A MultiAir / MultiFuel Approach to Enhancing Engine System Efficiency

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ACE062

Overview

Timeline

Project Start Date:	May 07, 2010
Project End Date:	April 30, 2014
Percent Complete:	72%

Barriers

- Downsized engines offer higher fuel economy, but the degree of downsizing is limited by transient performance and dynamic range
- For gasoline engines, abnormal combustion (knock) limits the geometric compression ratio, thereby limiting engine efficiency
- EGR improves engine efficiency, but increases in EGR (and efficiency) are limited by combustion instability
- Engine operation in vehicle is not at its most efficient (ideal) state

Budget

- Total: $29,992,676

Partner Cost Share:	$15,534,104
DOE Cost Share:	$14,458,572

Partners

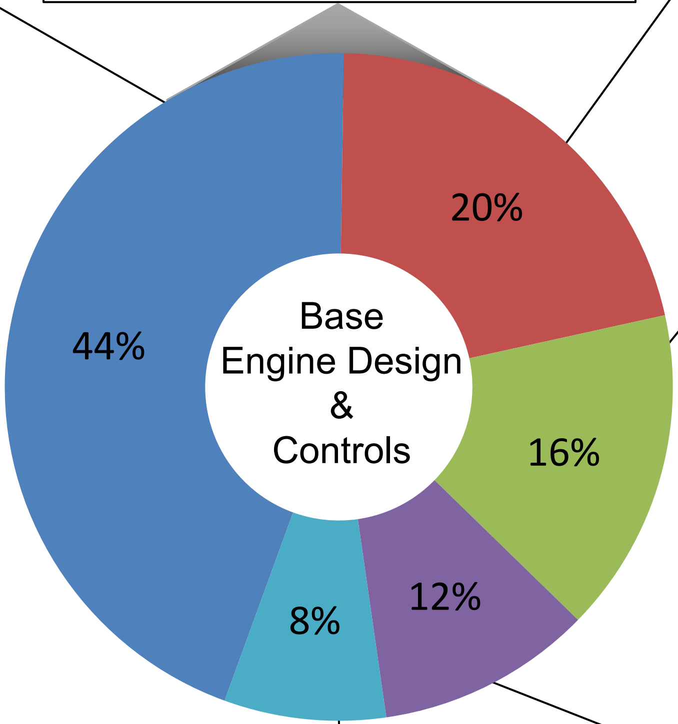
- Argonne National Laboratory
- Bosch
- Delphi
- The Ohio State University

Project Objectives

- Demonstrate a 25% improvement in combined City FTP and Highway fuel economy for the Chrysler minivan
  - The baseline (reference) powertrain is the 2009 MY state-of-the-art gasoline port fuel-injected 4.0L V6 equipped with the 6-speed 62TE transmission
  - This fuel economy improvement is intended to be demonstrated while maintaining comparable vehicle performance to the reference engine
  - The tailpipe emissions goal for this demonstration is Tier 2, Bin 2
- Accelerate the development of highly efficient engine and powertrain technologies for light-duty vehicles, while meeting future emissions standards
- Create and retain jobs in support of the American Recovery and Reinvestment Act of 2009
- Project content is aimed directly at the listed barriers

Technology Approach & Contribution

Goal ≥ 25% Improvement in Fuel Economy



Engine Efficiency

Engine downsizing, and 2-stage boosting

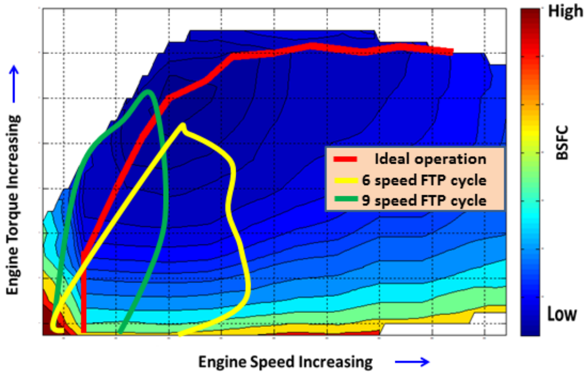
High compression ratio

Cooled EGR, DI, and spray bore liners, EtOH for improved knock resistance

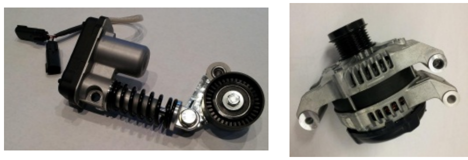
Advanced ignition for improved stability with high dilution

Low Lock-up Speed

Ideal Engine Operation

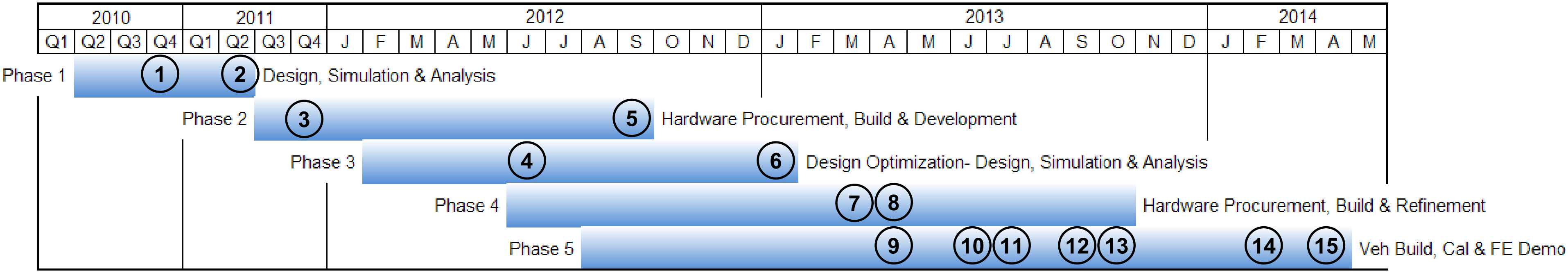


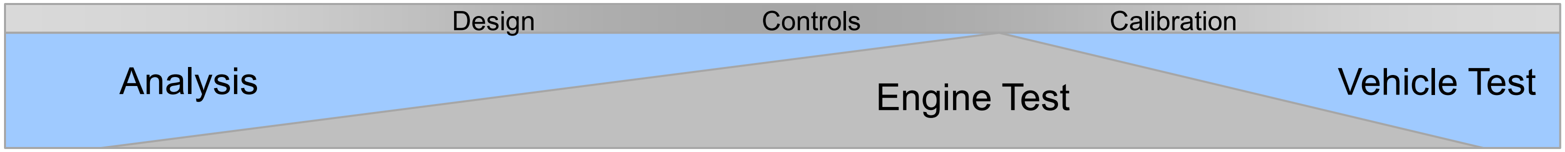
Reduced Losses



Thermal Management

Timeline and Major Milestones





#	Date	Milestone – Completed
1	Nov 2010	Performance Specs / Engine Selection Completed
2	Jul 2011	Dyno Engine Design Completed
3	Nov 2011	Procure, Build, Initial Test of Dyno Engine Completed
4	Jun 2012	Alpha 2 Engine Technology Selection Completed
5	Sep 2012	Testing Results for Alpha 2 Design Input Completed
6	Jan 2013	Alpha 2 Engine Design Completed
7	Mar 2013	Alpha 2 Engine Procurement Completed

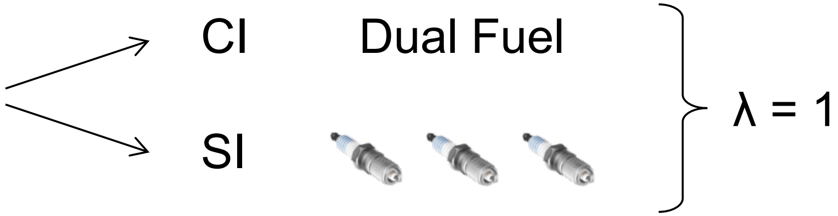
#	Date	Milestone – Remaining
8	Apr 2013	Complete Engine Controls and Vehicle Design
9	Apr 2013	Complete Alpha 2 Dyno Engine First Fire
10	Jun 2013	Complete Vehicle 1 Build
11	Jul 2013	Complete Vehicle Energy Simulator (OSU)
12	Sep 2013	Complete Engine Dyno Calibration
13	Oct 2013	Complete Vehicle 2 Build
14	Feb 2014	Complete Vehicle Calibration
15	Apr 2014	Complete Vehicle Demonstration

Combustion System Approach

Low: Combustion Temperature, Mechanical Losses

High: Boost Pressure, Compression Ratio, Dilution, Ignition Energy

2-Pronged Ignition Energy Approach:

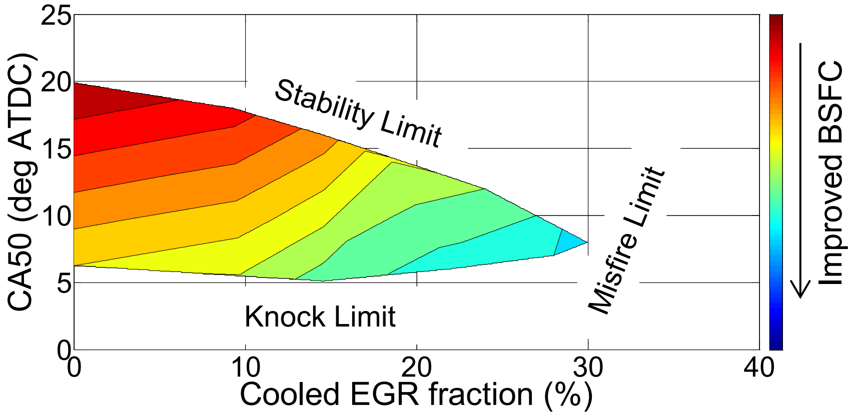


CI Dual Fuel

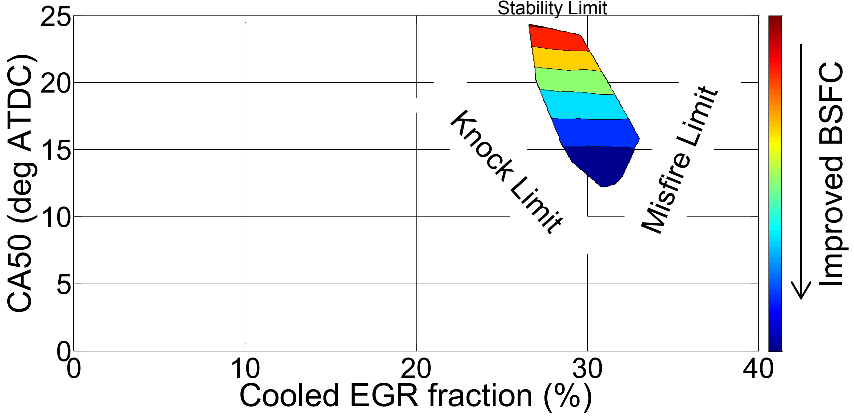
SI

λ = 1

Dual Fuel (CI):	Gasoline + Diesel @ ANL	Engine Only
Dual Fuel (SI):	Gasoline + Ethanol @ Chrysler	Engine + Vehicle



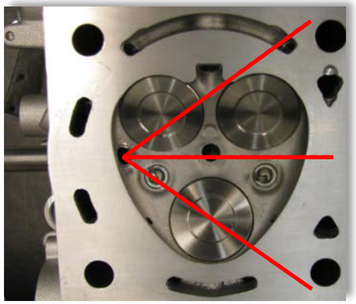
Typical SI case at 11.2:1 CR

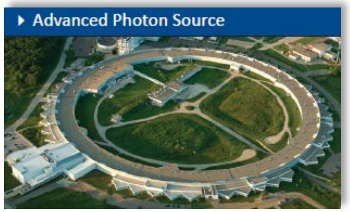


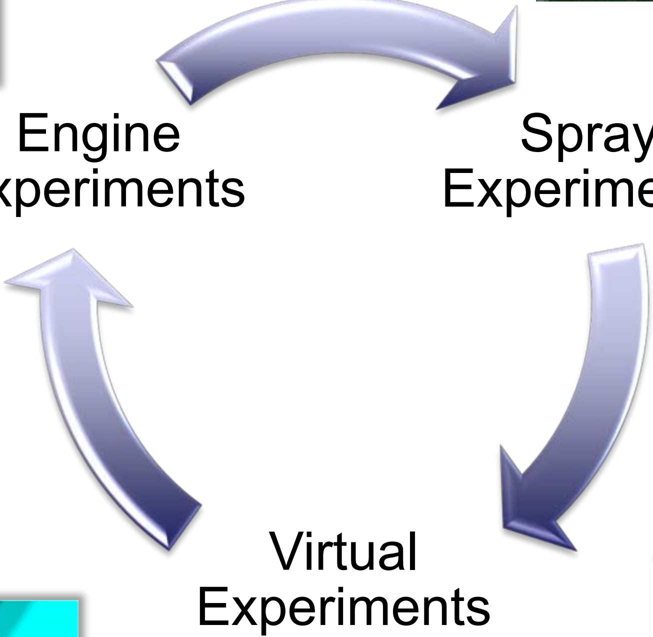
Typical CI case at 13.2:1 CR

Dual Fuel: Gasoline + Diesel @ ANL

Endoscopic Access



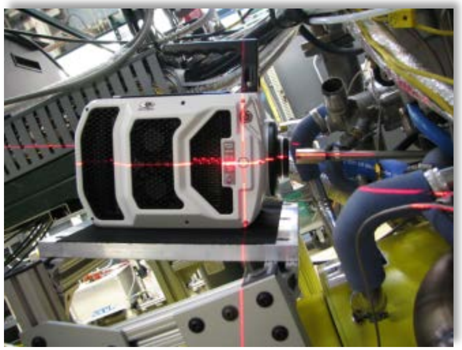




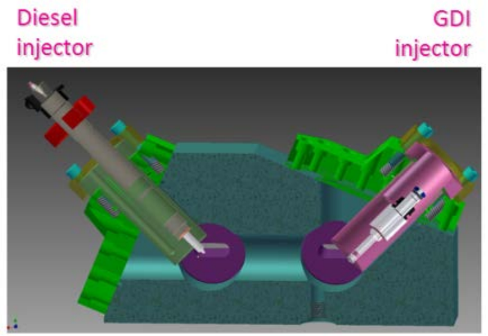
Engine Experiments

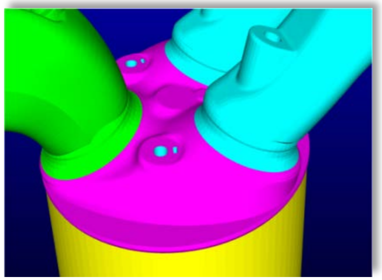
Spray Experiments

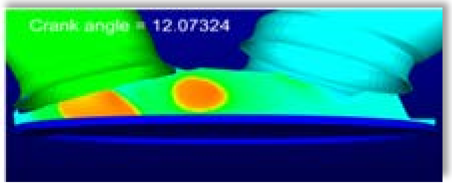
Virtual Experiments

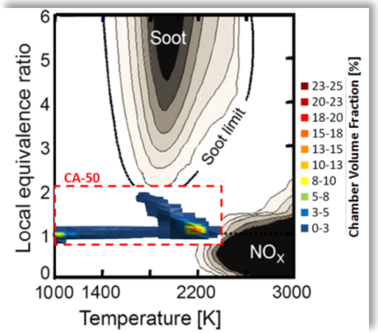


Camera w/1280x800 @ 12,000 fps
(1 frame/CA @ 2000rpm)









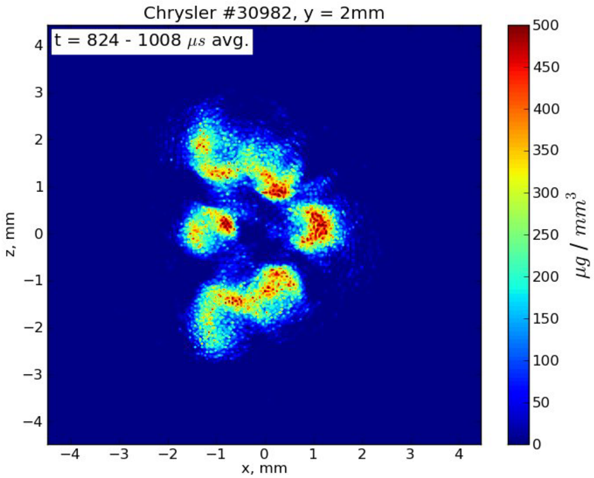
Spray Experiments @ ANL

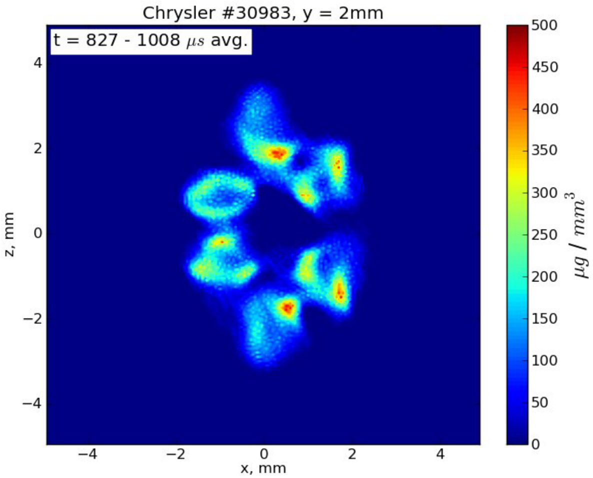
Gasoline

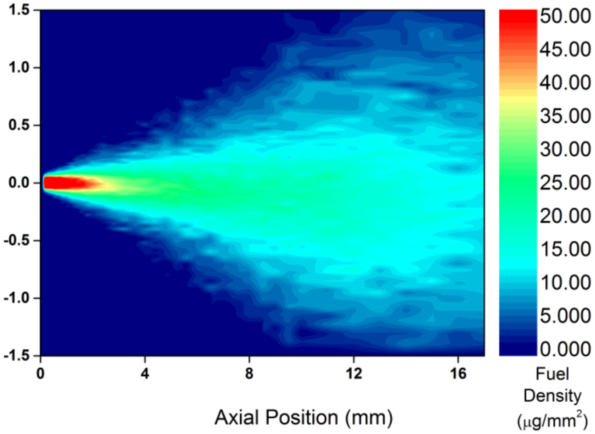
- 100 bar fuel pressure
- 1 bar ambient pressure
- X-ray tomography used to reconstruct fuel density in 3-D
- Cut plane 2 mm from nozzle shown below

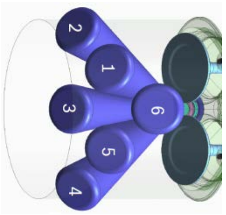
Diesel

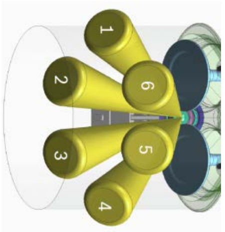
- 1000 bar fuel pressure
- 20 bar ambient pressure
- One of three nozzles shown

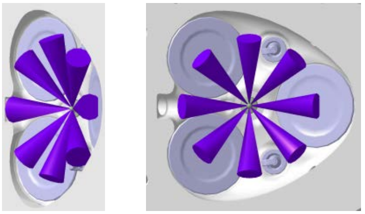




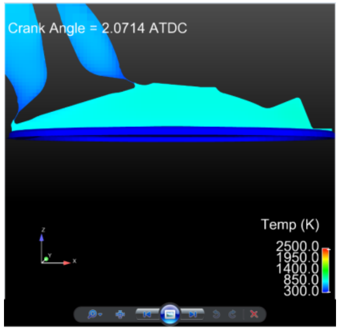
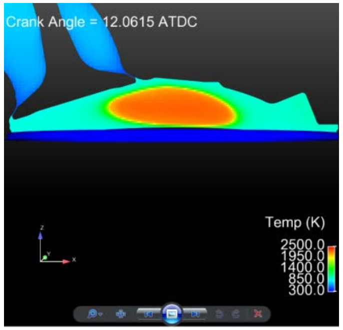
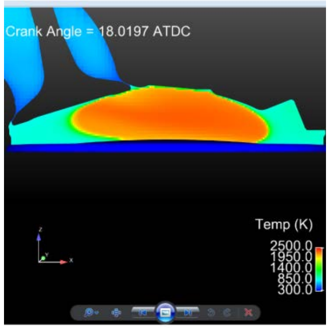
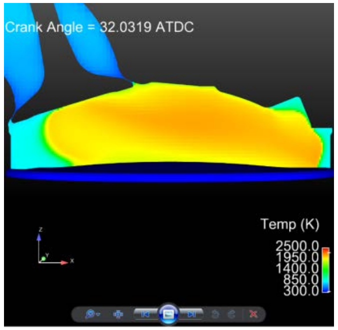
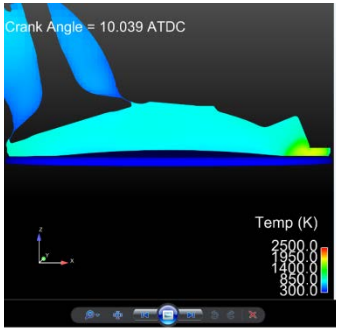
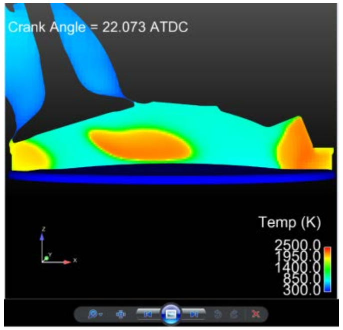
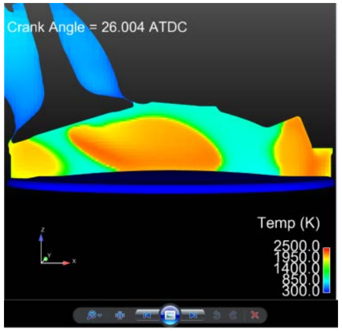
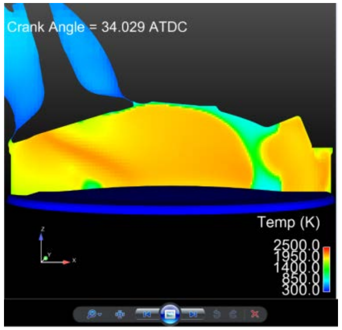
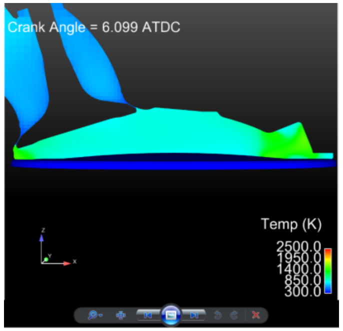
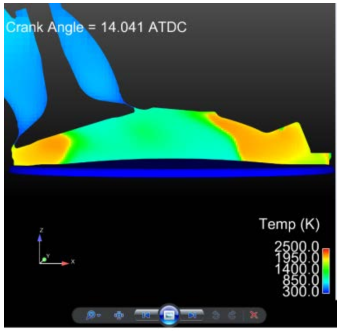
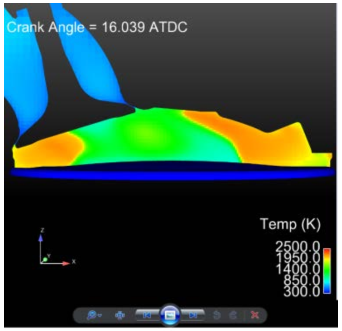
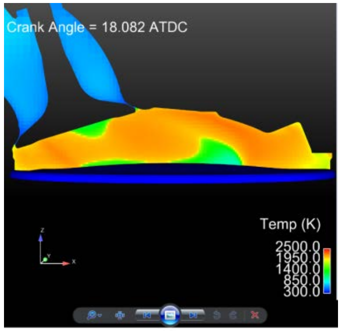






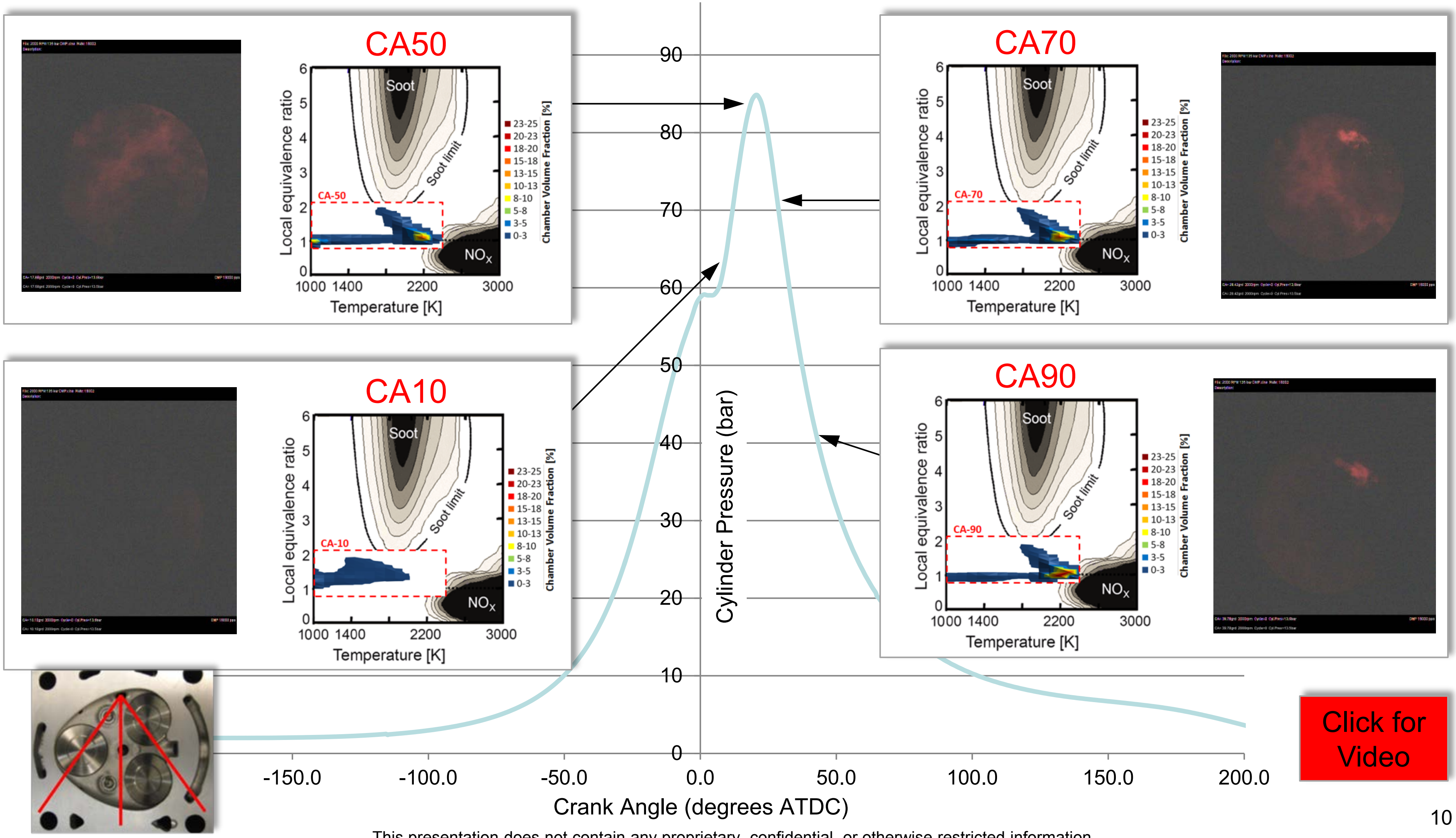


Virtual Experiments @ ANL (SI & CI)

	CA10	CA50	CA70	CA90
SI 8 bar				
DASI 11 bar Diesel-Assisted Spark Ignition				
DMP 13 bar Diesel-Micro-Pilot Ignition				

Engine Experiments @ ANL (CI)

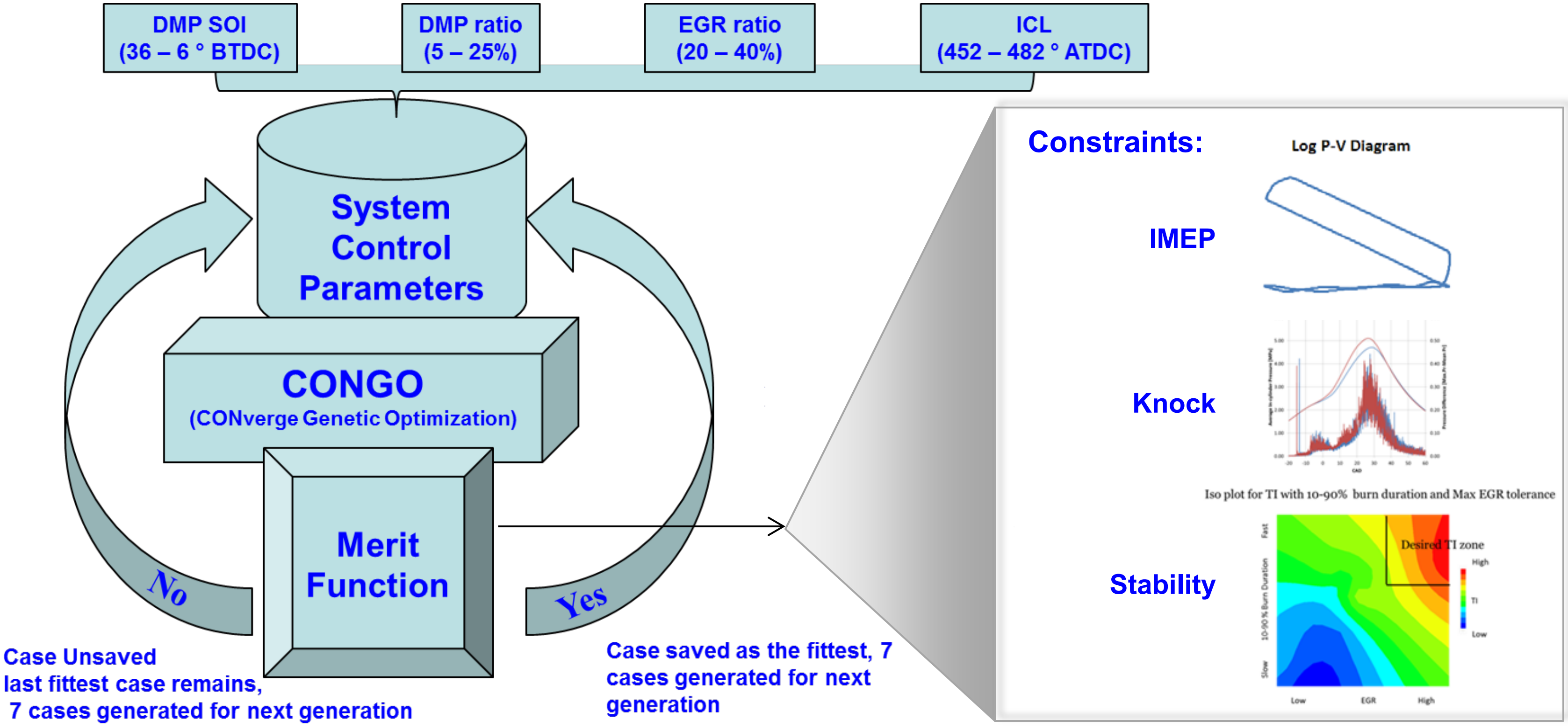
DMP - 13.4 bar BMEP @ 2000 rpm



Click for Video

Future Work @ ANL

- Objective is to improve engine efficiency AND improve control robustness
- Includes both the DASI transition mode and the DMP mode
- Approach outlined below is underway, and will be verified *via* engine test



DMP SOI
(36 – 6 ° BTDC)

DMP ratio
(5 – 25%)

EGR ratio
(20 – 40%)

ICL
(452 – 482 ° ATDC)

System Control Parameters

CONGO
(CONverge Genetic Optimization)

Merit Function

No

Yes

Case Unsaved
last fittest case remains,
7 cases generated for next generation

Case saved as the fittest, 7 cases generated for next generation

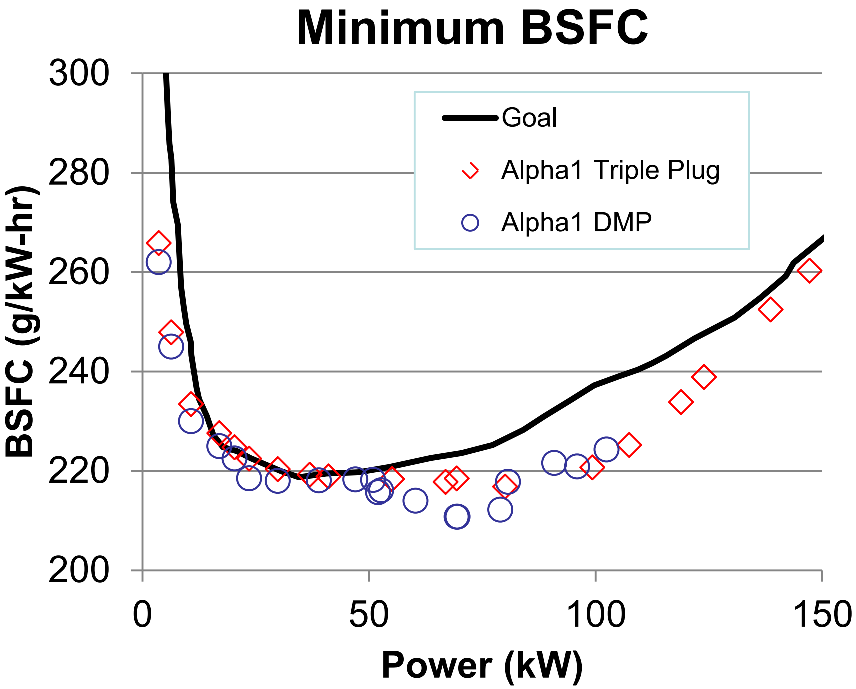
Constraints:

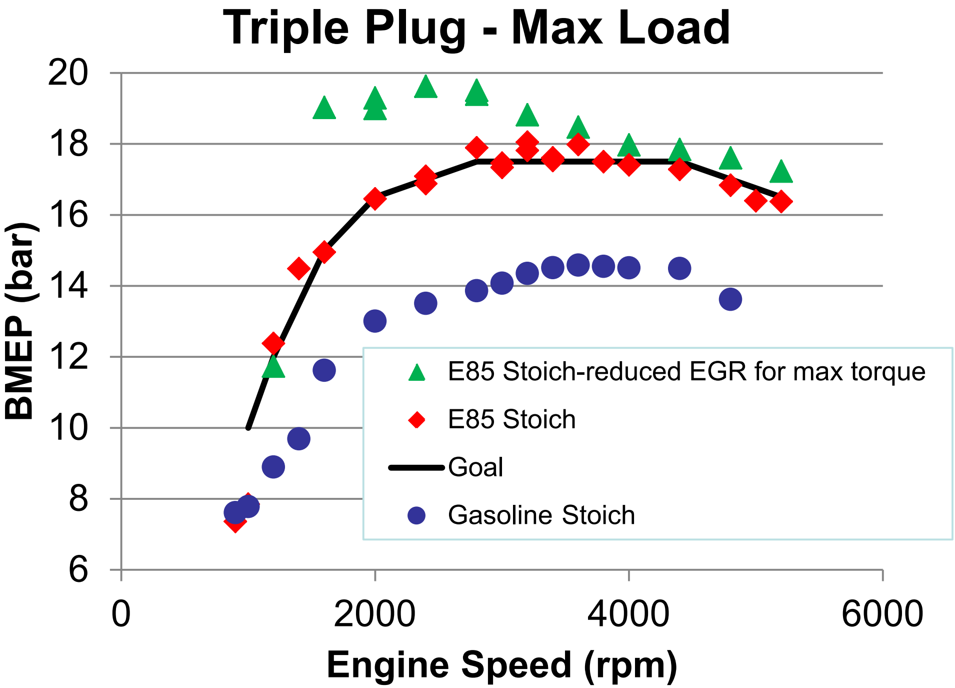
IMEP

Knock

Stability

Dual Fuel: Gasoline + Ethanol @ Chrysler (SI)

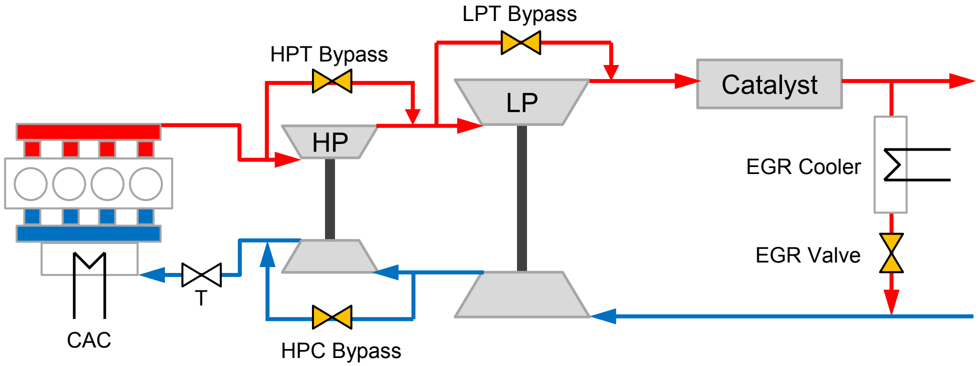


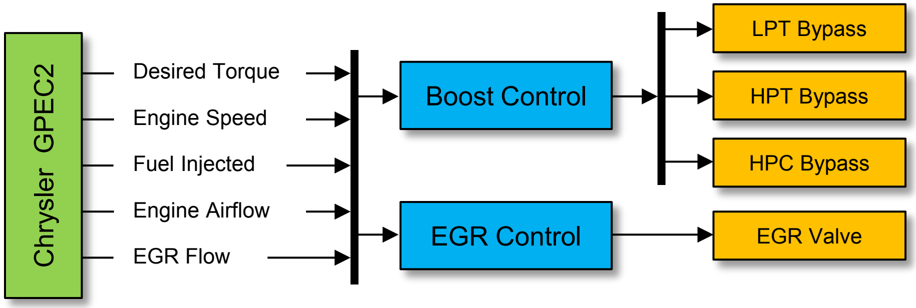


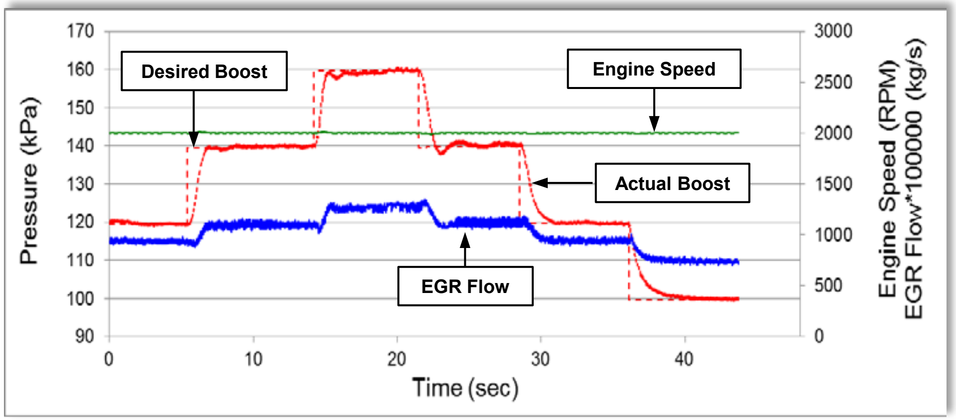
- Minimum fuel consumption is at or better than goal with the triple plug design
- PFI E85 reduces knock tendency / improves combustion phasing
  - Significant Octane benefit realized with PFI E85, providing significant load extension
  - Gasoline DI maintained for cold start catalyst heating, as well as charge cooling
  - With PFI E85, eliminates injector thermal concern during zero fuel flow (if E85 were DI)

Boost & EGR Control

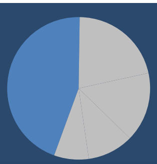
- Boost Control Model
  - Algorithm for LPT bypass (wastegate), HPT bypass, and HPC bypass control has been completed
  - Algorithm uses Turbocharger compressor maps to determine the most efficient operating conditions to minimize pre-turbine pressure and pumping work
  - Feed forward controls based on system design and operating conditions are used, along with closed loop control to achieve the desired transient response and steady state levels
- EGR Control Model
  - Algorithm for internal and external EGR control has been completed
  - Internal EGR is controlled by VVT and external EGR is controlled by EGR valve
  - Internal/external EGR control is based on operating conditions, and uses feed forward and closed loop controls to achieve the desired dynamic response



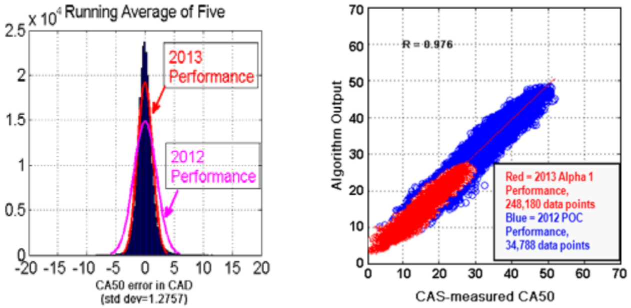




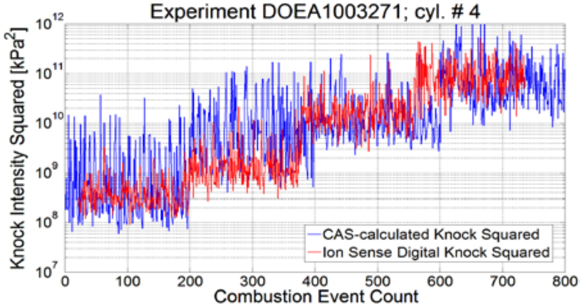
Combustion Sensing and Control



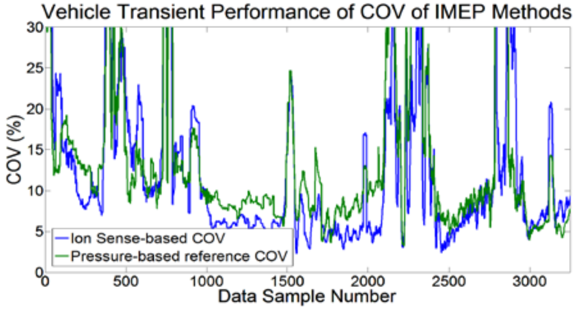
- Delphi Ion-Sense Combustion Sensing
  - Ignition Coil technology coupled to an Ion Sense Development Controller (ISDC)
  - Combustion parameters calculated and provided to Engine Controller for real-time combustion control, enabling optimal engine operation
- Combustion Phasing
  - Combustion phase detection accuracy has improved by 30% from last year's performance
- Knock Detection
  - Knock algorithms have been developed from ion-sense
  - Good agreement with pressure-based method as a reference; calibration is in process
  - Enabler for maximizing benefits of combustion phasing control
- Combustion Stability Estimation
  - Combustion stability (COV of IMEP) algorithms have been developed from ion-sense
  - Good agreement with cylinder pressure as a reference standard



Combustion feedback error has less than 1.4 degree standard deviation from reference



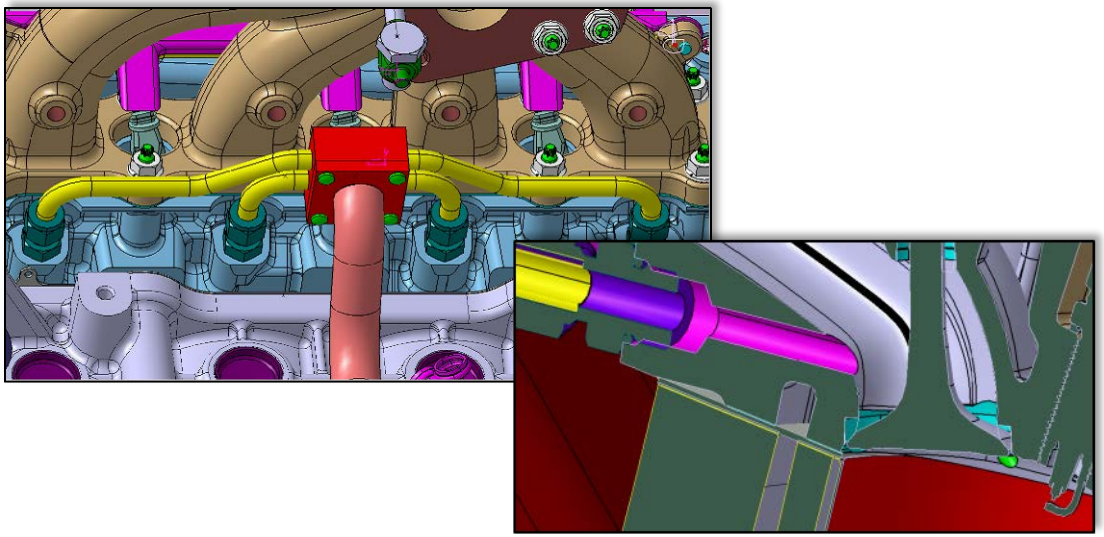
Ion-sense knock feedback compares well to pressure-based reference

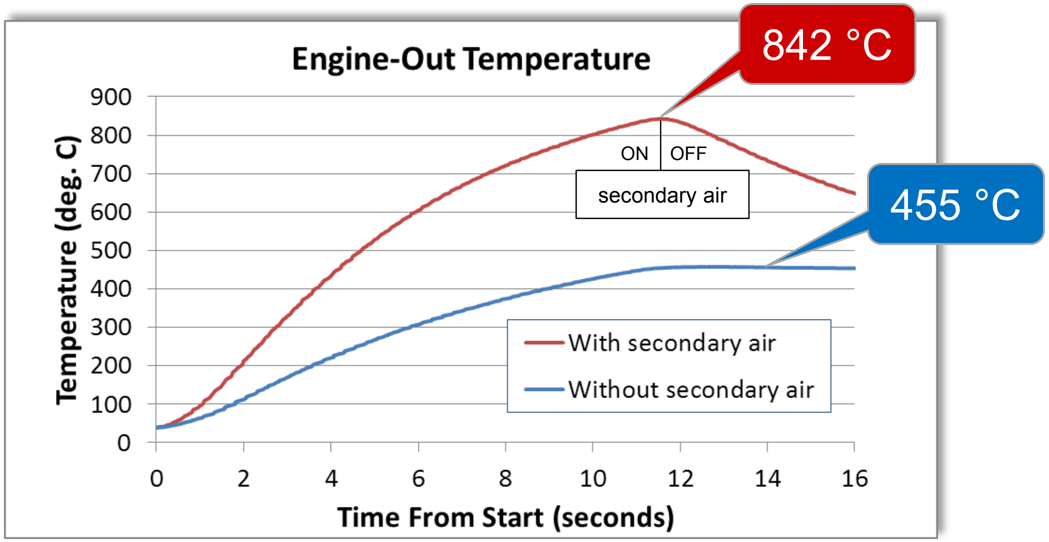


COV shows good agreement

Cold Start Emissions Control

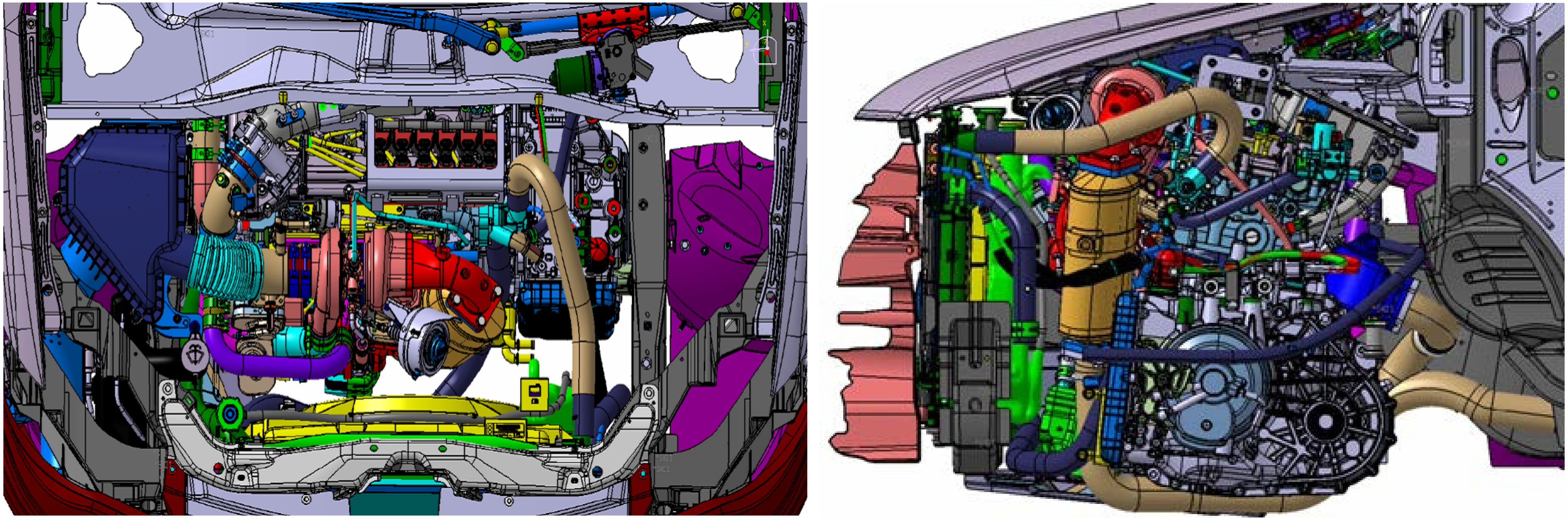
- Secondary Air Injection
  - Soon after cold start, the engine is operated rich
  - Air is introduced into the exhaust stream, near the exhaust valve
  - The rich combustion products react with the air to create an exo-therm in the exhaust runner
  - Control system has been developed to leverage secondary air system on DI engine, with very low engine out emissions
  - The result was a maximum exhaust temperature of 842 degrees C, which was reached in 11 seconds





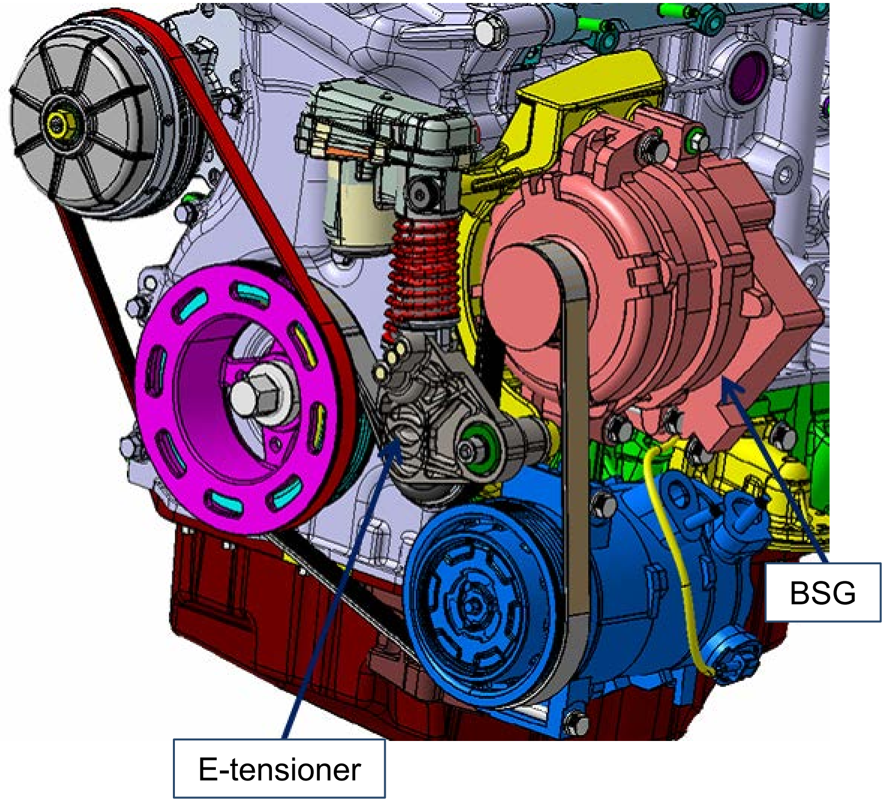
Base Engine Design

- Alpha 1 engine builds are complete; engine design has proven to be robust
- Alpha 2 designs (3D models and 2D prints), analysis and procurement completed
  - Optimized the entire powertrain module to accommodate minivan packaging
  - Refined turbo packaging which also included an integrated by-pass valve
  - Adopted three point engine mounting system for improved NVH
  - Completed 9 Speed transmission packaging
  - Belt Start Generator (BSG) was introduced



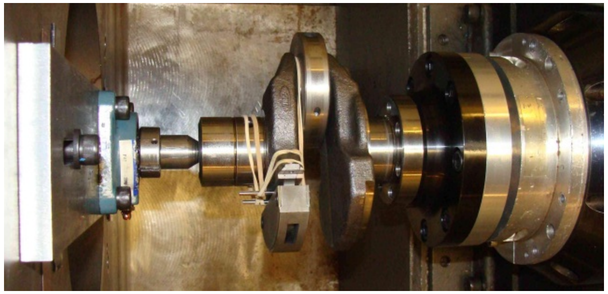
Reduced Losses (Fuel Shut Off, Stop/Start & Ancillary Load Reduction)

- Belt Starter Generator (BSG)
  - BSG system added to enable integrated Deceleration Fuel Shut Off (iDFSO) to zero mph
  - Standard (iDFSO) is available down to 15 mph
  - BSG provides enabler for iDFSO functionality from 15 mph to 0 mph
    - Simulated ~2% fuel savings potential on FTP Combined
  - Addition of the BSG requires electronic belt tensioner to reduce tension during generation mode and increase during motoring mode
  - Supplier selection is complete
  - Design is complete
  - Parts are being procured
  - Controls are being developed



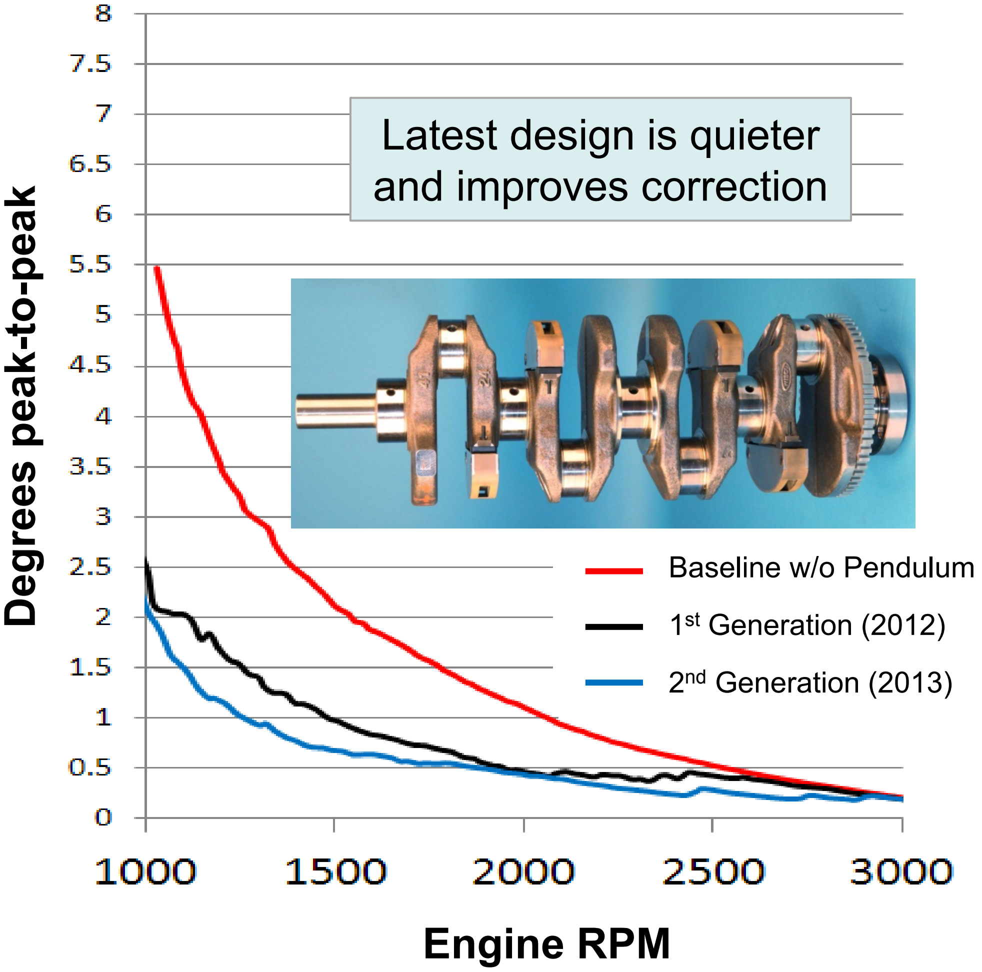
2nd Order Mitigation

- 2nd order mitigation is an enabler for lower torque converter lock-up speeds, and higher engine efficiency
- Two generations of crankshafts, and multiple iterations have been evaluated
- Established out-of-engine dyno-based test bench capability to refine design



1st Generation (in-vehicle tests)	**2nd Generation** (dyno-based tests)
• 45-50% correction • Low speed noise • Improved correction (see chart) • Quieter, noise only at idle speeds and slightly above	• More absorber inertia than Gen 1 • Weakness of 2nd Gen. iteration 1 revealed in testing • New design underway • Refined design planned for vehicle deployment

2nd Order Torsional Vibration at Full Load



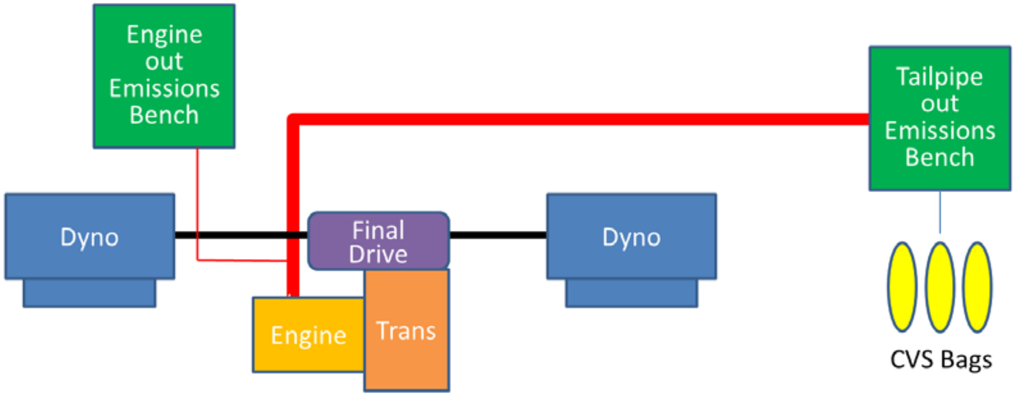
Latest design is quieter and improves correction

Partnerships / Collaborations

Argonne NATIONAL LABORATORY	Providing computational fluid dynamics (CFD) modeling, spray measurements, and in-cylinder combustion high-speed imaging to support combustion development and control
BOSCH	Supplied fuel injectors, lines, pumps, harnesses and controllers for the DI gasoline and DI diesel fuel systems, and collaborated with Chrysler to integrate the injector drivers
DELPHI	Supplied Ion Sense coils and developing combustion feedback system to allow closed loop combustion control
THE OHIO STATE UNIVERSITY	Developed Vehicle Energy Simulator (VES) and supervisory controller (Vehicle Energy Manager – VEM) that oversees and integrates energy management of vehicle subsystems

Future Work

- Complete implementation and verify operation of engine control system
- Verify performance and perform dynamometer-based calibration of Alpha 2 engine
- Complete vehicle-level calibration in powertrain test cell, making best use of time prior to vehicle availability



- Build two vehicles and complete vehicle calibration to ensure emissions, fuel economy, and drivability goals are met
- Final vehicle demonstration and assessment relative to goals

Summary

- Current modeling and test results show the 25% fuel economy improvement goal should be met with the selected technologies
  - Combustion system approach offers a controllable and effective solution to low temperature combustion, and is compatible with a highly-effective stoichiometric aftertreatment system
  - Pendulum absorber has proven effective at enabling lower lockup speeds, leading to higher engine efficiency
  - The 9-speed transmission allows engine operation closer to ideal state
  - Fast warm-up of fluids improves mechanical efficiency of engine and transmission
  - BSG, and enhanced voltage regulation/iDFSO are effective at reducing parasitic losses
- Alpha 1 engines have been very robust throughout the project
- Alpha 2 engine builds are in process, with verification and calibration tasks to follow

Thank You

Technical Back-Up Slides

Thermal Management System w/ OSU

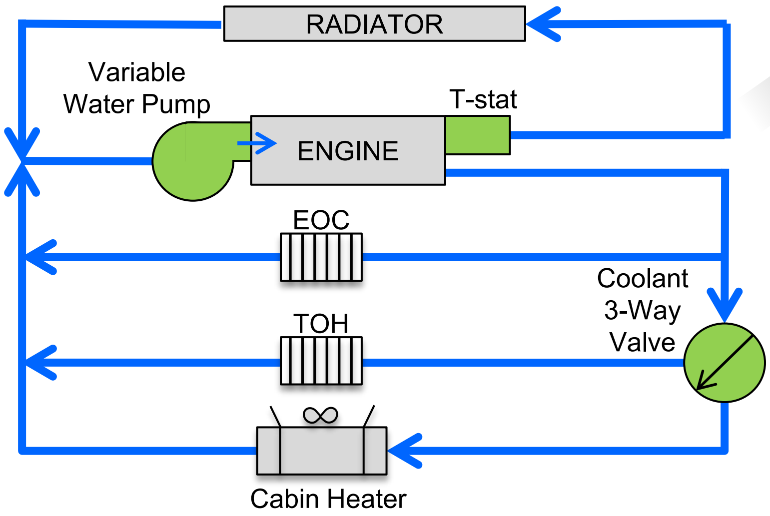
Approach

Faster warm-up of engine & transmission oils for improved mechanical efficiency via friction reduction

Accomplishments

- Vehicle Energy Simulator (VES) developed by OSU to be used for modeling of thermal controls
- System valve actuation strategy optimized for:
  - Fastest warm-up of each powertrain fluid
  - Lowest cumulative fuel consumption over FTP city drive cycle

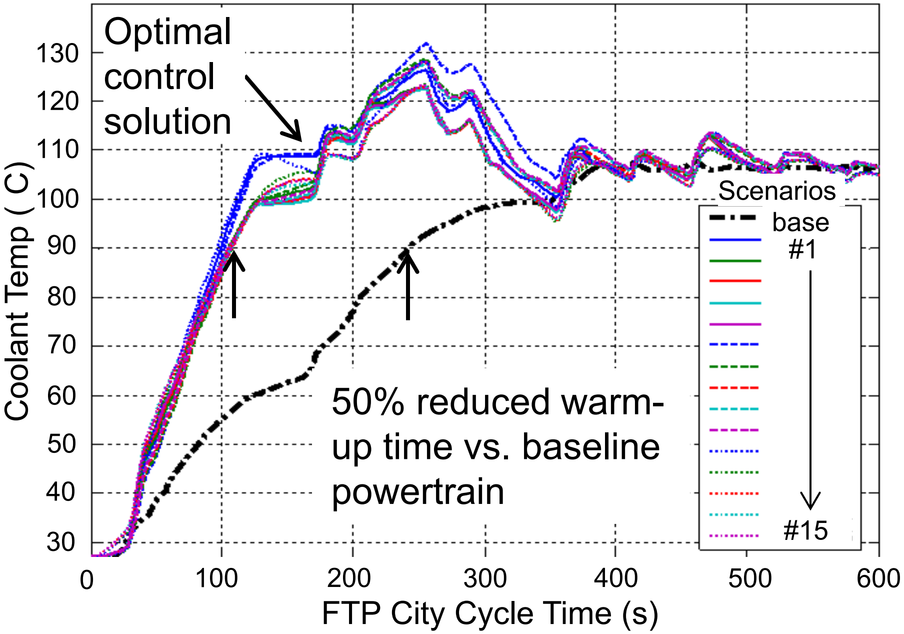
Alpha 2 Engine Thermal Schematic



Actuator Design of Experiments – Alpha2 Engine

2 independent variables

3 x 5 states each, total runs = 15



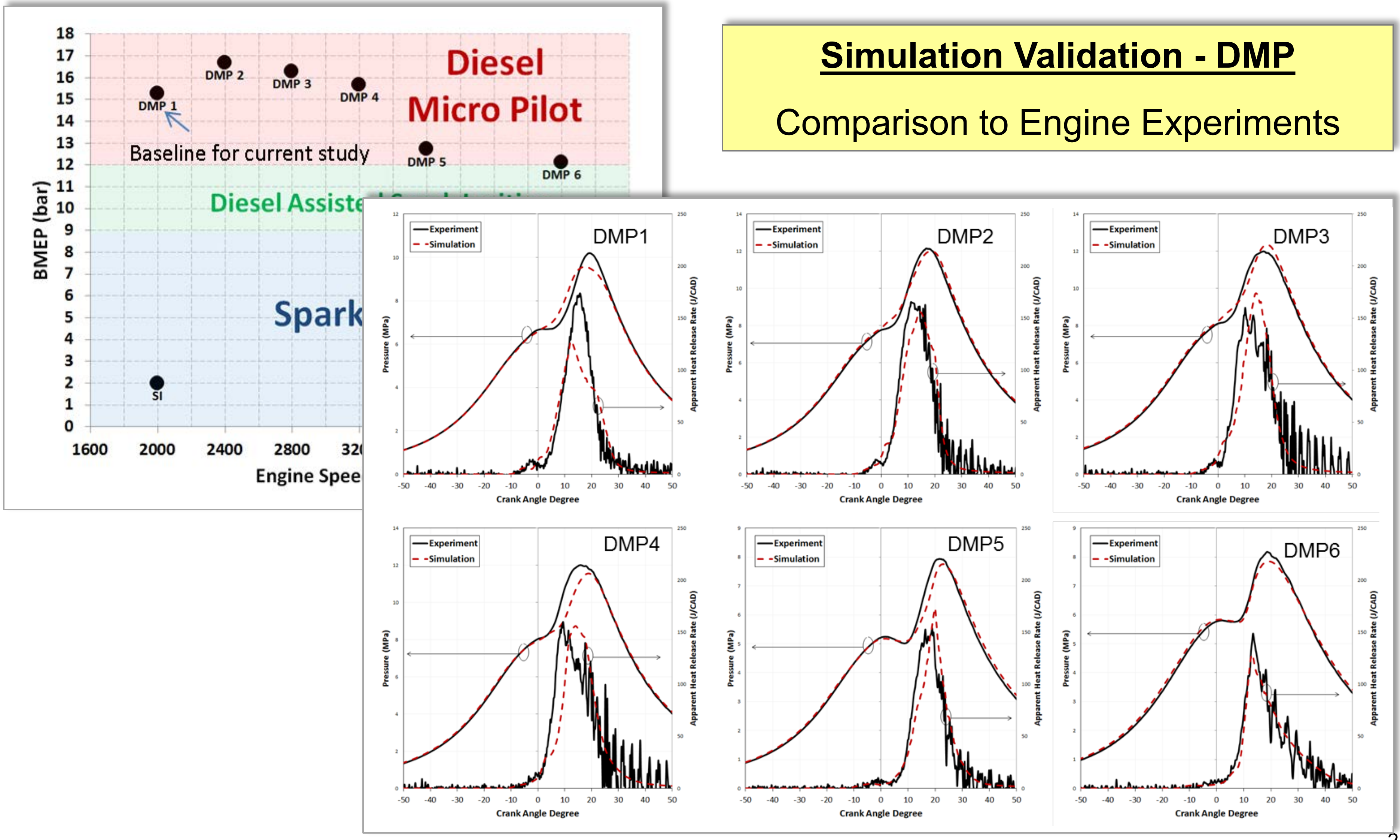
Exhaust Heat Recovery System (EHRS)

- EHRS removed from Alpha2 engine design due to less heat recovery than expected on thermal mule vehicle
  - EGR cooler location too far from engine = heat loss
  - EGR cooler thermal inertia too high for use as EHRS
- EHRS not needed to meet overall project FE target

Combustion Simulation (CI) – Validation

Simulation Validation - DMP

Comparison to Engine Experiments

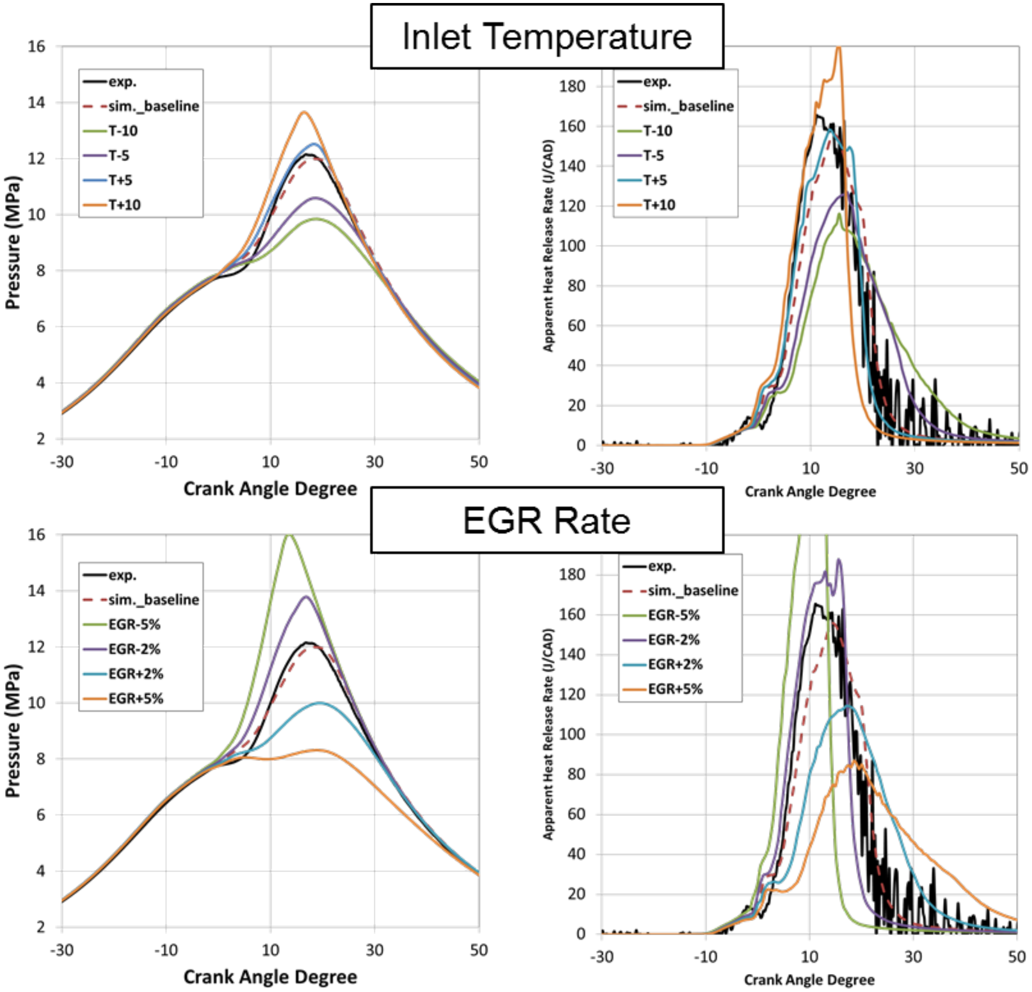


Combustion Simulation (CI) – Sensitivity

Sensitivity Analysis

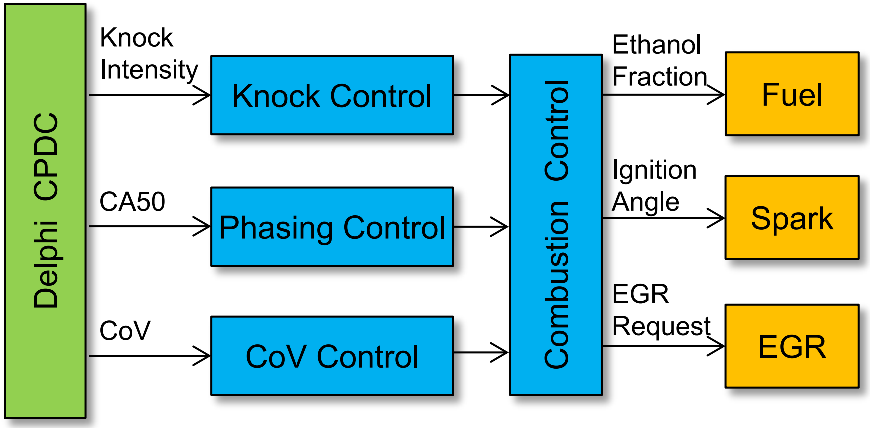
Only the simulation baseline is compared to an engine experiment. All other results are simulation only.

Very sensitive to inlet T and EGR ratio

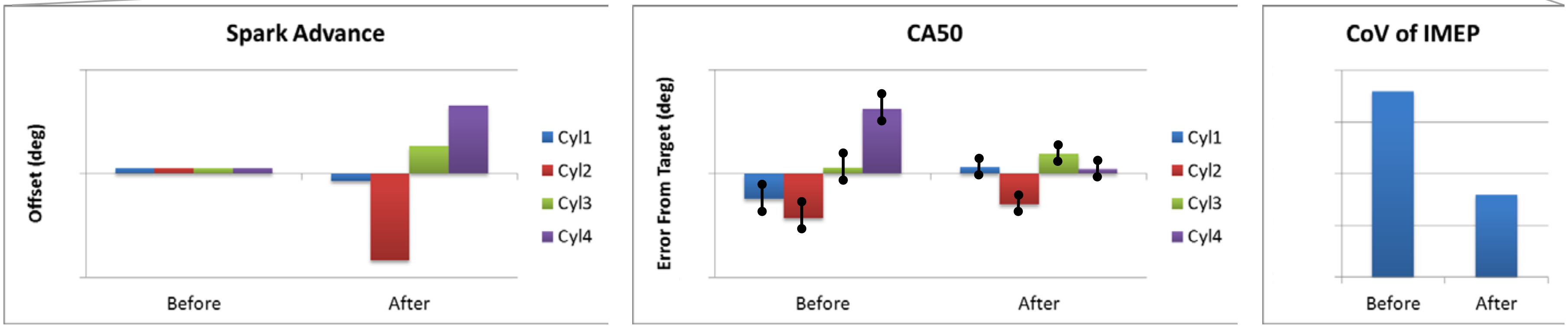


Combustion Control

- Current Status
  - Combustion phasing feedback control demonstrated in steady state conditions
  - Knock control implemented and awaiting final Delphi detection calibration
  - CoV (of IMEP) control under development
- Future Work
  - Verification of phasing feedback under transient conditions
  - Verification of knock / combustion phasing / ethanol interactions
  - Verification of CoV control

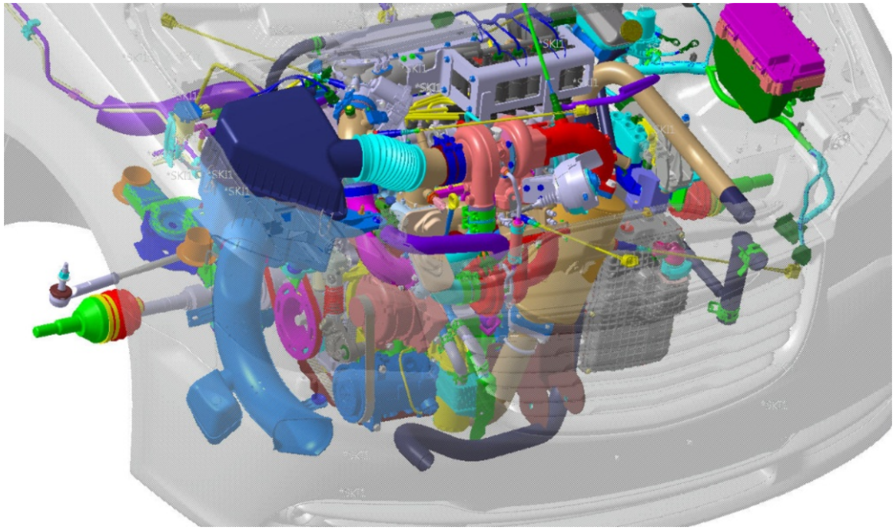


Before and After Phasing Control

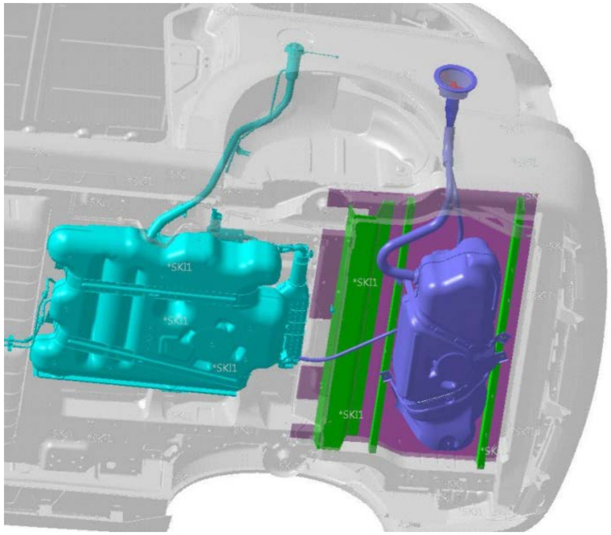


Vehicle Packaging

- Two vehicles are planned for development, calibration and demonstration
- Vehicle #1 - Development
  - Packaging for engine and dual fuel system is complete
  - Communication protocol verification in process
  - Build to be complete June 2013
- Vehicle #2 – Calibration / Demonstration
  - Build to be complete October 2013



Engine Packaged in-Vehicle



Dual Fuel Delivery System