Expanding Robust HCCI Operation

A CRADA project with Delphi Automotive Systems
Project ID: ACE053

2011 U.S. DOE Hydrogen and Vehicle Technologies Program Annual Merit Review and Peer Evaluation

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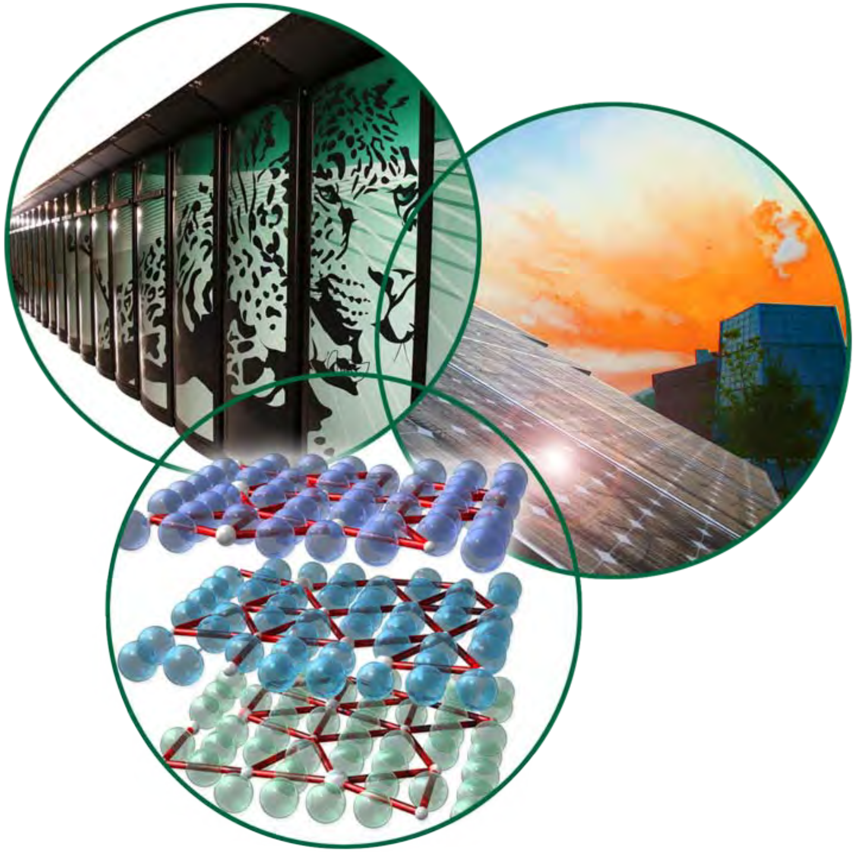

Investigators

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Organizations

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DOE Management Team

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Project Overview

OVT Programmatic Barrier: Lack of effective engine controls for robust and reliable operation in advanced combustion regimes such as lean-burn HCCI combustion.

Approach: Perform single-cylinder engine experiments to define operating strategies and controls authority for robust HCCI with an expanded load range. Apply single-cylinder findings to a multi-cylinder cam-based VVA engine experiment with help from engine modeling system.

Industrial Partner: Delphi Automotive Systems

Budget

- FY10: $300k
- FY11: $300k

Project Timeline

- Project began in Q3 FY10
- Total project duration is 2 years

Objectives and Relevance

Objective: Expand the range of robust HCCI operation using engine control strategies

Relevance: The potential efficiency and emissions benefits of HCCI combustion are well-known, but practical implementation of HCCI is challenging.

ORNL is working with Delphi to develop the necessary information to enable HCCI combustion in a robust manner with their production-intent cam-based VVA valvetrain.

FY2011 Milestone: Complete detailed evaluation of valve strategies on a single-cylinder research engine.

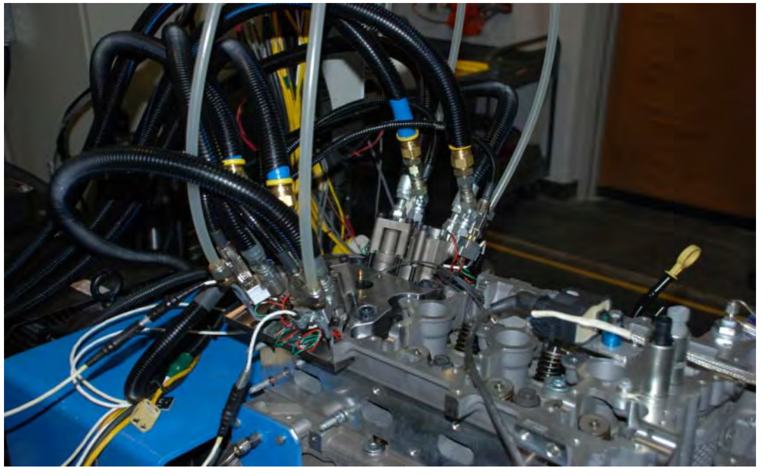
Status: Milestone Completed ☑

Approach combines engine experiments and modeling

Experiments on a single-cylinder engine with Hydraulic Valve Actuation (HVA)

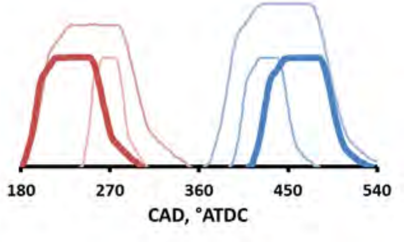
➢ ***Allows the effect of valve lift and duration to be rapidly studied***

- Modified 2.0L GM Ecotec engine with direct injection
- Cylinders 1-3 are disabled, cylinder 4 modified for Sturman HVA system
  - Fully variable valve timing and lift
- Engine management performed with DRIVVEN engine controller
- Custom piston to increase compression ratio to 11.85

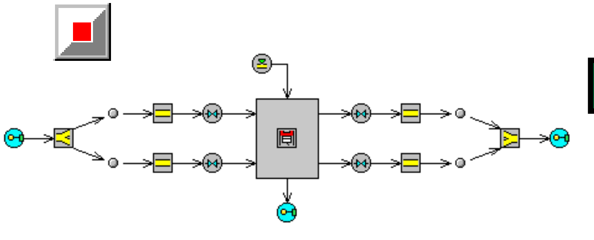


Modeling of the HVA engine using GT-Power provides guidance of how to translate the same conditions to a cam-based HCCI engine

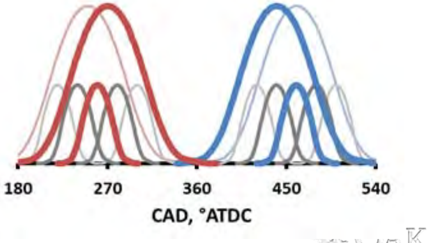
Sturman HVA



GT-Power Model



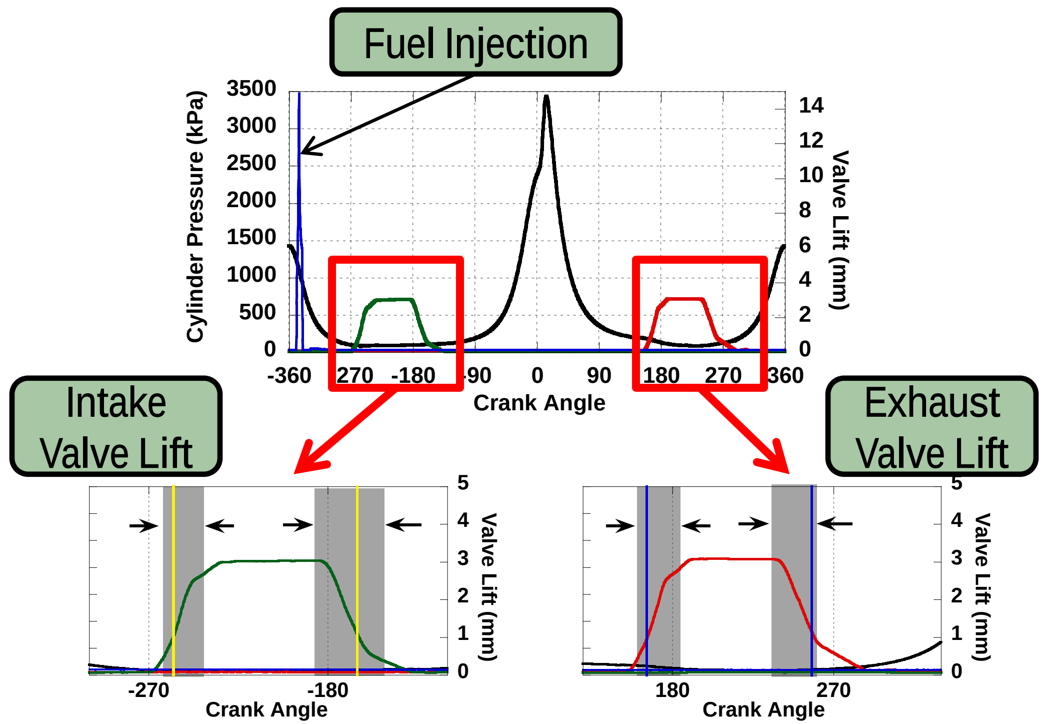
Cam-based VVA



Experimental approach: Investigate authority of engine controls on HCCI combustion

Engine Speed	2000 rpm
Fueling Strategy	GDI, Single Injection
Fueling Rate	7.9 to 12.5 mg/stroke
GDI timing	-300 to -460 deg aTDC$_f$
Fuel Rail Pressure	95 bar
Intake Valve Open	-260 to -236 CA aTDC$_f$
Intake Valve Close	-188 to -148 CA aTDC$_f$
Intake Valve Lift	3 mm
Exhaust Valve Open	160 to 184 CA aTDC$_f$
Exhaust Valve Close	236 to 260 CA aTDC$_f$
Exhaust Valve Lift	3 mm
Spark*	0 to -60 deg aTDC$_f$
NOx Emissions	<100 ppm
Ringing Intensity	<7 MW/m2
COV of net IMEP	5%

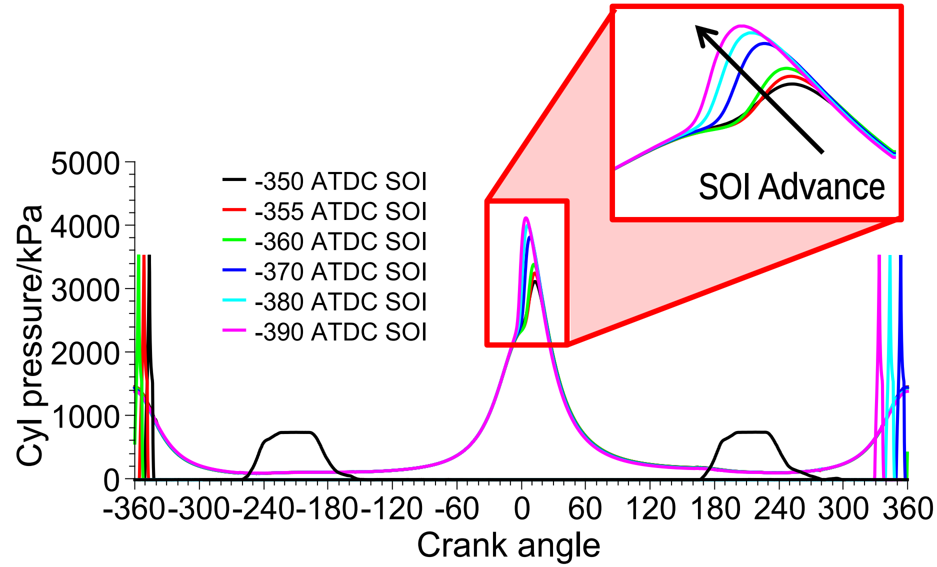
*not present in all cases

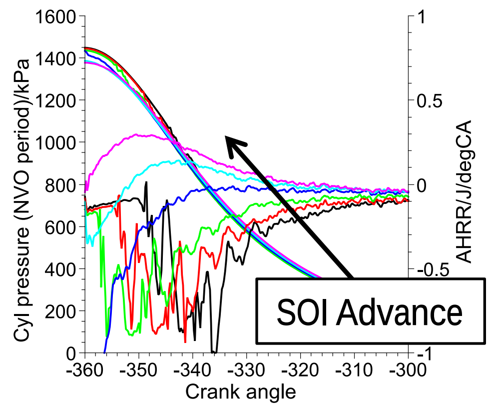


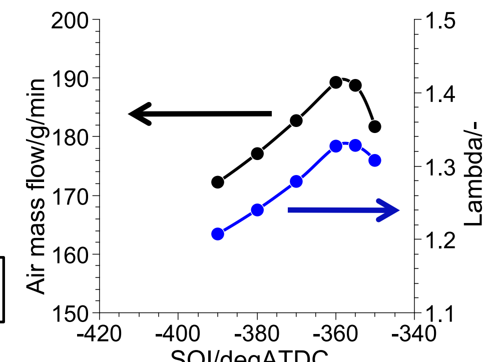
Fuel injection timing is effective at controlling HCCI combustion phasing

Control authority attributed to NVO heat release

- Advanced fuel injection timing results in advanced combustion
  - ➢ High pressure rise rate
- Retarded fuel injection results in retarded combustion
  - ➢ Eventually misfire
- Advanced fuel injection produces more heat release during NVO
  - Increases BDC temperature
  - Reduced air flow and lambda
  - Results in advanced combustion phasing

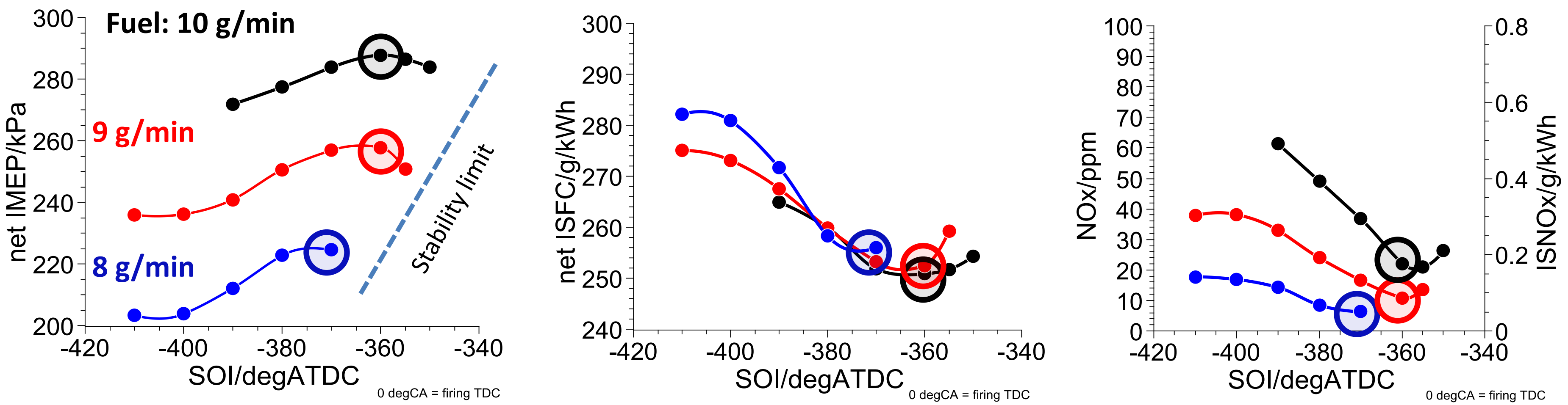






0 degCA = firing TDC

Fuel injection timing can be optimized at each fueling rate for high efficiency and low NOx



- Advanced fuel injection results in low efficiency and high NOx
- Both NOx emissions and efficiency improve with retarded injection timing
  - Near simultaneous optimum for NOx and efficiency in most cases
- Optimal fuel injection timing occurs near combustion stability limit

Effect of spark is dependent on fueling rate and SOI timing
Spark can improve stability and efficiency

Lowest fueling rate (8 g/min)

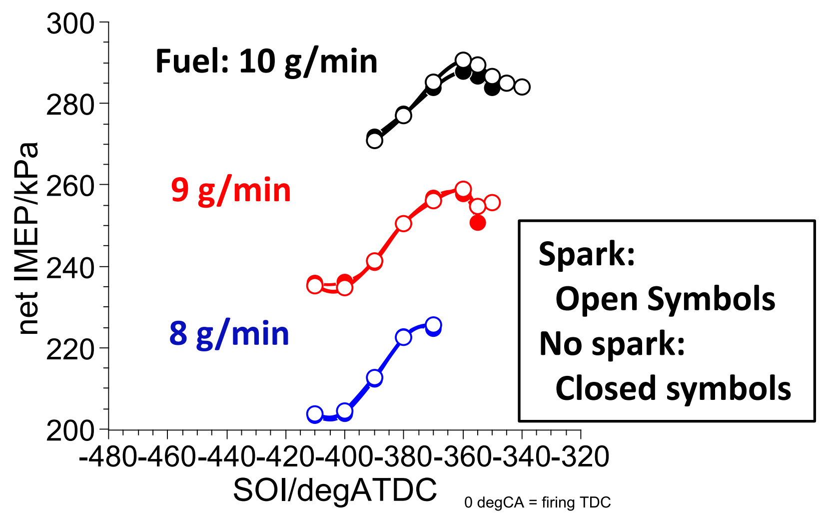
- No discernable effect of spark

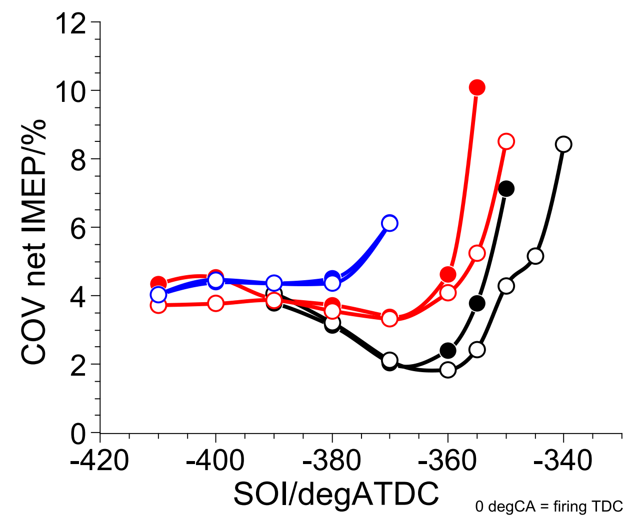
Mid fueling rate (9 g/min)

- No effect at advanced SOI timing
- Enhanced combustion stability at retarded SOI timing

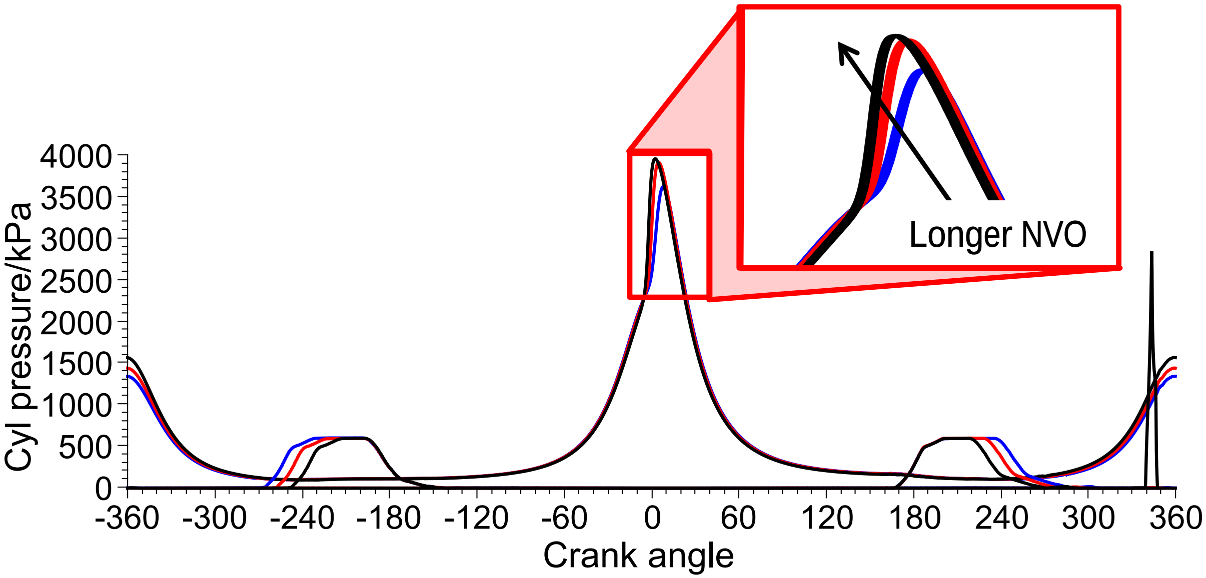
Highest fueling rate (10 g/min)

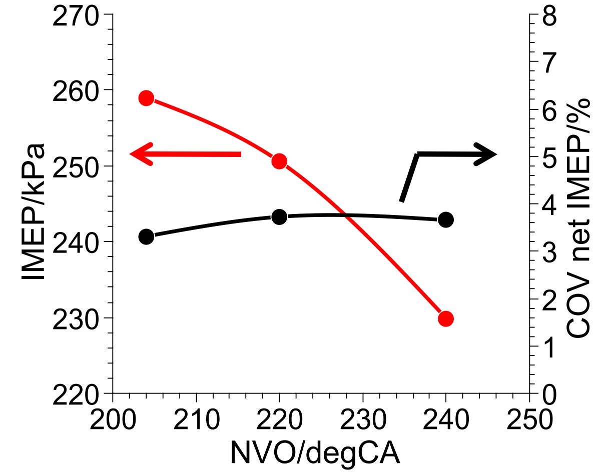
- Increased power and stability at optimal SOI timing
- Enables stable combustion at retarded SOI timing





At constant SOI timing, NVO duration affects combustion phasing and power





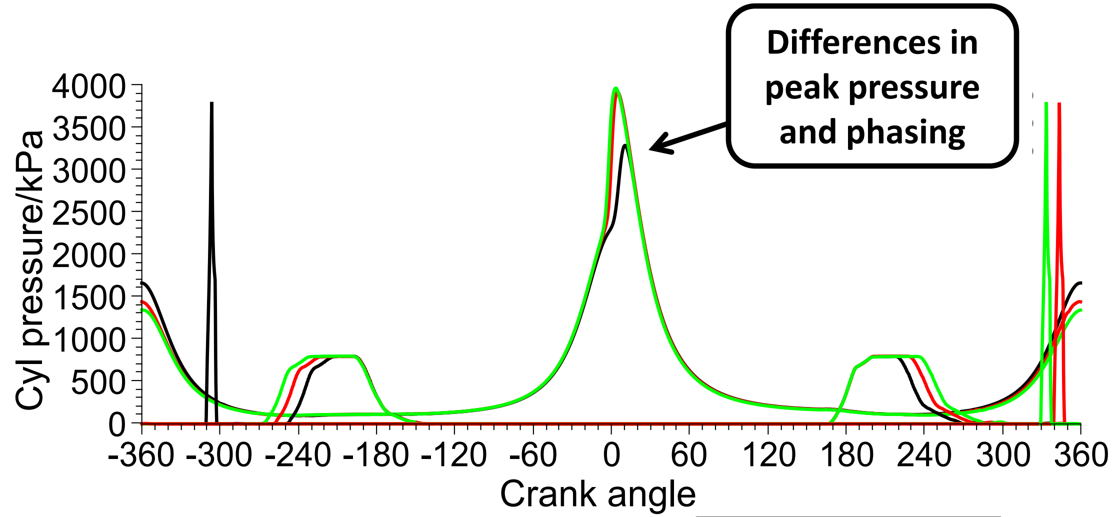
- As NVO duration increases, combustion phasing advances
  - Longer NVO increases mass of hot trapped EGR
  - Higher temperatures result in more advanced combustion phasing
- Power decreases with increasing NVO due to overly advanced combustion phasing

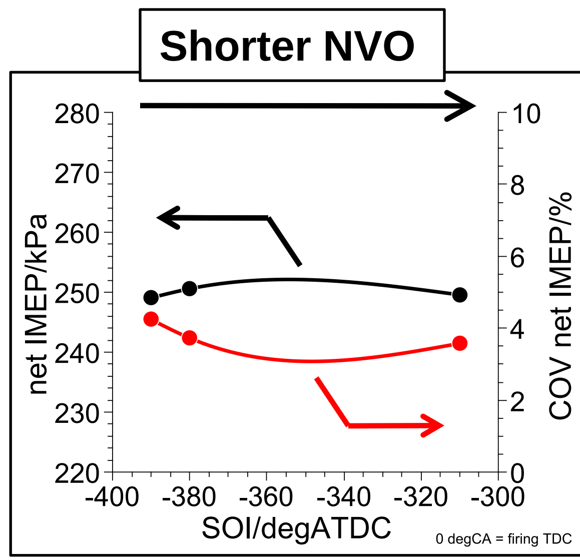
Comparable efficiency and stability achieved at different NVO durations by optimizing SOI

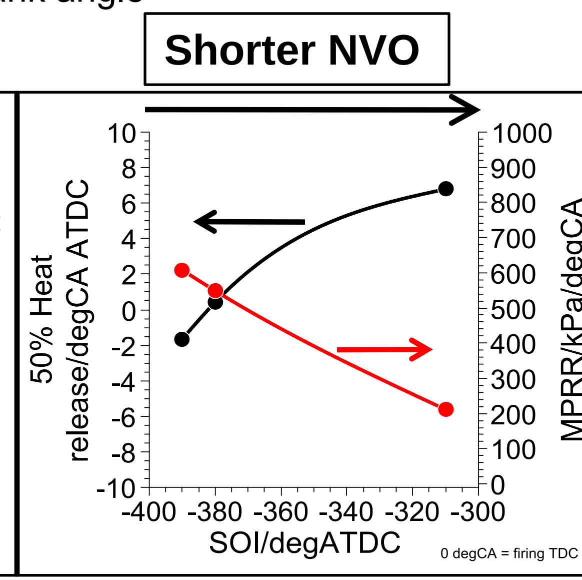
- Changes to NVO duration necessitate changes to SOI timing
  - ➢ Advanced SOI for short NVO
  - ➢ Retarded SOI for long NVO
- Comparable efficiency and combustion stability at multiple NVO

But…

- Combustion phasing and pressure rise rate dependent on NVO duration

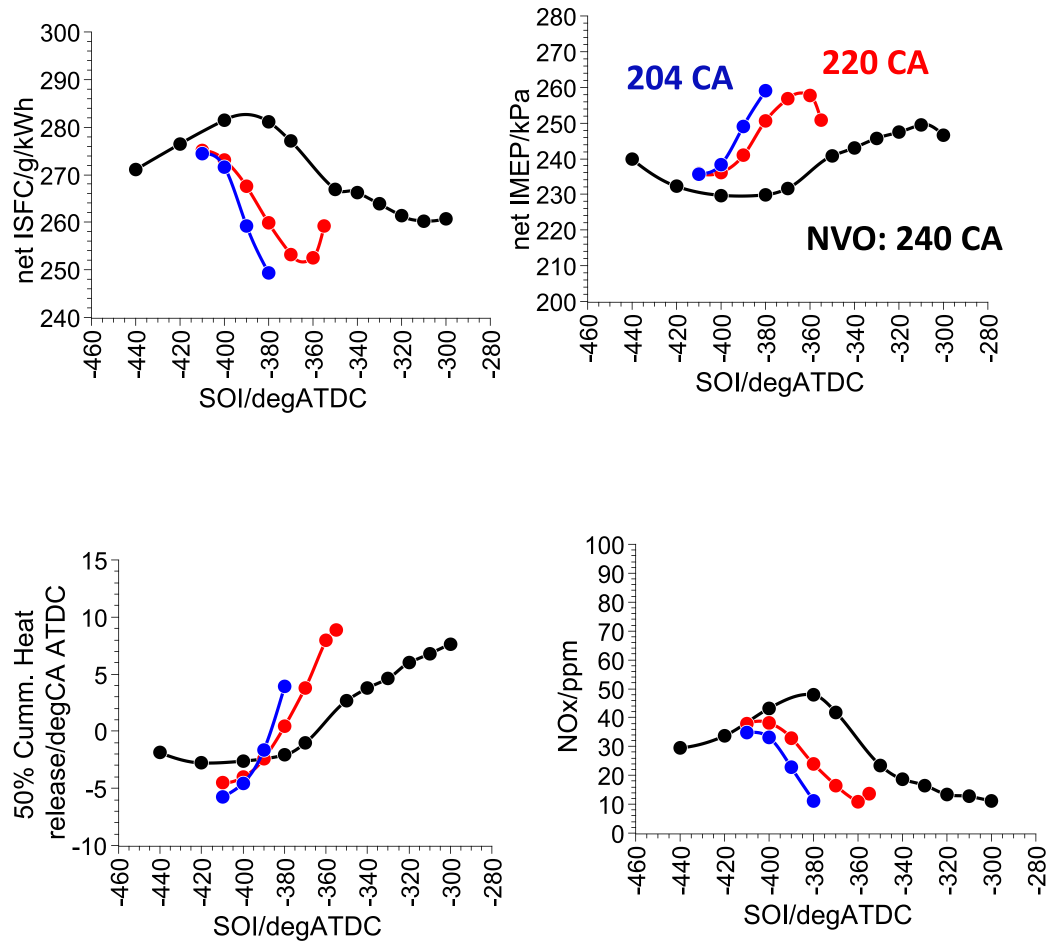






Each NVO duration has unique dependence on SOI timing

- Each NVO has a different optimal SOI timing
  - NVO duration controls pressure and temperature in NVO
  - Lambda dependent on NVO duration
- Best efficiency is achieved at the shortest NVO
  - Performance highly sensitive to SOI timing
- Performance less sensitive to SOI timing at longer NVO duration
  - Marginal efficiency penalty

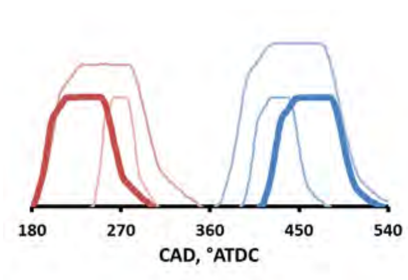


Modeling efforts guide transition from single- to multi-cylinder experiments

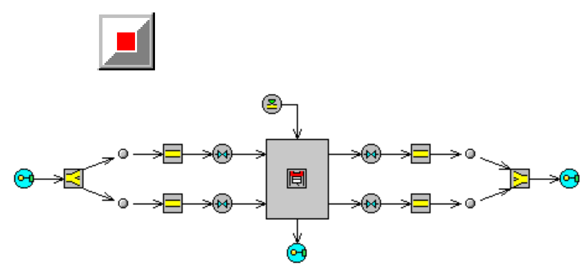
<u>***Goal:***</u> **Determine how to best match operating conditions of the HVA single-cylinder engine with the multi-cylinder engine using available cam profiles and phasing authority**

- **Experimental data from the single-cylinder HVA engine are used to calibrate engine model**
  - Combustion modeled using experimental heat release profiles obtained from cylinder pressure measurements
- **Available intake and exhaust cam profiles and phasings applied to model to determine combination which best reproduces gas exchange of the HVA engine**
  - Intake and exhaust valve mass flows
  - Cylinder pressure
  - Focus on start of compression and recompression events

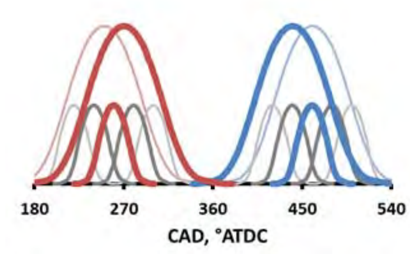
Sturman HVA



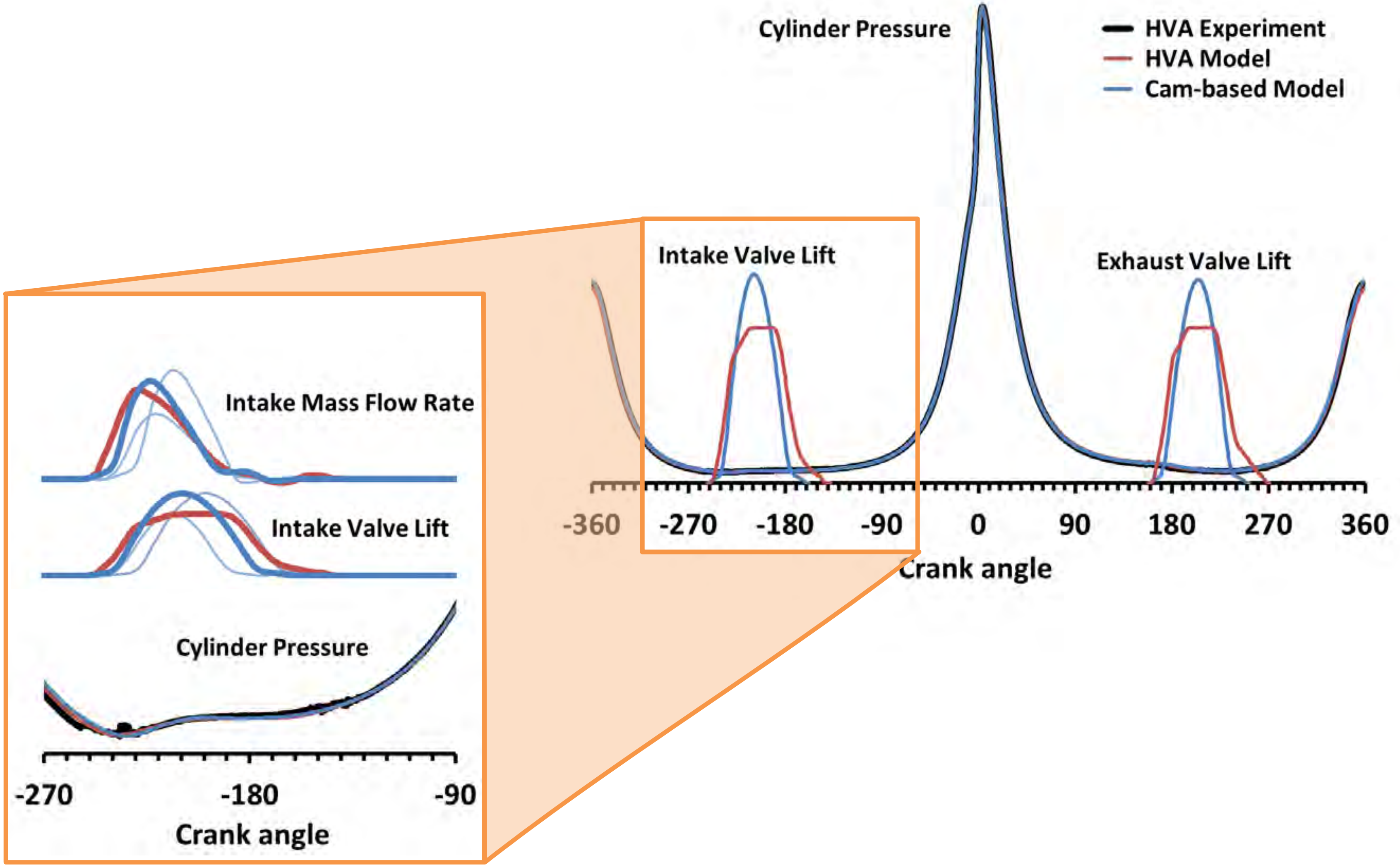
GT-Power Model



Cam-based VVA



Results show cam-based system is capable of matching single-cylinder HVA gas exchange



CRADA collaboration with Delphi Automotive Systems aimed at developing HCCI for production-intent hardware

Oak Ridge National Laboratory

- Perform single-cylinder experiments to identify HCCI operating limits and controls
- Apply GT-Power modeling to translate HVA valvetrain to cam-based valvetrain conditions

Delphi Automotive Systems

- Apply ORNL findings and model to multi-cylinder experiments
- Experimental effort at Delphi utilizes a multi-cylinder engine with cam-based VVA system

Proposed Future Work

Experimental Activities

- Purpose: Expand HCCI operating load range and stability by investigating additional hardware configurations and operating strategies
  - Multiple fuel injections per cycle (enabled by prototype fuel injector)
  - Cooled external EGR
  - Comparison of NVO and exhaust re-breathing HCCI strategies
  - Evaluate effectiveness of varying charge motion on HCCI

Modeling Activities

- Purpose: Provide a method to analyze, compare, and utilize experimental data between single and multi-cylinder engines with different valvetrain configurations
  - Continue to interpret HVA single-cylinder engine results
  - Analyze multi-cylinder cam-based experimental data from Delphi using GT-Power to validate model

Summary

Purpose: Expand robust HCCI operation for production-viable engines for improved efficiency and emissions

Approach combines engine experiments and modeling

- Flexible single-cylinder engine at ORNL with fully variable HVA
- GT-Power modeling to analyze modeling results and apply to cam-based valvetrains
- Multi-cylinder HCCI experiments with cam-based VVA engine at Delphi

Technical Accomplishments

- Investigated the authority of engine controls to optimize and control HCCI combustion
  - Fuel SOI timing is highly effective for control of HCCI, affecting emissions, efficiency, and stability
  - Spark becomes important at higher engine loads, stabilizing retarded combustion phasing
  - NVO duration changes trapped residual, combustion phasing, and stability
  - Similar efficiency and engine stability can be reproduced at multiple NVO durations
- GT-Power model indicates HVA breathing is reproducible on cam-based system

Future Work

- Experimentally investigate additional strategies and hardware configurations
- Model both single and multi-cylinder engine data for analysis using GT-Power