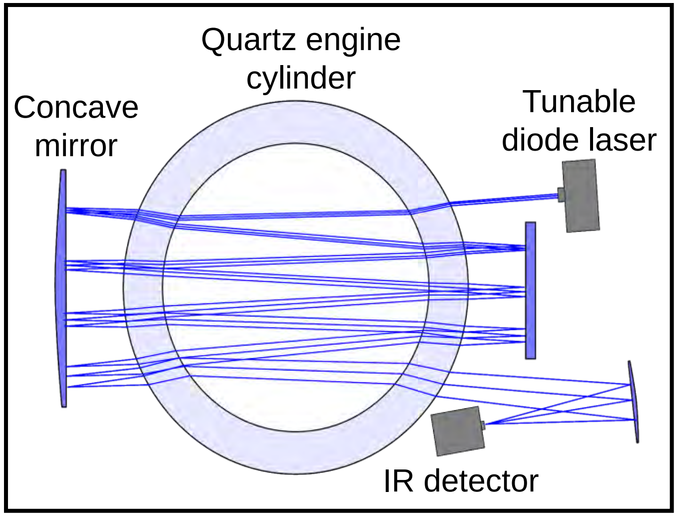
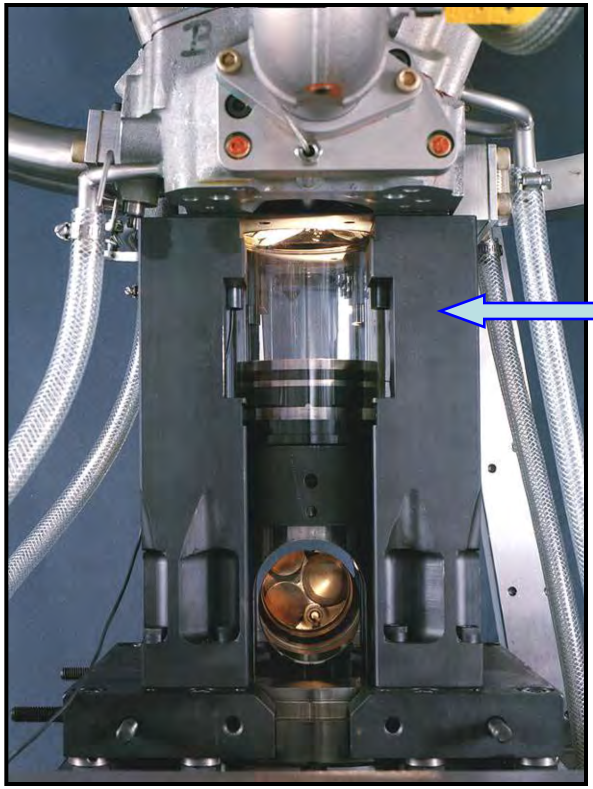
- Experiments testing acetylene (C_2H_2) have shown positive results:
  - Under certain operating conditions and seeding levels, early heat release is observed, strongly resembling that associated with late NVO fueling;
  - Late NVO fueling causes piston wetting, and C_2H_2 is a likely product of the resulting locally rich NVO combustion – thus providing a logically consistent hypothesis for the chemical effect.
  - Test results are preliminary; ongoing work includes:
    - Identifying the operating range over which the effect occurs;
    - Comparing results with chemical model predictions;
    - Possibly complementing seeding experiments with laser measurements…



Tunable diode laser-absorption diagnostic

- We have developed a laser-absorption diagnostic for in-cylinder measurement of CO.
  - Motivated by an OEM request to quantify the extent of NVO reactions.
- The compact instrument comprises:
  - Tunable diode laser,
  - Multi-pass geometry,
  - Fast infrared detector.

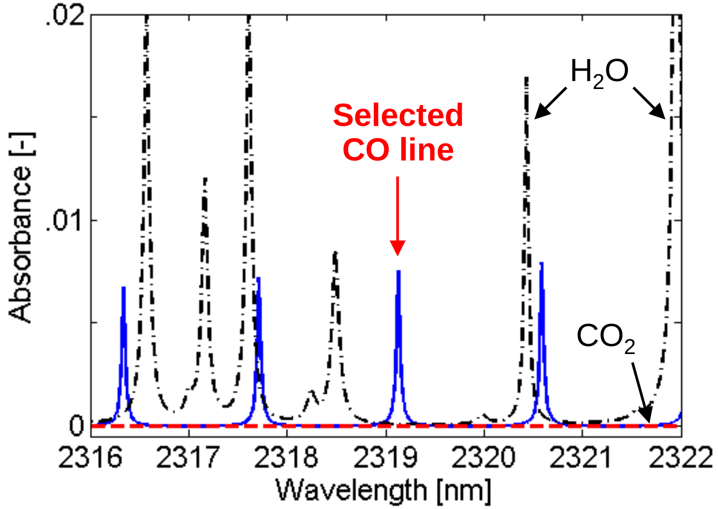




Mounted TDL diagnostic

TDL diagnostic background

- Diagnostic uses the CO absorption line at 2319 nm for a strong signal and minimal interference.



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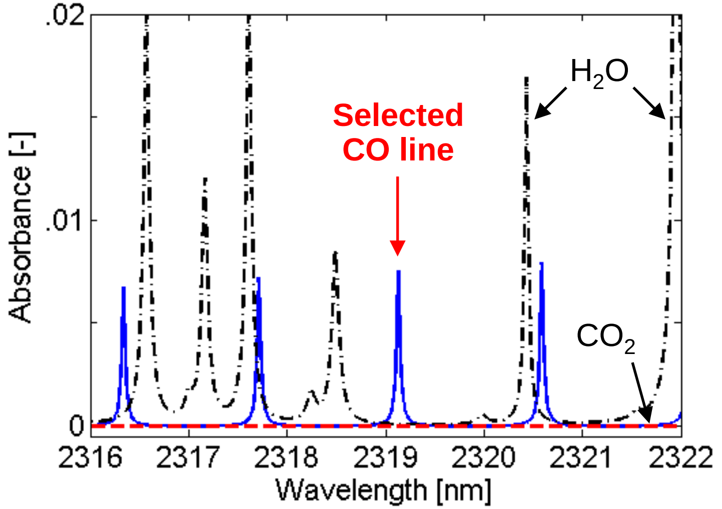

Nanoplus 10mW TDL

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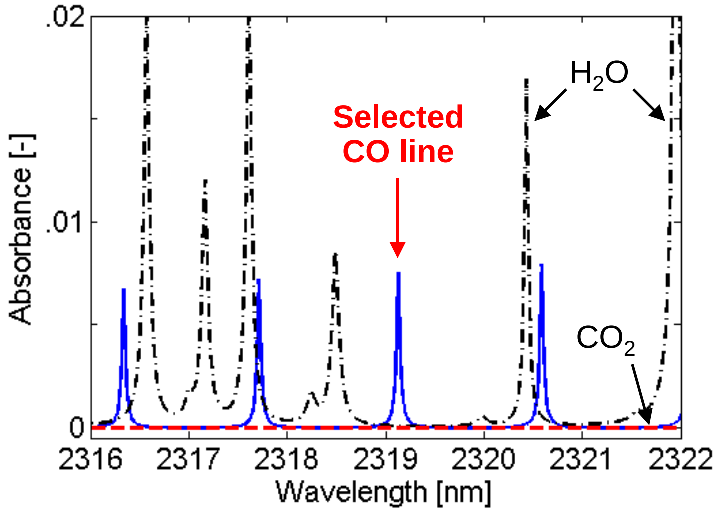
- Ability to rapidly tune wavelength is used to advantage:
  - TDL is slow-scanned (*ramp*) across CO line + background so that background noise can be subtracted;
  - TDL is rapid-scanned (*dither*) across CO line to enable advanced data processing techniques (WMS*) that significantly boost signal-to-noise ratios.



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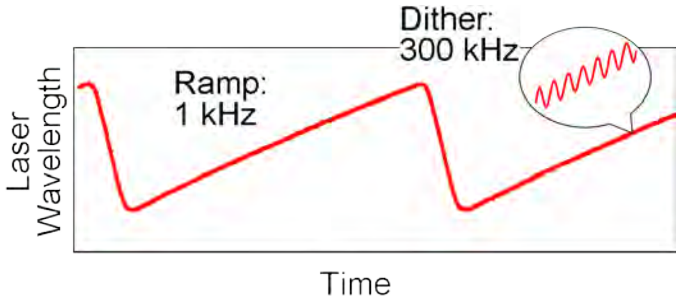

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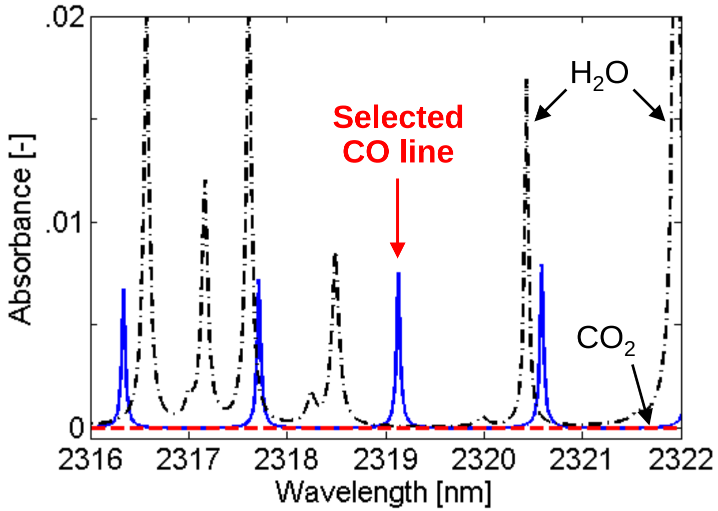
- Progress of TDL diagnostic development:
  - Last year we moved the diagnostic from bench-top to engine.
  - This year we:
    - Calibrated in-cylinder performance;
    - Improved time-resolution;
    - Documented diagnostic development and testing: *SAE Int. J. Engines* **3**(2):396-407, 2010.



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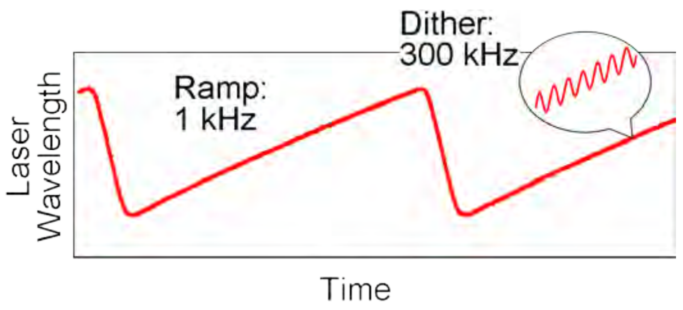

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Calibration of diagnostic performance

- Linearity tested during motored/seeded operation:
  - CO metered into intake air via sonic orifice over a wide range of concentrations;
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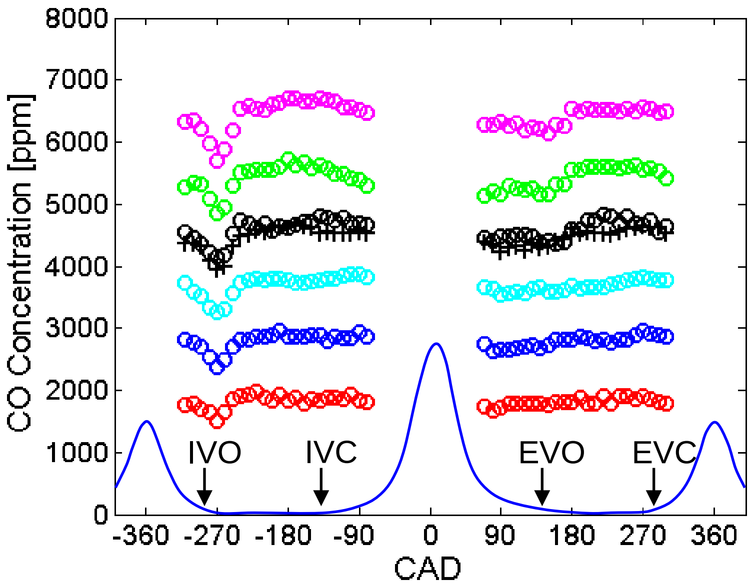
  - Data compared to independent measures of [CO] from sonic orifice + emissions bench.



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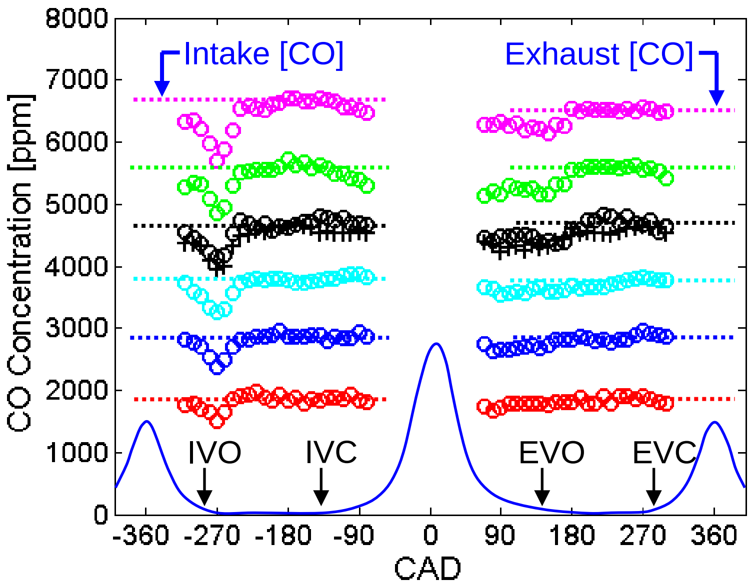

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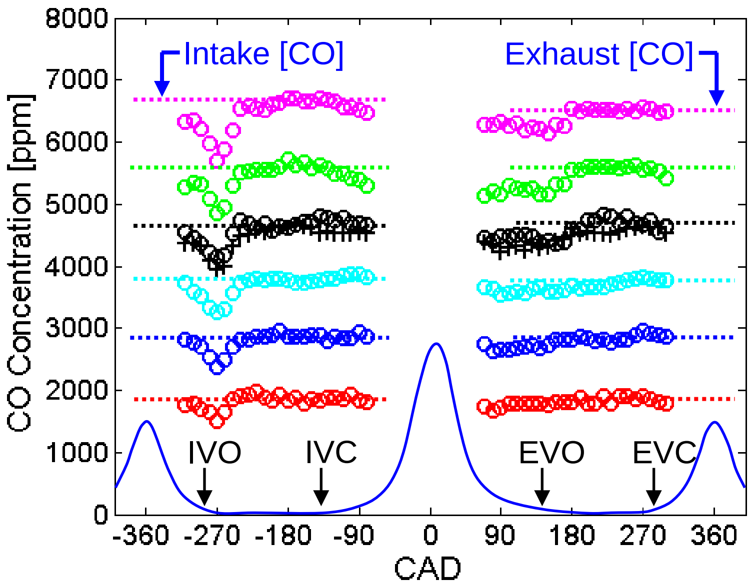
- Significance of the work:
  - Established linearity of measurements over range of [CO] representative of NVO operation (model prediction).
  - Verified repeatability over typical experiment timescales, i.e., an initial calibration is valid throughout tests.
  - Finally, by optimizing laser modulation we were able to gain a 40x improvement in temporal resolution.



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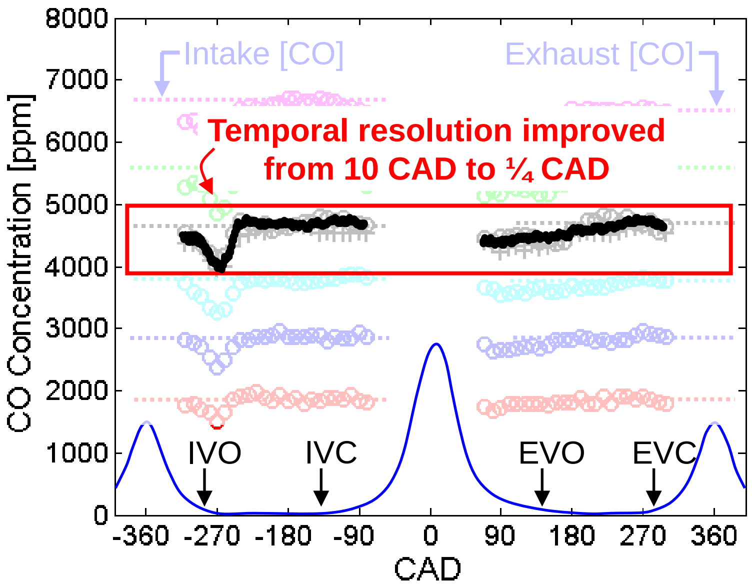
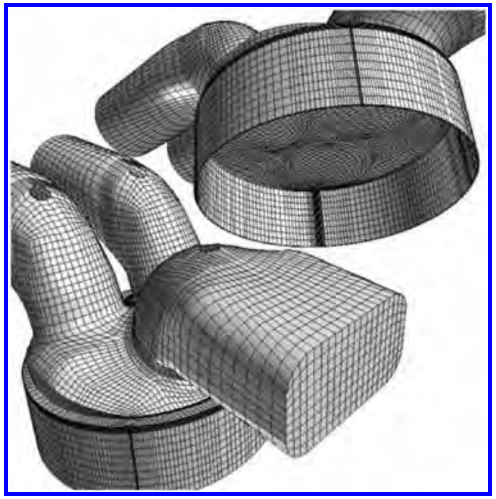


Modeling the automotive HCCI engine

- We develop and apply multiple computational tools to interpret our NVO experiments:
  - CHEMKIN 0-D cylinder combustion model;
  - GT-Power 1-D engine simulator;
  - In-house cycle-temperature analysis tool;
  - KIVA CFD/kinetics 3-D engine model.
- FY11 progress includes:
  - Updating geometry of our GT-Power model and validating with high-speed intake- and exhaust-port pressure data.
  - Packaging our cycle-temperature tool for export by request of an OEM.
  - Validating the KIVA model for NVO-fueled operation…



KIVA optical engine grid

KIVA model validated for NVO fueling

- KIVA model of our optical engine is a multi-year collaboration by LLNL, UW, and Sandia.
- This year Randy Hessel (UW) completed HCCI-NVO simulations that we validated against engine expers.
  - Results published in SAE 2010-01-2236.
- Conditions were selected to shed light on NVO-fueling strategy. Four fired cases included:
  - 3 NVO-fueled cases with early, mid, and late NVO split-fuel injection;
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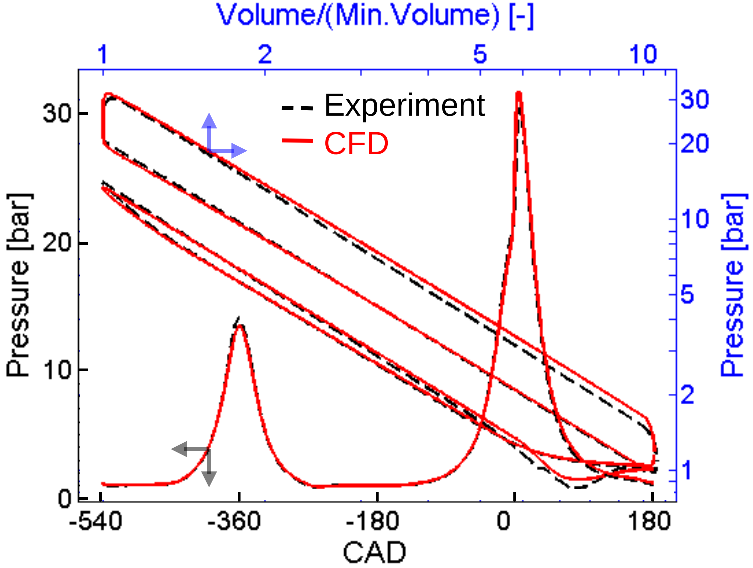
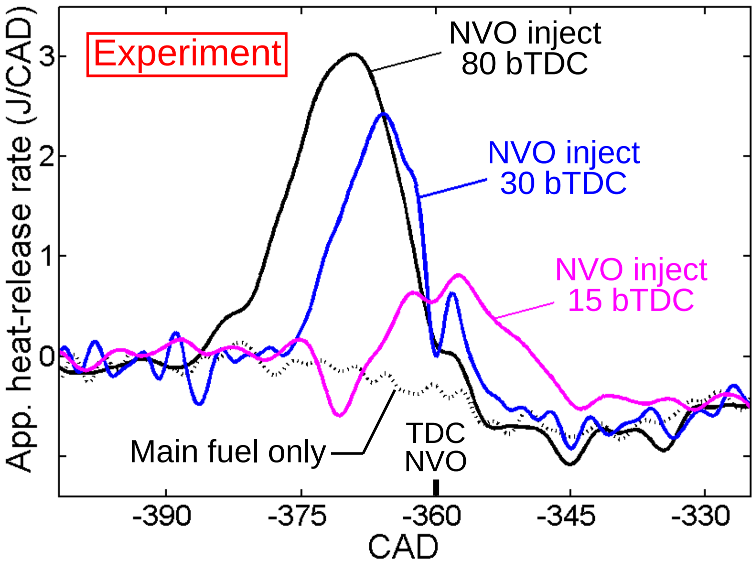
  - 1 main-fuel-only case.
- Sample pressure results show good match throughout cycle, including both main and NVO heat release…



Cycle pressure traces for early-NVO split injection

Sample validation results: NVO heat release

- Experiments show that injection timing affects HR:
  - Top plot shows experiment AHRR during NVO period.
  - Heat release retards, peak drops, and duration increases as NVO injection is retarded.



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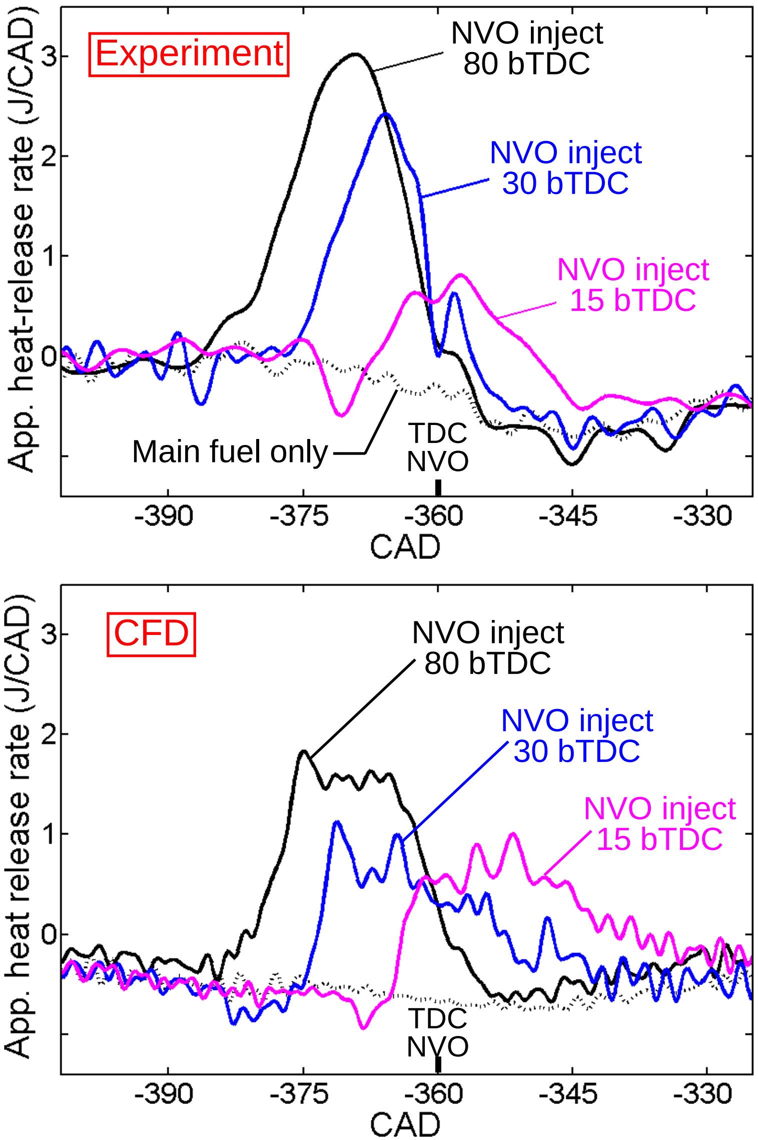
- CFD successfully captures most trends:
  - Simulations match absolute phasing of NVO heat release.
  - Peak values are lower, but the downward trend of peak rates is generally captured.
  - For the latest NVO-injection case, cumulative HR (not shown) is over-predicted. – Likely due to inaccurate piston wetting in the model.
  - Trends during main combustion (not shown) also agree well overall. – However, KIVA does *not* predict the early main heat release observed in our experiments.



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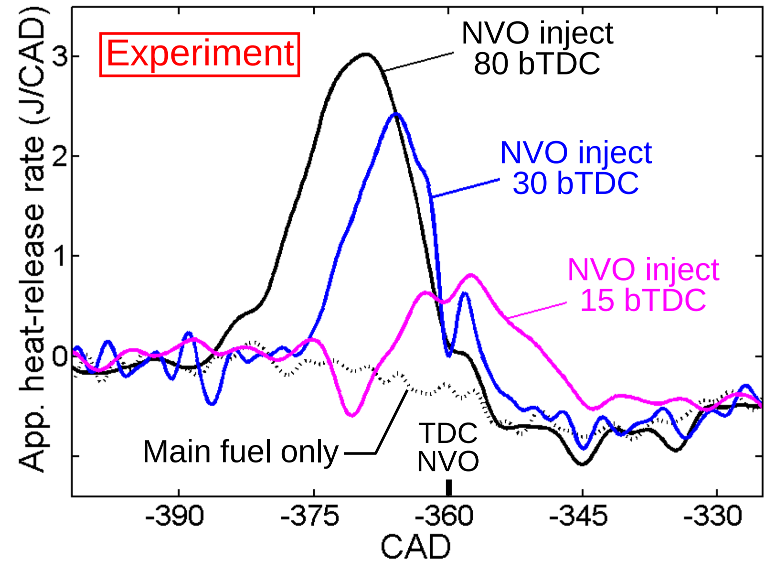
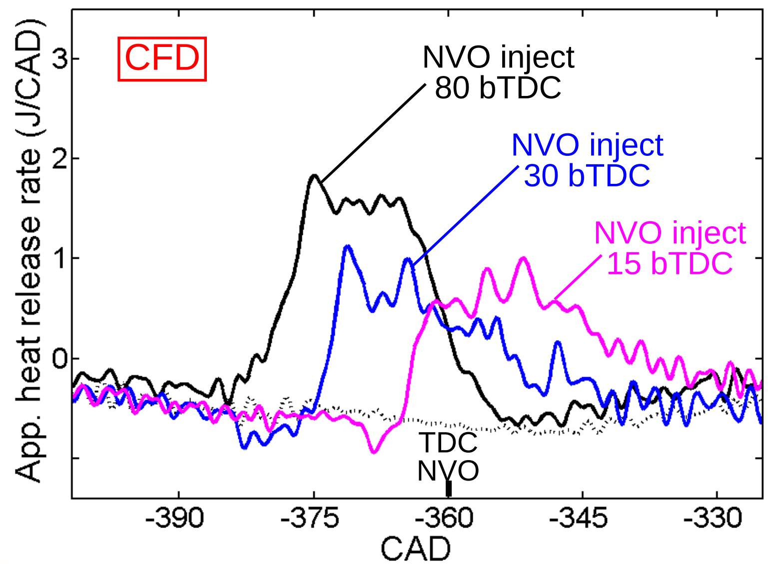
- Significance of KIVA work:
  - We can now successfully model NVO-fueled operation, and use results to interpret experimental results.
  - TDL CO data can be used to validate KIVA chemistry.
  - CHEMKIN cylinder combustion model complements KIVA via rapid testing of complex kinetics mechanisms.





Collaborations

- University partners:
  - University of Wisconsin and Lawrence Livermore National Lab: Joint development and application of a KIVA model of the Sandia automotive HCCI optical engine.
  - Stanford University and University of Michigan: Invaluable cooperation during diagnostic and model development.
- 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 at semi-annual meetings.

Future Work

- Engine experiments:
  - Conduct optical engine experiments to reveal underlying chemistry/physics of NVO operation.
  - Characterize spray, mixing, and combustion environment uniquely associated with late NVO injection.
  - Add fuel sensitivity to investigation of NVO chemical effects on main combustion.
- TDL absorption diagnostic:
  - Apply diagnostic to quantify CO production and consumption during NVO-fueled operation.
  - Extend diagnostic to detect additional species such as C_2H_2, CO_2, H_2O.
- Engine models:
  - Validate KIVA and CHEMKIN chemistry models using measured in-cylinder CO concentrations.
  - Apply chemistry models to identify reactive products of NVO fueling.
- Engine hardware upgrade (contingent on funding availability):
  - Schedule installation of a new optical engine head:
    - An advanced design, direct-injection head has been provided by GM.
    - Project will benefit from recent installation of the same head on the same base engine in the Lean-Burn DI Spark-Ignition Fuels Lab (Sjöberg).
    - Upgrade will improve optical access, strengthen components, and extend operating conditions in order 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;
  - OEMs provide intensive technical and material support;
  - National lab and university partners collaborate on model and diagnostic development.