Project ID: ace155

Low-Mass and High-Efficiency Engine for Medium-Duty Truck Applications

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General Motors

6/4/2020

Overview

Timeline

Project start date: 10/2019

Project end date: 12/2023

Percent complete: ~ 7%

Budget

Total project funding
- DOE share $7,007,878
- Contractor share $3,294,329

Funding received in FY19
- $0

Funding for FY20 planned
- $1,847,314

Barriers/Technical Targets

Combustion Technology
- Advanced gasoline stoichiometric dilute combustion

Materials Technology
- Lightweight, high performance, and low cost

Partners

Oak Ridge National Laboratory

The Ohio State University

Michigan Technological University

ECK Industries Inc

Project lead General Motors

Relevance

Objectives:

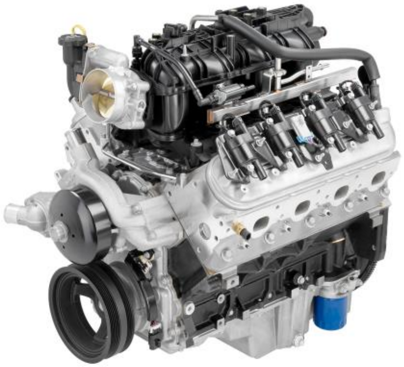
To develop a high performance gasoline engine equipped with advanced materials and combustion technologies capable of ≥10% fuel efficiency improvement and ≥15% engine weight reduction when compared to the baseline 2015 L96 VORTEC 6.0L V8 engine.

Solution to be compliant with applicable EPA emission standards with performance demonstrated via simulation coupled with engine dynamometer testing.

Impact:

- The integrated R&D of advanced propulsion materials, manufacturing, and combustion strategies can not only expand engine operating parameters but also enable lighter weight engines for better performance and efficiency
- The technologies developed and demonstrated in this project will help bridge the technology gap between light and heavy duty engines.
- The approach and methodologies developed and implemented in this project can be readily applied to other material/component systems to shorten development time and cost.

Reduce energy usage & increase energy security



2015 L96 6.0L V8 Engine (Baseline)

Chevrolet Silverado 3500HD truck with the baseline engine

Milestones

Month/Year	Description of Milestone or Go/No-Go Decision	Status
March 2020	Determine target material property requirements for key engine components (GM)	Completed
June 2020	Complete layout and performance simulation of normally aspirated and boosted engine architectures (GM)	On Schedule
Sept 2020	Select material and manufacturing solutions for key engine components (GM, ORNL, OSU, MTU, ECK)	On Schedule
Dec 2020	Go/No Go Decision #1 - Select Engine Architecture to Achieve Project Objectives (All)	On Schedule
March 2021	Complete development and selection of lightweight high-performance materials (All)	On Schedule
June 2021	Develop advanced overcasting technologies (OSU)	On Schedule
Sept 2021	Complete development and optimization of materials and casting process for crankshaft (MTU)	On Schedule
Dec 2021	Go/No Go Decision #2 - Selected Engine Technologies Demonstrated Potential to Achieve Performance and Mass Objectives (All)	On Schedule

GM – General Motors, ORNL – Oak Ridge National Lab, OSU – Ohio State University, MTU – Michigan Technological University, ECK – Eck Industries Inc

Approach

- The project begins with large scale engine architecture design and analysis activity, advanced materials and manufacturing process development and down selection. It culminates in an engine test cell evaluation with optimal materials and manufacturing solutions supporting final vehicle simulation. The final engine test will verify engine weight reduction and performance to the FOA objectives. The project is planned for four budget periods (two phases).

PHASE 1 – Technology Research and Development

Budget Period 1: Engine architecture concepts, advanced combustion system and materials weight-saving technologies evaluated via simulation & experiments

Budget Period 2: Evaluation using current equivalent architecture with novel combustion, material and process development

PHASE 2 – Technology Validation and Demonstration

Budget Period 3: Design, build and initial development testing of proposed medium duty truck engine capable of meeting requirements

Budget Period 4: Demonstration of performance to requirements using engine test cell and vehicle simulation

Approach (Cont.)

➢ It is proposed to breakdown the project into four key tasks

Task 1
- Simulate advanced combustion technology combinations
- Simulate durability at higher temperature and pressure
- Choose best combinations

Task 2
- Proof of concept physical testing using "basis" engine
- Develop materials and processes for Phase 2 testing on new engine
- Select technologies for Phase 2 new engine

Task 3
- Detailed design of new Phase 2 engine
- Fabricate parts for new engine
- Verify feasibility of new material and process innovations

Task 4
- Build and calibrate new engine
- Verify performance
- Post test evaluation of parts fabricated by new material and process innovations

Phase 1 (Tasks 1–2) → **Phase 2** (Tasks 3–4)

Approach (Cont.)

- The project integrates advanced combustion technologies with innovative material and manufacturing process developments to assure that the higher thermal loads and cylinder pressures associated with efficiency gains can be practically implemented and leveraged by mass reduction.

New Combustion Technology

- Stoichiometric combustion focus
- Increased Compression ratio
- Aggressive EGR Dilution
- Load point optimization

Combustion Areas of Focus

- Optimal cylinder deactivation
- Advanced valvetrain phasing and lift strategies
- Advanced fuel systems including "ultra" high pressure DI
- Advanced ignition systems including pre-chamber spark plug
- Advanced EGR dilution systems including E-EGR
- Atkinson or Miller cycle strategies
- Variable induction system strategies
- Combustion chamber cooling strategies

Advanced Materials

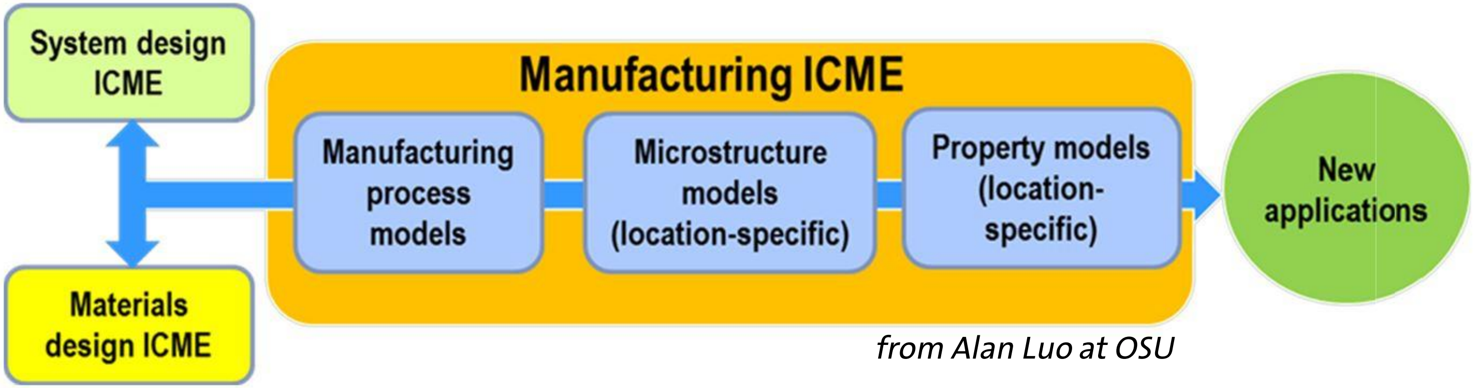
- High-temp Al alloys
- High strength high-modulus cast steel/iron
- Al alloy MMC
- High entropy alloys (HEA)
- Multi-materials

New Manufacturing Technologies

- Additive manufacturing
- 3D printing intricate cores
- Novel Al casting processes
- Overcasting
- Overmolding PMC
- Local reinforcement

Approach (Cont.)

- The project is integrated with other research or deployment projects within the pertinent VTO subprogram (https://www.energy.gov/eere/vehicles/annual-progressreports)
  - Advanced combustion engines (i.e. ace121, ace127, ace 133, etc.)
  - Propulsion materials (I.1.A, I.1.B, I.1.C, I.2.C, etc.)
  - Lightweight materials (II.2.D, II.3.D, etc.)
- Integrated Computational Materials Engineering (ICME) approach will be applied in this project to accelerate development, reduce risk, and enable tailored properties that lead to cost effective mass reduction.



from Alan Luo at OSU

Technical Accomplishments

➢ Task 1.1 Layout and Performance Simulation of Engine Architectures

❑ **Determine approximate overall engine displacement, cylinder size and number of cylinders for peak efficiency at high fuel usage medium-duty truck engine operating points while meeting peak power and torque targets**

- The baseline 2015 GM medium duty truck engine has been simulated using the PHASE 2 GEM simulation model.
- The speed-load points of high fuel usage and impact on fuel economy based on this drive cycle simulation have been established.
- The top 14 points, representing 95% of fuel energy used during the test cycle, define the key operating points at which the fuel economy improvement potential will be evaluated.

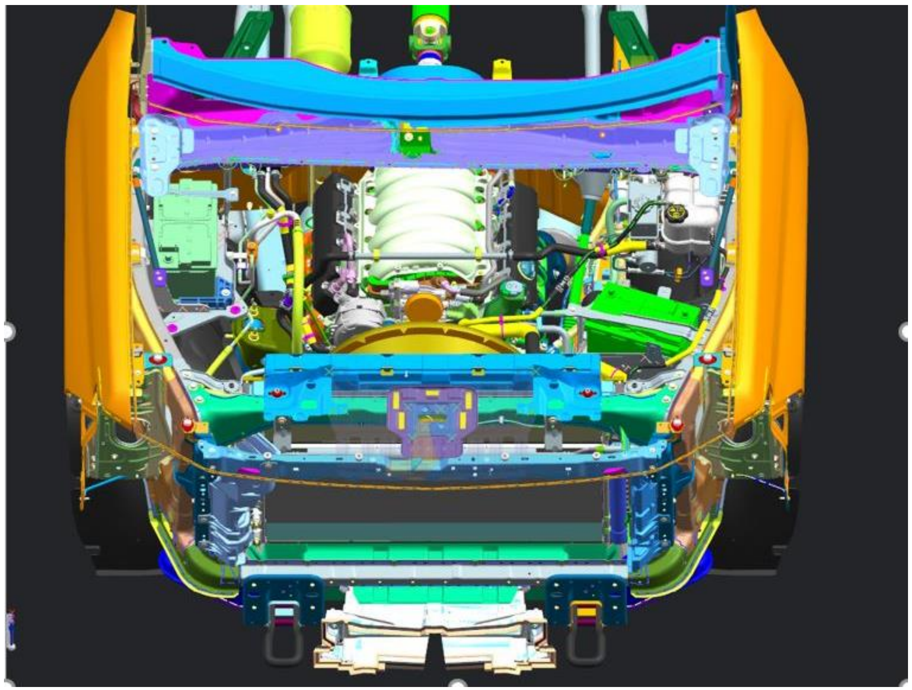
Engine Speed (rpm)	Engine Brake Torque (Nm)	Fraction of Total Fuel (%)
2000	367.6	22.08%
1750	236.3	20.51%
1750	472.7	18.92%
1500	315.1	7.31%
2000	105.0	5.02%
2500	420.2	4.70%
1000	420.2	4.56%
2000	577.7	4.22%
2200	212.7	2.22%
1300	154.9	1.76%
2800	577.7	1.34%
1500	52.5	1.23%
2000	10.5	1.09%
1000	10.5	0.66%

2015 Baseline Medium Duty Truck Fuel Usage Points

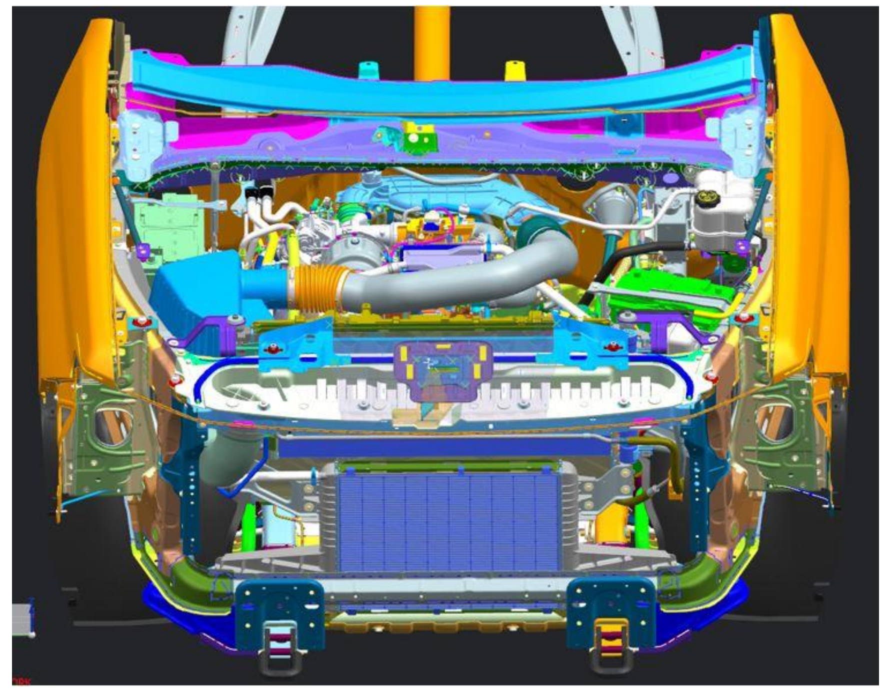
Technical Accomplishments

➢ Task 1.1 Layout and Performance Simulation of Engine Architectures

- ❑ **Execute basic layout of V8 engine and L6 downsize boosted engine in medium-duty truck to understand packaging opportunities and challenges**



Large Displacement Normally Aspirated Engine Concept Packaged in an existing Medium Duty Truck Engine Compartment

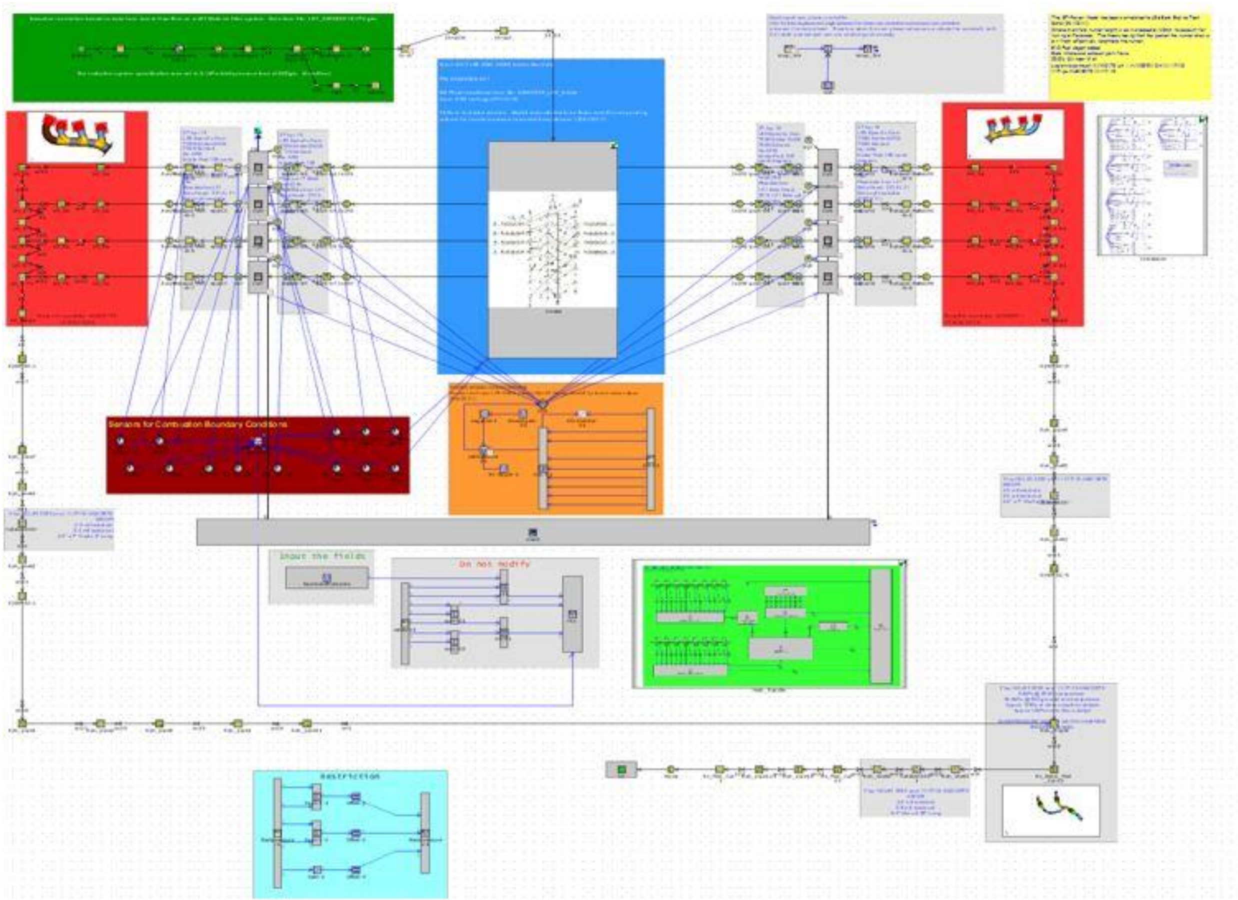


Small Displacement Boosted Engine Concept Packaged in an existing Medium Duty Truck Engine Compartment

Technical Accomplishments

➢ Task 1.1 Layout and Performance Simulation of Engine Architectures

- Develop 1D simulation model of engine concepts to establish initial performance prediction



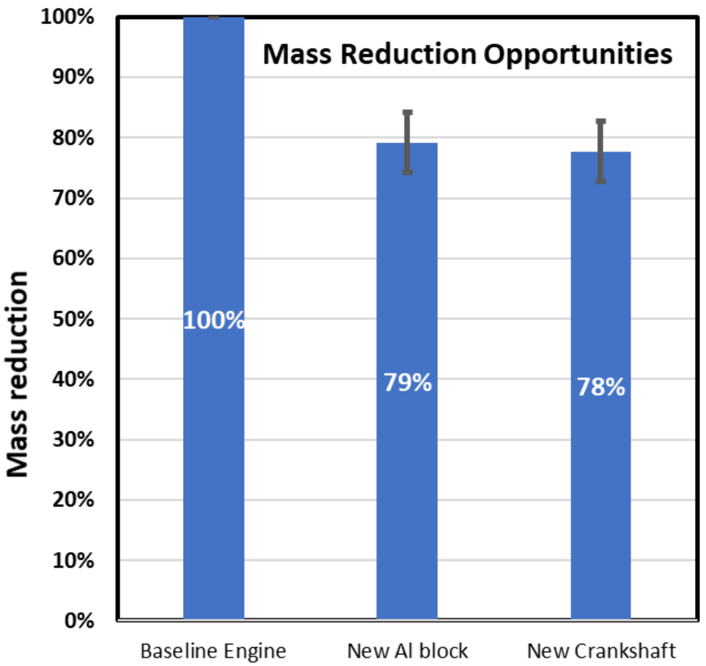
Large Displacement Normally Aspirated Engine Concept 1D Simulation Model Overview

Technical Accomplishments

➢ Task 1.2 Weight Saving Material and Manufacturing Technologies

❑ Understanding mass reduction opportunities

2015 VORTEC 6.0L V8 PFI Engine (L96 Baseline)-HT3500			Mass Reduction Opportunities	
			Advanced Materials & Manufacturing	
Key Parts	Materials	Weight (Kg)	Option 1	Option 2
Engine Block:	Cast Iron (250)	96.9	Cast high strength high temperature Al	Multi-Materials
Cylinder Head:	Cast Aluminum (A356+0.5%Cu)	10.8	Cast high strength high temperature Al	Multi-Materials
Crankshaft:	Cast nodular iron with undercut and rolled fillets	23.5	High strength cast steel	High strength high modulus nodular iron
Camshaft:	Hollow steel (5150)	4.4	High strength ADI	
Piston (Each)	Hypereutectic Al	0.5	High strength high temperature Al for Additive Manufacturing	High entropy alloys (HEA) for Additive Manufacturing
Exhaust manifold (each)	Cast ductile iron	6.5	High temperature stainless steel	
Total Engine Weight (Kg):		243.1		

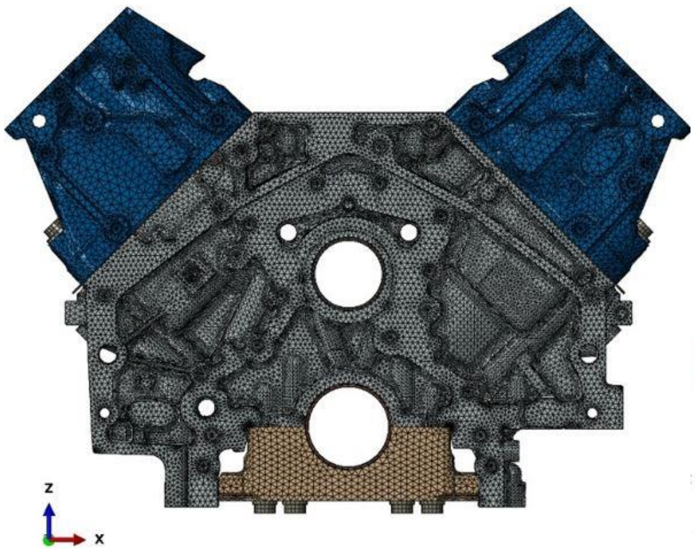


Cast Al engine block offers the great potential for mass reduction

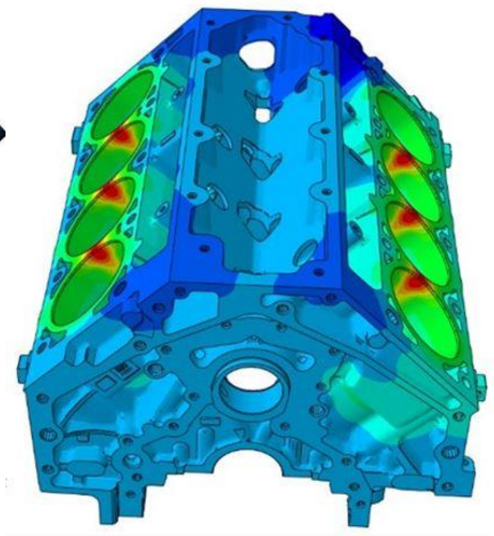
Technical Accomplishments

➢ Task 1.2 Weight Saving Material and Manufacturing Technologies

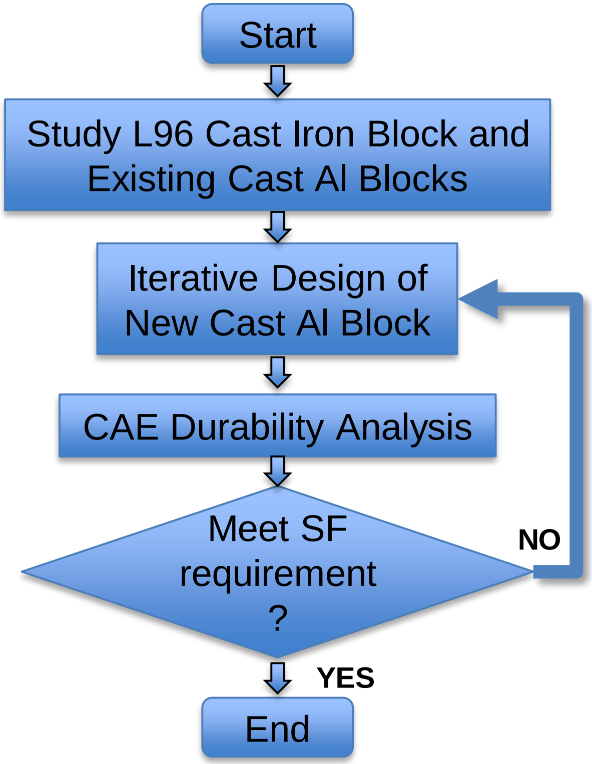
❑ **Design of cast aluminum engine block**



FEA Durability Model Assembly



Cast Al Block

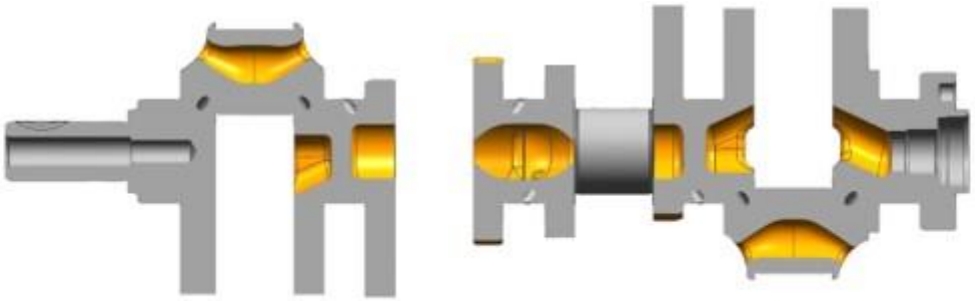


Design criteria: mass reduction, functionality & performance (durability & NVH - Noise, vibration, and harshness)

Technical Accomplishments

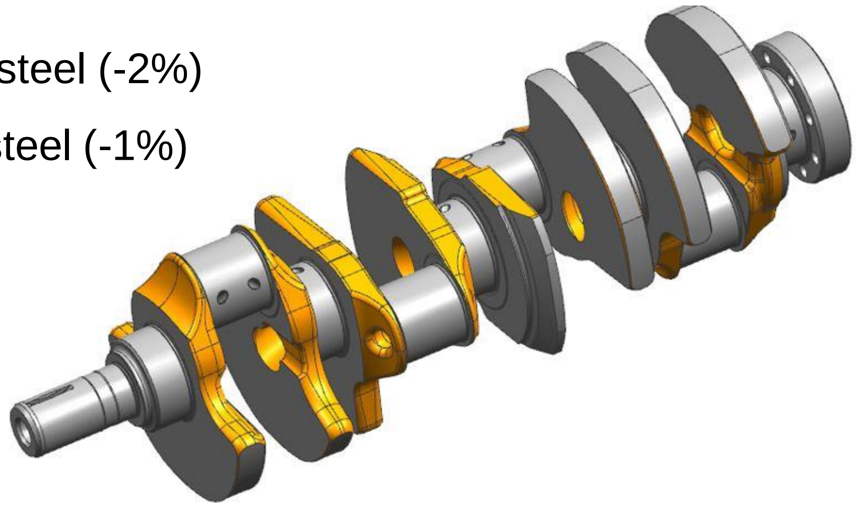
➢ Task 1.2 Weight Saving Material and Manufacturing Technologies

❑ **Design of cast steel crankshaft**



Highlights of a preliminary design

- Oil film targets met
- Balance targets met
- Torsional stiffness close to forged steel (-2%)
- Bending stiffness close to forged steel (-1%)
- As-cast hollow structure
- Mass savings: 0.246 Kg

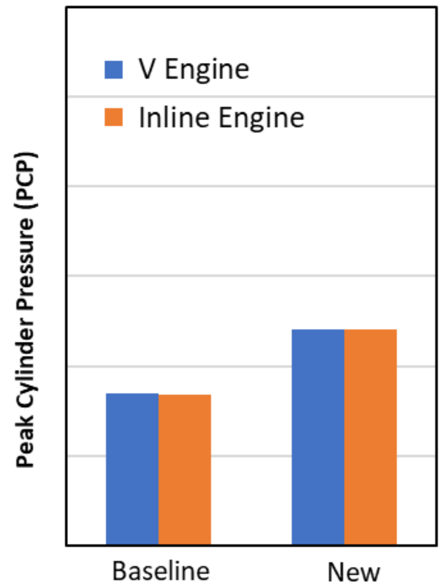


Technical Accomplishments

➢ Task 1.2 Weight Saving Material and Manufacturing Technologies

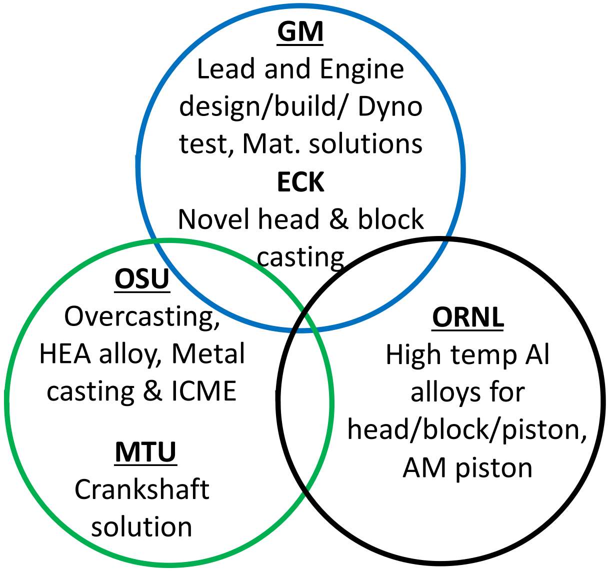
❑ Target Material Properties of Key Components (e.g. Engine Block & Crankshaft)

Component	Property	Baseline	DOE Project Targets
Engine Block	Room Temperature Performance	@25C (cast iron)	@25C (Cast Al)
	Ultimate Tensile Strength (MPa)	265	>280
	Yield Strength (MPa)	240	>240
	Elongation (%)	0.5	>1
	Density (g/cm^3)	7.2	<3.5
	Fatigue strength (MPa)	76	100
	Hot Tearing Resistance	Excellent	Excellent
	High Temperature Performance*	@300C	@300C
	Ultimate Tensile Strength (MPa)	222	145
	Yield Strength (MPa)	200	100
	Fatigue strength (MPa)	64	48
Crankshaft	Room Temperature Performance	@25C (DI)	@25C
	Ultimate Tensile Strength (MPa)	707	≥850
	Yield Strength (MPa)	390	≥580
	Elongation (%)	>3%	>2%
	Hardness (HBN)	>200	>250
	Density (g/cm^3)	7.16	<8.0
	Fatigue strength (MPa)	237	≥400
	Young's modulus (GPa)	172	>180



To meet fuel efficiency target, peak engine pressure and temperature will greatly exceed current material properties and thus materials need to be improved

Collaborations and Coordination



ORNL - Dr. Amit Shyam's team	Develop high strength high temperature Al alloys for head, block and piston & AM process for piston
OSU - Prof. Luo's team	Develop overcasting technology & local reinforcement, lightweight high entropy alloy (HEA), and computer simulation of defects in AM piston.
MTU - Prof. Sanders' team	Develop cast steel and ductile iron alloys and casting technology for high performance crankshaft
ECK - Mr. Dave Weiss' team	Develop novel casting technologies to cast flawless Al blocks and heads, MMC, cast-in-place inserts
GM	Develop combustion technologies and high integrity low mass solutions; design, build and test new engine

Team Expertise	**ORNL**: R&D 100 Award - ACMZ High Temperature Cast Aluminum Alloys for Automotive; Additive manufacturing (AM) with >10 machines **OSU**: High entropy alloy for high temp applications; Lab-scale overcasting, high pressure die casting, ICME, AM with 7 machines **MTU**: World-class expertise in nodular iron and cast steel; Lab-scale casting of nodular iron and steel as well as aluminum **ECK**: Extensive experience and expertise in MMC; Prototype and production non-ferrous casting supplier to OEMs and aerospace; novel metal casting technologies **GM**: One of the world's largest automakers, sold over 10 million vehicles in 2019. GM has a long history of developing world class award-winning engines. over 10 patents recently on Al, cast iron, cast steel, etc.; Production of over 500 million lb Al castings annually; many AM machines

Remaining Challenges and Barriers

FOA Minimum Performance Targets

Vehicle Size Class	Weight Reduction	Vehicle Fuel Economy Improvement	Emissions Compliance	Test Cycle
Class 3-6 (Midsize Trucks)	15%	10%	CI Engines: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100O9ZZ.pdf SI Engines: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100OA01.pdf	Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-duty Engines and Vehicles Phase 2 (40, 49 CFR)

* Relative to 2015 baseline vehicle

Cost-Effective Combustion, Material and Manufacturing Technologies

- Advanced gasoline stoichiometric dilute combustion that achieves the target fuel economy requirement while delivering outstanding value to the customer
- High strength lightweight materials incorporated with advanced metal casting and additive manufacturing (AM) to produce highly durable engine structures to maximize performance with minimum mass and cost

Proposed Future Work in FY20 & FY21

- **FY2020 (Technology Research and Development)**
  - Complete layout and performance analysis of both engine concepts ((#1 Large Displacement, Normally Aspirated and #2 Small Displacement, Boosted) through simulation and preliminary experiments
  - Evaluate and develop material and manufacturing solutions for key engine components through simulation and preliminary experiments
  - Prioritize potential technologies for fuel efficiency improvement and mass reduction capable of meeting objectives
- **FY2021 (Technology Research and Development)**
  - Complete development and selection of lightweight high-performance materials for key engine components
  - Complete development and selection of manufacturing processes for key engine components
  - Select engine technologies and materials/manufacturing solutions that demonstrate potential to achieve performance and mass objectives

Summary

- Two engine architecture CAD representations (#1 large displacement, normally aspirated and #2 small displacement, boosted) have been developed to evaluate packaging in a current GM medium duty truck application.
- 1D simulation models of two engine concepts have been developed to establish initial performance predictions.
- Mass reduction and performance improvement opportunities have been studied and high potential key engine components have been identified.
- Iterative design and performance analyses of some key engine components such as cast aluminum engine block, cast steel crankshaft, and high modulus cast ductile iron crankshaft have started.
- Target material properties have been investigated and defined for the key engine components to achieve the improved performance compared with baseline engine.

Technical Back-Up Slides

FY 2020 Project Plan

TASK 1 (Technology Research & Development) Engine architecture concepts, advanced combustion system and materials weight-saving technologies evaluated via simulation & experiments

Task 1.1. Layout and Performance Simulation of Engine Architectures (#1 Large Displacement, Normally Aspirated and #2 Small Displacement, Boosted)

- ✓ Determine approximate overall engine displacement, cylinder size and number of cylinders
- ✓ Execute basic layout of engine in medium-duty truck to understand packaging opportunities and challenges
- ✓ Establish approximate cost differential of engine assembly
- ✓ Employ 3D CFD analysis to create and evaluate potential combustion system design and technology enhancements
- ✓ Use 1D model to baseline and add projected benefits of proposed combustion system technology enhancements developed through 3D CFD analysis
- ✓ Select engine architecture for further development

FY 2020 Project Plan (Cont.)

TASK 1 (Technology Research & Development) Engine architecture concepts, advanced combustion system and materials weight-saving technologies evaluated via simulation & experiments

Task 1.2. Weight Saving Material and Manufacturing Technology Selection and Development

- ✓ Develop target material property requirements for key engine components such as engine block, cylinder head, piston and crankshaft
- ✓ Develop high strength and high performance ferrous & lightweight materials
- ✓ Evaluate and down-select material and manufacturing solutions for key engine components
- ✓ Develop novel metal casting processes for making flawless heads and blocks
- ✓ Develop advanced overcasting technologies for dissimilar materials
- ✓ Develop novel local material reinforcement technologies
- ✓ Evaluate and develop additive manufacturing process for high performance engine component

FY 2021 Project Plan

TASK 2 (Technology Research & Development) Evaluation and down-selection of proposed individual technology concepts using current equivalent architecture GM production or development engines

Task 2.1. Design and Build Hardware to Evaluate Advanced Combustion Technologies and Weight Reduction Techniques Using Current Equivalent Architecture

- ✓ Advanced combustion system(s)
- ✓ Optimal cylinder deactivation
- ✓ Advanced valvetrain phasing and lift strategies
- ✓ Advanced fuel systems including “ultra” high pressure DI
- ✓ Advanced ignition systems including pre-chamber
- ✓ Advanced EGR dilution systems including E-EGR
- ✓ Atkinson or Miller cycle strategies
- ✓ Variable induction system strategies
- ✓ Combustion chamber cooling strategies

FY 2021 Project Plan (Cont.)

TASK 2 (Technology Research & Development) Evaluation and down-selection of proposed individual technology concepts using current equivalent architecture GM production or development engines

<u>Task 2.2. Test Cell Evaluation of Advanced Combustion Technologies and Weight Reduction Techniques Using Current Equivalent Architecture GM Development Engine</u>

- ✓ Install and test existing development engine to establish initial performance
- ✓ Update and test new basic combustion system(s) in development engine
- ✓ Update and evaluate optimal cylinder deactivation hardware in test cell
- ✓ Update and evaluate advanced fuel systems including “ultra” high pressure DI
- ✓ Update and evaluate advanced ignition system(s) in test cell
- ✓ Update and evaluate advanced dilution system(s) in test cell
- ✓ Update and evaluate advanced Atkinson or Miller cycle hardware in conjunction with advanced variable valve duration and/or lift hardware
- ✓ Update and test advanced variable induction system hardware in test cell

FY 2021 Project Plan (Cont.)

TASK 2 (Technology Research & Development) Evaluation and down-selection of proposed individual technology concepts using current equivalent architecture GM production or development engines

Task 2.3. Development of Advanced Material and Manufacturing Solutions for Mass Saving and Performance

- ✓ Develop and optimize single cast Al solution for head and block
- ✓ Develop and optimize multi-material solutions for head and block
- ✓ Develop and optimize material and manufacturing solutions for high performance piston
- ✓ Evaluate and select high strength cost-effective cast iron alloy(s) for Al block liners
- ✓ Develop and optimize material and manufacturing solutions for crankshaft
- ✓ Conduct a Pareto study to choose the highest payoff materials and manufacturing technology options.