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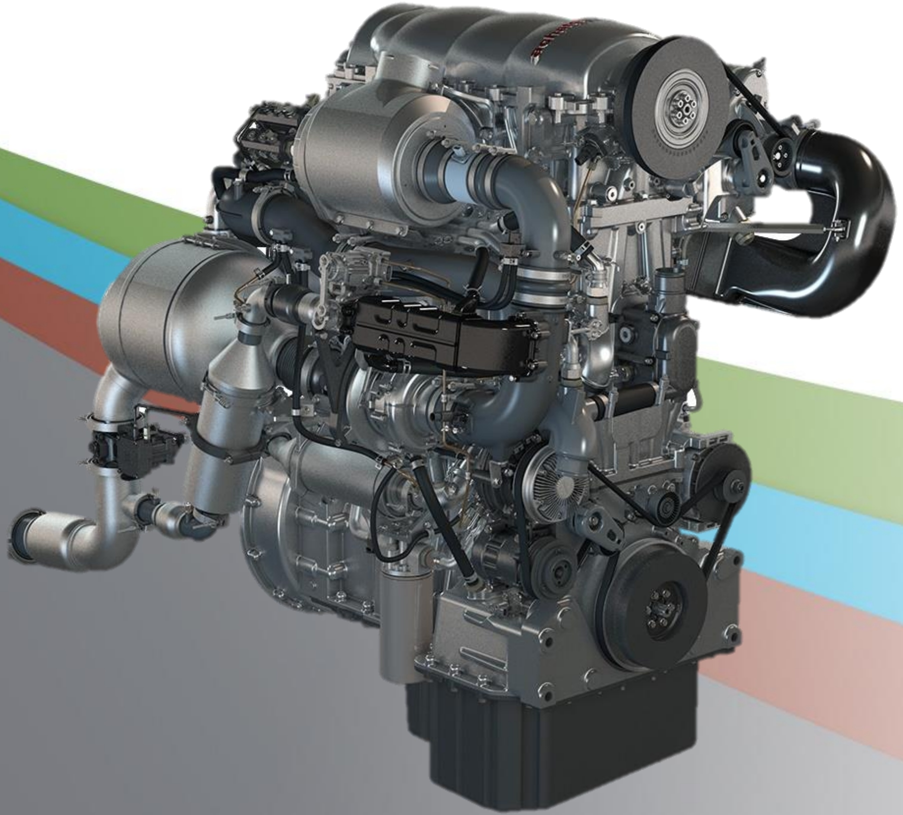

New Two-Cylinder Prototype Demonstration and Concept Design of a Next Generation Class 3-6 Opposed Piston Engine

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Overview

Timeline

- Start: October 2020
- End: December 2022
- Completion 25%

Budget

- Total project funding $6.25M
- DOE: $5M
- Cost share: $1.25M

Partners

- Isuzu Technical Center of America
- Clemson University
- University of Wisconsin - Madison

Barriers

- The efficiency of diesel engines is limited by a significant amount of heat transfer losses
- 4-stroke diesel engines face challenges treating NO_X emissions at low loads due to low exhaust temperatures
- The power density of conventional diesel engines is limited by their 4-stroke characteristics
- Ultra-clean and highly-efficient 4-stroke diesel combustion is costly
  - Inadequate understanding of air/fuel mixing and piston geometry optimization
  - Clean diesel combustion requires costly fuel injection, air system, and aftertreatment components
  - Tailoring of combustion for exhaust aftertreatment operation and engine performance

Relevance

The opposed piston two-stroke engine can resolve all of the barriers face by conventional diesel engines by reducing heat transfer losses and increasing efficiency, allowing better control over the exhaust temperature at low load by controlling scavenging, and increasing the power density through two-stroke operation.

This project seeks to improve the cost-effective development of high efficiency, low emissions diesel opposed piston (OP) engines for the commercial vehicle sector.

Objectives

- Demonstrate cost-effectiveness of the opposed-piston engine by developing a new two-cylinder/four-piston OP engine, validating simulation models, and simulating a four-cylinder/eight-piston engine to support a family of engines concept
- Optimize the air system to reduce heat rejection, improve turbocharger performance for 2- / 3- / 4- cylinder configurations, optimize the combustion chamber
- Demonstrate at least 10% fuel economy improvements over a Class 4 Isuzu vehicle over the customer derived real-world drive cycles
- Demonstrate the viability of bore, stroke, and block structure commonality for a family of OP engines concept
- The new two-cylinder OP design will be evaluated for the ability to meet the ultralow NO_X standards of 0.02 g / bhp-h on the EPA Transient Test Procedure

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Milestones

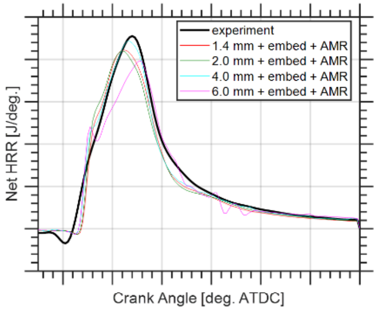
Milestone (status)	Quarter	Description
Critical System Profile (complete)	Dec, 2020	A critical list of factors relevant to the Class 3-6 vehicles will be developed.
Transfer and Update Open-cycle CFD Model and 1D Model for OP Architecture (complete)	March, 2021	1D and 3D open-cycle models have been updated to reflect the latest engine hardware based on the air system configuration.
1D, Open-cycle CFD Models Validated with Three-cylinder Test Data (on schedule)	June, 2021	Three-cylinder open-cycle CFD model has been successfully validated against experimental data
Two-cylinder Hardware Part Ordering Complete (on schedule)	Sept, 2021	All parts to support the new two-cylinder OP engine have been ordered
Shakedown of New Two-cylinder OP Engine (on schedule)	Dec, 2021	Successful mechanical operation of the new two-cylinder OP engine demonstrated
Experimental Validation of Two-cylinder Combustion System (on schedule)	March, 2022	Closed-cycle CFD optimized combustion volume and open-cycle CFD optimized ports will be tested in hardware on a two-cylinder engine.
Simulation of Four-cylinder Open-cycle CFD (on schedule)	June, 2022	Four-cylinder open-cycle CFD model is created and ready to be calibrated with experimental data from two-cylinder experiments.

Approach

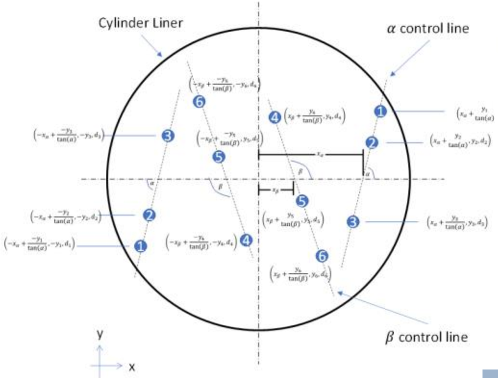
- We propose to enhance the cost-effectiveness, efficiency, and emissions of opposed-piston diesel engines with advanced simulation and testing of a family of engines concept
  - Determine engine specifications required to span class 3-6 vehicle range
  - Develop a new prototype two-cylinder OP engine from a three-cylinder engine but with a simulation optimized air system
  - Experimentally validate simulation models using three-cylinder data and simulate and optimize a two-cylinder configuration
  - Build and test a new two-cylinder engine and validate simulation models and utilize to model four-cylinder engine performance
  - Utilize machine learning algorithms to determine optimal engine calibration using a large engine calibration parameter space, maximizing efficiency and minimizing emissions
  - Model target vehicle over customer drive cycles using test and simulation data to show >10% MPG improvement
  - Utilize measured and simulated data to design a new family of engines to span a broad range of vehicle classes and power requirements

Technical Accomplishments and Progress

Achates Power 3 Cylinder Engine at Clemson University



Experimental vs predicted heat release, effect of CFD grid size on prediction accuracy



Control Parameters

x_α:	distance from centerline to crossing point of α control line
x_β:	distance from centerline to crossing point of β control line
α:	angle of α control line in the x-y plane
β:	angle of β control line in the x-y plane
y_i:	y position of the i_{th} control point
d_i:	depth of the bowl at the i_{th} control point

Wisconsin Setup for CFD-based Piston DOE Optimization

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- Critical system profile for family of engines spanning a range of Class 3-6 vehicles complete
- Prototype three-cylinder engine built and tested
  - Baseline dataset generated at Achates Power
- Prototype sent to Clemson for installation and test cell shake down
- Two-cylinder GT Power model developed
- 3D CFD piston bowl optimization setup
- 3D combustion CFD predicting heat release and emissions
- 3D open cycle CFD correlated to three-cylinder test data and two-cylinder optimization is setup
- Two-cylinder engine mechanical analysis complete
  - Multibody simulation for vibrational analysis, cylinder block off concept, two-cylinder crankshaft design
- Two-cylinder part procurement in process (piston blanks, two-cylinder crankshafts, electric turbocharger, electric EGR pump)

Efforts on track to support new two-cylinder prototype testing in Fall 2021

Responses To Previous Year Reviewers' Comments

- This is the first year that the project has been reviewed

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Collaboration and Coordination with Other Institutions

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Prime, industry

- Build, test three- and two- cylinder OP engines
- Concept design family of engines

ISUZU

Sub, industry

- Engine and vehicle specification
- Target definition for prototype vehicle on customer drive cycles

CLEMSON UNIVERSITY

Sub, university

- 1D air path optimization, 3D air path optimization for maximum efficiency and low emissions
- Three- and two- cylinder OP prototype testing, model predictive controls
- Vehicle simulation

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

Sub, university

- 3D CFD combustion simulation
- CFD piston bowl optimization

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Proposed Future Research

FY21

- Initiate three-cylinder prototype testing at Clemson University
  - Shake down test cell and validate test results at Clemson with baseline data collected at Achates Power
  - Investigate opportunities for model predictive calibration for high efficiency and catalyst light off modes
- Complete two-cylinder prototype design and build
  - Perform CFD optimization for combustion chamber and air system design
  - Procure components to support two-cylinder build (e-turbo, e-EGR pump, manifolding) – Go/No-Go

FY22

- Build two-cylinder prototype and shake down at Achates Power
  - Assemble two-cylinder prototype with electric air components and shake down to verify mechanical robustness
- Install two-cylinder prototype at Clemson
  - Utilize model predictive control (MPC) to identify high efficiency calibration
  - Validate 1D, 3D combustion, 3D open cycle models and use to predict four-cylinder perform in simulation
  - Test prototype to achieve ultralow NOx emissions (0.02 g NOx/bhp-h)
- Vehicle simulation to validate >10% MPG improvement over baseline vehicle using test and simulation data
- Concept family of engine design for two-, three-, four- cylinder OP engines in target vehicle

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

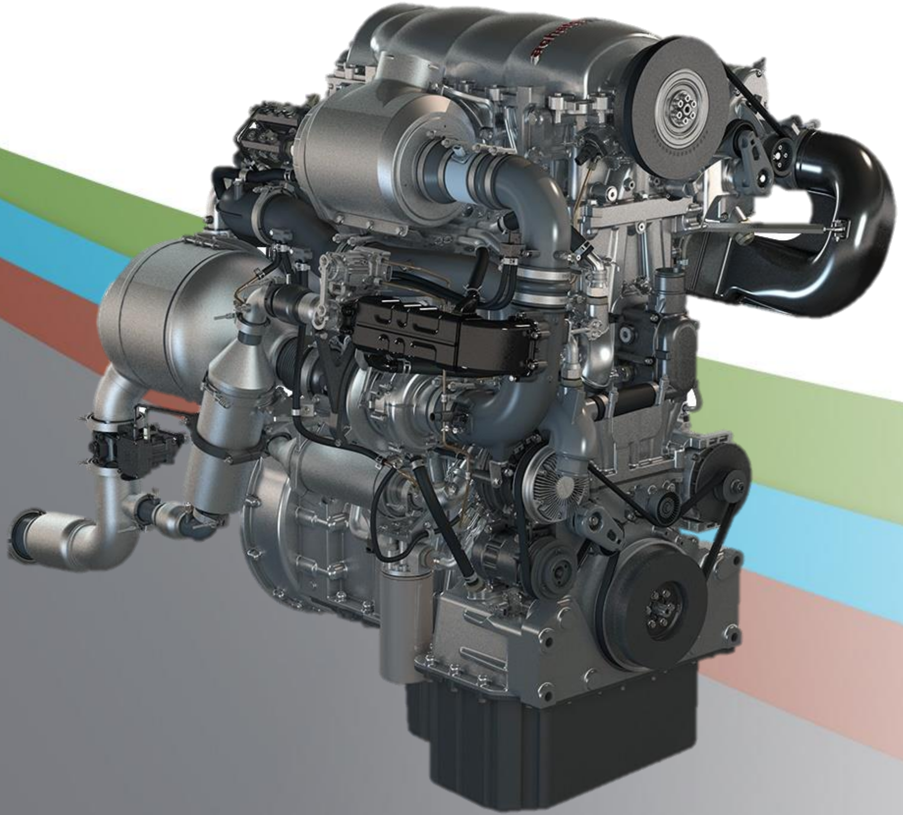
Summary Slide

Accomplishments

- Critical system profile for family of engines concept complete
- 1D, 3D combustion, 3D open cycle models updated and nearing validation for three-cylinder prototype
    - Optimization efforts for air path and combustion chamber pending
- Prototype three-cylinder engine baselined
    - Comparison data acquired for Clemson test cell shake down
    - Prototype engine installed in Clemson, nearing readiness for first fire
- Two-cylinder procurement commenced
    - E-turbo, e-EGR pump, piston blanks, and two-cylinder crankshafts have been designed and procurement has commenced

Relevance toward VTO objectives

- This project seeks to use model simulation, optimization efforts, and testing data for air path and combustion design in order to support clean and efficient combustion in the two-, three-, and four-cylinder family of OP engines concept. Testing and simulation results will be used in vehicle modeling to validate fuel economy improvement of the OP engine as well as validating the family of engines concept, enhancing the cost-effectiveness of ultra clean and ultra efficient engine technology that is capable of meeting future regulations



Technical Backup

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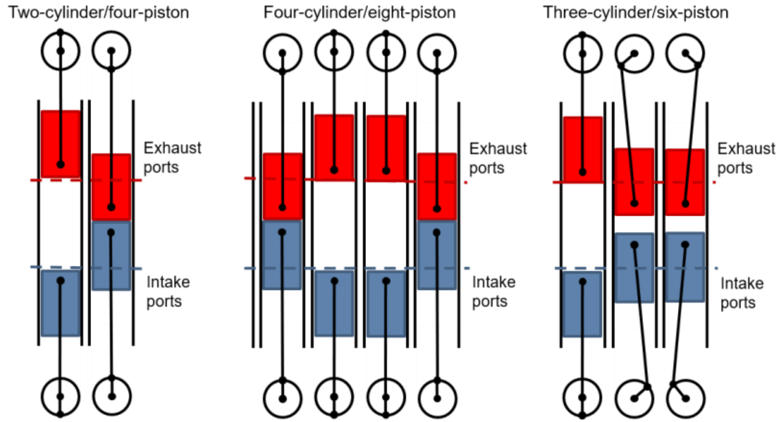
Importance of Family of Engines

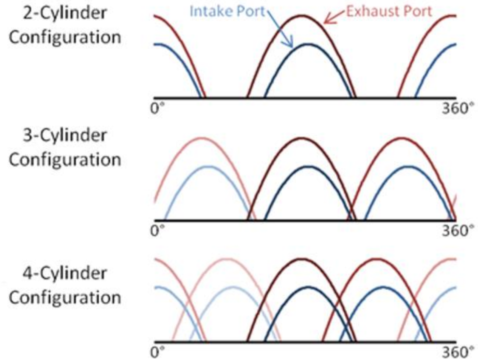
- Launching a new engine architecture is a major initiative. Moreover, since the application range for commercial and industrial vehicles is so broad, a considerable number of new engines are required to address the full market
- Launching a family of engines with a common power cylinder system can create economies in design, development, manufacture, and production
- Because the gas exchange duration in a two-stroke engine is about 120 degrees crank angle, a 3-cylinder OP engine is most efficient for scavenging and pumping. To create a viable family of engines, we need to improve the efficiency of 2- and 4- cylinder variants



Family of engines schematic

The turbocharger loses energy due to the temporary separation of blow-down events in a 2-cylinder engine

Cross-charging in a 4-cylinder engine increases backpressure in adjacent cylinders, increasing pumping work requirements



Port openings schematic for family of engines concept

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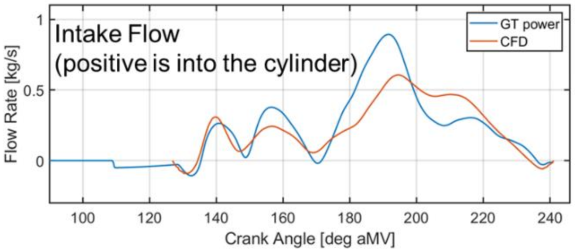
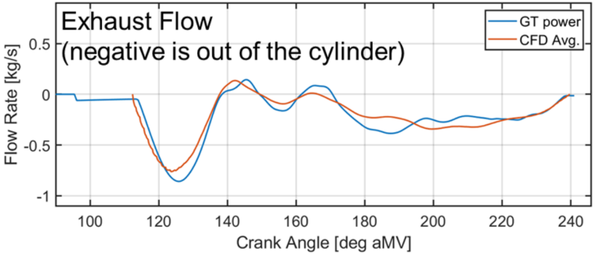
Scavenging Model Update and Correlation

- Good agreement between open cycle CFD and experimental results
- Good agreement between open cycle CFD and GT power
- Heat release comparison between open cycle CFD and experimental data matches well

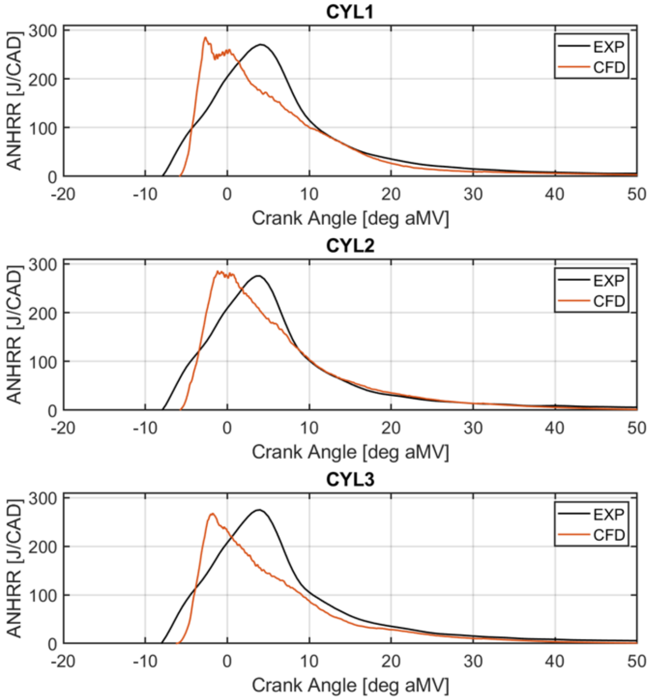
	CYL1	CYL2	CYL3	CFD avg.	EXP	ΔPE
Trapped Mass	3589.3 mg/cycle	3366.5 mg/cycle	3445.5 mg/cycle	3467.1 mg/cycle	3459.0 mg/cycle	0.23%
Trapped Temperature	422 K	419 K	435 K	425 K	410 K	3.7%
Scavenging Efficiency	80.1%	79.1%	79.8%	79.7%	80.7%	1.2%

Good agreement between open cycle CFD scavenging vs experimental results





Good flow rate agreement into and out of cylinder between open cycle CFD and GT Power



Good heat release agreement between open cycle CFD vs experimental results