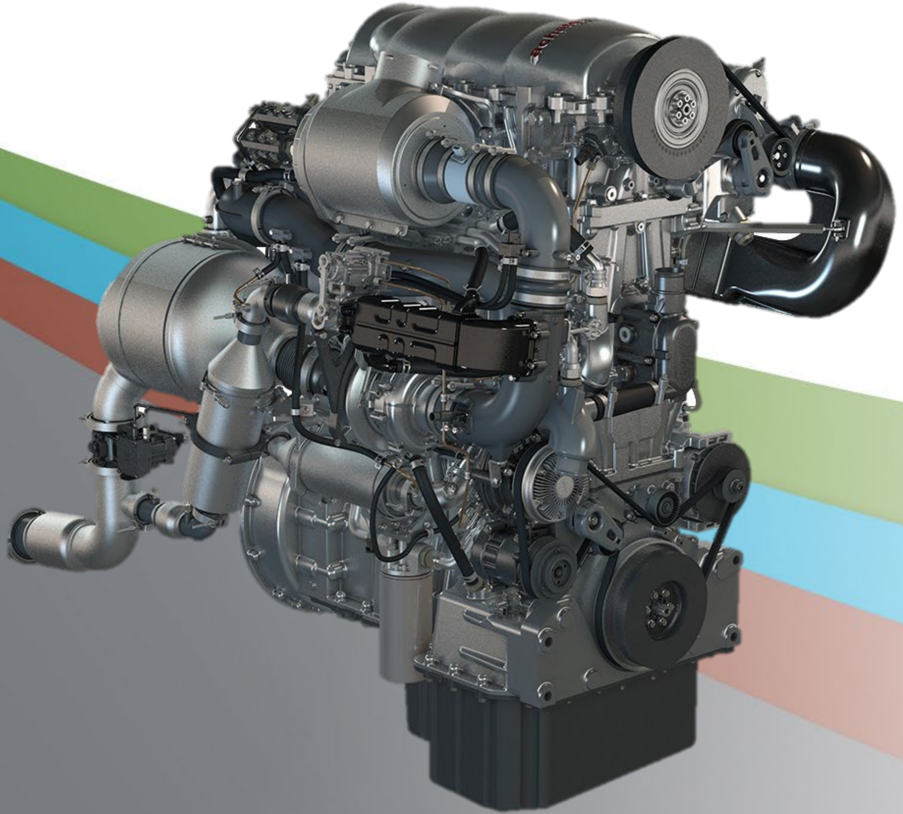
Project ID: ace166



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

Presenter, PI: Fabien Redon, Achates Power Inc.

achates POWER™ Fundamentally Better Engines®

Overview

Timeline

- Start: October 2020
- End: December 2022
- Completion 60%

Budget

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

Partners

- Isuzu Technical Center of America (ITCA)
- 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

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 (complete)	June, 2021	Three-cylinder open-cycle CFD model has been successfully validated against experimental data
Two-cylinder Hardware Part Ordering Complete (complete)	Sept, 2021	All parts to support the new two-cylinder OP engine have been ordered
Shakedown of New Two-cylinder OP Engine (delayed 1Q)	March, 2022	Successful mechanical operation of the new two-cylinder OP engine demonstrated
Experimental Validation of Two-cylinder Combustion System (on schedule)	June, 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)	Sept, 2022	Four-cylinder open-cycle CFD model is created and ready to be calibrated with experimental data from two-cylinder experiments.

Approach

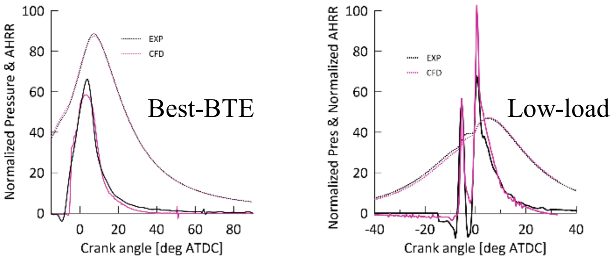
- We propose to enhance the cost-effectiveness, efficiency, and emissions of opposed-piston diesel engines with advanced simulation and testing of a family of engines concept
  - Determine engine specifications required to span class 3-6 vehicle range
  - Develop a new prototype two-cylinder OP engine 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
Combustion Chamber and Injector Optimization – 1 of 2

- Objective: Closed-cycle simulations performed to optimize the OP engine at a minimum of two relevant operating points with fixed port timings and injector locations
- Target: Optimization target is to increase Gross Indicated Efficiency (GIE) with little change in soot & NO_x.
- Software developed to facilitate performing CFD DoE/Machine Learning (ML) optimizations
  - Wrote surface-shaper software to generate OP-style piston surfaces automatically
    - Matlab language, runs in seconds, called by DoE Setup software to generate surfaces on the fly
  - Wrote DoE setup software to automate setup and running of DoE's on local computer cluster
    - Matlab language, reads one input file that defines all DoE parameters and ranges, constructs Converge CFD input file sets and submits DoE to computer cluster, all automatically
  - Writing Matlab program to automate post-processing of DoE results, as well as generate and apply Machine Learning model (in process)
- The DoE optimizes piston-bowl shape (7-shape parameters), swirl and SOI of each injector
- Piston shape optimized at best-BTE operating point and checked at low-load operation
- STL piston model delivered to Achates – Achates updated model to improve mechanical integrity
- The updated piston model was tested in CFD and predicted combustion performance improved further

Technical Accomplishments and Progress
Combustion Chamber and Injector Optimization – 2 of 2

a



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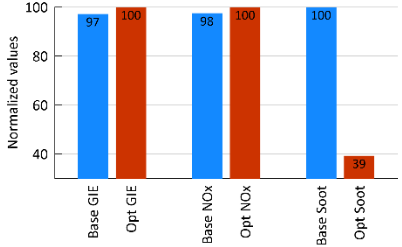

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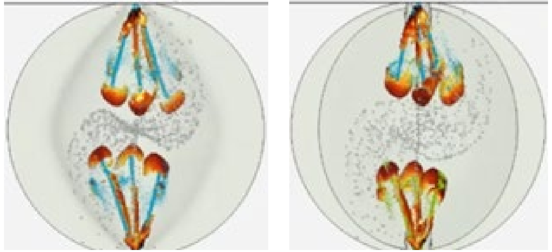
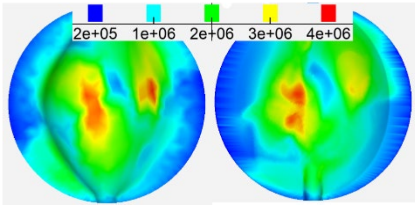


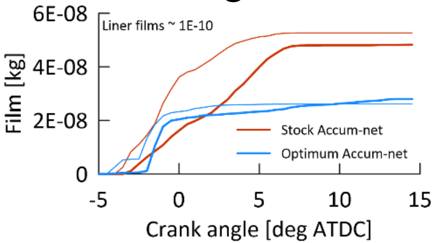
- CFD model is validated at best-BTE and low-load OC's (Fig. a)
- GIE improved (3%), NO_x increased (2%), soot decreased (61%) (Fig. b)
- Optimized geometry is predicted to:
  - Promote improved mixing, resulting in lower Soot emissions (Fig. c)
  - Reduce heat transfer and wall wetting (Figs. d-e) which lead to improved GIE
- Mean vs. Stratified initial condition study
  - Determine closed-cycle simulation sensitivity to initial-field stratification
  - GIE is most sensitive to velocity field stratification, GIE differs by 2%
  - NOx is most sensitive to temperature field, EVO NO_x differs by 10%
  - Little sensitivity to species, turbulence and pressure fields
- Injector-focused DoE completed and results analysis in process. Params:
  - SOI, injector orientation, clocking angle, included angle, # of holes, seven geometry parameters

d



Heat flux: blue-low, red-high

e



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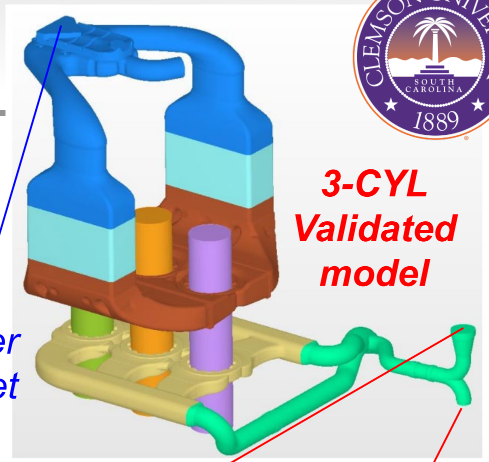
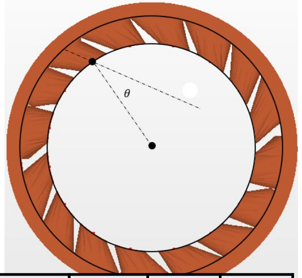
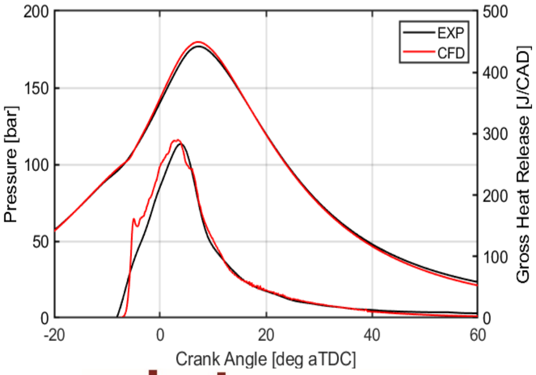
Technical Accomplishments and Progress
Open-Cycle CFD Investigations of Scavenging

- A full three-cylinder engine CFD model with detailed chemical kinetics and turbulence modeling was validated against experimental data
  - 2.1M cells, took 16 days to reach steady-state on 112 computational cores
- Simulated different port angles (or swirl ratios) and their effect on scavenging performance
  - More swirl concentrates residual mass in center of combustion chamber
  - Less swirl → best residual purging with least short circuiting







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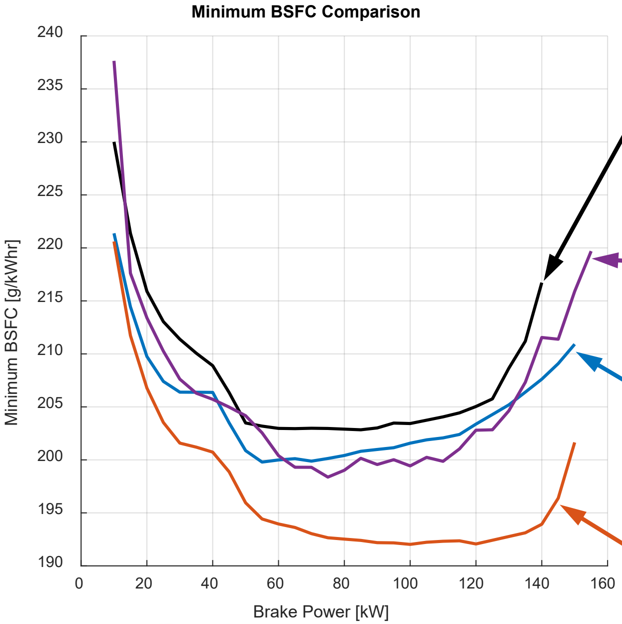
Port Angle [deg]	12	19	23	26	29
Bulk Swirl ratio [-]	1.36	2.60	3.00	3.35	3.72
SE [%]	85.4	82.8	81.7	80.4	79.2
Heat Loss [J]	483	536	556	586	608
Soot Emissions [g/kW-hr]	0.65	0.38	0.32	0.36	0.33
NOx Emissions [g/kW-hr]	2.14	2.53	2.67	2.52	2.50
Ind. Thermal Efficiency [%]	48.9	48.9	48.5	47.8	47.3
CA50 [CAD aMV]	5.3	4.5	4.5	4.6	4.5
Burn Duration [CAD]	27.0	22.5	21.6	23.7	23.8

Technical Accomplishments and Progress
1D GT-Power Engine Modeling

- 1D GT-Power efforts have focused on improving brake efficiency while maintaining a consistent cylinder composition at a given speed and fueling
  - In cylinder conditions were held to that of the emissions validated experimental prototype engine
- Efforts have yielded an operating range averaged BSFC improvement of 7% compared to the Isuzu baseline



Non-optimized 2-cylinder baseline based on larger 3-cylinder experimental engine

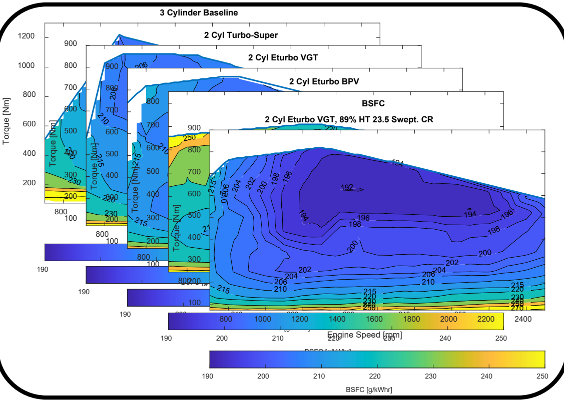
Isuzu target engine

2-cylinder with VGT eturbo and electric EGR pump

Current best solution: revised 2-cylinder with VGT eturbo and electric EGR pump

Investigation into different airpath layouts and components
- 4 boost device configurations
- 5 scavenging control devices
- 3 EGR loops
- 3 Exhaust systems

Full map comparisons of promising layouts



- Insight from Wisconsin on heat transfer of new piston bowl
- Insight from Achates on revised PCP and CR Limits
- ~900 iteration optimization of CR and turbocharger sizing

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Technical Accomplishments and Progress
2 Cylinder Model Validation

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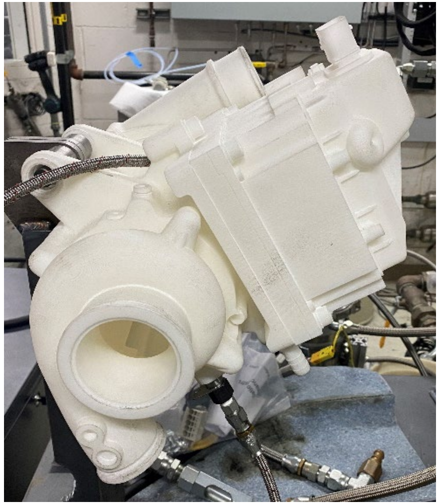
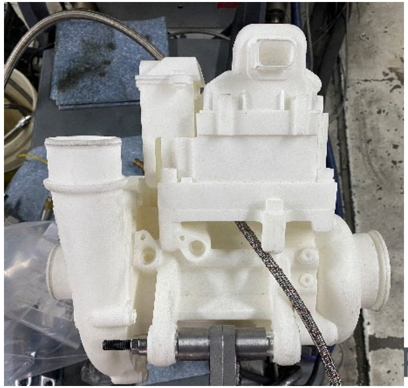
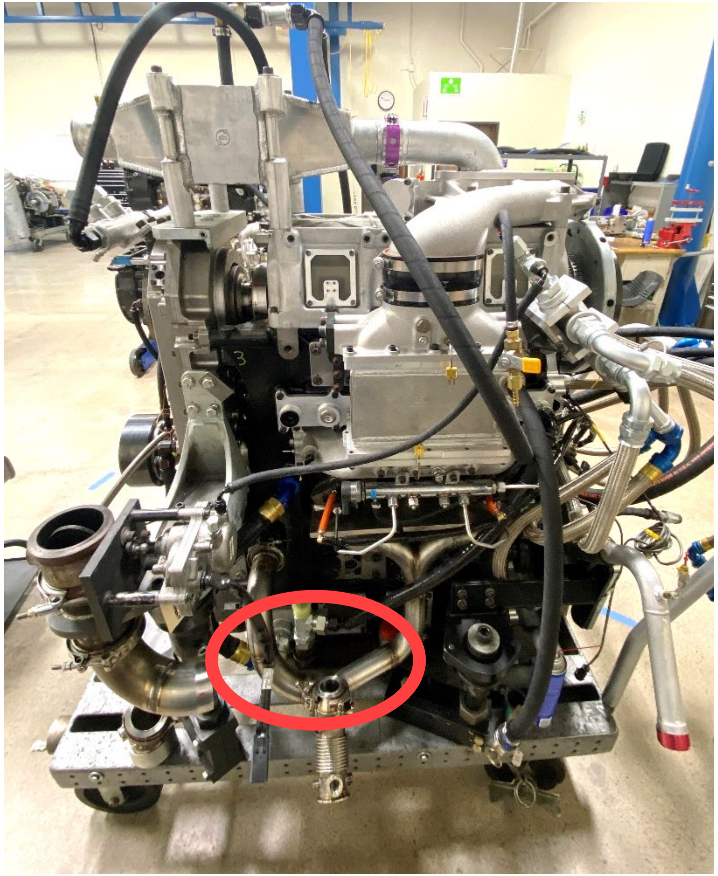






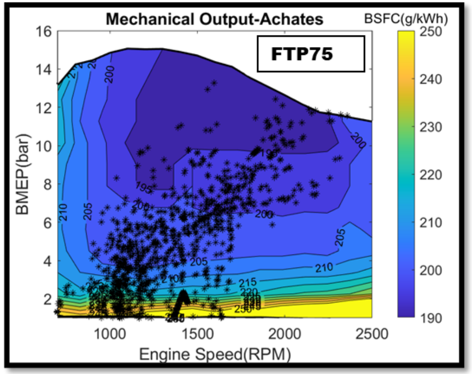
- All 2 cylinder engine parts have been received except the e-turbo
- COVID semiconductor shortages have delayed the program by 1 quarter
- This part is expected in May, 2022 with no impact on program timeline
- 3D printed turbo was procured in order to mockup air system plumbing on engine
- Controls have been updated to incorporate e-turbo and to minimize development time
- Rest of engine hardware is built and ready for model validation

Technical Accomplishments and Progress
Vehicle-Level Modeling and Experimental Investigation

Vehicle Drive Cycle Modeling

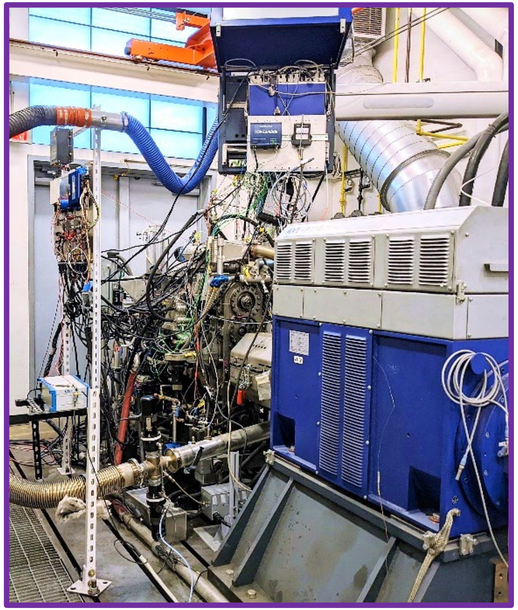
- ITCA provided the team with vehicle models in GT-Suite for a Class 3 truck with a current Isuzu engine in the model
- Using the improvements described on the previous slides, an Achates engine map was substituted into the vehicle model and the final drive ratio was adjusted
- The table shows initial MPG improvements using the Achates engine over various drive cycles
- Further optimization of shift schedules, as well simulations of hybrid vehicle architectures will be conducted in the following months

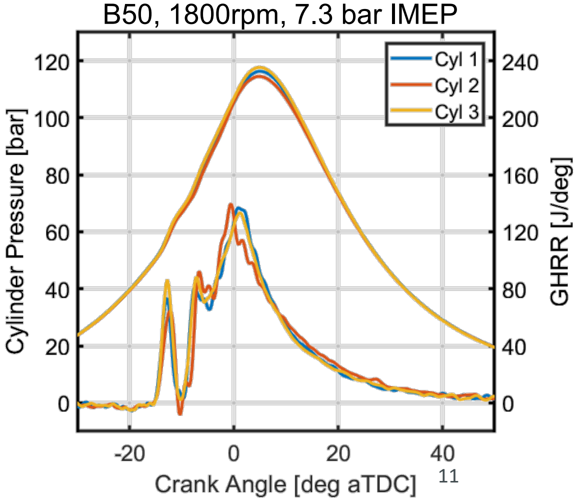
Drive Cycle	FE (MPG)		% Change
	ISUZU	AP48	
Interstate	14.3	16.7	14.1
Congested Interstate	12.4	12.9	3.9
GM-city	14.5	15.6	7.4
HWFET	16.0	17.3	8.0
FTP	13.3	14.1	5.8



Experimental Engine-Dyno Investigations

- A 3-cylinder OP2S engine has been installed and debugged on a test cell at Clemson University
- Collect model validation data for the CFD, GT-Suite, and MPC modeling tasks
- This effort is also intended to prepare the test cell for 2-cyl. model validation over the next quarters





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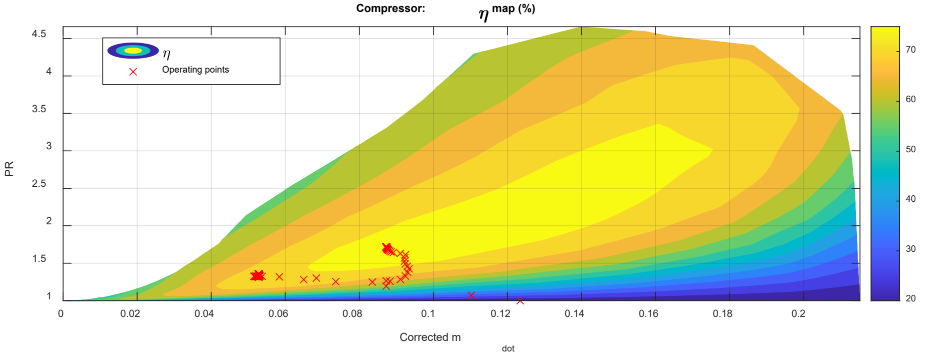
Technical Accomplishments and Progress
Model Predictive Control

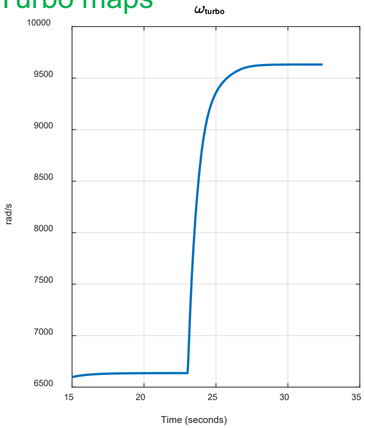
Model Predictive Control (MPC) for airpath control of the OP2S engine

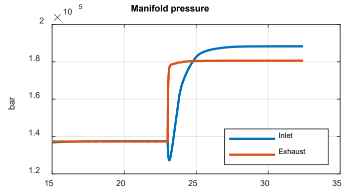
- Control objectives:
  - Provide desired cylinder charge composition
  - Coordinate all airpath actuators
  - Consider constraints of actuator rate/magnitude, and system states
- Current progress:
  - Constructed a 0D airpath model in state-space form
  - Validating its accuracy with the GT-Power model

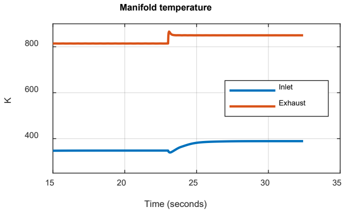


Cylinder charge model: lookup tables from GT-Power

Turbo maps







Responses To Previous Year Reviewers' Comments

- "…the reviewer indicated that specific barriers related to the DOE VTO mission are not clearly linked to the work or the approach"
  - Response - thank you for the comment. This program seeks to resolve the barriers faced by conventional engines by improving the cost-effectiveness of high efficiency and low emissions through an opposed piston design. This is achieved by reducing heat transfer losses through combustion optimization, improving exhaust temperatures at low load by controlling scavenging and manifold optimization, and improving power density through two stroke operation. The reduced cost of an OP engine (7% lower than convention engines) further improves the cost-effectiveness of the technology.
- "According to the reviewer, the project approach does not adequately address the challenges of meeting ultra-low emission requirements. Efficiency gains made in this project will not be transferable to the automotive commercial sector unless emissions are adequately addressed, and there is insufficient emphasis or concern for emissions as this project is currently constructed. If the approach is to move this engine design toward meeting efficiency goals in this project and then meeting emission requirements in some future effort, then that should be stated in the presentation."
  - Response – thank you for the comment. While explicit emissions targets were not set for the project, a baseline 2017 calibration is being utilized to set baseline limits. These limits were then used as part of the optimization process. ULNOX will be explored on the prototype engine.

Responses To Previous Year Reviewers' Comments

- "A key flaw is targeting high-level barriers (challenges) of conventional diesel engines whereas the more appropriate barriers would be the persisting technical barriers facing this particular engine architecture. The specific approach to the important, relevant barriers is not really complete. It would be constructive to show the technical issues that have been resolved for the Achates design over 17 years of research and show the few issues that still need more work. The reviewer indicated that the target of 10% efficiency gain over standard engines is too conservative for the relatively high risk of an unconventional engine. The demonstration of emissions target is unclear whether by hardware, vehicle, or simulation "
    - Response – thank you for the comment. Achates has been identifying and solving the challenges with the opposed piston engine since the conception of the company. A significant fraction of that material has been published and is available on our website. The target of 10% efficiency gain over standard engine was a criteria of the FOA and was adopted as the target for the project. While some challenges remain, we do not believe the engine is of high risk as we have a prototype in revenue service with Walmart achieving ULNOX while providing an improvement in MPG and an advanced combat engine with Cummins for the military. An emissions target was not specified for the program, but the baseline calibrations being used support a 2017 emissions standard. ULNOX capability will be explored as part of this project
- "The comment about Clemson possibly not being able to perform the model predictive control (MPC) work was concerning to the reviewer. This would allow the test matrix to be expanded and optimized; the absence of this aspect of the work will increase the testing required at reduced overall benefit."
    - Response – the previous slide shows the MPC progress thus far. Although the task was delayed due to foreign national approvals, the team is working hard to catch up to the original timeline and the team expects to be able to accomplish all of the MPC work that was originally proposed.

Responses To Previous Year Reviewers' Comments

- "According to the reviewer, the investigation of improvements to IC engine efficiency and reduced emissions is still an essential part of automotive development. The use of low-carbon or zero-carbon fuels in a highly efficient engine architecture is another area worth pursuing."
  - Response – thank you for the comment. Low carbon or zero-carbon fuels are an active area of research for Achates Power.
- "The reviewer found that relevance is a weak spot for this project. The projected benefits of this engine (10%) for DOE's mission are not large enough to justify investment at this time of emerging electric vehicles and continuing improvements being seen in "conventional" ICE vehicles that are moving the needle much more than 10%. If the engine showed a vastly superior applicability of low-carbon fuels, its relevance could be re-argued. Similarly, there are already efforts to exploit hybrid systems with this engine. The emissions from the engine are only as good as conventional engines, apparently not targeting lower levels."
  - Response – thank you for the comment. The 10% improvement target was developed from the FOA. Low carbon fuels are an active area of research with the OP engine. The current hybrid research program was targeting decoupling the crankshafts from each other. The hybrid systems pursued in this program as investigating the impact of series/parallel/powersplit configurations and optimization opportunities. ULNOX will be explored as a part of this project.
- "The reviewer indicated that this project overlaps with other federally funded research on a slightly larger engine design. That work should be completed and assessed prior to investing more funds into this engine design."
  - Response – thank you for the comment. The other federally funded program is a light duty gasoline compression ignition project that does not overlap with this project, which is a medium duty diesel focus.

Collaboration and Coordination with Other Institutions

Prime, industry

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

Sub, industry

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

Sub, university

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

Sub, university

- 3D CFD combustion simulation
- CFD piston bowl optimization

Remaining Challenges and Barriers

- Covid / global supply chain issues associated with the procurement of hardware, including the e-turbo, have imparted a delay in the experimental model validation tasks, which are tied to other efforts including the MPC, combustion CFD, and GT-Suite modeling tasks

Proposed Future Research

FY22

- Build two-cylinder model validation engine and shake down at Achates Power
  - Assemble two-cylinder engine with electric air components and shake down to verify mechanical robustness
- Install two-cylinder engine 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 engine 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

Summary Slide

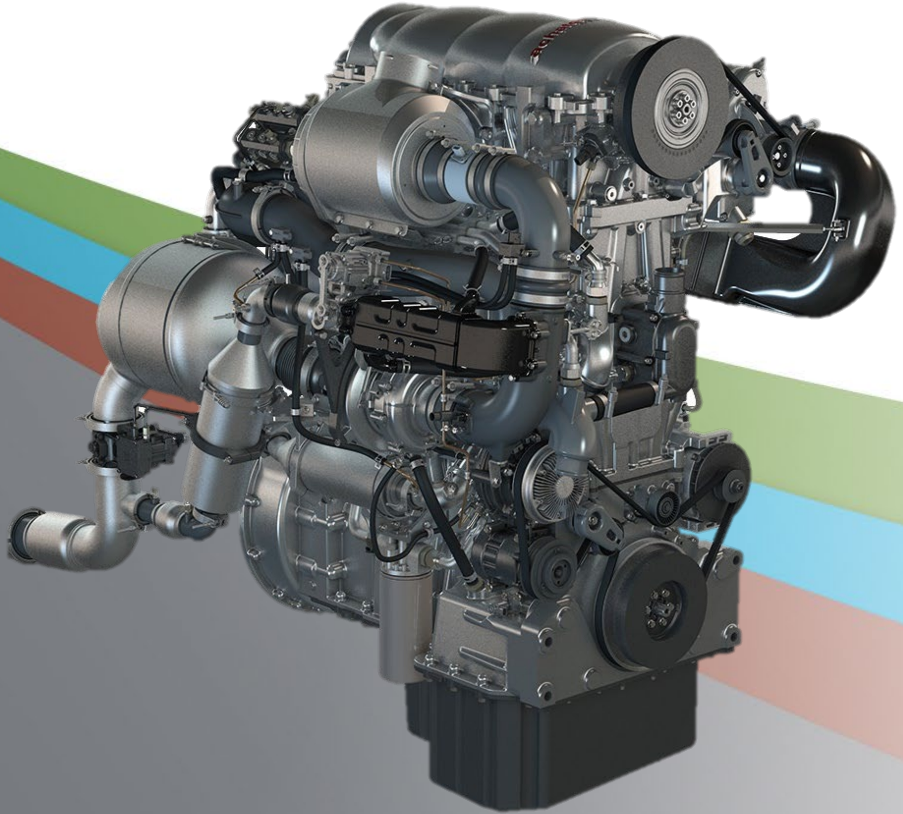
Accomplishments

- 2 cylinder model validation engine is ready for testing once the e-turbo arrives, initial controls have been developed
- Validated CFD model of OP engine at Best-BTE and low-load operating conditions
- Developed software programs needed to perform piston geometry optimizations, improving GIE, soot, and NO_X
- An injector-focused DoE is run, and results analysis is forthcoming
- A full engine open cycle CFD model was validated against experimental data and the open cycle CFD was used to understand the effects of port angle and swirl on the uniflow scavenging process of the OP2S engine
- Designed and optimized the 2-cylinder model validation engine including airpath geometry, comparisons of boosting devices, turbocharger sizing efforts, selection of scavenging control devices, and an evaluation of e-turbo location/packaging
- Vehicle drive cycle modeling has commenced with comparisons between the baseline Isuzu engine and a 2-cylinder OP engine in a conventional powertrain first; future work will include hybridized powertrains
- A prototype 3-cylinder OP engine has been installed in the test cell at Clemson and is providing validation data for modeling efforts, as well as preparing the test cell for the 2-cylinder validation engine in the following quarters
- MPC model development efforts have begun and will be able to deliver the proposed work by the end of the project

Summary Slide

Relevance toward VTO objectives

- This project seeks to use model simulation, optimization efforts, and experimental validation data for air path and combustion optimization 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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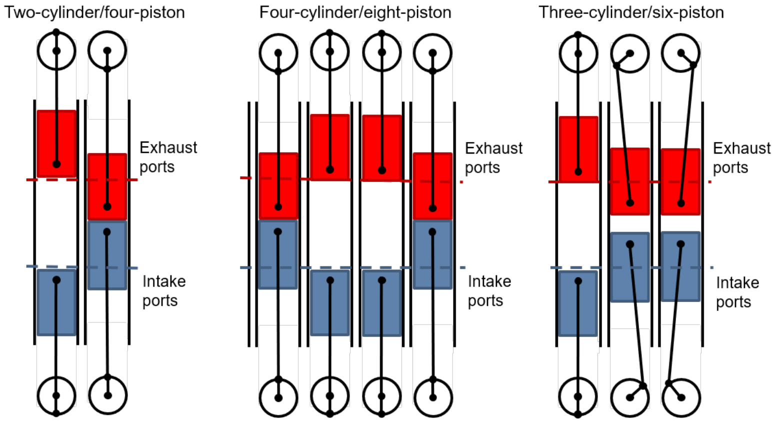
Importance of Family of Engines

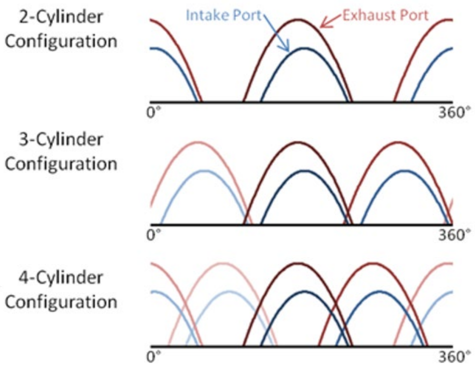
- Launching a new engine architecture is a major initiative. Moreover, since the application range for commercial and industrial vehicles is so broad, a considerable number of new engines are required to address the full market
- Launching a family of engines with a common power cylinder system can create 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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