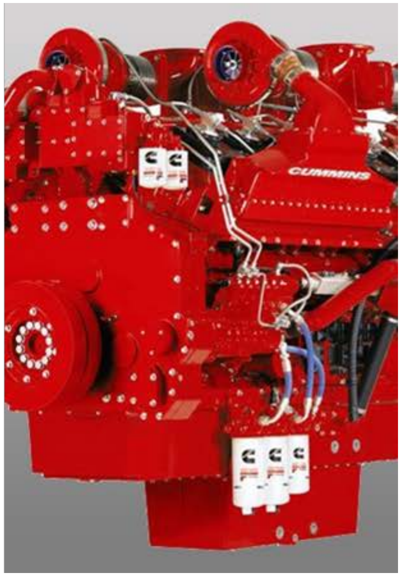
Cummins 55% BTE Project

Lyle Kocher – Principal Investigator
Cummins Inc.

June 9, 2016

Project ID: ACE098



Overview

Timeline

- Start: 12/1/2015
- End: 12/31/2017
- 5% Complete

Budget

- $9.0M Total Budget
  - $4.5M DOE
  - $4.5M CMI
- $0k in Funding for FY2015
- $2.9M for FY2016

Technical Targets / Barriers

- Advanced Combustion Engine
  - Engine thermal efficiency of 55%
  - Lack of fundamental knowledge of advanced engine combustion regimes
  - Lack of effective engine controls

Partners

- Cummins Fuel Systems
- Cummins Turbo Technologies

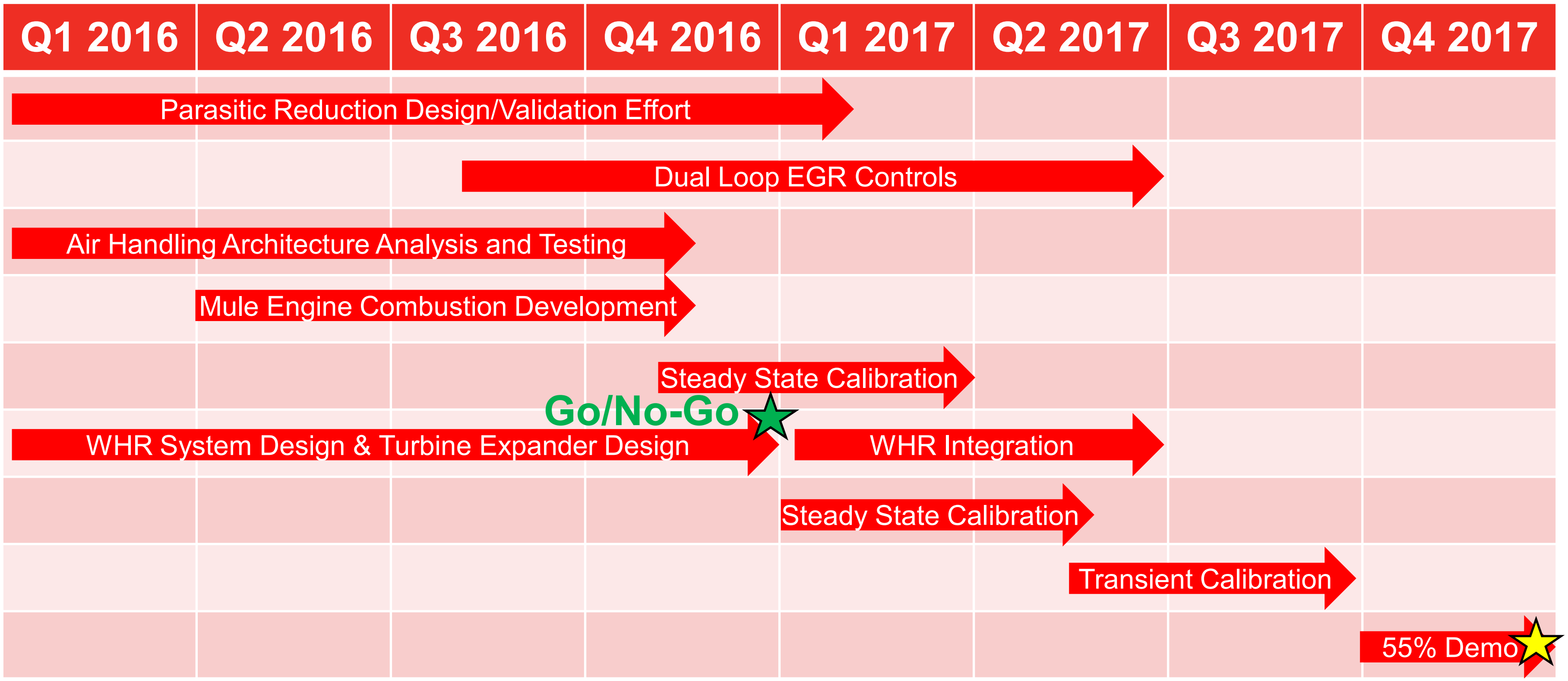
Relevance

- Overall Project Objectives
  - Use a diesel engine system to demonstrate in a test cell peak engine system efficiency of 55%
  - Develop and demonstrate an engine and aftertreatment system to achieve 2010 emissions compliance
- Goals align with VT Multi-Year Program Plan 2011-2015
  - Engine thermal efficiency of 55%
  - Prevailing emissions compliance

Milestones – 2016/2017

Budget Period	Milestone	Description	Delivery Date	Status
1	M1	Lube Pump Design Complete and Procured	3/31/2016	**Complete**
1	M2	Air Handling Controls System Design Selection Complete	6/30/2016	**In-Process**
1	M3	Lube Pump Design Integration Complete	9/30/2016	**In-Process**
1	M4	WHR Turbine Expander Design Complete	12/31/2016	**In-Process**
1	GNG1	50% BTE (Engine Only) Demonstration Complete	12/31/2016	**In-Process**
2	M5	Aftertreatment System Design Complete	3/31/2017	
2	M6	SET Emissions Demonstration Complete	6/30/2017	
2	M7	Hot FTP Emissions Demonstration Complete	9/30/2017	
2	M8	55% BTE Final Demonstration Complete	12/31/2017	

Technical Approach



Go / No-Go Decision Point

- Test cell demonstration of 50% BTE
  - Engine only performance
  - No WHR

Final Demonstration

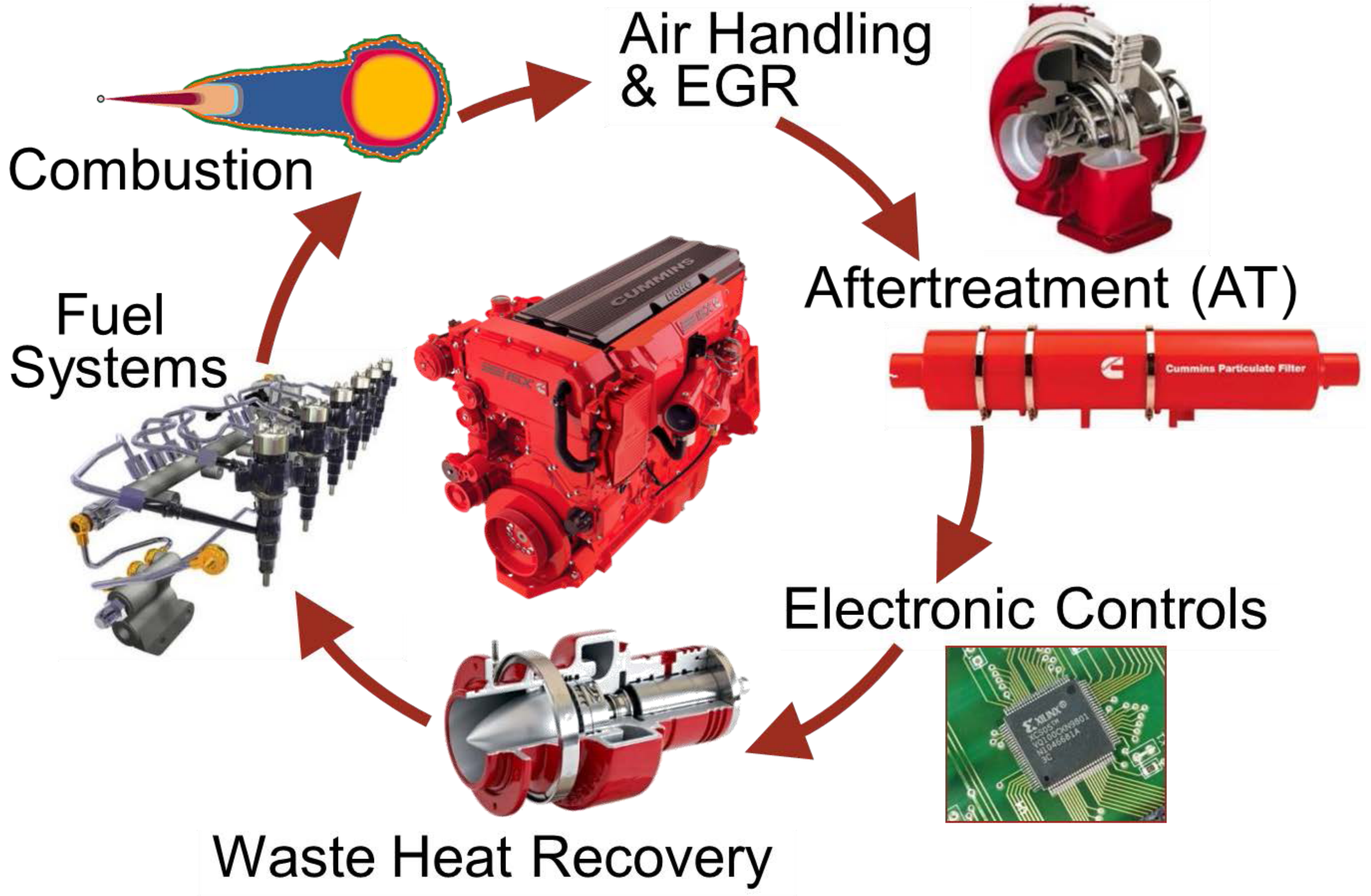
Final demonstration will include emissions demonstration and 55% BTE peak point

Technical Challenges / Barriers

- Combustion system design to achieve 50% BTE without WHR
- Design integration of parasitic reduction efforts
- Optimization of Dual Loop EGR architecture

Technical Approach

Approach - Integration of Cummins Component Technologies

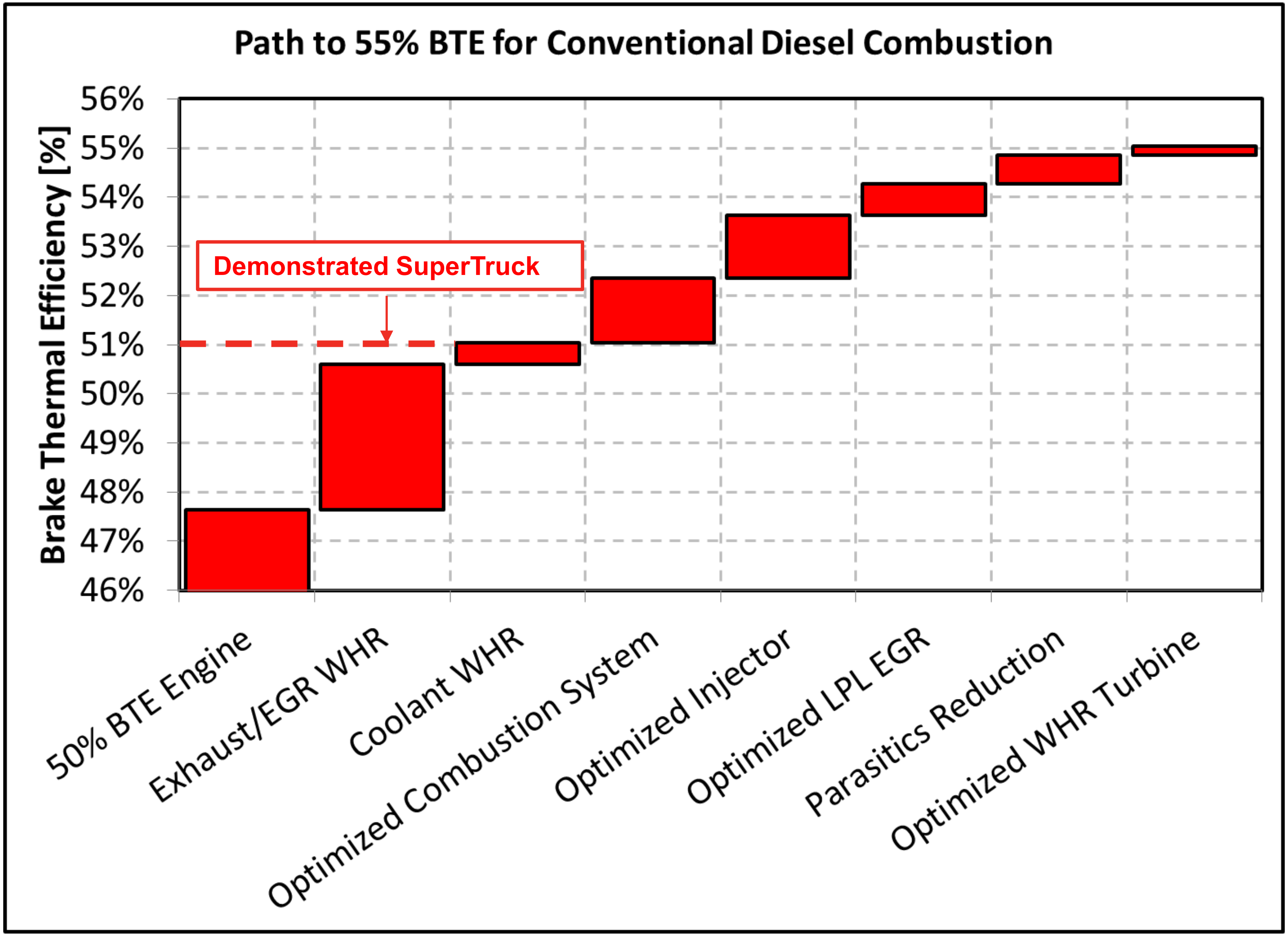


This presentation does not contain any confidential, proprietary, or otherwise restricted information.

Technical Accomplishments

- Cummins has created an analytical path to 55% BTE
  - Demonstrated Performance To Date
    - Initial fuel system injector designs have been completed
      - Injectors will be robust to cavitation and are expected to meet performance targets
    - Combustion system development is progressing
      - Analysis supports target improvement levels in path to 55% BTE
    - Initial air handling architecture has been evaluated
      - Analysis support gains in path to 55% BTE
      - Might need to run higher engine out NOx levels to hit BTE goal
    - Parasitic reduction are being pursued with rig validation planned
    - WHR system is being optimized for new heat sources
      - New turbine expander being designed for best BTE point

Technical Accomplishments: Path

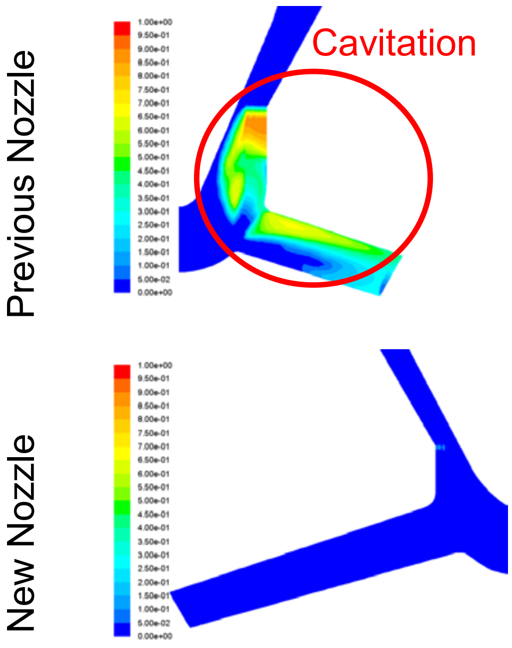


Technical Accomplishments: Path

Subsystem	SuperTruck 51% BTE (Baseline)	55% BTE Proposal (Additional or Replace)	Expected Benefit
Combustion System	Steel Piston, Piston Cooling	Higher CR Piston, Insulated Surfaces No/Low Piston Cooling, Higher Coolant Temperature	+1.3% BTE Point
Fuel System	Traditional Common Rail Injector	High Flow Injectors (3 times faster injection)	+1.3% BTE Point
Air Handling	High Pressure Cooled EGR, Variable Geometry Turbocharger	Dual Loop EGR & Larger Turbocharger, Consider Twin Entry WG	+0.6% BTE Point
WHR	EGR, Exhaust, Coolant, Lube	HP EGR, LP EGR, Exhaust, Coolant, Lube, Charge Air Cooler	+0.2% BTE Point
Aftertreatment	DOC+DPF+SCR Conventional	DOC+SCRF Close-Coupled + SCR	NOx Conversion Efficiency
Mechanical System	Low Tension Oil Ring, Variable Flow Lube Pump, Plasma Coated Liners, Reduced Piston Cooling	Low Tension Piston Rings, DLC Coated Rings, New Plasma Coated Liners, No/Low Piston Cooling, Variable Flow Pumps, Reduce Valvetrain Parasitic	+0.6% BTE Point

Technical Accomplishments: Injectors

- Diffusion combustion is mixing controlled/limited
- Shorten combustion duration by increasing fuel injection rate
- Challenge for injector design is avoiding cavitation
- Cummins Fuel Systems
  - Analysis led design process
  - Enables robust, cavitation-free operation
- Next generation injectors are designed, procured and ready for testing

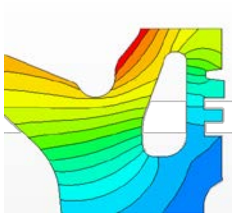


Lift = 150µm

Technical Accomplishments: Pistons

Kicked Off and In-process

Projected Timing Q3



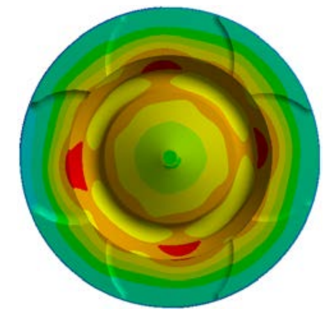
- Thermal Sensitivity
- Material Selection

Structural Analysis

Conjugate Heat Transfer Analysis

- Temperature Prediction
- HT & Perf. Prediction

Projected Timing Q4

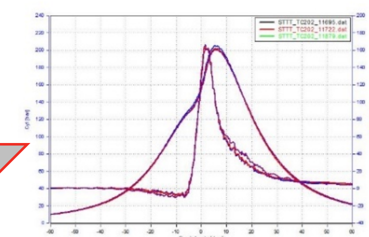


Thermal Survey

- Temperature Validation
- Model Verification

Performance Evaluation

- Brake Thermal Eff and Closed Cycle Eff



This presentation does not contain any confidential, proprietary, or otherwise restricted information.

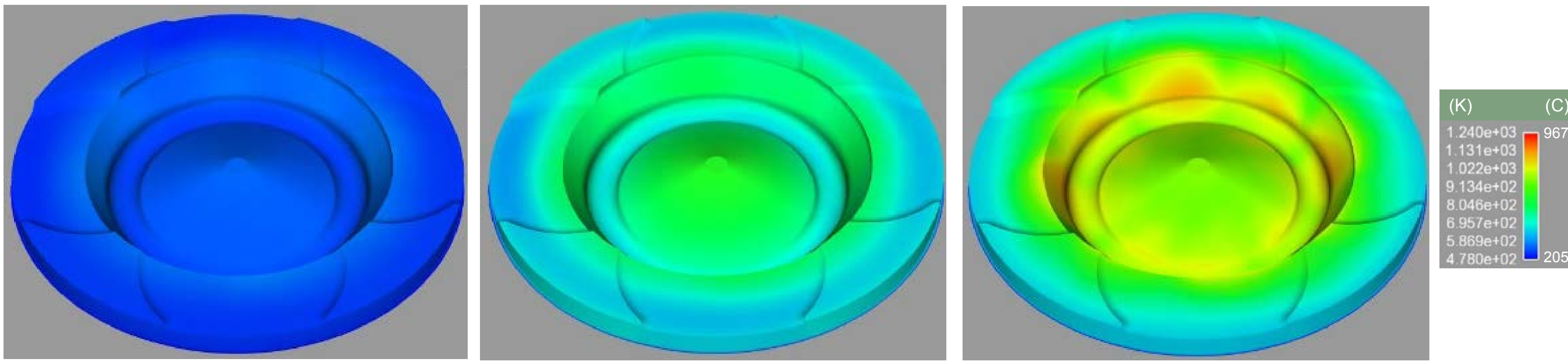
Technical Accomplishments: Pistons

Piston Crown Temperatures

Standard Steel Piston Design

Moderate Temperature Increase Design

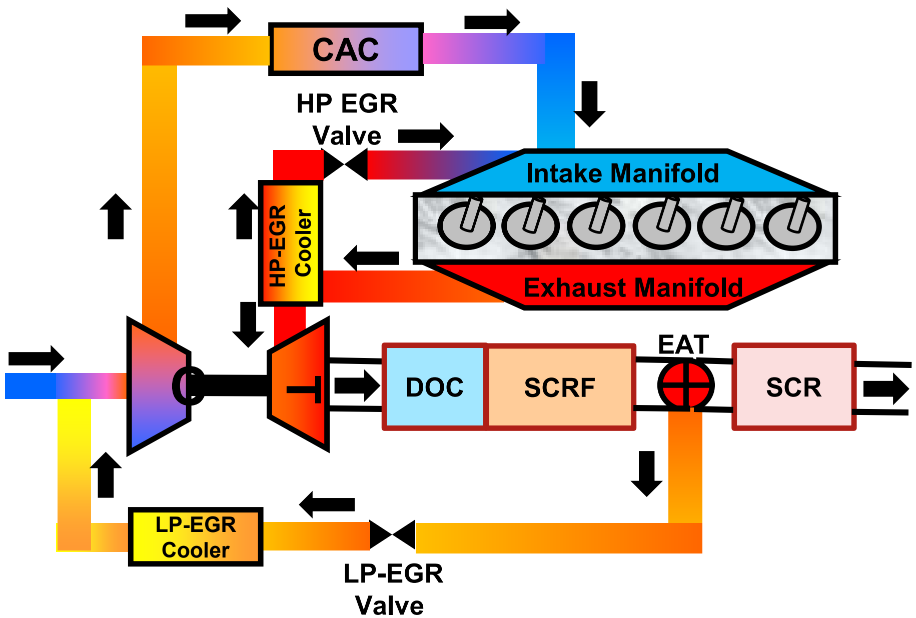
Aggressive Temperature Increase Design



- Working with multiple suppliers on piston designs
- Conjugate Heat Transfer analysis is guiding the work
  - Performing CHT with suppliers in the analysis process
- Challenge is to turn heat transfer reductions into efficiency
  - This has been limiting factor in previous work

Technical Accomplishments: EGR

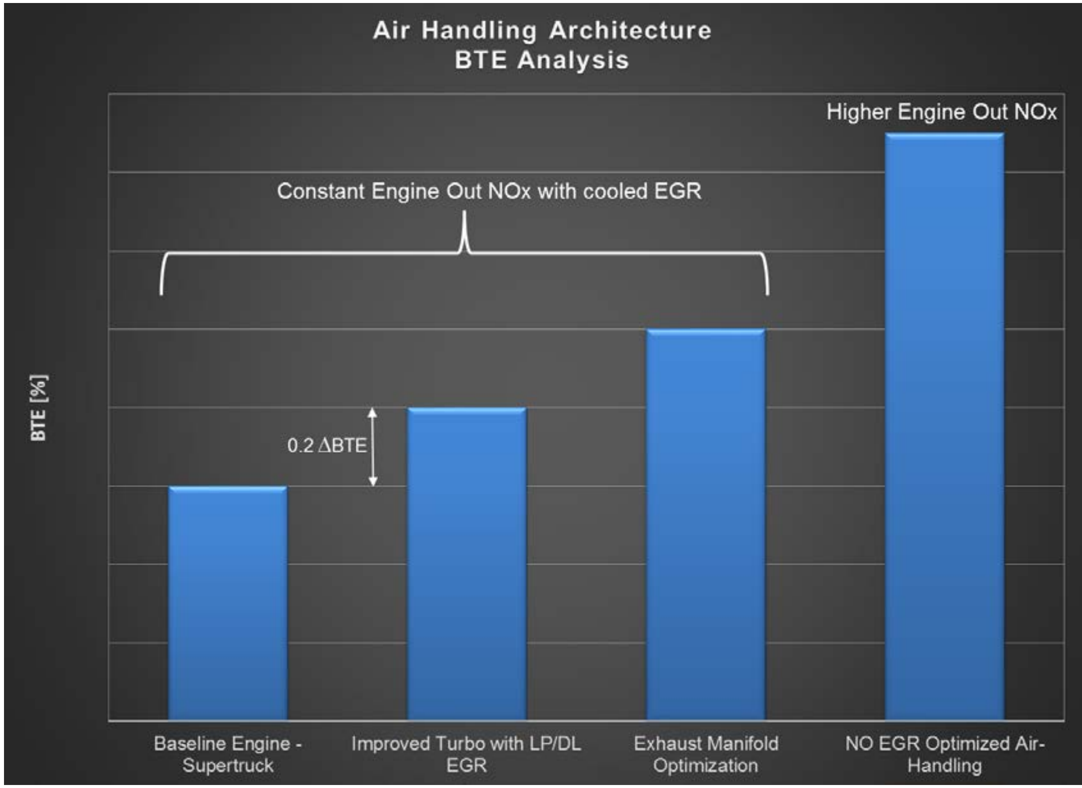
- HP & LP Cooled EGR
  - Dual Loop
- Advanced turbo technologies
  - Larger turbocharger
  - Abradable coatings
  - Turbine diffuser
  - Roller bearings
  - Extrusion honed turbine casing
- Optimized exhaust manifold design
  - Pulsation utilization
- Cam timing optimization



Innovation You Can Depend On™

Technical Accomplishments: EGR

- Initial EGR Loop architecture analysis is underway
- Baseline is the 51% BTE SuperTruck Engine
  - HP EGR Loop
- Dual Loop EGR solution paired with larger turbocharger showing potential for 0.2dBTE-unit improvement
- Exhaust manifold optimization showing potential for additional 0.2 dBTE-unit
- Higher Engine Out NOx & turbocharger improvements can provide additional BTE improvements



Technical Accomplishments: Parasitic

Coolant and Lube System	Valve Train	Power Cylinder
• Variable Coolant Pump • Variable Lube Oil Pump • Improved Lube System Flow Losses • Reduced Oil Flow of Valve Train	• Reduced Component Inertias • Reduced Stiffness Springs • Reduced Oil Flow	• Lower Friction Ring Coatings • Lower Ring Tension • Improved Piston Skirt Coatings • Improved Piston Profiles

Analysis Model

- Valve Train Models
- Power Cylinder Models
- Flow/Power Calculations

Rig Validation of System

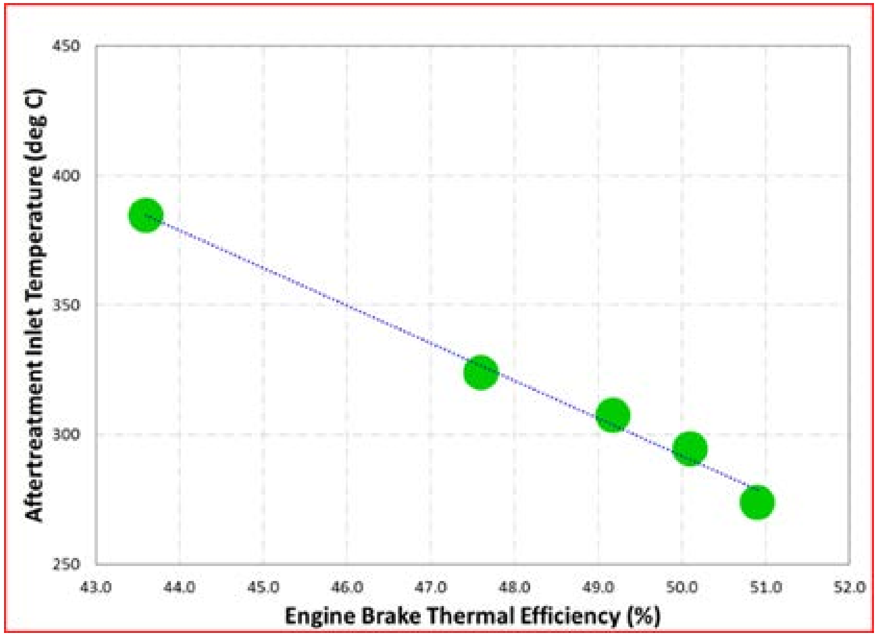
- Cylinder Head Rig
- Engine Friction Assessment
- Pump Flow Testing & System Validation

Transfer of Systems onto Performance Demonstration

- Validated Parasitic Signature

Technical Accomplishments: AT

- Two main challenges for aftertreatment system on high BTE engines
  1. Low exhaust temperatures
  2. Higher engine out NOx
     - Due to hotter combustion temperatures

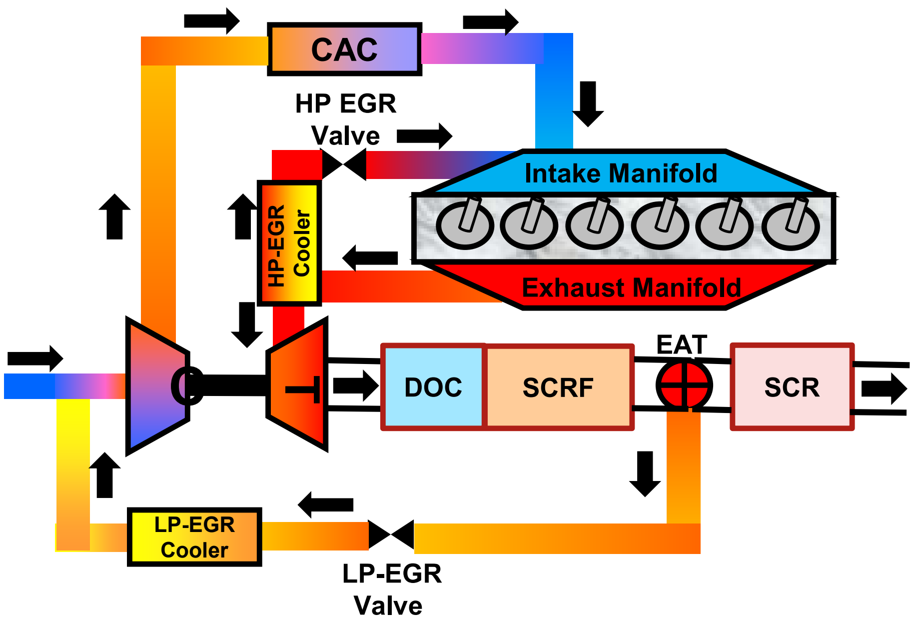


- Performance Requirements
  – Comply to 2010 HD EPA
  – Enable LP EGR by close coupling
  – Minimize heat loss to ambient to maximize WHR efficiency
  – Maximize open cycle efficiency by lowered back pressure penalty

Innovation You Can Depend On™

Technical Accomplishments: WHR

- Waste Heat Sources
  - Engine Coolant/Lube
  - EGR (LPL & HPL)
  - Exhaust
  - Charge Air Cooler
- Turbine Expander
  - New turbine expander design
  - Optimized for best BTE point
- WHR Temperature Control
  - Avoid condensation in LPL EGR



Response to Reviewer Comments

- This project was not reviewed last year.

Collaborations

- Cummins Fuel Systems
  - Provide Advanced XPI Fuel System (Direct Injection)
    - Higher flow rate injectors
    - Analysis led design process
      - Robust, cavitation-free injectors
- Cummins Turbo Technologies
  - Provide Advanced Turbocharger Technologies
    - Larger turbocharger
    - Advanced coatings
    - Turbine diffuser

Remaining Challenges & Barriers

- High flow rate injectors can potentially have worse shot-to-shot performance
  - Need additional testing and analysis to ensure injector dynamics will not become unstable
- Higher engine out NOx will likely be required to achieve BTE goal
  - How much NOx can be tolerated by AT system?
- Previous work with insulated combustion systems have been challenged to demonstrate improved efficiency

Proposed Future Work

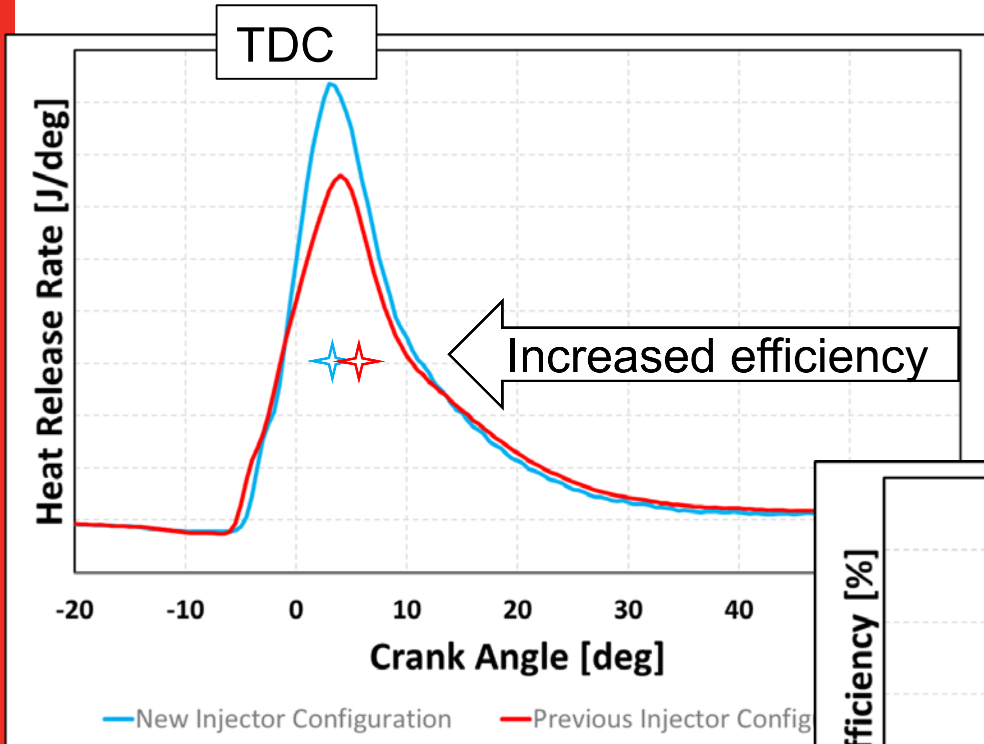
- Continue engine system developments
  - Reduce in-cylinder heat losses
  - Shorten combustion duration
- Continue air handling optimization
  - Dual loop EGR optimization
  - Turbocharger efficiency improvements
- Continue WHR system optimization
  - Develop new turbine expander
  - System optimization at best BTE point
    - Consider new waste heat sources

Summary

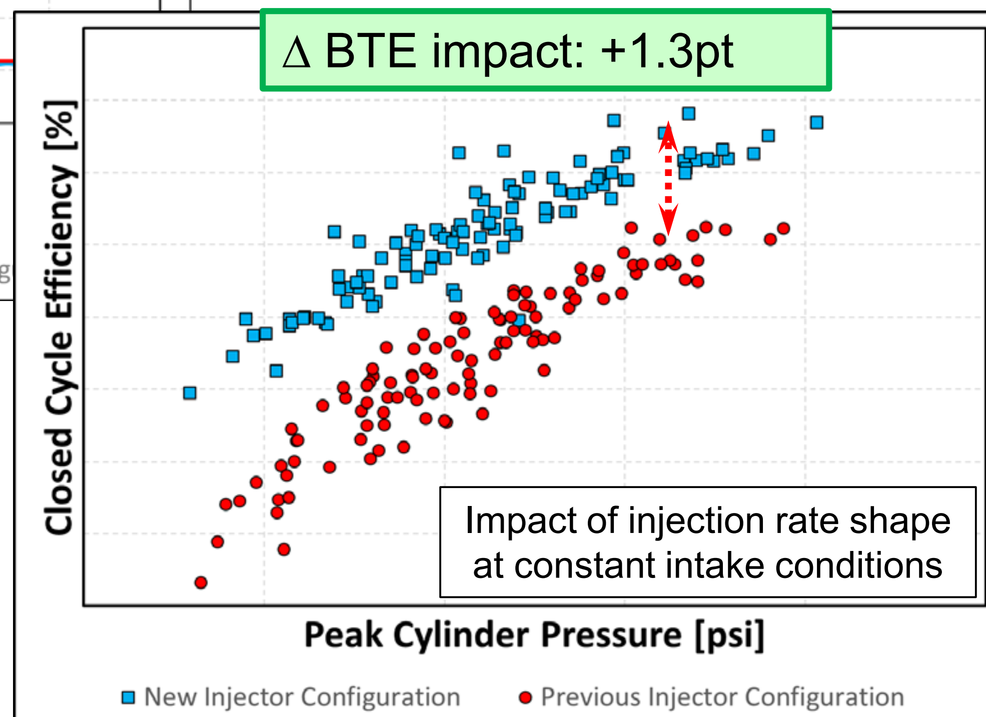
- Cummins has created an analytical path to 55% BTE
  - Demonstrated Performance To Date
    - Initial fuel system injector designs have been completed
      - Injectors will be robust to cavitation and are expected to meet performance targets
    - Combustion system development is progressing
      - Analysis supports target improvement levels in path to 55% BTE
    - Initial air handling architecture has been evaluated
      - Analysis support gains in path to 55% BTE
      - Might need to run higher engine out NOx levels to hit BTE goal
    - Parasitic reduction are being pursued with rig validation planned
    - WHR system is being optimized for new heat sources
      - New turbine expander being designed for best BTE point

Technical Back-Up Slides

Technical Progress
Optimized Injector – Single Cylinder Engine Results



- 3rd injector design completed
  - Robust cavitation design
  - Heat release improvements shown
  - Injector shot-shot work remains



- Single cylinder engine results show up to 2pt closed cycle efficiency gain
- Multi-cylinder results show ~1.3pt closed cycle gains
  - Air handling enhancements needed

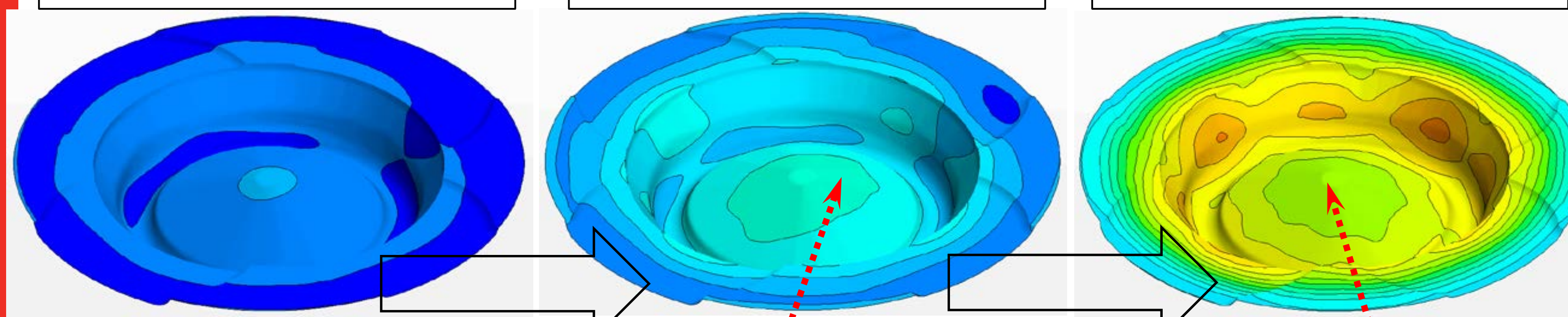
Koeberlein AMR 2015

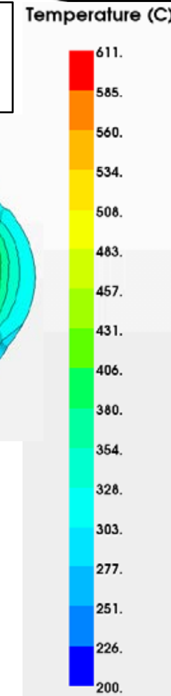
Technical Progress –
Piston Thermal Solution Validation Results

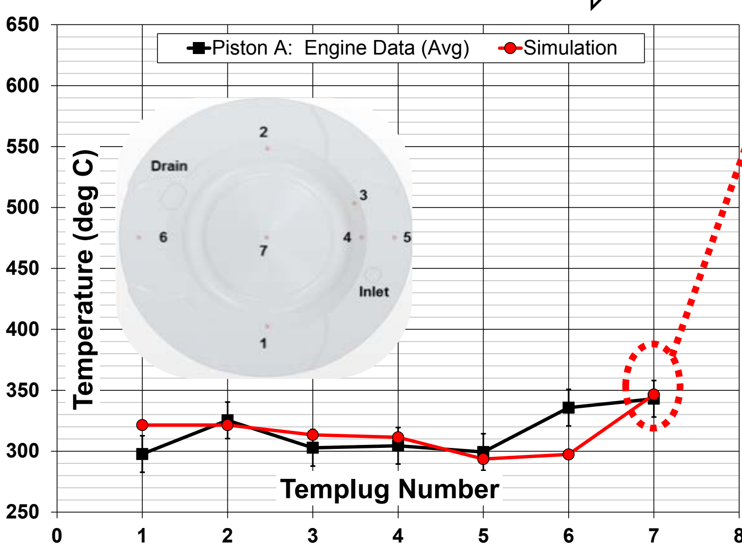
Base Piston:
Max Temperature = 254° C

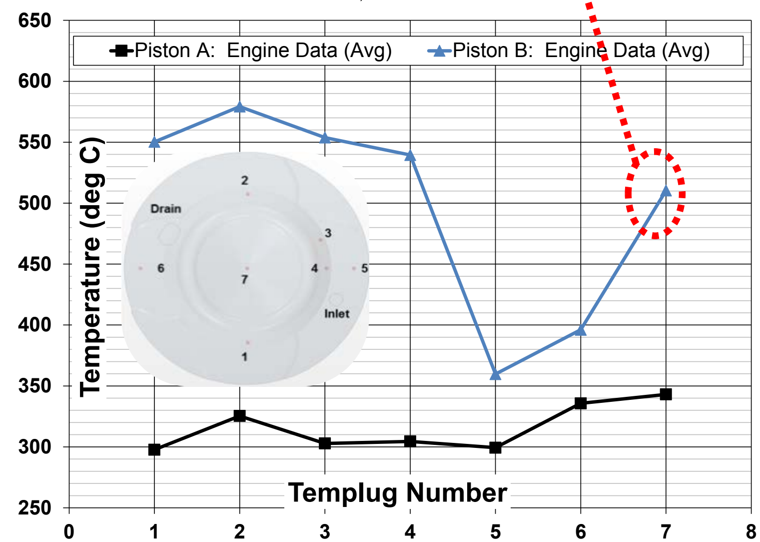
Piston A:
Max Temperature = 345° C

Piston B:
Max Temperature = 574° C





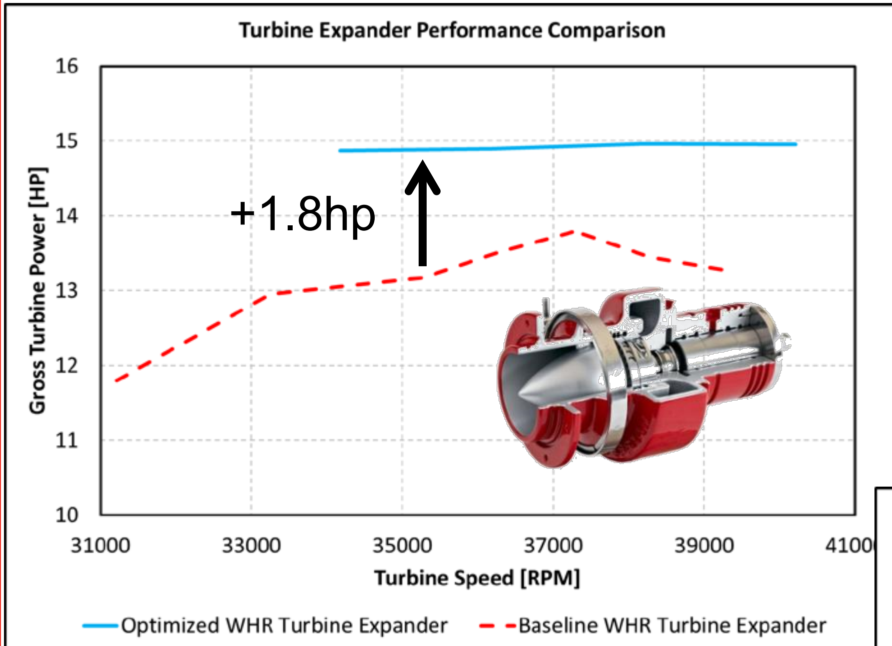




Net Cycle Δ BTE impact: + 1.7%
Includes open and closed cycle gains

Koeberlein AMR 2015

Technical Progress –
Improved WHR Turbine Expander & Parasitic Reduction Results

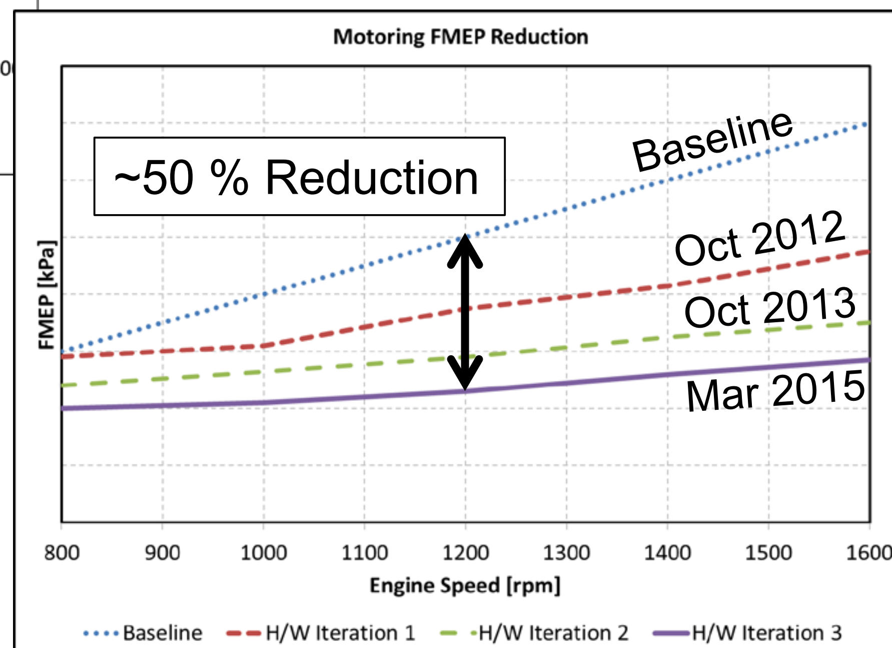


- Improved turbine efficiency
- System heat exchanger architecture arrangement
  - Pre-heat of low pressure loop

Total BTE contribution: 3.6%
Δ BTE impact: + 0.7% BTE

- Friction and Parasitic reduction validated on multi-cylinder engine
  - Piston/ring pack/liner changes
  - Piston cooling flow reduction
  - Fuel pump parasitic reduction
  - Lube pump improvements

Δ BTE impact: + 0.9% BTE



Koeberlein AMR 2015