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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

<table>
<thead>
<tr>
<th>Budget Period</th>
<th>Milestone</th>
<th>Description</th>
<th>Delivery Date</th>
<th>Status</th>
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<tr>
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<td>M1</td>
<td>Lube Pump Design Complete and Procured</td>
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## Technical Approach

<table>
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<tr>
<th>Q1 2016</th>
<th>Q2 2016</th>
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<th>Q1 2017</th>
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<td>Go/No-Go</td>
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<td>WHR System Design &amp; Turbine Expander Design</td>
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</table>

### Go / No-Go Decision Point
- Test cell demonstration of 50% BTE
  - Engine only performance
  - No WHR

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

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

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Technical Approach

Approach - Integration of Cummins Component Technologies

- Combustion
- Fuel Systems
- Air Handling & EGR
- Aftertreatment (AT)
- Electronic Controls
- Waste Heat Recovery

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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

Path to 55% BTE for Conventional Diesel Combustion

50% BTE Engine
Exhaust/EGR WHR
Optimized Combustion System
Optimized Injector
Parasitics Reduction
Optimized WHR Turbine

Demonstrated SuperTruck

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# Technical Accomplishments: Path

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

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Technical Accomplishments: Pistons

Kicked Off and In-process

- Structural Analysis
- Conjugate Heat Transfer Analysis
- Thermal Survey
- Performance Evaluation

- Temperature Sensitivity
- Material Selection
- Temperature Prediction
- HT & Perf. Prediction
- Temperature Validation
- Model Verification
- Brake Thermal Eff and Closed Cycle Eff

Projected Timing Q3
Projected Timing Q4

Technical Accomplishments:
Pistons
Technical Accomplishments: Pistons

Piston Crown Temperatures

- 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**
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 improvement
- Higher Engine Out NOx & turbocharger improvements can provide additional BTE improvements
# Technical Accomplishments: Parasitic

<table>
<thead>
<tr>
<th>Coolant and Lube System</th>
<th>Valve Train</th>
<th>Power Cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Variable Coolant Pump</td>
<td>• Reduced Component Inertias</td>
<td>• Lower Friction Ring Coatings</td>
</tr>
<tr>
<td>• Variable Lube Oil Pump</td>
<td>• Reduced Stiffness Springs</td>
<td>• Lower Ring Tension</td>
</tr>
<tr>
<td>• Improved Lube System Flow Losses</td>
<td>• Reduced Oil Flow</td>
<td>• Improved Piston Skirt Coatings</td>
</tr>
<tr>
<td>• Reduced Oil Flow of Valve Train</td>
<td></td>
<td>• Improved Piston Profiles</td>
</tr>
</tbody>
</table>

## 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

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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
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
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Technical Back-Up Slides
Technical Progress
Optimized Injector – Single Cylinder Engine Results

- 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

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

Δ BTE impact: +1.3pt

Impact of injection rate shape at constant intake conditions
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
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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%
△ 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

△ BTE impact: + 0.9% BTE

Koeberlein AMR 2015
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