Cummins 55% Brake Thermal Efficiency Project

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Cummins Inc.

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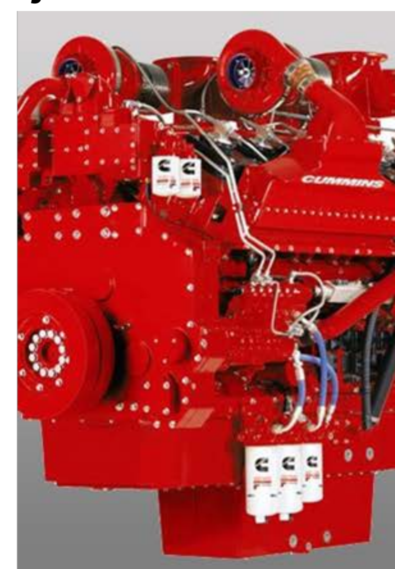
Project ID: ACS098



Overview

Timeline

- Start: 12/1/2015
- End: 12/31/2017
- 60% Complete

Budget

- $9.0M Total Budget
  - $4.5M DOE
  - $4.5M CMI
- $2.3M in Funding for FY2016
- $2.2M for FY2017

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

Internal Collaborations

- Cummins Fuel Systems
- Cummins Turbo Technologies

Suppliers

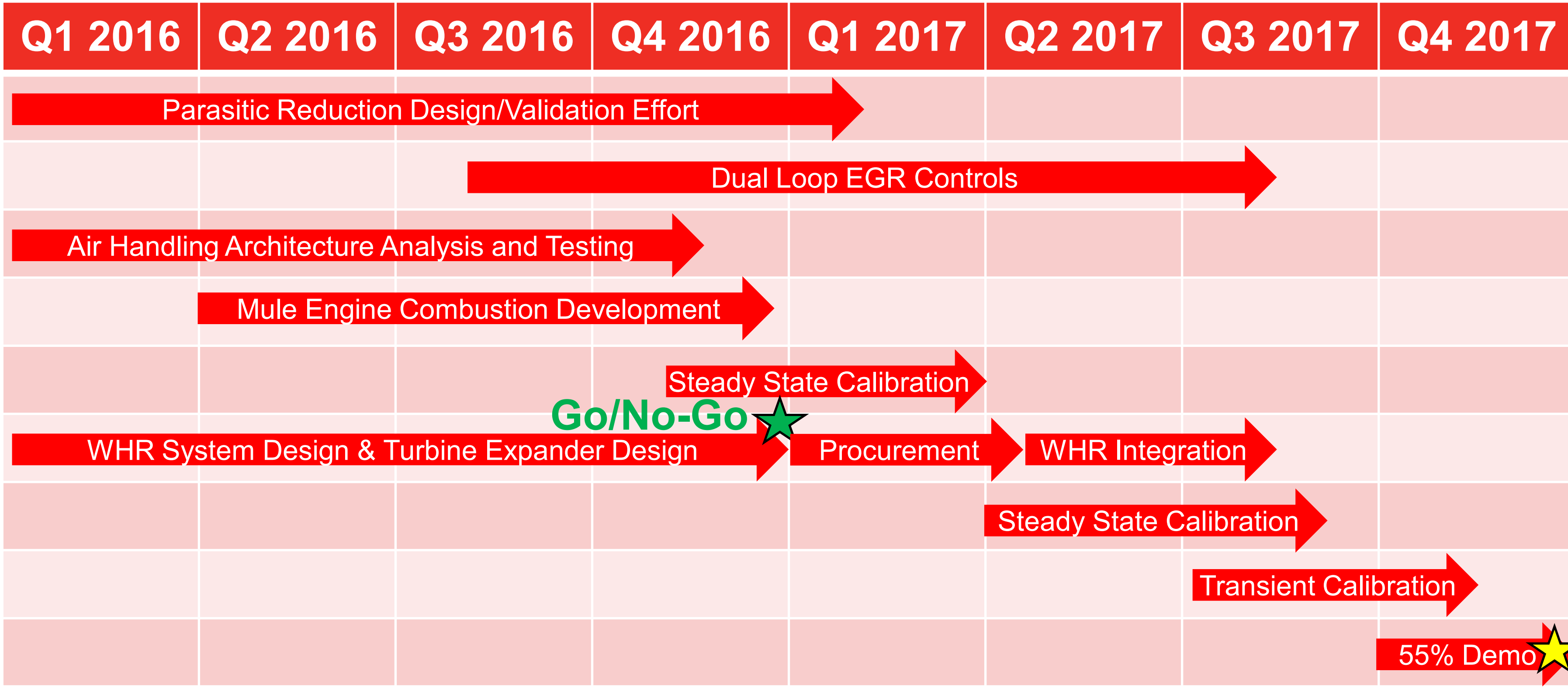
Relevance

- Overall Project Objectives / 2016 Progress
  - Use a diesel engine system to demonstrate in a test cell peak engine system efficiency of 55%
    - Demonstrated 49.2% BTE (engine only)
    - Designed WHR system
  - Develop and demonstrate an engine and aftertreatment system to achieve 2010 emissions compliance
    - Designed aftertreatment system to meet emissions limits
    - Developed dual loop EGR system
- 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	**Complete**
1	M3	Lube Pump Design Integration Complete	9/30/2016	**Complete**
1	M4	WHR Turbine Expander Design Complete	12/31/2016	**Complete**
1	GNG1	50% BTE (Engine Only) Demonstration Complete	12/31/2016	**In-Process**
2	M5	Aftertreatment System Design Complete	3/31/2017	**Complete**
2	M6	SET Emissions Demonstration Complete	6/30/2017	**In-Process**
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

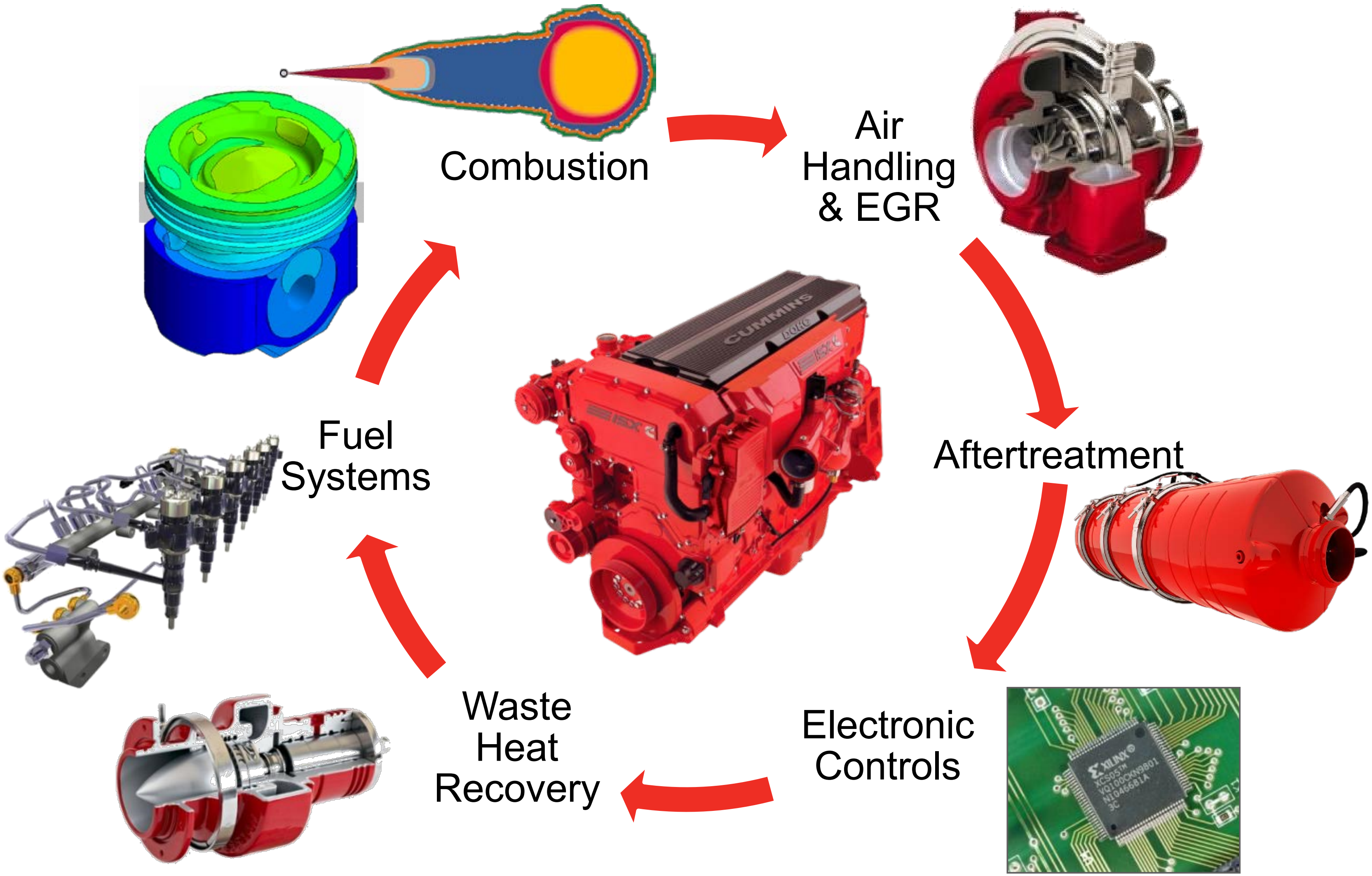
Final demonstration will include emissions demonstration and 55% BTE peak point

Technical Challenges / Barriers

- Combustion system design with low heat transfer
- Design integration of parasitic reduction efforts
- Optimization of Dual Loop EGR architecture and mitigation of condensate

Technical Approach

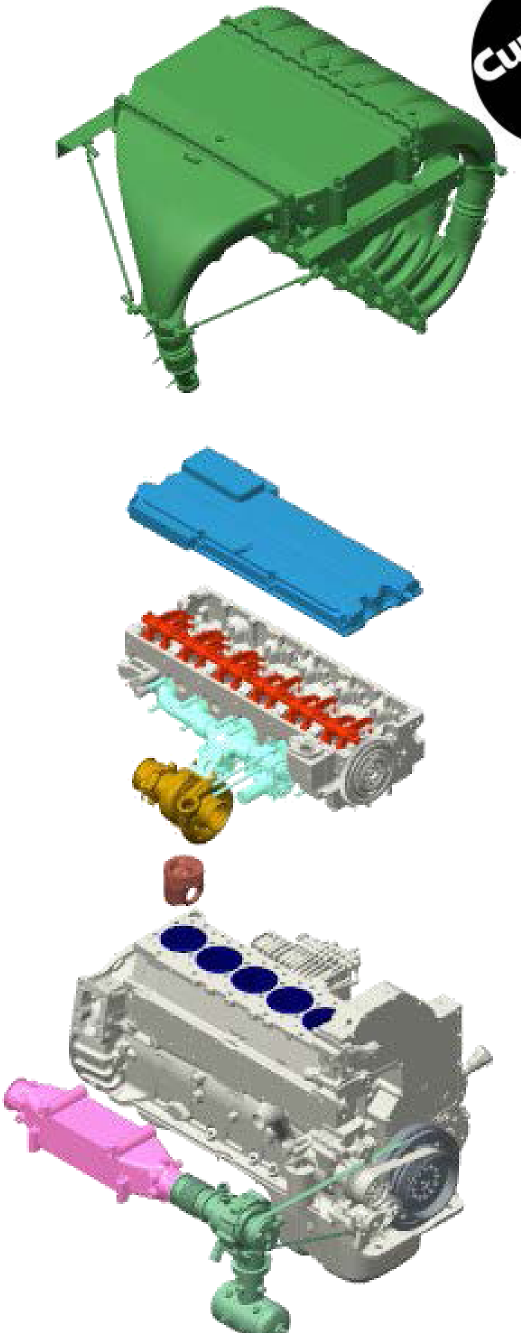
Approach - Integration of Cummins Component Technologies



Technical Approach

Virtually All Subsystems Updated

- Subsystems Capable
  - Engine Block
  - Crankshaft
  - Base Cylinder Head
- This level of efficiency increase requires improvements in all areas
- Highly integrated design required to maximize potential benefits from selected technologies



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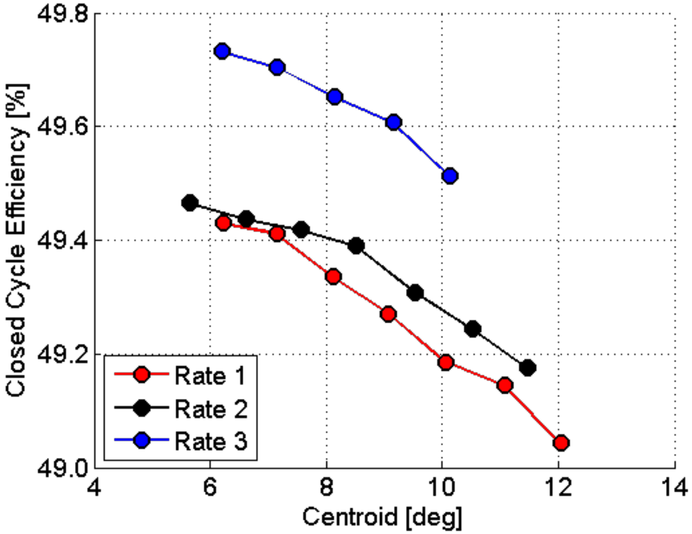
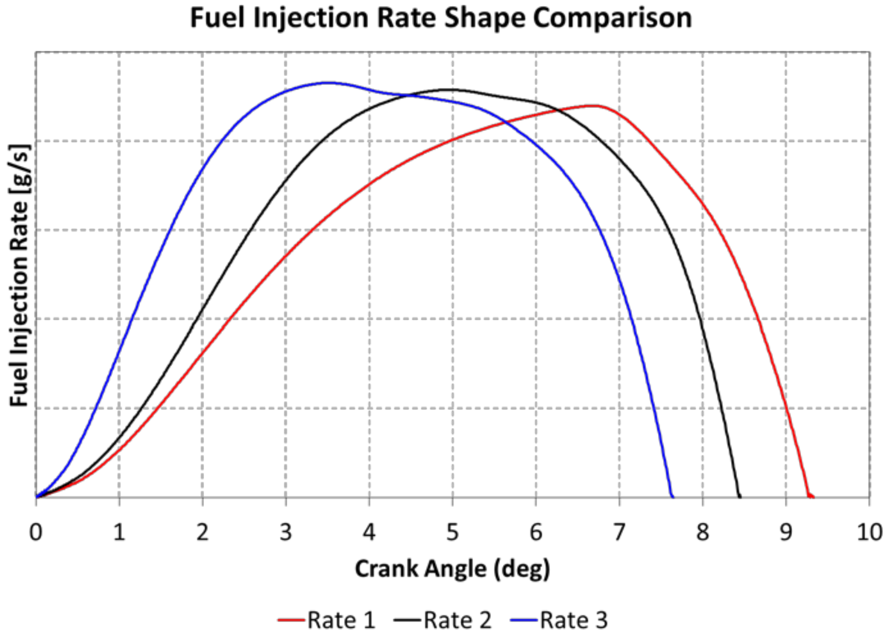
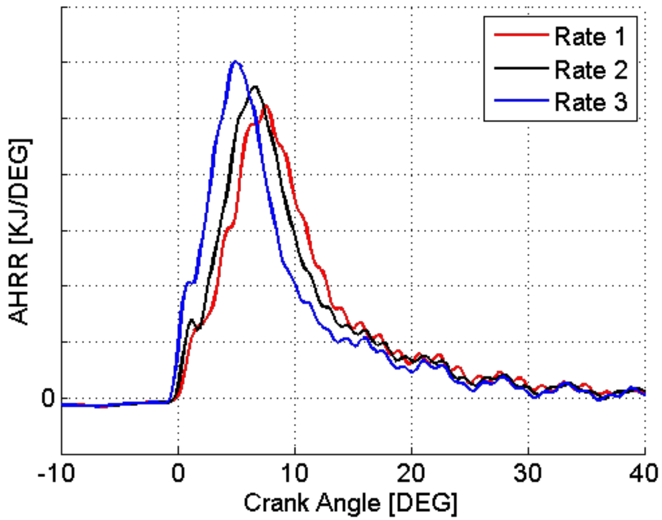
Technical Accomplishments: Injectors

- Optimizing injection rate shape can yield significant CCE improvements
  - New designs have yielded +0.3% dCCE
- Improved shot-to-shot performance

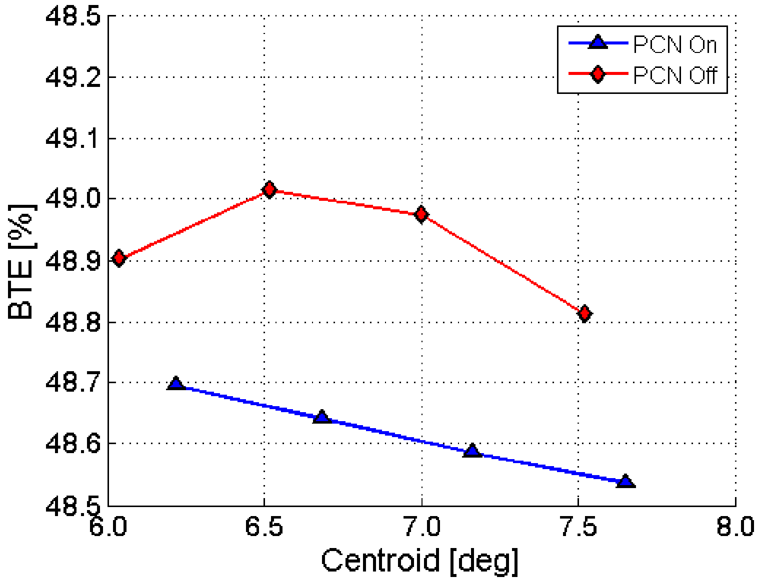






Technical Accomplishments: Pistons

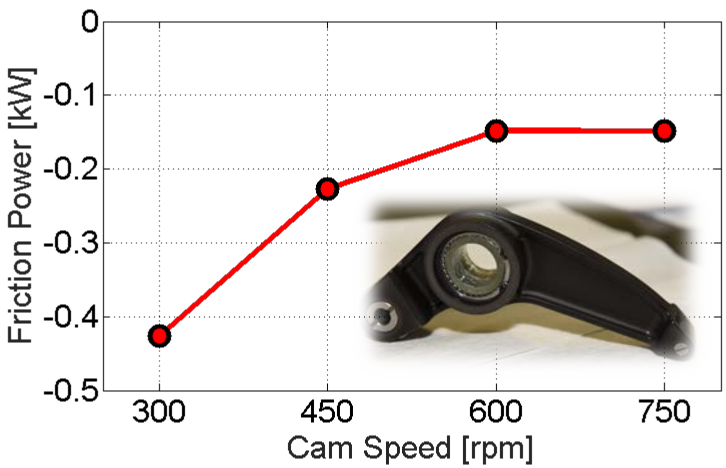
- Development has continued on low heat transfer (LHT) combustion system
- LHT pistons enable piston cooling nozzle flow to be reduced or eliminated
- Test results demonstrate +0.3 dBTE improvement
- Waiting on next set of LHT hardware to be available



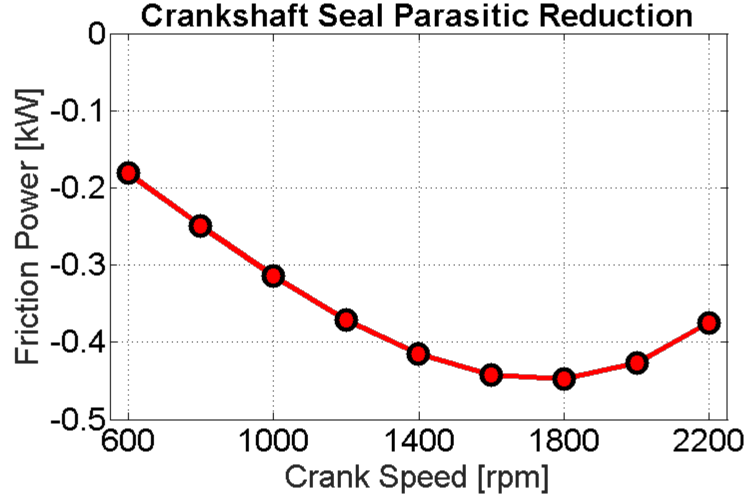
Technical Accomplishments: Parasitic

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 • Improved Crank Seals

Rollerized Valvetrain Parasitic Reduction



Crankshaft Seal Parasitic Reduction



Total parasitic reductions have demonstrated >1 kW of improvement to date

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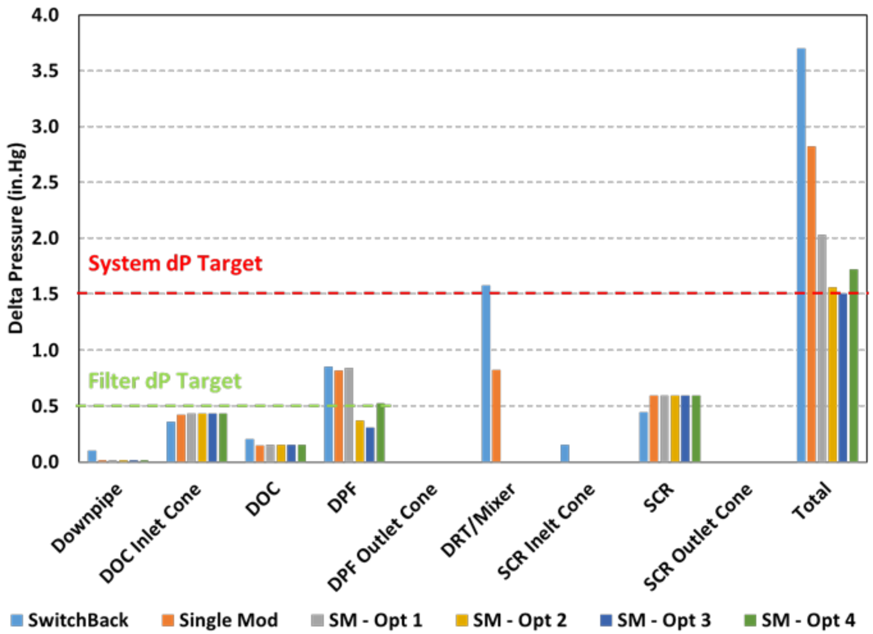
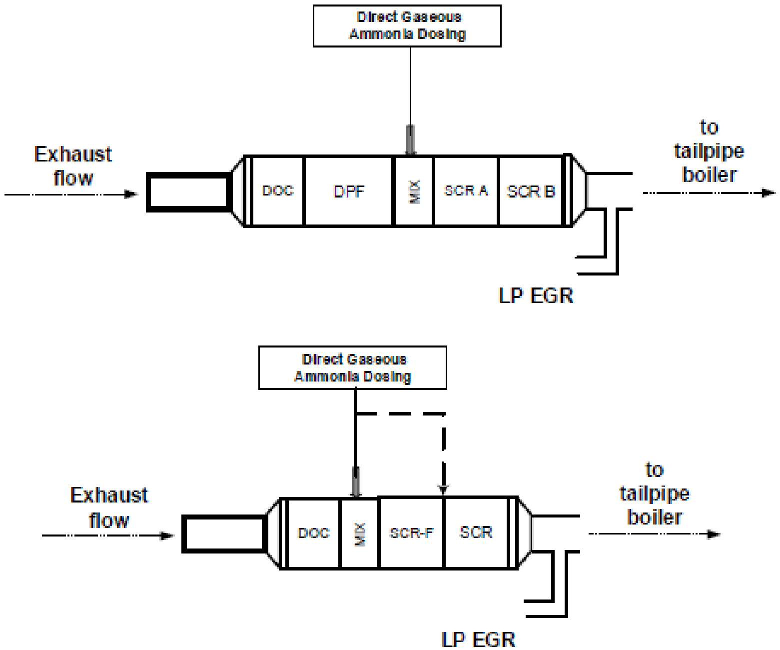
Technical Accomplishments: AT

- Architectures address expected lower temperatures and higher NOx from BTE improvements
- Enable LP EGR packaging
- Enable low back pressure

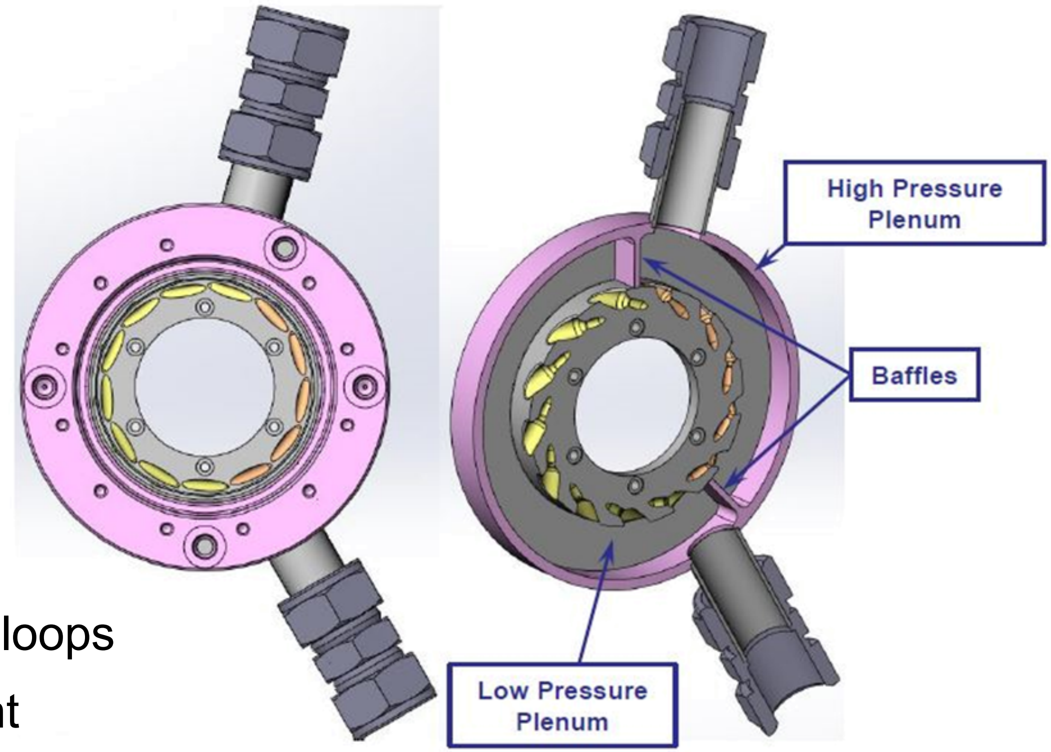
- Levers for earlier DeNOx
  - Shorter downpipe
  - SCR function pulled forward
  - Gaseous NH3 dosing





Technical Accomplishments: WHR

- Waste Heat Sources
  - Engine Coolant/Lube
  - EGR (LPL & HPL)
  - Exhaust
  - Charge Air Cooler
- Dual Loop System
- New Turbine Expander
  - Single turbine handles both loops
  - Optimized for best BTE point
- WHR Temperature Control
  - Avoid condensation in LPL EGR



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Response to Reviewer Comments

Many complimentary comments:

- The reviewer stated that the approach for this project is very good. There is a recognition that, to push to the maximum efficiency, every component on the engine system needs to be evaluated. There is no single silver bullet.

Concerns:

- LP EGR condensate
  - Response: Condensate from the LP EGR circuit is being managed in two ways. First, the WHR system is being utilized to try and control the heat exchanger temperatures to stay above the dew point when possible. Second, condensate collection paths and traps have been designed into the system to mitigate corrosion on key engine components. Our approach is to minimize and manage.
- Risk mitigation and contingency plans
  - Response: Additional technologies have been analyzed and considered in the program, such as water injection, but remain in the back-up category. A two year program and limited budget unfortunately do not allow full development of all contingency options to be possible. The short AMR presentation does not allow all these options to be discussed in detail.
- Collaboration
  - Response: The short length of the project and budget makes collaboration difficult and this was expressed during the proposal for the project. The program has engaged the supply base extensively touching virtually every part of the engine.

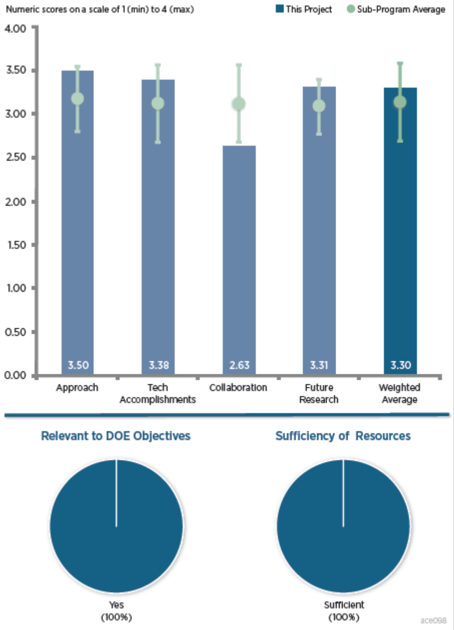

Figure 4-40 - Cummins 55% BTE Project: Lyle Kocher (Cummins) - Advanced Combustion Engines

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Collaborations

Internal Collaborators

- Cummins Fuel Systems
  - Provide Advanced XPI Fuel System
    - Tailor fuel injection rate shape
    - Analysis led design process to provide robust, cavitation-free injectors
- Cummins Turbo Technologies
  - Provide Advanced Turbocharger Technologies
    - High efficiency wheel designs
    - Advanced coatings
    - Turbine diffuser

Supply Base

- Mahle, Federal-Mogul, Bontaz, Modine, RBC, NGK, BorgWarner, Bosch, Pierburg, Continental, Johnson Matthey, Corning, Concentric, Honeywell

Remaining Challenges & Barriers

- Procurement times for hardware is long compared to overall program length
  - Many items such as optimized turbochargers and LHT pistons have extremely long lead times
    - Limits ability to recycle designs for improved performance
- Previous work with insulated combustion systems have been challenged to demonstrate improved efficiency
  - Program has demonstrated improvement but more is needed to meet program goals
- Higher engine out NOx will likely be required to achieve BTE goal
  - How to handle OBD implications

Proposed Future Work

- Continue engine system developments
  - Reduce in-cylinder heat losses
    - Currently waiting on piston hardware to become available
  - Shorten combustion duration
- Continue air handling optimization
  - Dual loop EGR optimization
  - Turbocharger efficiency improvements
- Continue WHR system optimization
  - Validation of new dual loop turbine expander
  - System optimization at best BTE point

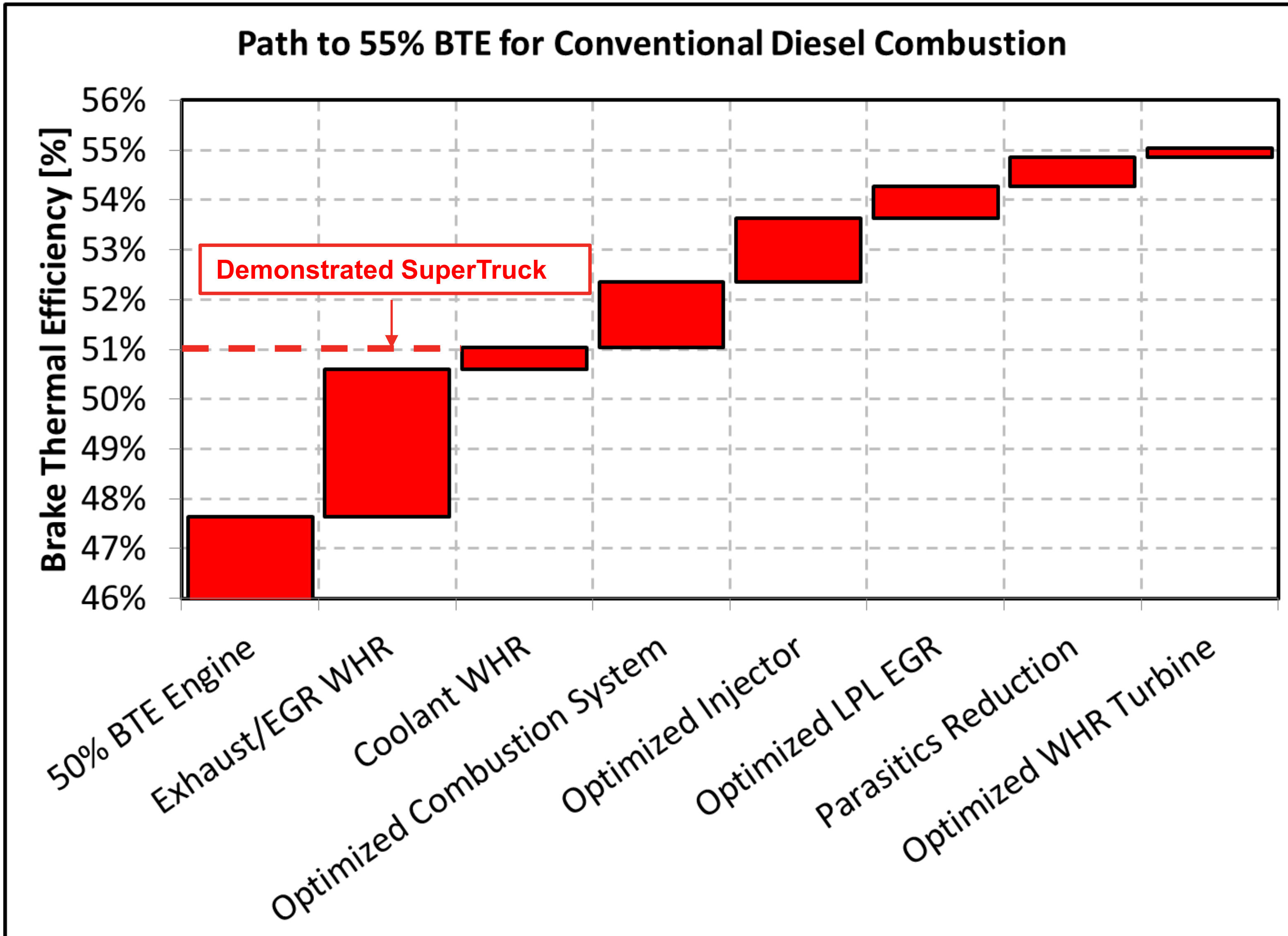
Any proposed future work is subject to change based on funding levels.

Summary

- Cummins is validating the path to 55% BTE
  - Demonstrated Performance To Date
    - Demonstrated 49.2% BTE engine only
    - Fuel system injector designs have been completed
      - Further rate shape optimization has demonstrated +0.3% dCCE
    - LHT piston development enables PCN flow to be eliminated
      - Enables +0.3% dBTE improvement with current hardware
    - Parasitic reduction validation work has been completed
      - Demonstrated for rollerized overhead and crankshaft seals
      - Demonstrated > 1 kW parasitic improvement
    - Aftertreatment architectures have been selected
      - Architecture simulations show capability to meet program targets
    - New WHR turbine expander has been designed
      - Dual loops feed single turbine expander

Technical Back-Up Slides

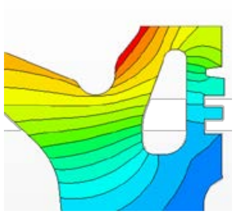
Technical Accomplishments: Path



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: Pistons

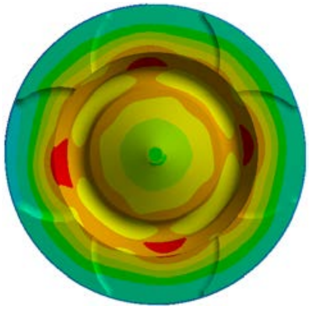


- Thermal Sensitivity
- Material Selection

Structural Analysis

Conjugate Heat Transfer & Combustion Analysis

- Temperature Prediction
- Performance Prediction



Analysis ⬆

Testing ⬇

Analysis ⬆

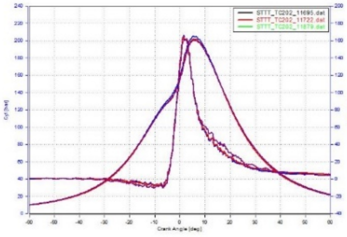
Testing ⬇

Thermal Survey

- Temperature Validation
- Model Verification

Performance Evaluation

- Brake Thermal Efficiency
- Closed Cycle Efficiency



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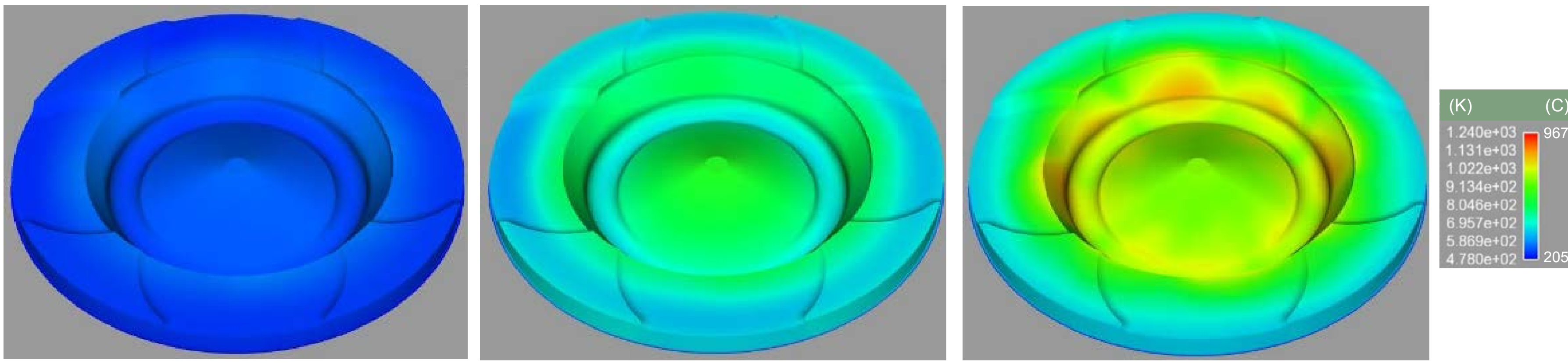
Technical Accomplishments: Pistons

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