



Project ID  
DORMA032 (ACE185)

# High Efficiency, Ultra Low Emissions Heavy-Duty 10 Liter Natural Gas Engine Project

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Public

# Overview

## Timeline

- **Start:** February 2022
- **End:** April 2025
- **Percent Complete:** 42%

**Will be managed in three Budget Periods (BP)**

- **BP1:** Feb 2022 – Apr 2023
- **BP2:** Mar 2023 – Apr 2024
- **BP3:** Mar 2024 – Apr 2025

## Budget

- **Total:** \$6.67M Total/3.25 years
- **DOE:** \$4.00M
- **Cummins:** \$2.67M
  
- **Budget Period 1:** \$1.60M Total (Feb 22-Apr 23)
- **DOE:** \$0.96M
- **Cummins:** \$0.64M

## Barriers

- **Knock avoidance with high power density combustion system**
- **High exhaust temperatures associated with high power density, stoichiometric combustion**
- **Misfire avoidance and accurate fueling control at low loads to improve TWC performance**

## Partners

- **None**
  - **Cummins is the sole participant in this project**

# Relevance

## Objective

- Develop and Demonstrate a high efficiency, high power output natural gas engine capable of meeting low NOx
- Power & Torque
  - 400 hp Peak Power
  - 1350 lb-ft Peak Torque
- BTE
  - 42% Peak
  - 36% cycle average over HD FTP
  - 39% cycle average over RMCSET
- Emissions
  - 0.02 g/hp-hr bsNOx while meeting all other criterial pollutant limits for 2027 EPA/CARB
- Cost
  - 12-24% cost savings compared to current production L9N
  - No increase in cost for emissions control systems

## Impact

- Natural Gas Offers:
  - An inherent advantage for CO2 emissions over other fossil fuels
    - Renewable natural gas has a potentially negative carbon impact
  - Reduced dependence on foreign energy sources
  - A low carbon opportunity for hard to electrify transportation sectors
- This project will address barriers to adoption of natural gas in heavy duty transportation by
  - Increasing power density to meet demands of this market
    - Significantly reduce potential for knock and misfire through combustion system development
    - Improved engine efficiency
    - Manage exhaust temperatures
  - Reducing overall greenhouse gas (GHG) impact by reducing tailpipe methane emissions
  - Maintaining ability to hit ultra low NOx targets of 0.02 g/hp-hr while meeting all other 2027 EPA/CARB requirements for criteria emissions
- A high efficiency natural gas engine provides an excellent platform to build upon for future development of hydrogen engines



# Milestones

| Budget Period 1 Milestones                                                                                                                                                                                                                                                                                                                                                                                                                                       |             |                                                        |           |                                                                                        |                                  |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|--------------------------------------------------------|-----------|----------------------------------------------------------------------------------------|----------------------------------|
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Month/Year  | Milestone                                              | Type      | Description                                                                            | Status                           |
| ✓                                                                                                                                                                                                                                                                                                                                                                                                                                                                | May 2022    | Rating Target Determine                                | Technical | Cylinder head design work started and simulation work started                          | Complete                         |
| ✓                                                                                                                                                                                                                                                                                                                                                                                                                                                                | June 2022   | Engine Simulation Model Created                        | Technical | Initial Engine Simulation model created                                                | Complete                         |
| ✓                                                                                                                                                                                                                                                                                                                                                                                                                                                                | August 2022 | EGR decision                                           | Technical | Simulation work complete to determine if EGR is needed/desired to meet program targets | Complete<br>(See comments below) |
| ✓                                                                                                                                                                                                                                                                                                                                                                                                                                                                | March 2023  | Cylinder Head design complete                          | Technical | Cylinder Head design complete                                                          | Complete                         |
| ✓                                                                                                                                                                                                                                                                                                                                                                                                                                                                | April 2023  | Simulation analysis shows that engine can meet targets | Go/No Go  | Simulation shows that engine can meet torque, power, and BTE targets                   | Complete                         |
| <ul style="list-style-type: none"> <li>Simulation work showing ability to meet program targets without EGR is complete</li> <li>Current direction is no-EGR               <ul style="list-style-type: none"> <li>There is uncertainty in predictions of both exhaust temperature and knock.</li> <li>This direction may be revisited in BP2 if engine testing shows exhaust temperature is excessive or knocking is greater than expected</li> </ul> </li> </ul> |             |                                                        |           |                                                                                        |                                  |

***All Budget Period 1 Milestones are Complete***  
*We have begun work against BP2 Milestones*

# Approach

Current state of the art natural gas engines are based on their diesel counterparts, retaining much in common with the diesel engine

## Cooled EGR

Reduces combustion & exhaust temperatures  
Moderate Efficiency and Power Density Improvement

Challenges:

- Misfire
- Condensation
- Reliability

0.02 g/hp-hr NO<sub>x</sub>

Stoichiometric combustion with three way underfloor catalyst

**This is the most cost effective approach when the engine is a diesel derivative**

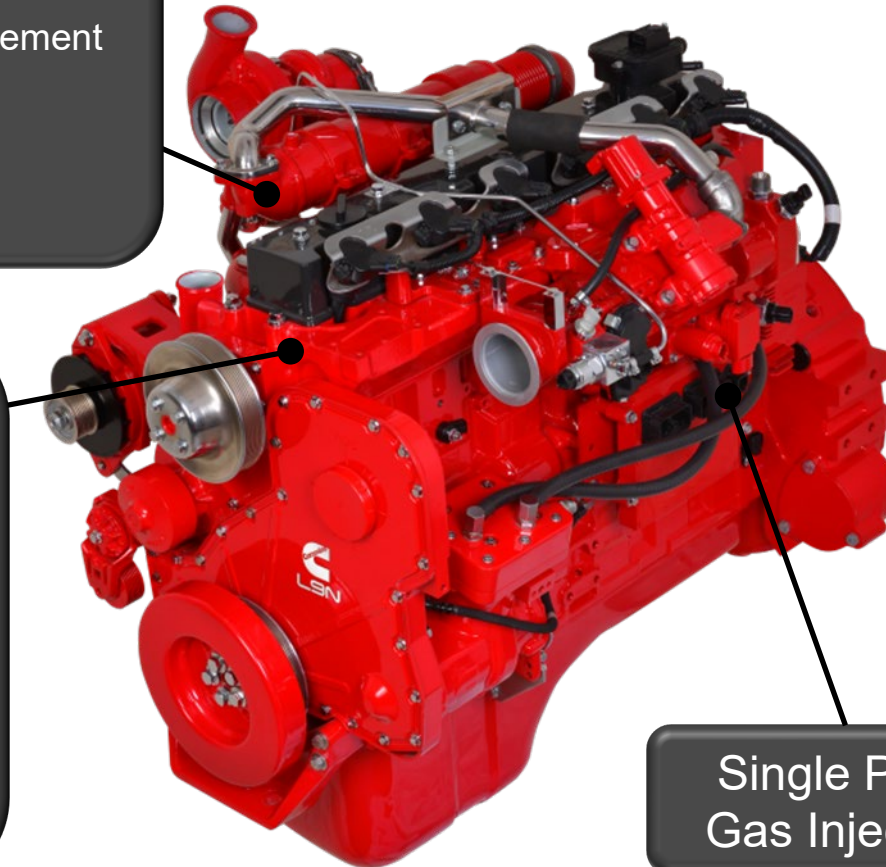
## Combustion System

Flat Deck Head with Swirl

- Does not promote fast combustion
- Limits power density due to knock
- Misfire risk at low load
- Thermal stress challenges

Low Compression Ratio Piston

- Required for knock mitigation & power density
- Reduces efficiency



Single Point Gas Injection

What could be possible if key performance components were designed *specifically* for natural gas?



# Approach

**We will design and optimize engine components specifically for high power density, efficient natural gas combustion**

- Variable valve timing will be used to reduce effective compression ratio at high loads, enabling high power density while maintaining high geometric compression ratio for high efficiency at part load
- Engine cycle simulation will be used to optimize valve profiles and timing across the operating range

- Exhaust system design will be designed for efficient flow to minimize residual gas trapped in the cylinder and reduce knock
- CFD flow and heat transfer analysis will be used to optimize flow passages and assess ability to manage exhaust temperature
- Premium exhaust system materials may be used if required
- Close coupled three way catalyst for efficient NOx reduction and CH4 oxidation

- Intake ports with port fuel injectors will be designed using CFD analysis to generate charge motion that promotes fast, efficient flame propagation
- A high compression ratio piston and other combustion system features will be developed using combustion CFD to optimize efficiency and minimize knock risk

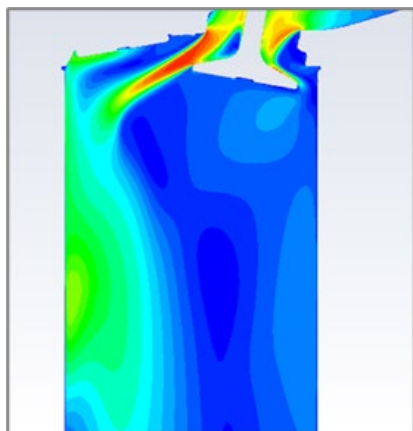
# Technical Accomplishments and Progress

## Exhaust System

- High temperature material capable to 850 C
- Twin entry wastegated turbine capable to 850 C
- Close coupled three way catalyst (not shown)

## Combustion System Development

- CFD Port Design for efficient tumble flow
- Combustion CFD with closed cycle efficiency > 43%



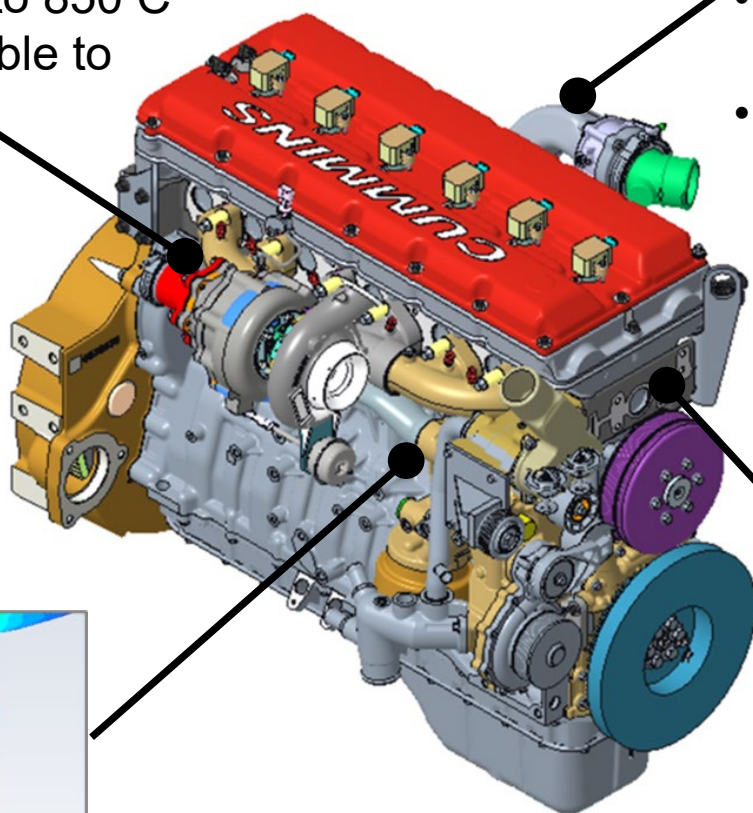
## Intake Manifold

- CFD for flow balancing & fuel cross talk
- Port injectors installed in the manifold



## Cylinder Head & Valvetrain Design

- Pent roof
- Conjugate heat transfer analysis for water jacket design to limit temperatures and thermal stresses
- Dual overhead camshafts with both lobe switching and phasing capability

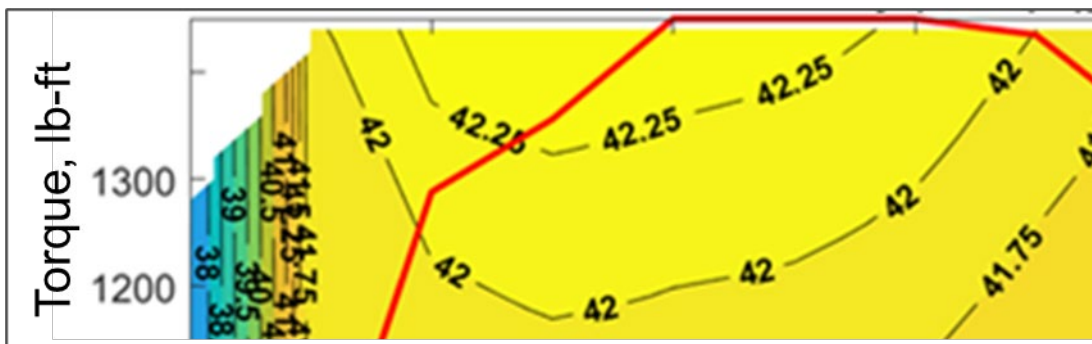


# Technical Accomplishments and Progress

## Cycle Simulation (GT Power)

### Predicted BTE

- Island of operation with BTE > 42%
- Miller cycle cam (LIVC)



Cycle simulation prediction shows ability to meet program deliverable of 42% BTE

While predicted turbine inlet temperature is higher than desired, there is uncertainty in the model.

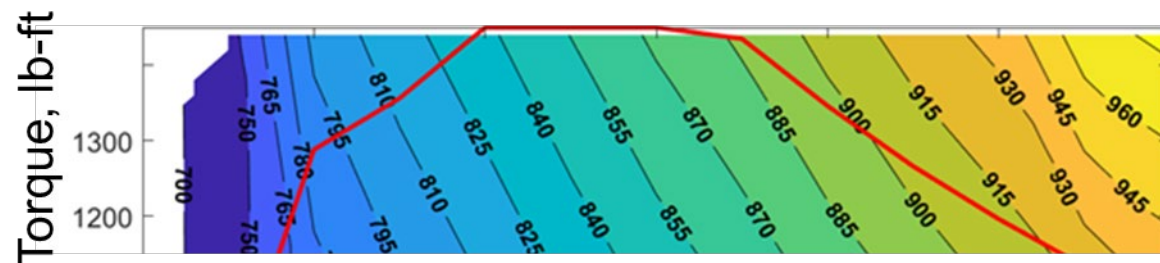
We will refine and calibrate models in Budget Period 2.

There are pathways to mitigate this if actual temperatures prove to be too high.

## Cycle Simulation (GT Power)

### Predicted Turbine In Temp (Deg C)

- Some regions of operation remain above 850 C target
- Challenges remain that will be addressed in BP2
  - Calibrate models against engine test data
  - Consider water cooled manifold, other manifold materials
  - Possibly revisit use of EGR



# Responses to Previous Year Reviewers' Comments

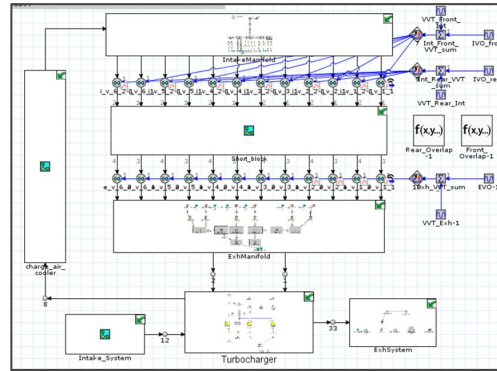
This project was not reviewed last year

# Remaining Challenges and Barriers

- There is significant uncertainty in model predictions of key performance parameters
  - There are limitations to analytical capability and also practical limitations to computational resources and computational time that can be accommodated within development timelines
  - We will continue to develop and refine analytical models and include learnings as we calibrate against test data

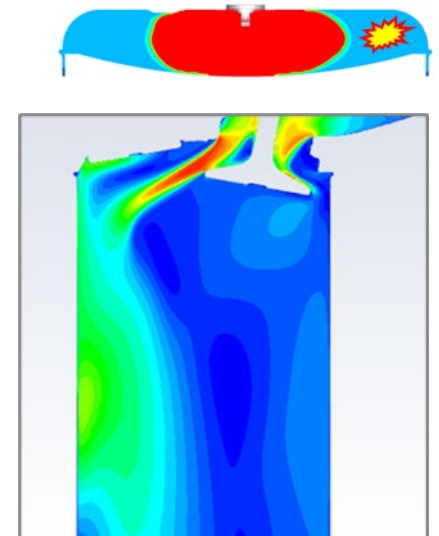
## Exhaust temperature predictions are a critical input to exhaust system design and material selection.

- Limitations in heat transfer models result in significant uncertainty in temperature predictions
- This is especially challenging with new designs where hardware and calibration data does not exist yet



## Challenges also exist in the ability to predict knock

- This is critical for combustion system development of natural gas engines and is especially difficult before calibration data is available
- Dependent on local conditions
  - Temperature & Pressure
  - Mixing of fuel and air
  - Mixing of residuals
  - Flame speed
  - Kinetic Mechanisms



# Proposed Future Research

## To Be Completed in Budget Period 2 (FY 23 & FY24)

- Complete analysis and design of all engine components
- Build and test one engine
  - Engine will be capable of steady state testing and meeting BP2 milestone of demonstrating performance at 75% of the power and torque targets
  - Limited transient testing may also be done
- Apply learnings from engine testing to calibrate and refine models
- Complete design and analysis of performance components for second engine to demonstrate performance against goals in BP3

# Summary

- All Budget Period 1 Milestones are complete and we have begun work against Budget Period 2 milestones
- Challenges remain, but we have a solid plan to address these

- Engine testing to calibrate and refine models
- Apply learnings from testing and improved models to refine design of performance components for second engine build

| Budget Period 1 Milestones                                                                                                                                                                                                                                                                                                                                                                                                                                                      |             |                                                        |           |                                                                                        |                                  |
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Q+A



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