Cummins EDPCI Project

E85/Diesel Premixed Compression Ignition

Lyle Kocher – Principal Investigator
Cummins Inc.

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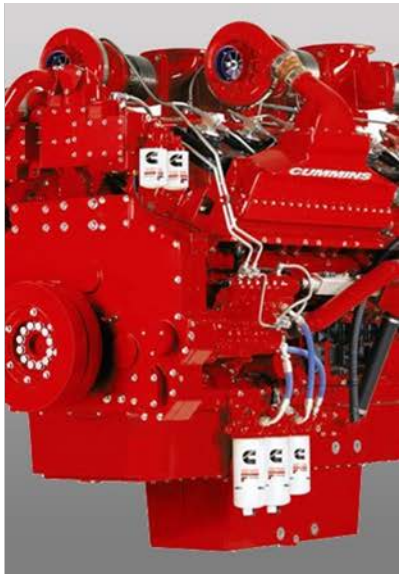
Project ID: FT043



Overview

Timeline

- Start: 1/1/2015
- End: 12/31/2016
- 60% Complete

Budget

- $5.4M Total Budget
  - $2M DOE
  - $3.4M CMI
- $880k in Funding for FY2015
- $1.12M for FY2016

Partners

- Cummins Fuel Systems

Technical Targets / Barriers

- Fuels Technology
  - Potential for replacement of petroleum (50%)
  - Inadequate data and predictive tools for fuel property effects on combustion and engine efficiency optimization
- Advanced Combustion Engine
  - Lack of fundamental knowledge of advanced engine combustion regimes
  - Lack of effective engine controls

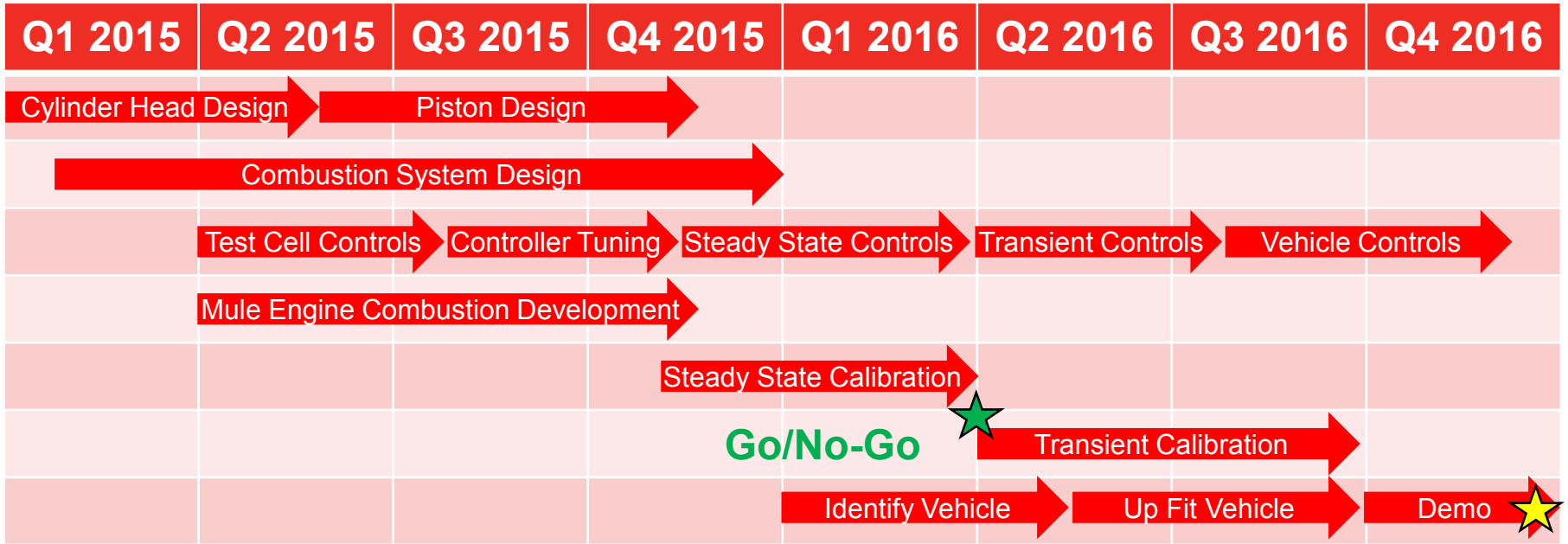
Relevance

- Overall Project Objectives
  - Use a dual-fuel engine to reduce the petroleum usage of a Class 8 vehicle by at least 50%
  - Develop and demonstrate a dual-fuel engine and aftertreatment system to achieve 2010 emissions compliance
- 2015 Project Objectives
  - Engine (combustion/controls/AT) system designed to meet 50% petroleum reduction target and emissions compliance
- Goals align with VT Multi-Year Program Plan 2011-2015
  - Potential for replacement of petroleum (50%)

Milestones: 2015/2016

Budget Period	Milestone	Description	Delivery Date	Status
1	M1	ICP Development and Testing Complete	7/27/2015	Complete
1	M2	Cylinder Head Design Complete	9/30/2015	Complete
1	M3	Mule Engine Testing Complete	11/5/2015	Complete
1	M4	Nominal Combustion Analysis Complete	12/31/2015	Complete
1	GNG1	Steady-State Calibration Delivered	3/30/2016	Complete
2	M2	Tractor and Trailer Delivered	4/7/2016	Complete
2	M3	Transient Calibration Delivered	9/30/2016	In-Process
2	M4	Final Vehicle Demonstration Complete	12/20/2016	In-Process

Technical Approach



Go / No-Go Decision Point

- Completion of Steady State Calibration
  - **Q1 2015 - COMPLETE**
- Demonstrate ability to achieve 50% petroleum reduction in steady state

Final Demonstration

Final demonstration will include vehicle operation on developed calibration

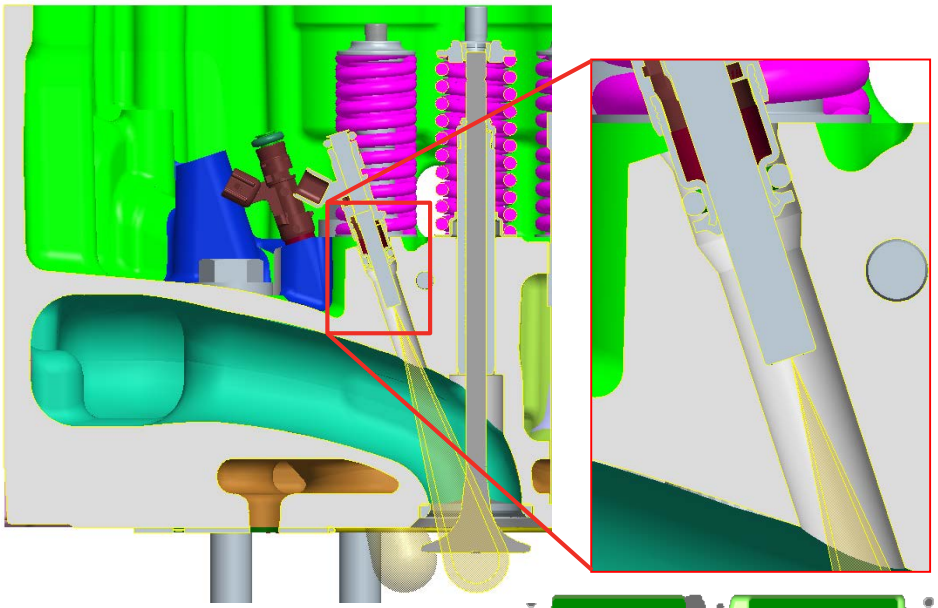
Technical Challenges / Barriers

- Combustion/engine system design to operate over entire speed/torque map
- Design integration of secondary fuel system and in-cylinder pressure sensors
- Closed-loop controls development to ensure robust operation over entire map and during transient operation

Technical Accomplishments

- Cummins has successfully designed and demonstrated a dual-fuel engine for a Class 8 heavy duty truck
  - Demonstrated Performance To Date
    - 51 % Petroleum Reduction over SET 13 Mode Roll Up
    - 53% Petroleum Reduction over FTP Look Up (Fuel Map)
    - Engine Out NOx & PM Reductions over Diesel Counterpart
    - Full Engine Map and Torque Curve Operation

Technical Accomplishments: Design

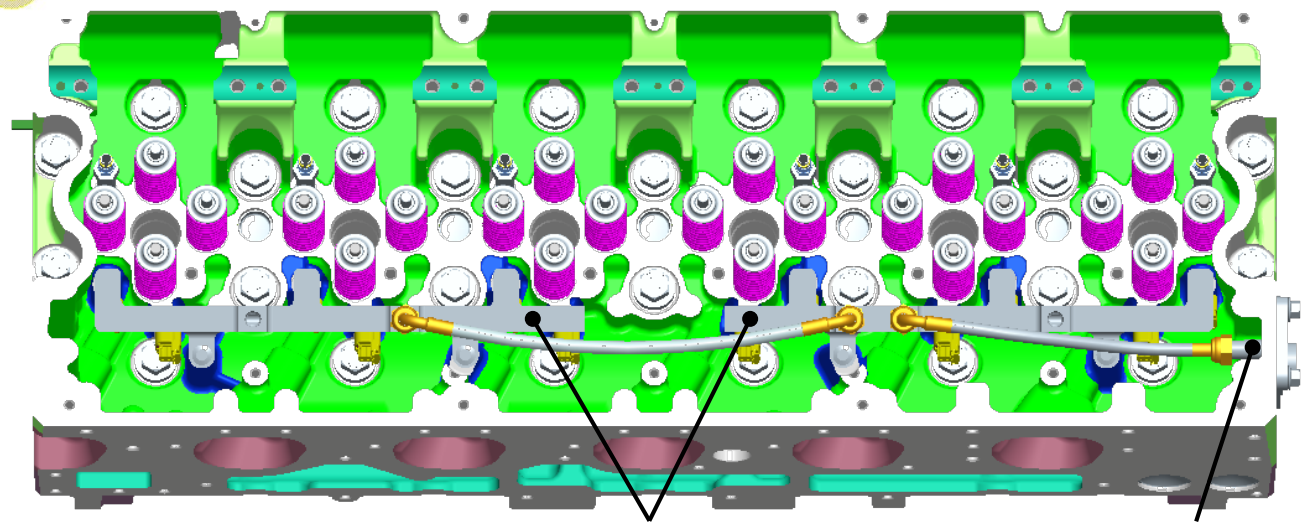


Open Valve Injection

Both α=10° and α=14° spray plume angles shown

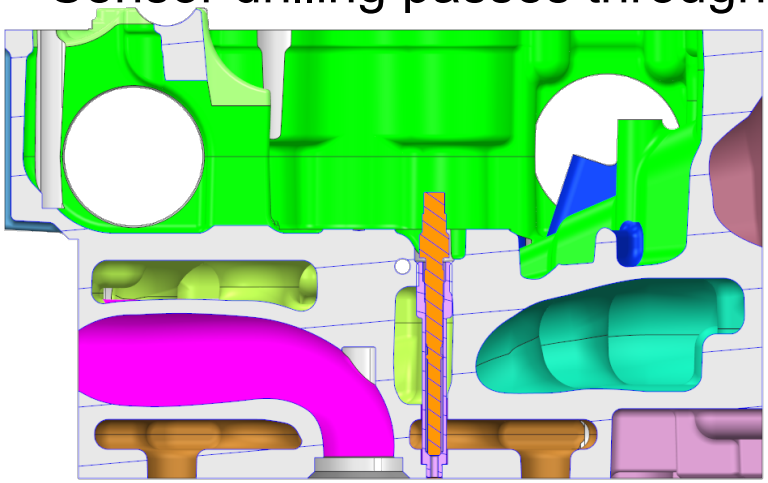
- PFI system packaged underneath valve cover
  - Initial testing during SuperTruck program

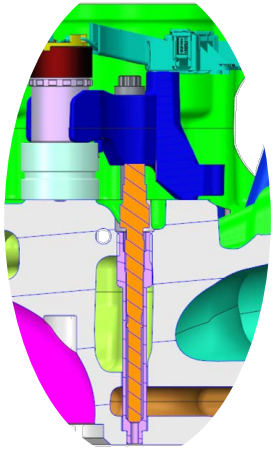
- Modifications required in program for ICPS

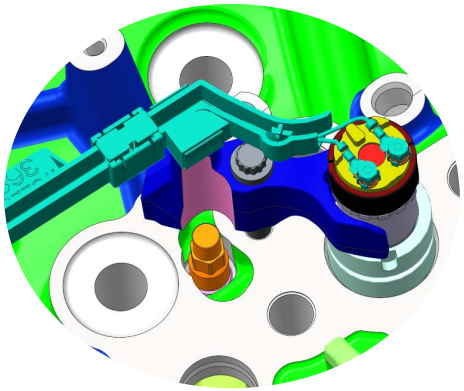


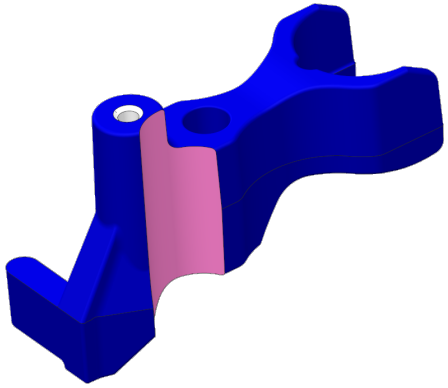
Technical Accomplishments: Design

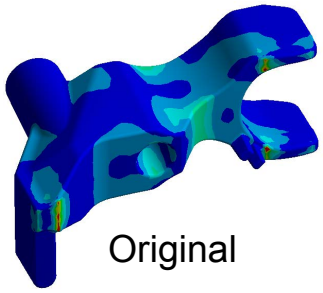
- Production in-cylinder pressure sensor (ICPS) packaged
- Sensor drilling passes through 2 cooling jackets



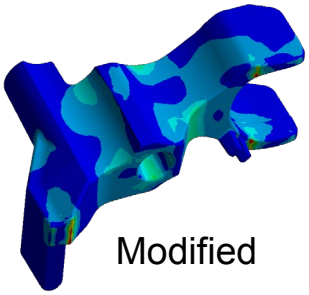








Original

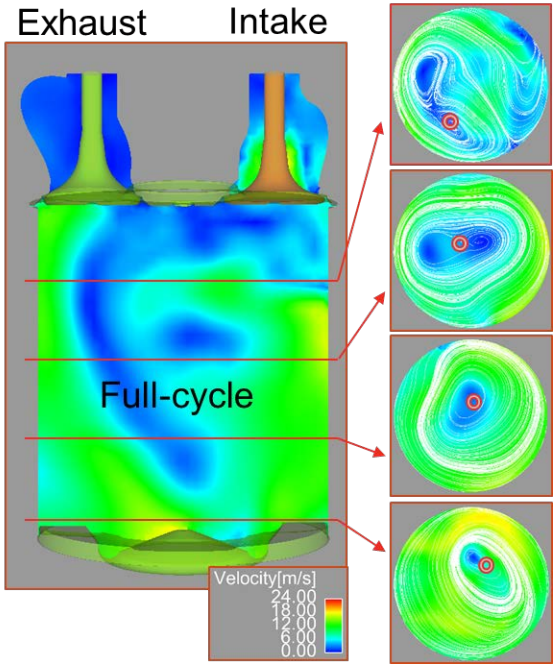


Modified

*Structurally acceptable modification

Technical Accomplishments: CFD

- Analysis-Led Combustion System Design
  - Key Combustion System Design Elements
    - Compression Ratio
      - Piston bowl shape
    - Diesel Injector Configuration
      - Number of nozzle spray holes
      - Size of nozzle spray holes
    - In-Cylinder Charge Motion
      - Swirl
      - Tumble
  - Robustness and Controllability of Combustion Process

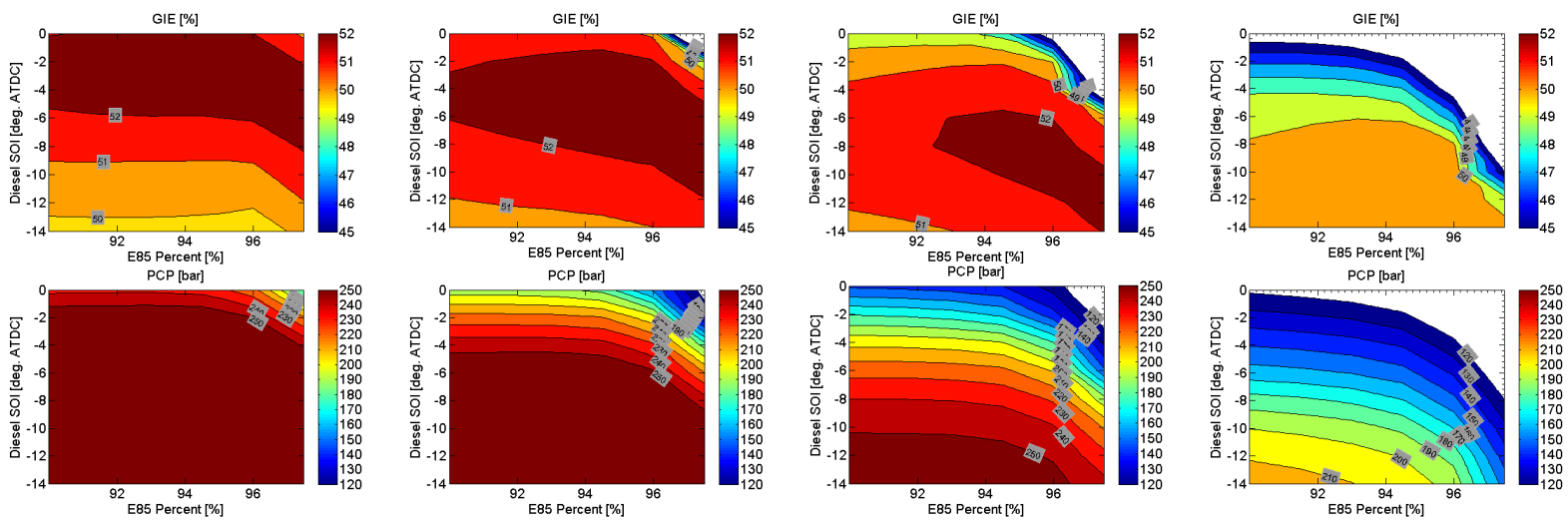


Technical Accomplishments: CFD

Selection of Compression Ratio (CR)

- Based on A100 engine operating point since it is most challenging point (pre-ignition)
- CR swept from 13:1 to 16:1
- DoE calculation for different CR pistons (vary EGR, PFI ratio, DI SOI)

Selected DoE results at 20 % EGR



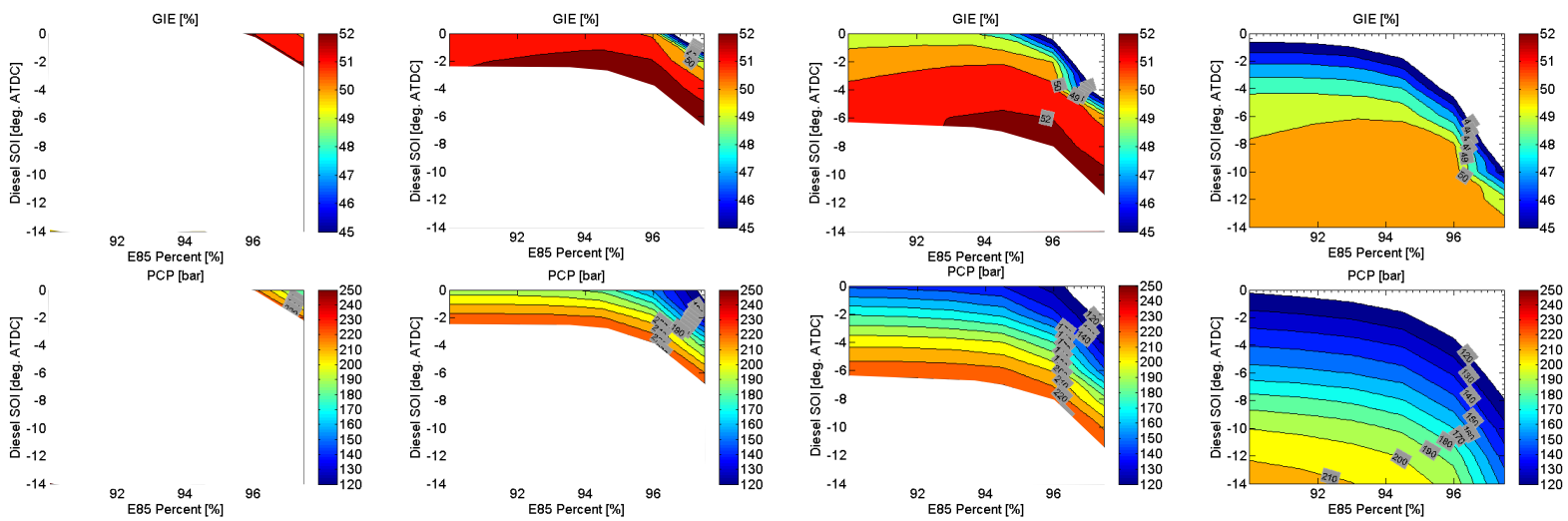
CR16:1 CR15:1 CR14:1 CR13:1

Technical Accomplishments: CFD

Selection of Compression Ratio (CR)

- Based on A100 engine operating point since it is most challenging point (pre-ignition)
- CR swept from 13:1 to 16:1
- DoE calculation for different CR pistons (vary EGR, PFI ratio, DI SOI)
- Apply mechanical limits for engine
- Larger engine operating window for a lower compression ratio
  - Lower peak engine efficiency
- CR of 14:1 is selected for best compromise of high and low load performance

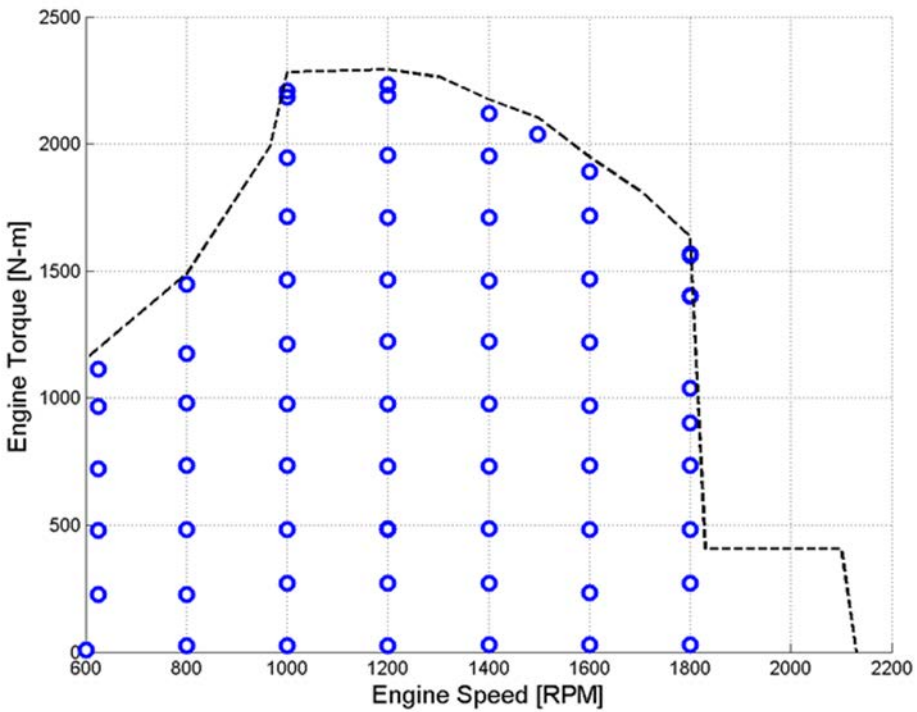
Selected DoE results at 20 % EGR



CR16:1 CR15:1 CR14:1 CR13:1

Technical Accomplishments: Testing

- Highly premixed combustion systems have been traditionally challenged to achieve torque curve operation
- The dual fuel approach developed in the program is capable of operating across the entire engine operating map



Technical Accomplishments: Testing

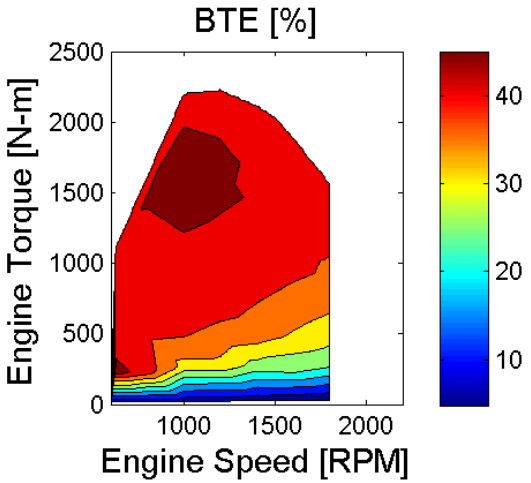
- Test cell development efforts have demonstrated capability to reduce petroleum usage by greater than 50%
- On-going work is focusing on reducing the HC/CO emissions

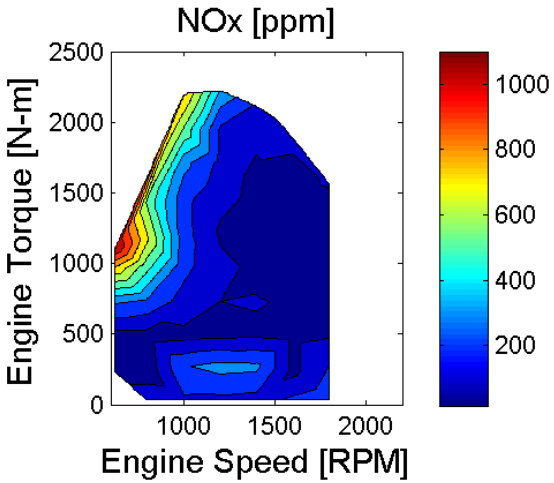
13 Mode SET Composite*		
Petroleum Reduction	[%]	50.9
BTE	[%]	43.5
BSFC	[g/kW-hr]	254
BSNOx	[g/kW-hr]	1.43
BSHC	[g/kW-hr]	2.53
BSDPM	[g/kW-hr]	0.118
BSCO	[g/kW-hr]	4.21
BSCO2	[g/kW-hr]	618

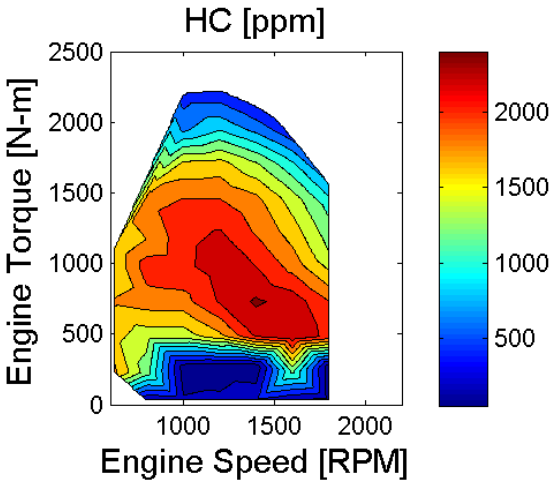
*Engine Out Emissions

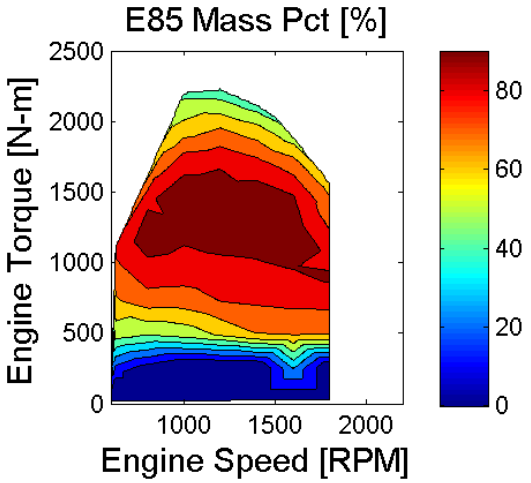
Technical Accomplishments: Testing

- The new steady state calibration balances emissions, efficiency and petroleum reduction
- Additional work remains to minimize HC emissions at mid load conditions



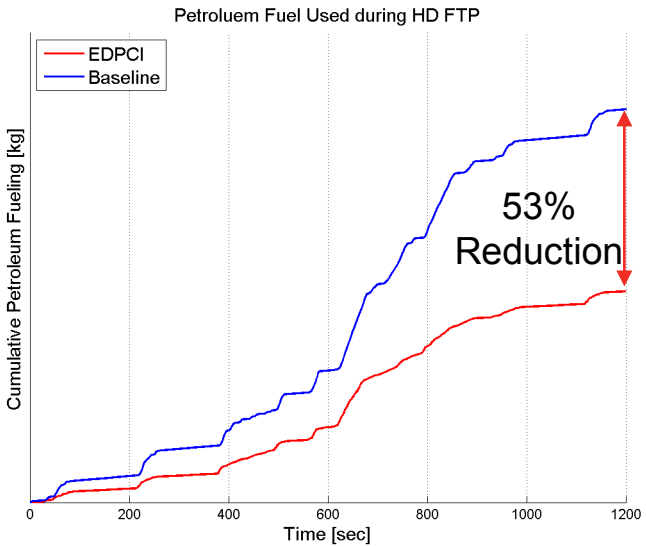


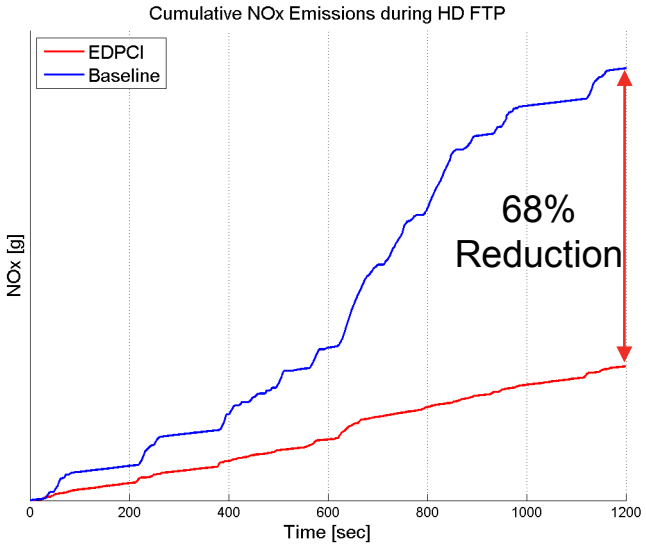




Technical Accomplishments: Testing

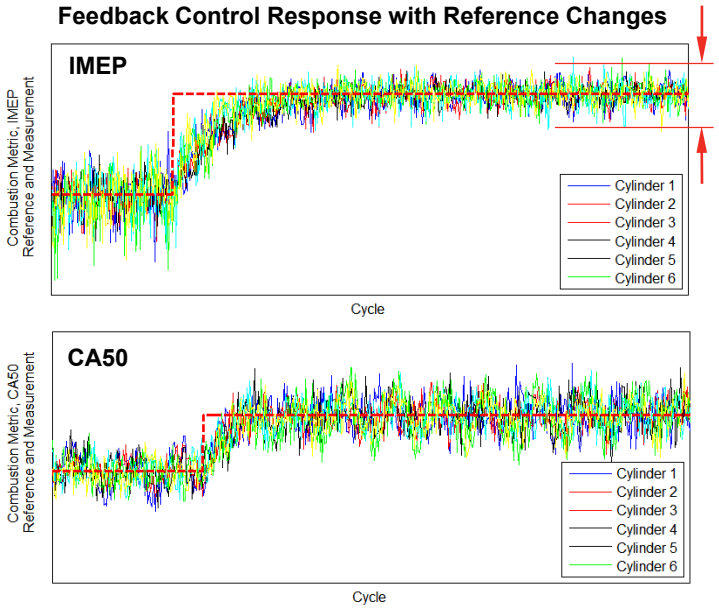
- Interpolated HD FTP cycle from fuel map data
- HD FTP cycle analysis
  - 53% petroleum reduction
  - 68% NOx reduction
    - Engine out NOx
- Transient control and calibration efforts are currently being performed

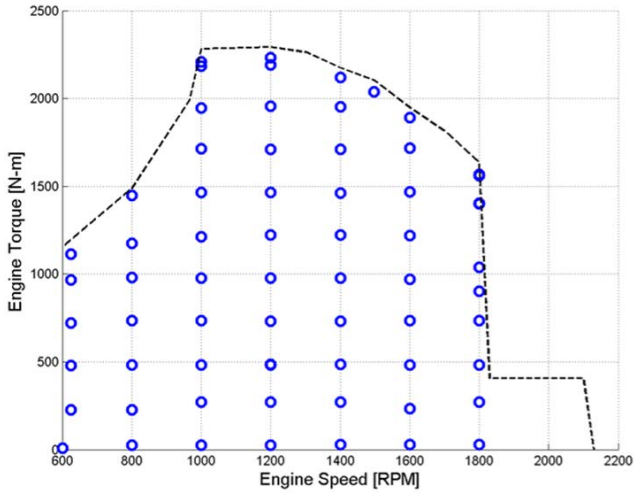




Technical Accomplishments: Controls

- Key Requirements for Controls System Technologies
  - Cylinder-to-cylinder and cycle-to-cycle control
  - Feed forward + Feedback control implementation
  - Closed-loop control system reference to encompass entire speed and torque operating zone



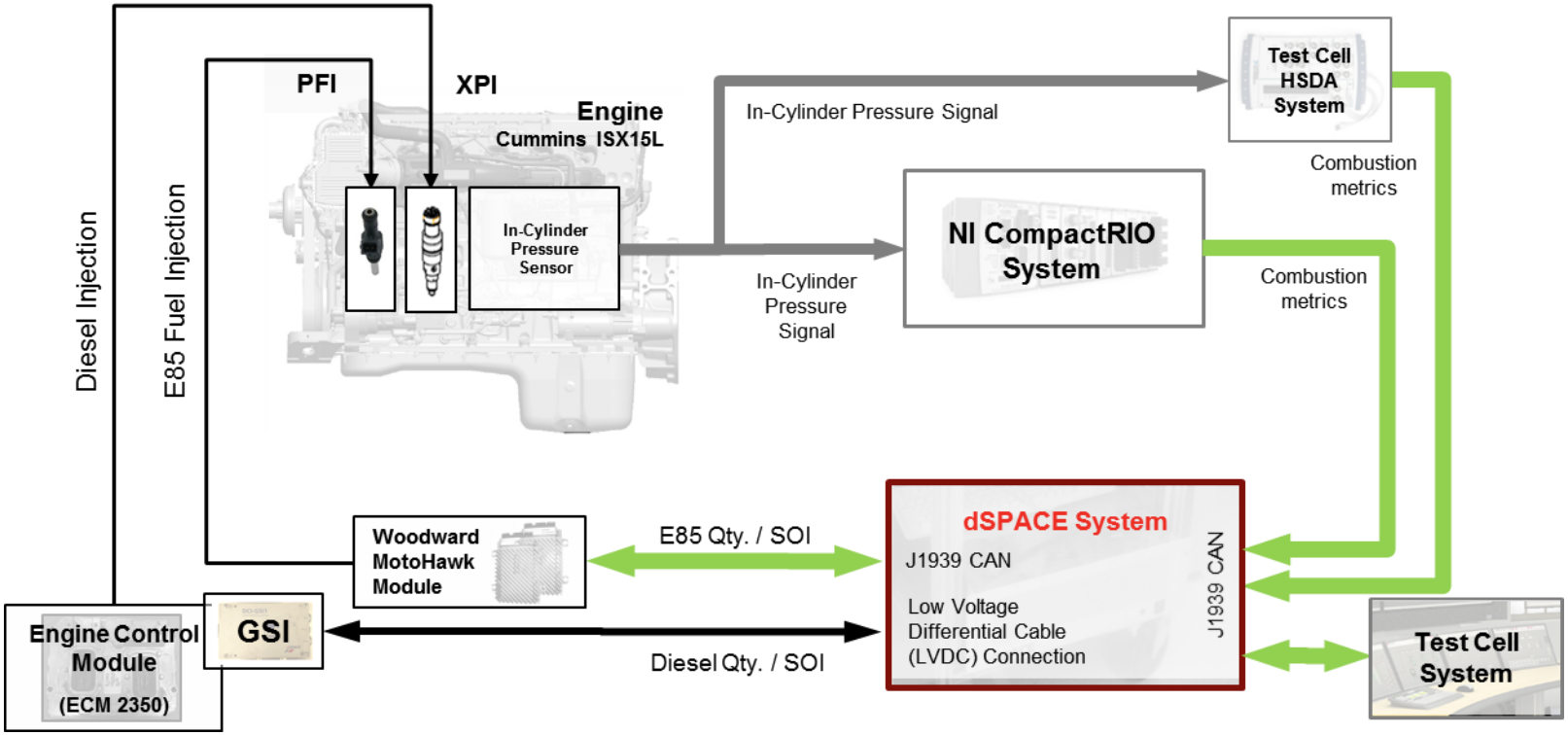


Cylinder-by-cylinder closed-loop controls using cycle-by-cycle combustion metrics minimize combustion variations.

Successful data collections at key operating points and max torque curve show capabilities of controls system at steady state.

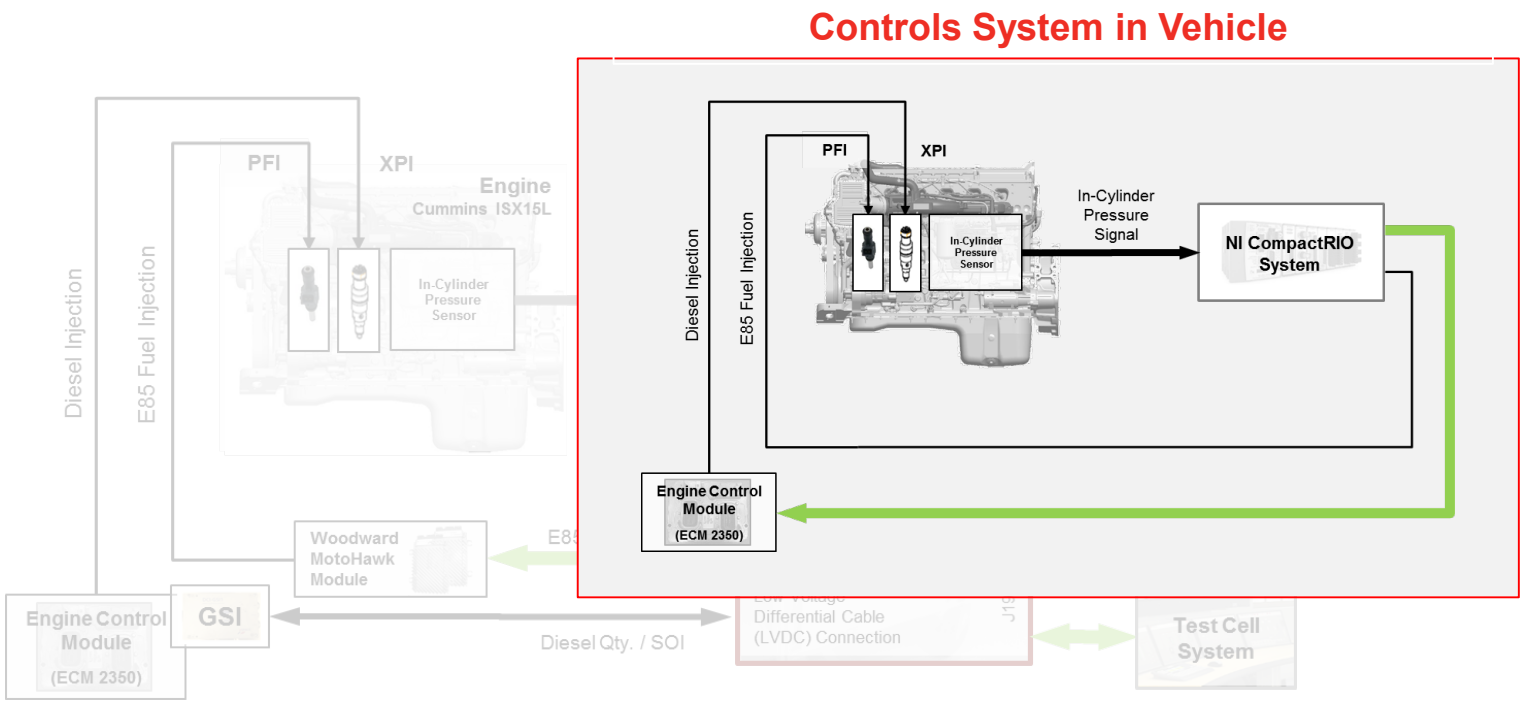
Technical Accomplishments: Controls

Configuration in Test Cell (2015)



Technical Accomplishments: Controls

Configuration in Test Cell (2015)



- Moving controls to a simplified architecture for use in vehicle
- Flexible NI CompactRIO system provides controls and DAQ capabilities

Response to Reviewer Comments

- This project was not reviewed last year.

Collaborations

- Cummins Fuel Systems
  - Provide Advanced XPI Fuel System (Direct Injection)
    - Modified injector configurations
    - Instrumented injectors for tip temperature
      - Critical to avoid injector coking/fouling
      - Small injected diesel quantity reduces injector tip cooling
  - Provide High Pressure Fuel Pump
    - Modified high pressure fuel pump
      - Rail pressure control was problematic at small quantities
      - Modified pump greatly improved rail pressure control

Remaining Challenges & Barriers

- Engine out hydrocarbon emissions are challenging at mid load conditions
- Cold start and warm-up strategies will require additional work
  - Low compression ratio is a challenge
  - May need to consider additional aids (i.e. glow plugs)
- Mixed mode combustion on torque curve poses modeling challenges

Proposed Future Work

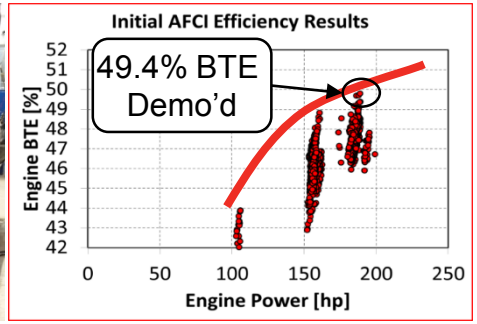
- Continue development of transient calibration
- Continue development of transient controls
- Complete vehicle build
- Perform emissions validation testing
- Perform vehicle testing

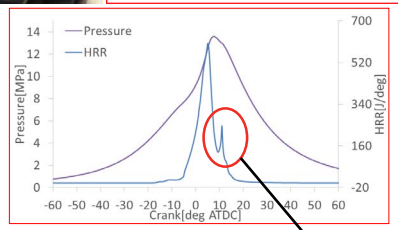
Summary

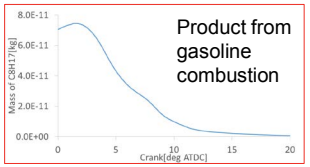
- Cummins has successfully designed and demonstrated a dual-fuel engine for a Class 8 heavy duty truck
  - Demonstrated Performance To Date
    - 51 % Petroleum Reduction over SET 13 Mode Roll Up
    - 53% Petroleum Reduction over FTP Look Up (Fuel Map)
    - Engine Out NOx & PM Reductions over Diesel Counterpart
    - Full Engine Map and Torque Curve Operation
- Demonstration of transient capability is in-process
  - Transient emissions demonstration
- Vehicle build is in-process
  - Vehicle demonstration

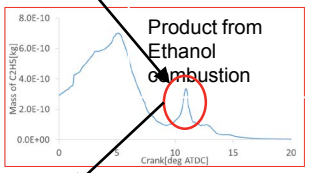
Technical Back-Up Slides

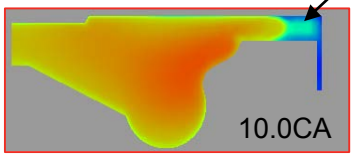
SuperTruck 55% BTE AFCI Results







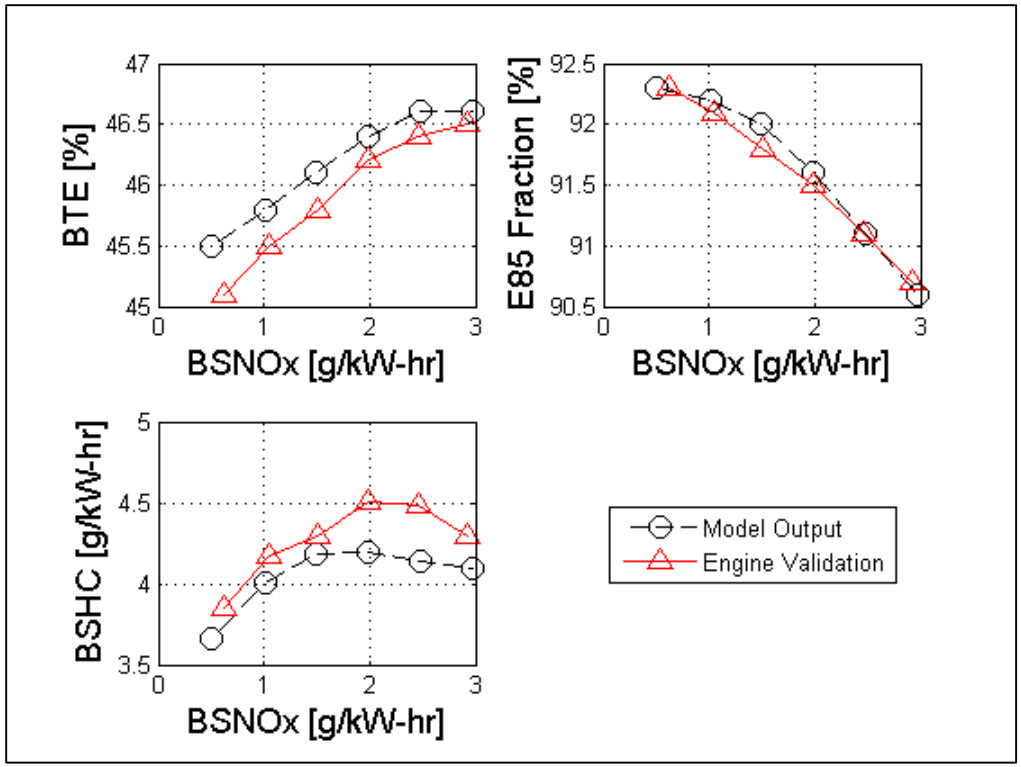




1. Dual fuel approach showed load limitation @ 10 bar BMEP
2. A new version of Comb CFD analysis tool identified auto-ignition source
   - Abnormal heat release around 10 CA is mainly caused by the auto-ignition of Ethanol at the piston top

B50 Optimization

- Decent matching between model and engine curves
  - Can be improved with more data in poorer matching areas



- Can leverage such trade-offs to improve rollups/cycle performance