2016 DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting

Integrated Boosting and Hybridization for Extreme Fuel Economy and Downsizing

Project ID: VSS162

Principal Investigator: Dr. Vasilios Tsourapas
Eaton Corporation
June 9, 2016

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Overview

Timeline

- Project Start Date: October 1, 2014
- Project End Date: December 31, 2017
- % Complete: 35%

Budget Period	Start Date	End Date
1	10/1/2014	12/30/2015
2	1/1/2016	12/30/2016
3	1/1/2017	12/30/2017

Budget

- Project Value: $3,499,640
  - DOE Share: $1,749,820
  - Cost Share: $1,749,820 (50%)

- DOE Funding for BP1: $267,500
- DOE Funding for BP2: $987,079
- DOE Funding for BP3: $495,241

Barriers & Technical Targets:

- Improve the efficiency of light-duty engines for passenger vehicles (cars and light trucks) and heavy-duty engines for commercial vehicles (heavy trucks) through and minimization of thermal and parasitic losses;
- Explore waste energy recovery with mechanical and advanced thermoelectric devices to improve overall engine efficiency and vehicle fuel economy.

Partners

- Prime: Eaton Corporation
- Subcontractor: SwRI, Isuzu (Subcontract Pending)

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Relevance

Program Objective

The objective of the program is to develop and demonstrate a highly efficient downsized engine for passenger vehicle that will combine roots Waste Heat Recovery (WHR) in the exhaust and an Electrically Assisted Variable Speed (EAVS) supercharger in the intake

Technical Targets

Type	Metric
Fuel economy	>20% fuel economy improvement over a turbocharged and downsized engine
Cost	<$50/% of fuel economy improvement net impact
Performance	Achieve peak engine torque at <1100rpm
Performance	300ms time to peak torque
Efficiency	>80% of required energy from regeneration (brake and waste heat)

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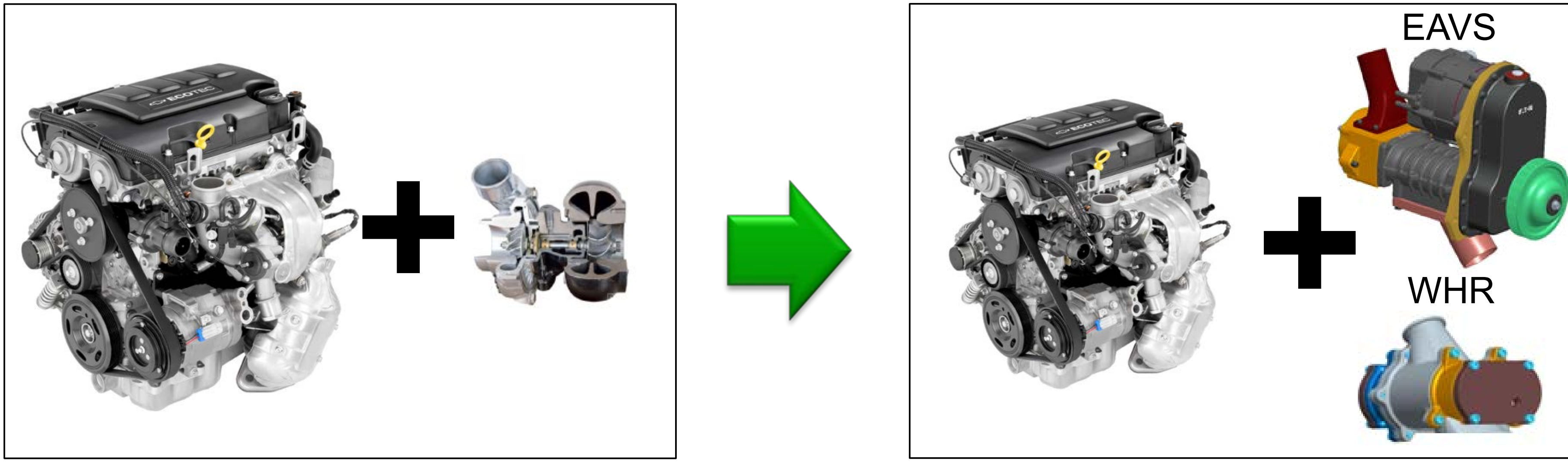
Milestones

Milestone	Status	Due
Vehicle and Engine Selected	Completed	2/20/2015
System Model Developed	Completed	6/30/2015
Modeling Report	Completed	9/30/2015
WHR functional test completed	Completed	12/20/2015
GO/NO GO: System Design Complete and WHR System Functional at Rated Temp.	Completed	12/20/2015
EAVS and WHR Designed	On Track	3/30/2016
Durability Test Complete	On Track	6/30/2016
Engine Hardware Integration Completed	On Track	9/30/2016
Engine preliminary calibration completed	On Track	12/20/2016
GO/NO GO: Engine Dynamometer Testing Achieves Efficiency Requirement	On Track	12/20/2016

Approach / Strategy

Baseline Turbocharged Engine

EAVS/WHR Downsized Engine



- Compare baseline turbocharged engine vs. downsized same engine with:
  - Electrically Assisted Variable Speed TVS Supercharger (EAVS)
  - Roots Based Direct Waste Heat Recovery (WHR)
- Integrate Boosting with Hybridization features to minimize system cost
- Maintain performance while improving on emissions and fuel economy

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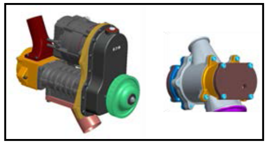
Approach – Budget Period 1-3

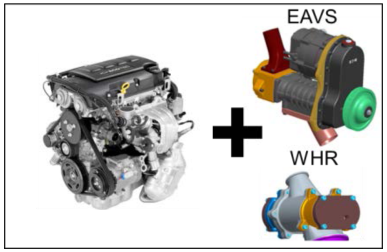
Period 1 – Component Development

Develop and test individual components. Develop component efficiency maps and durability



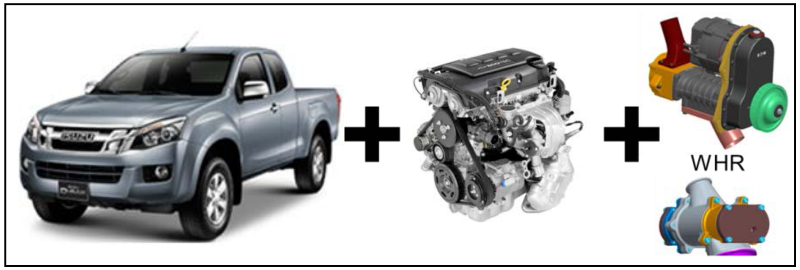
Period 2 – Engine Integration

Integrate components into downsized engine and calibrate controls and test performance/FE



Period 3 – Vehicle Integration

Integrate engine into vehicle and test performance and FE



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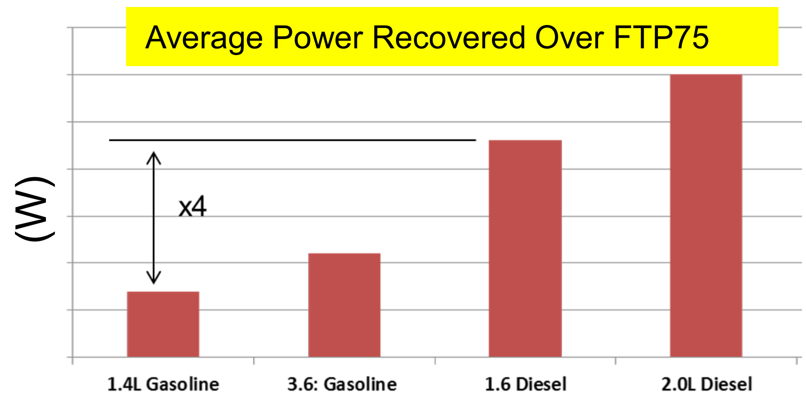
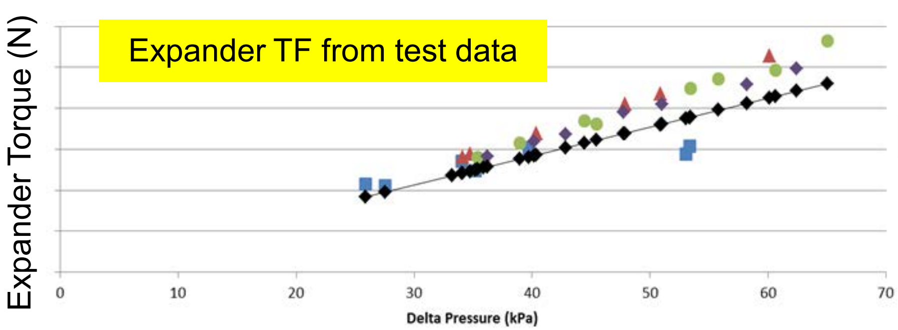
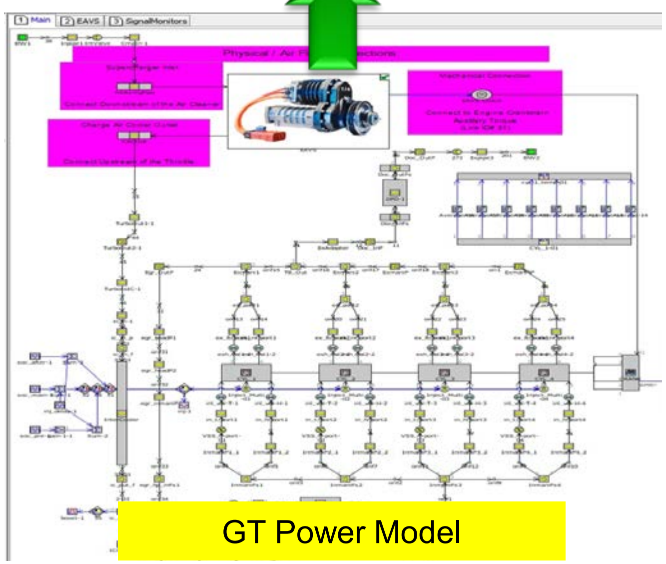
Technical Accomplishments and Progress

Analytical / Modeling Progress

- Roots expander is a volumetric device and volumetric flow rate is critical for energy recuperation
- Using test data, a transfer function was developed to calculate power generated given a PR, T and flow conditions
- Based on simulation analysis a gasoline application was excluded given the throttled operation and low volumetric flow rates over a cycle
- Significant more energy is recovered on a diesel engine application at low PR

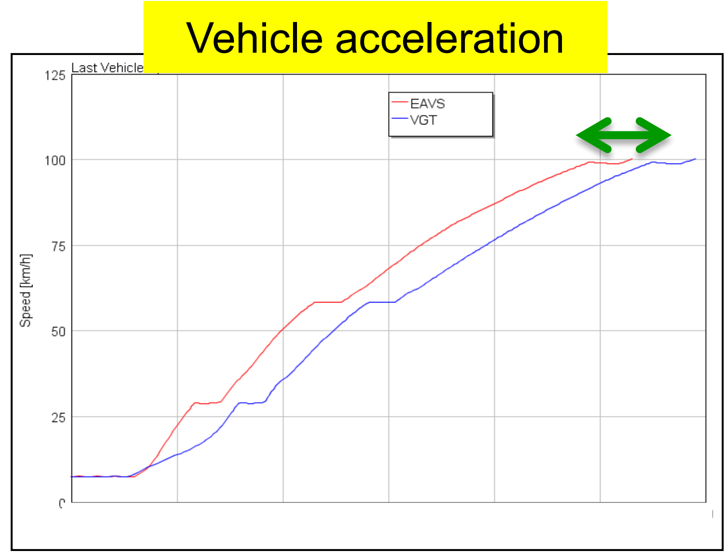


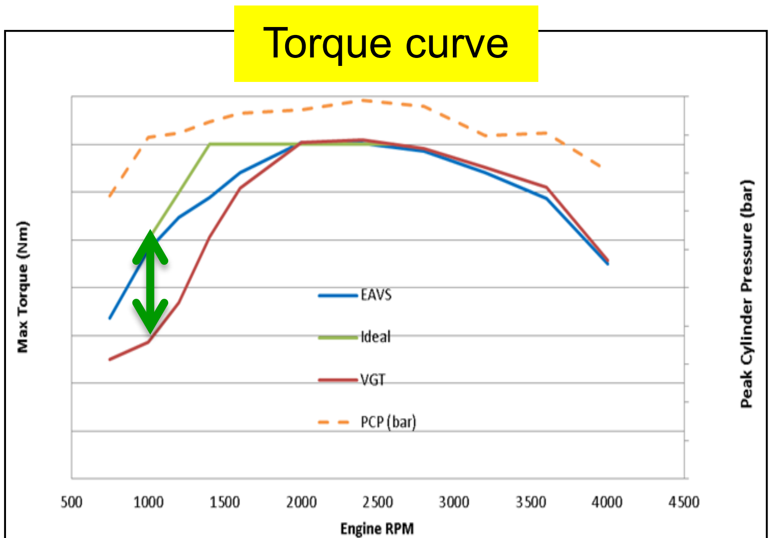


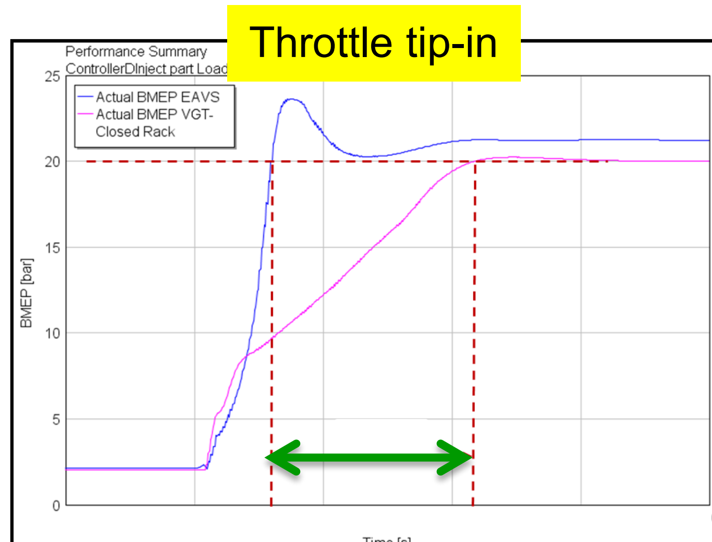


Simulation Results - Performance

- **Improved Drivability**: Reduced time-to-BMEP
- **Improved Performance**: Reduced time to 60mph
- **Improved low end torque:** Increased engine torque at low rpm
- Downspeeding/Downsizing analysis ongoing to trade off performance with FE







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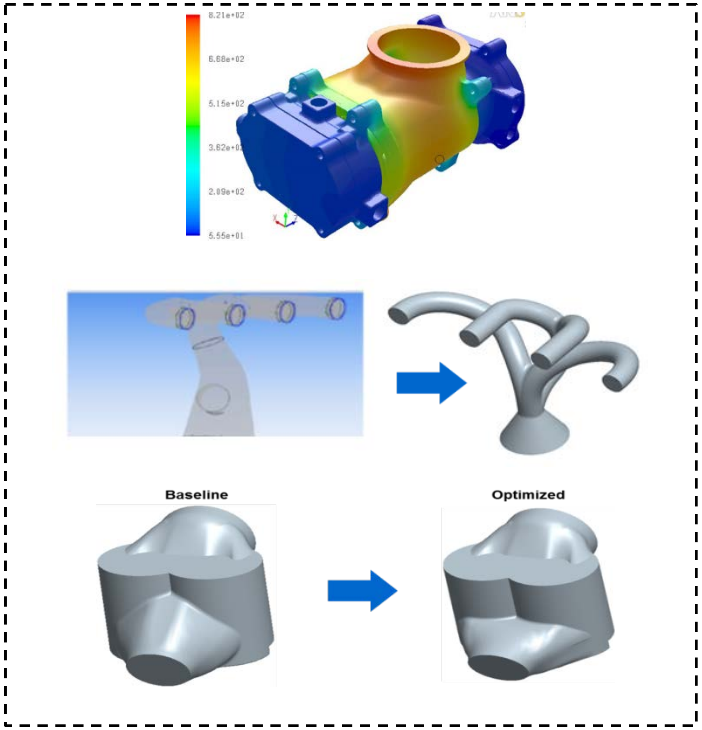
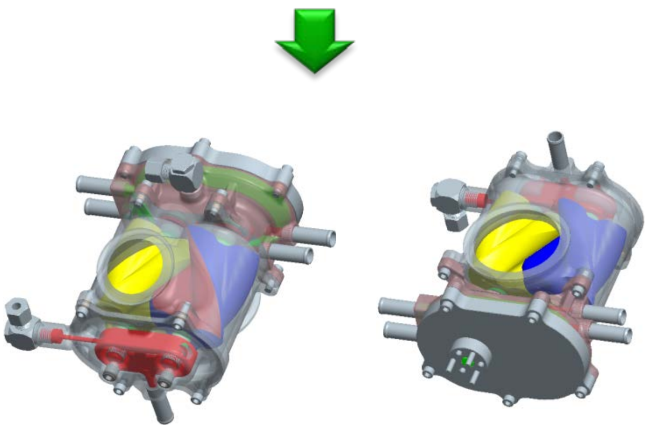
Technical Accomplishments and Progress

WHR Component Development

- Expander thermal modeling to completed material selection, structural integrity and clearances
- Exhaust manifold optimization completed to ensure capture of exhaust pulse energy and avoid cylinder cross-talk
- Outlet/Inlet port optimization completed to ensure improve isentropic efficiency of device



- Resulting expander design with optimized clearances, cooling ports and material

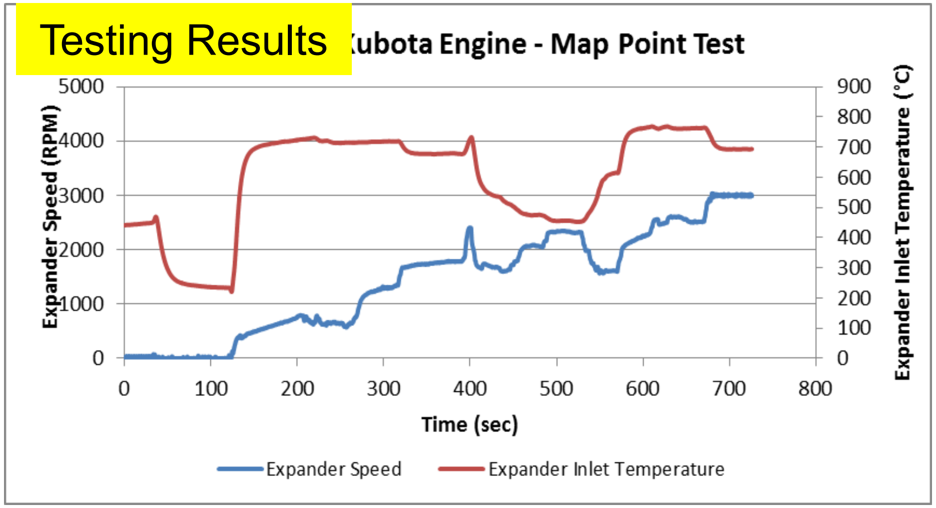


Technical Accomplishments and Progress

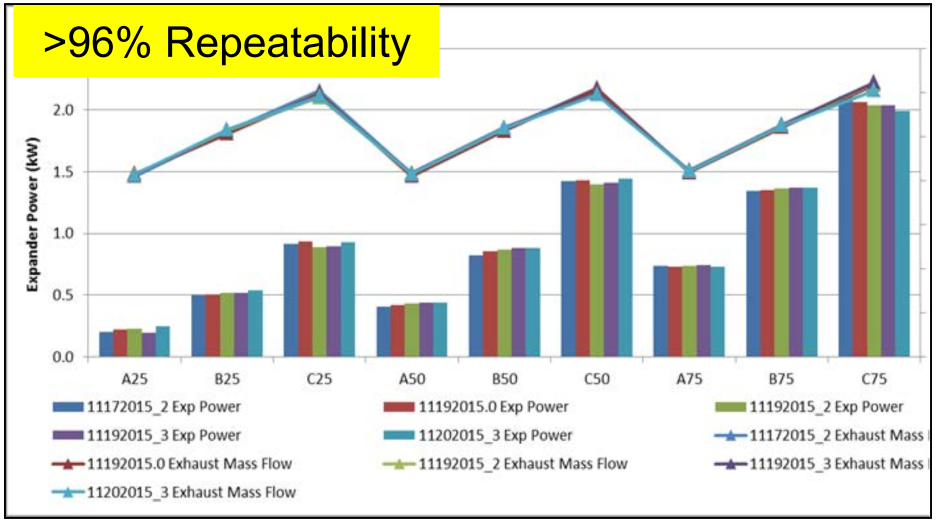
WHR Test Results

- First WHR prototypes were tested successfully on diesel engine at rated temperature of up to 700C
- Up to 3kW of generated energy at low backpressure and flow rates
- Used data to validate WHR model
- Shown >96% repeatability on testing

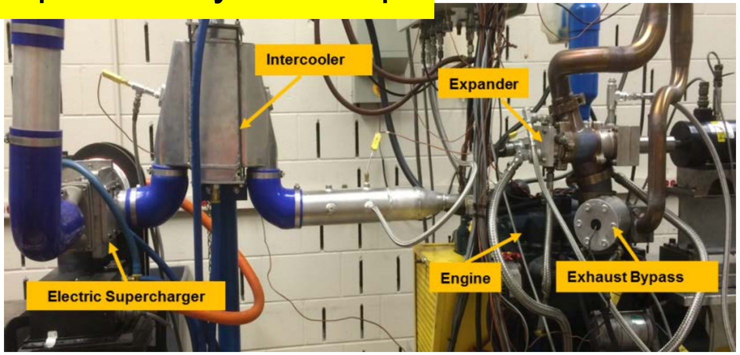
Testing Results



>96% Repeatability



Expander Dyno Setup



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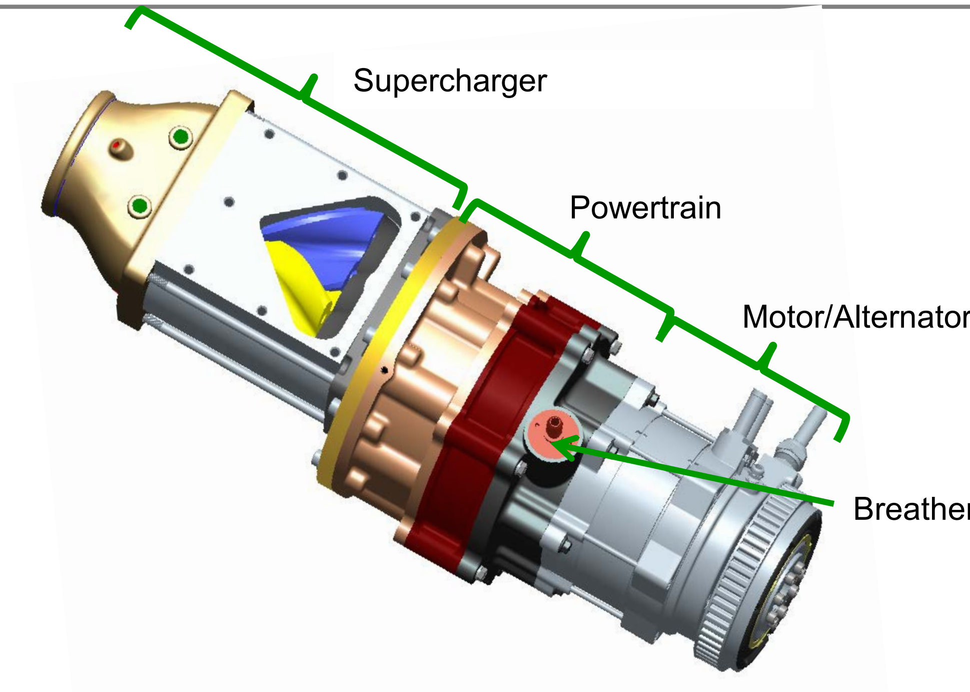
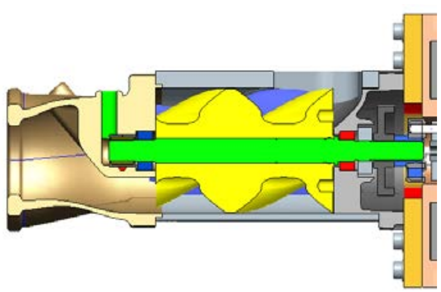
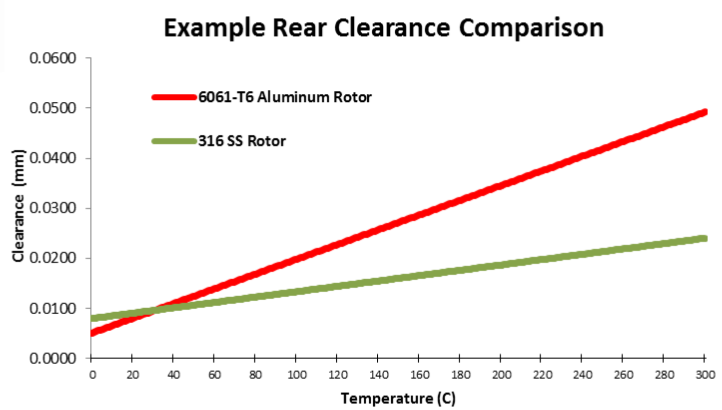
Technical Accomplishments and Progress
EAVS Component Development

- Diesel application required higher pressure ratios for boosting device
- New material combinations for higher temperature conditions and clearance control
- Improved seal and bearing designs for higher pressure ratios
- Forced engine oil lubrication for gear cases
- Investigating Soot tolerance with SwRI to develop low pressure EGR device for this application







Responses to Last Year Reviewers' Comments

Questions / Comments	Responses
-The reviewer stated that it would be nice to have a comparison of how these technologies compare in **cost** to other alternatives for improving fuel economy. The Roots expander and hybrid supercharger are interesting technologies. The reviewer indicated that a comparison with other technologies might help justify the selection of these technologies for application on an engine	System cost will be addressed in budget period 2 after the design and prototypes have been build for engine and the team has a better understanding of the materials and components that need to be included. Also once the fuel economy improvement of the system is established we will be able to calculate a $/% of FE number and evaluate the competitiveness of the system compared to other technologies.
-The reviewer stated that collaboration seems reasonable. Addition of a **partner that actually manufactures engines** might improve the project (not clear if that is possible). -The reviewer stated that the project could improve collaboration by using partners from national laboratories and industry. -The reviewer noted an interesting combination of systems into one project; the controls required to balance these two systems to achieve optimization may require additional **vehicle-related tuning**	Eaton has identified the need for deep system integration with the engine and has partnered with an engine manufacturer and is in the process of finalizing the subcontract. This will help us calibrate the engine to the best extent possible and have access to the engine calibration variables without the need for using a prototype controller.
The reviewer indicated that one area for potential future research is further exploration of the interactions of these systems with **engine calibration**. The reviewer questioned how the engine calibration might be optimized to help improve overall system performance. It was not clear how much work in the future will be focused on engine calibration development, but it seems this would be an important area to get the best performance from the powertrain system as a whole. The reviewer stated that understanding the impact of the Roots system on backpressure, and how the backpressure impacts **peak cylinder pressure constraints**, engine durability, and efficiency will be important to understanding the potential impact of the system.	Peak cylinder pressure constraints were taken into account when increasing low end torque curve of the engine. Even though the EAVS system can provide peak boost at low rpm the cylinder pressure constraints were accounted for and the torque curve was adjusted accordingly. Further investigation will be done in BP2 during the dyno development.

Collaborations / Team

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- Prime Contractor / Program management
- Requirement definition and System Design
- Component Development and Testing
- System assembly
- End-user demonstration Commercialization

ISUZU

(Subcontract Pending)

- Vehicle Provider
- Engine and vehicle calibration
- Aftertreatment development
- Chassis Dyno testing

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- SC EGR Durability analysis
- Test stand development for EGR testing

Remaining Challenges and Future Work

FY	Challenges	Future Work
2016	WHR Durability and Cost	Q2 will focus on testing the WHR system under heavy loads for extender periods of time to ensure durability. Based on final design cost will be assessed
	System Control for efficiency and drivability	Dyno development and calibration with target engine. Implement controls from BP1 and calibrate.
2017	Emissions and Fuel Economy Optimization	Integrate components in target engine and develop/ calibrate control strategies on dynamometer
	Vehicle Integration	Further component durability testing and prepare mechanical/ electrical layout of demonstration vehicle

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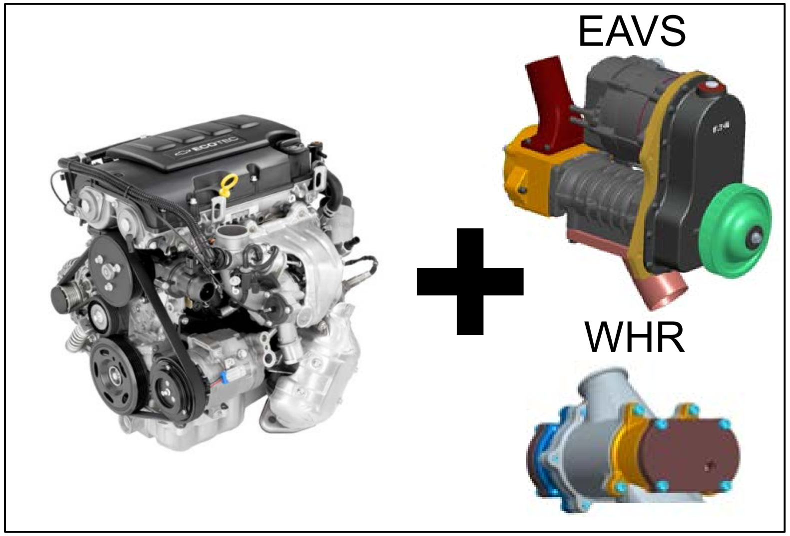
Summary

- Completed simulation analysis to identify right application for proposed technology
- Completed WHR thermal, structural and CFD optimization and designed/build prototypes
- Successfully designed and tested the WHR unit at rated temperature on diesel engine
- Added critical partners for engine calibration and EGR analysis



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