2017 DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting

Integrated Boosting and Hybridization for Extreme Fuel Economy and Downsizing

Project ID: ACS112

Principal Investigator: Dr. Chinmaya Patil
Eaton Corporation
June 9, 2017

Powering Business Worldwide

"This presentation does not contain any proprietary, confidential, or otherwise restricted information."

Overview

Timeline

- Project Start Date: October 1, 2014
- Project End Date: September 30, 2018
- % Complete: 55%

Budget Period	Start Date	End Date
1	10/1/2014	12/30/2015
2	1/1/2016	9/30/2017
3	10/1/2017	9/30/2018

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

Relevance

Program Objective

The objective of the program is to develop and demonstrate a highly efficient downsized engine for passenger vehicle that will combine electrified Waste Heat Recovery (eWHR) 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)

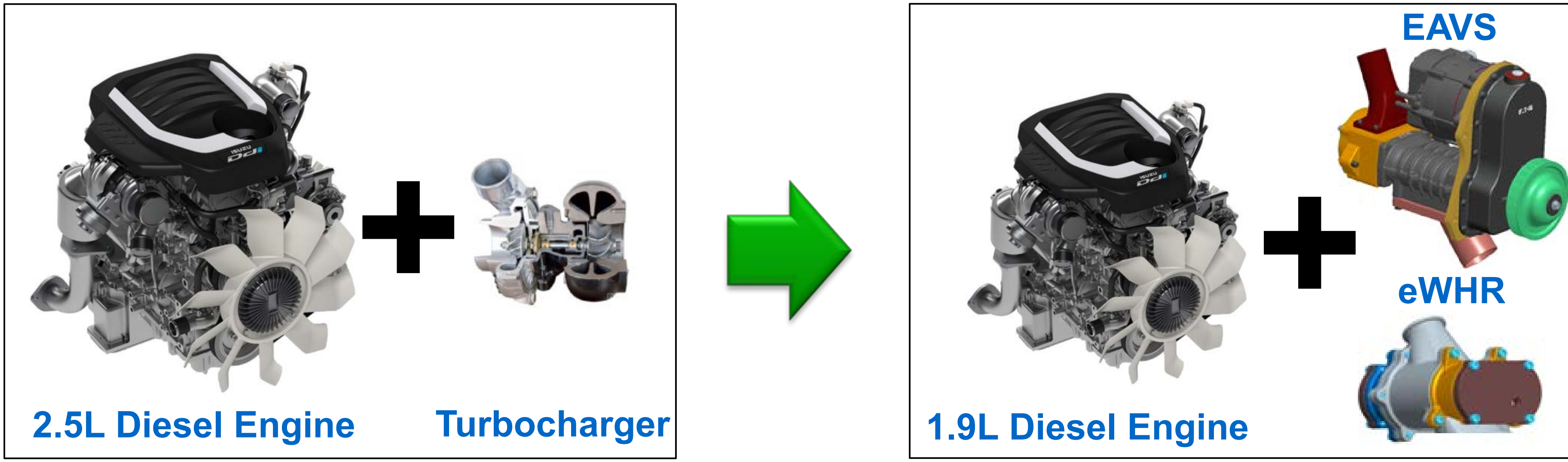
Milestones

Milestone	Status	Due
Vehicle and Engine Selected	Completed	2/20/2015
System Model Developed	Completed	6/30/2015
Modeling Report	Completed	9/30/2015
eWHR functional test completed	Completed	12/20/2015
BP1 GO/NO GO: System Design Complete and WHR System Functional at Rated Temperature	Completed	12/20/2015
EAVS and eWHR Designed	Completed	9/30/2016
Durability Test Completed	Completed	12/30/2016
Engine Hardware Integration Completed	On Track	5/30/2017
Engine Preliminary Calibration Completed	On Track	8/30/2017
BP2 GO/NO GO: Engine Dynamometer Testing Achieves Efficiency Requirement	On Track	9/30/2017
EAVS and eWHR Systems Calibration Completed	On Track	12/30/2017
Vehicle Integration of EAVS and eWHR systems Completed	On Track	4/30/2018
Vehicle Performance Evaluation Completed	On Track	9/30/2018

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 Electric Direct Waste Heat Recovery (eWHR)
- Integrate Boosting with Hybridization features to minimize system cost
- Maintain performance while improving on emissions and fuel economy

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

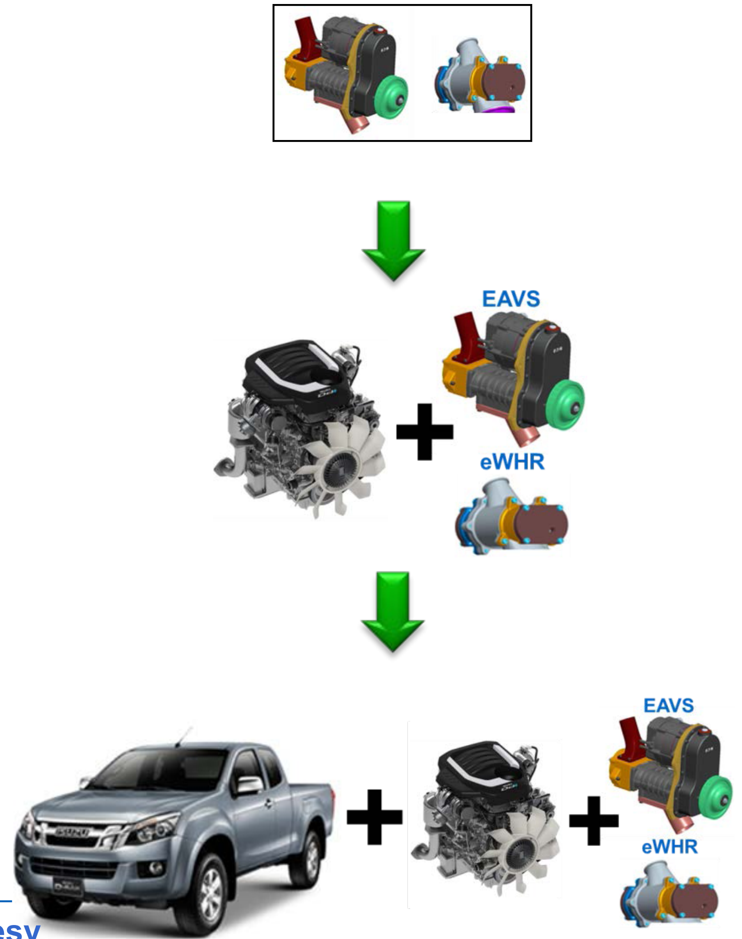


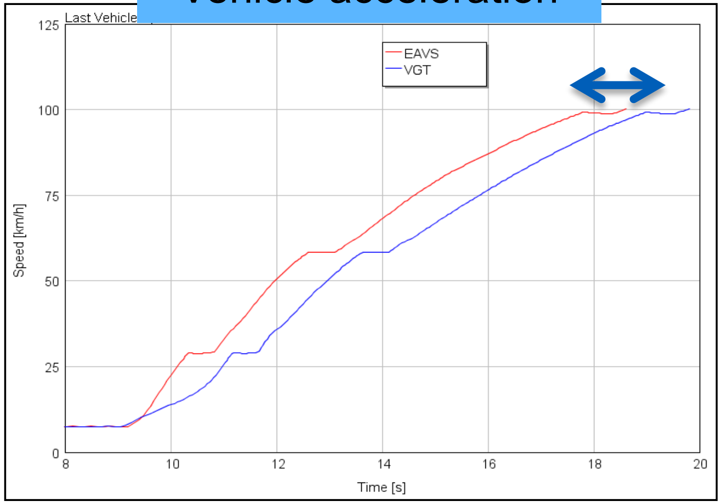
Image courtesy of Isuzu

Technical Accomplishments and Progress

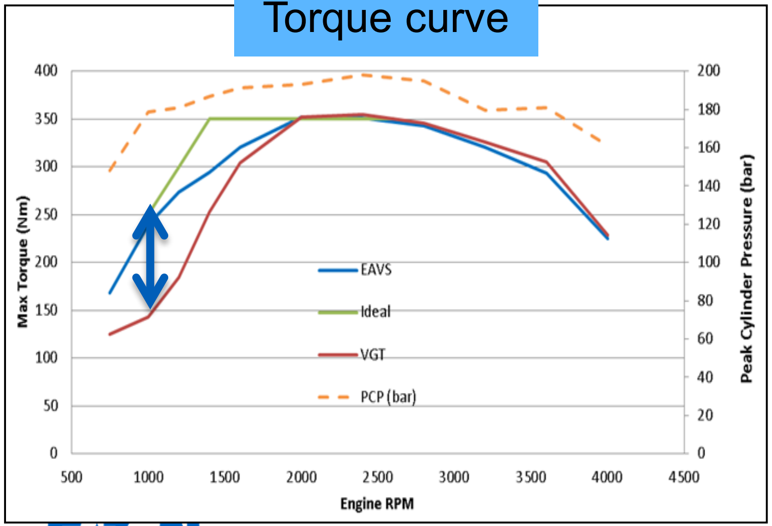
Simulation Results – System Performance

- **Improved low end torque:** Increased engine torque at low rpm up to 100Nm
- **Improved Drivability**: Reduced time-to-BMEP by 1.6s
- **Improved Performance**: Reduced time to 60mph by 1.2s

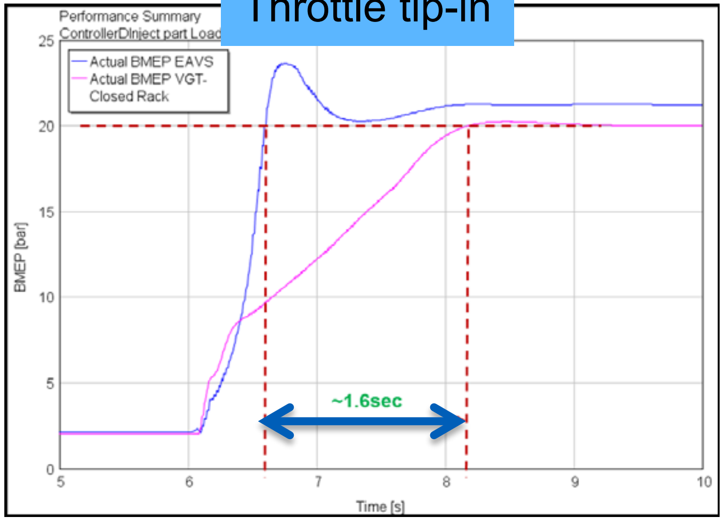
Vehicle acceleration



Torque curve



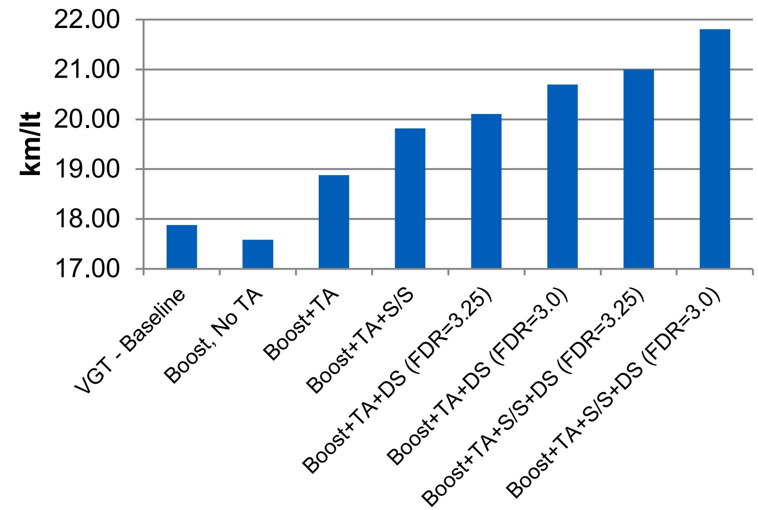
Throttle tip-in



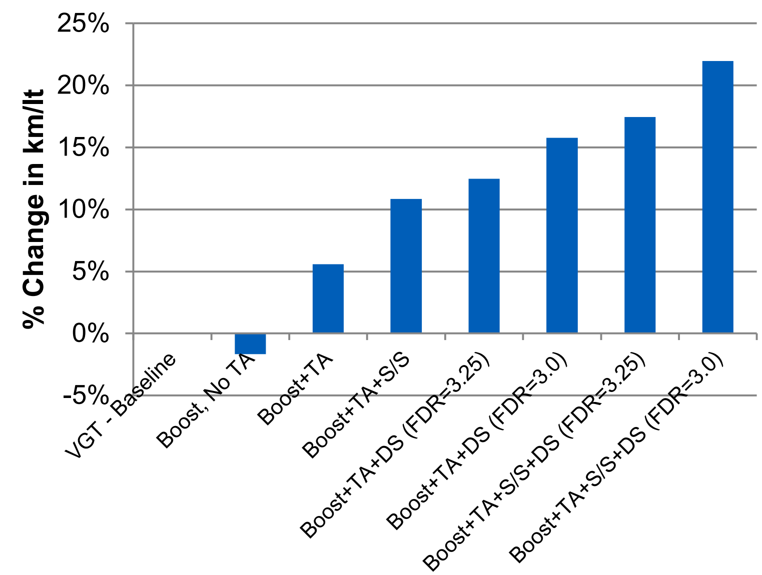
Technical Accomplishments and Progress

Simulation Results – Fuel Economy

#	Architectures	km/lt	%
1	VGT – Baseline (17.5km/lt measured)	17.88	0.00%
2	EAVS/eWHR - Boost+No TA	17.58	-1.68%
3	EAVS/eWHR - Boost+TA	18.88	5.59%
4	**EAVS/eWHR - Boost+TA+S/S**	**19.82**	**10.85%**
5	EAVS/eWHR - Boost+TA+DS (FDR=3.25)	20.11	12.47%
6	EAVS/eWHR - Boost+TA+DS (FDR=3.0)	20.70	15.76%
7	EAVS/eWHR - Boost+TA+S/S+DS (FDR=3.25)	21.00	17.45%
8	EAVS/eWHR - Boost+TA+S/S+DS (FDR=3.0)	21.81	21.98%



- US06 drive cycle
- Non optimized EAVS/eWHR add 10.85% FE
- Additional benefit from downspeeding up to 22% FE
- Engine combustion, gear ratios and optimized controls expected to add more FE

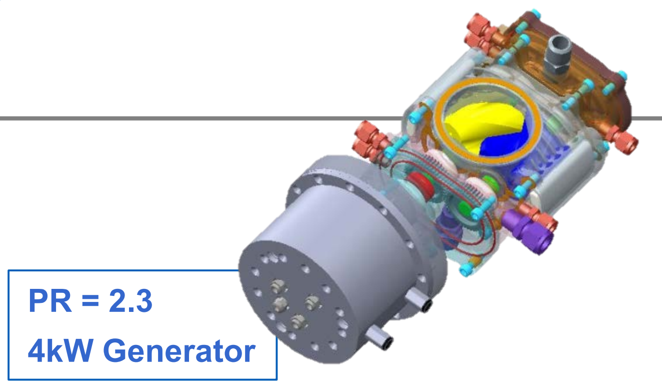


Simulation indicates >20% fuel economy improvement achievable

EATON
Powering Business Worldwide

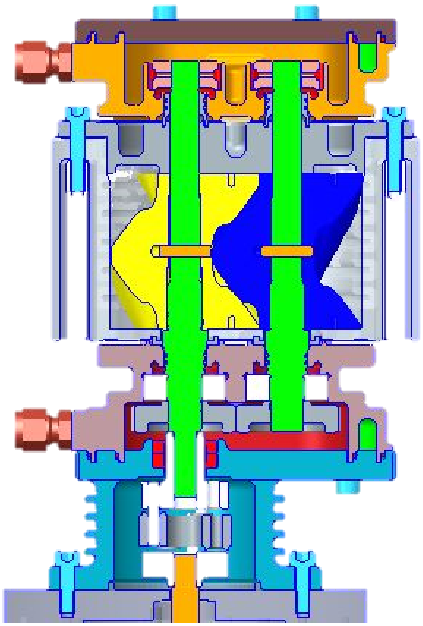
Technical Accomplishments and Progress

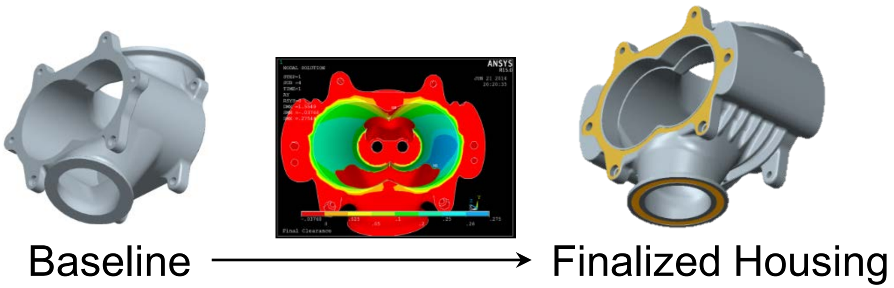
eWHR Design Overview



Design Content

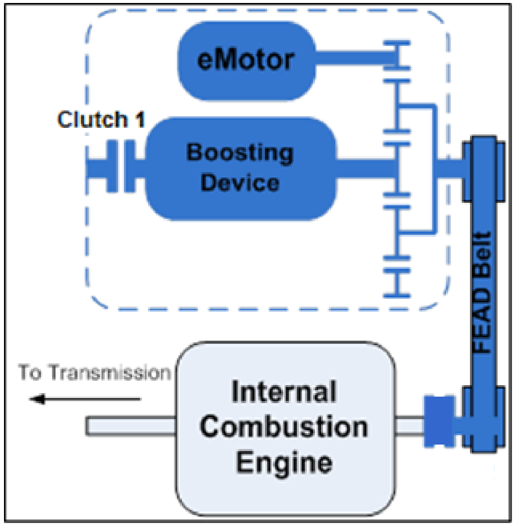
- Component material selection to enable 700°C operation
- Heat dissipation mechanisms
- Application specific thermal barrier and rotor coating
- Journal bearings with forced engine oil lubrication
- Low inertia hollow printed rotor – billet rotor alternative
- Optimized inlet, outlet, and rotor profile to maximize efficiency





Analysis complete, design finalized and procurement underway

Technical Accomplishments and Progress
EAVS Design

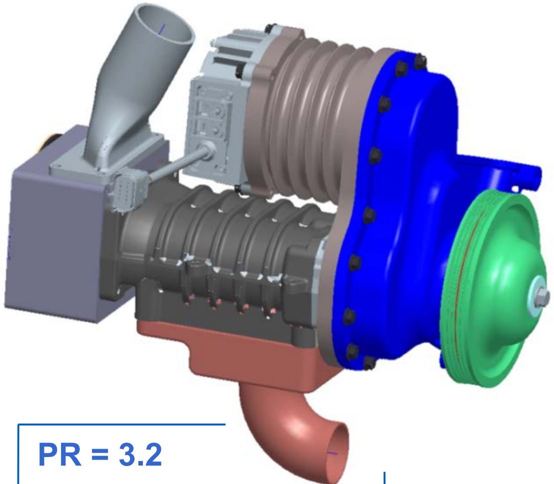


Mule 1 Architecture

- "Off the shelf" EAVS – 2.4 PR supercharger
- 9kW Electric Motor
- Eaton V400 Supercharger
- Single/Dual Planetary Connected to ICE

Mule 2 Architecture

- Simulation shows need for 3.2 PR supercharger, increased displacement, change motor/ring gear ratio
- Planning and design initiated
- 2 concepts selected for parallel development



PR = 3.2

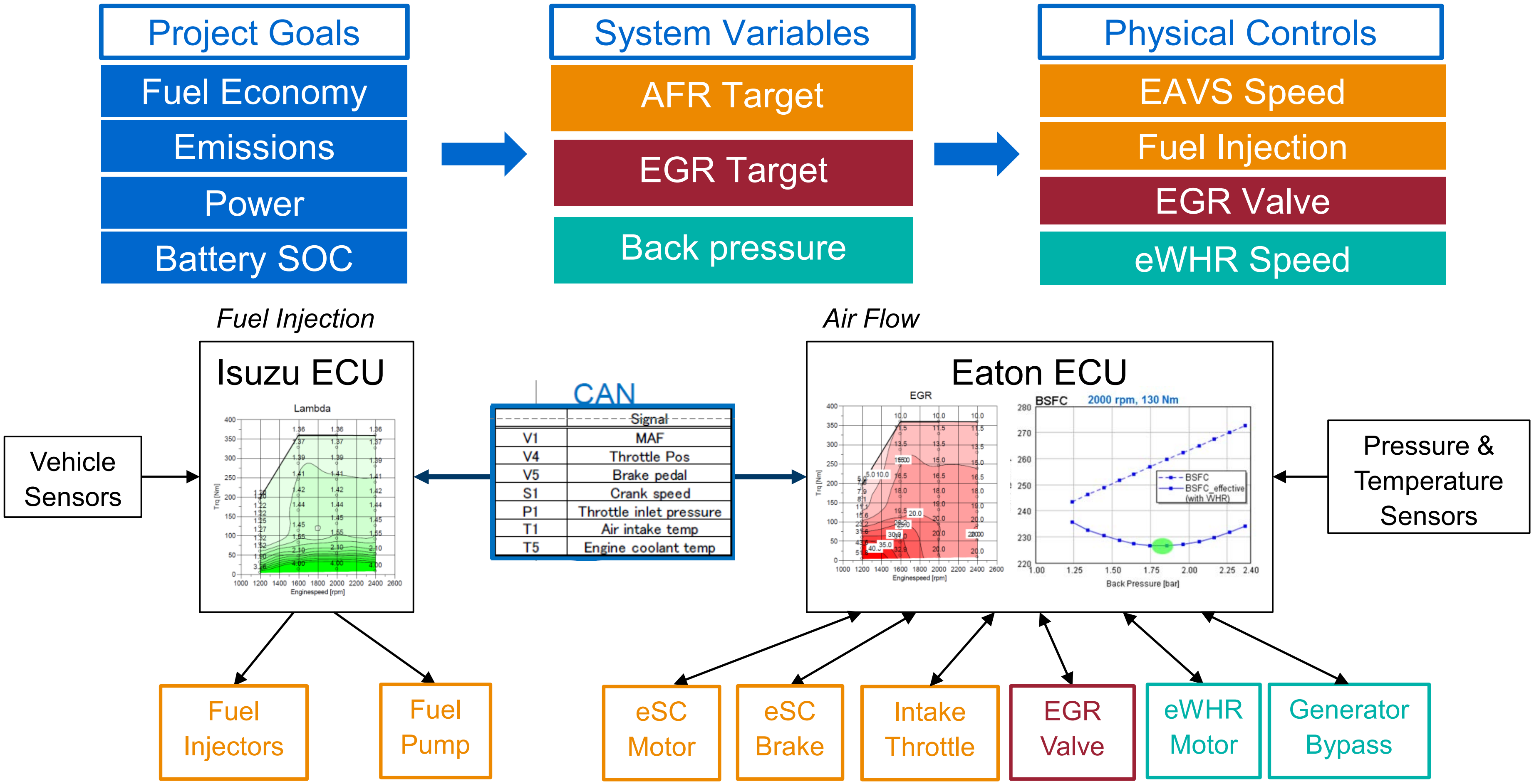
9kW Motor/Generator

Development of 3.2PR SC in progress

EATON Powering Business Worldwide

Technical Accomplishments and Progress

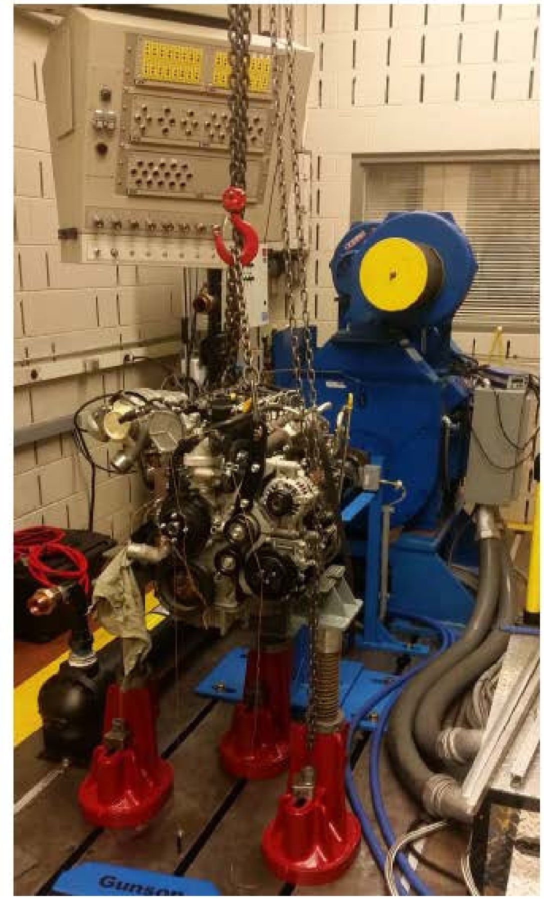
System Controls



Control will be developed and implemented jointly between Eaton and Isuzu

Technical Accomplishments and Progress

Dyno Setup – Engine installation complete



Next Steps

1. **Baseline engine testing**
2. **EAVS & eWHR Controls Calibration**

EATON
Powering Business Worldwide

Technical Accomplishments and Progress

Hardware Development and Evaluation

- Baseline engine - 3/30/17
- Mule 1 EAVS - 6/14/17
- Mule 1 EAVS + eWHR - 8/15/17
- ***BP2 Go/No-go – 9/30/17***
- Mule 2 EAVS +eWHR - 10/25/17
- Mule 2 EAVS + eWHR + Aftertreatment - 1/10/18
- Vehicle integration and testing - 4/11/18

EATON
Powering Business Worldwide

Responses to Last Year Reviewers' Comments

Questions / Comments	Responses
The reviewer inquired if one only looks at the closed system of these two components, by what percent of efficiency does the electricity recovered compare to the energy needed to utilize the supercharger.	Based on vehicle level simulation of the EAVS and eWHR systems for NEDC drive cycle, we find that the recovered exhaust waste energy from eWHR and vehicle kinetic energy under braking from EAVS are sufficient to maintain the battery state of charge. This indicates that the recovered energy is sufficient to provide energy for all the system functionality including boosting, torque assist and engine start/stop.
The reviewer observed that the project made good progress over the last year with the models at the component level. The reviewer also noted that milestone slide indicates the design of the electrically assisted variable speed supercharger and WHR were delayed. The reviewer remarked that because these are the primary components in the project strategy, it is important that they stay on schedule.	The team engaged Isuzu to partner for developing EAVS and eWHR systems for diesel engine. The contract negotiations caused delays in BP2 execution. We requested a no-cost extension to BP2 and as per the updated project plan, we are on schedule with the systems development.
The reviewer stated that the project team should clearly find the best application and solidify for next steps to best demonstrate this disruptive technology, adding that it is good to tradeoff items to exploit the fuel economy opportunity.	Vehicle level simulations show potential for meeting the 20% fuel economy improvement using EAVS and eWHR systems and downsized engine over a baseline turbo-diesel engine. The improved acceleration performance from EAVS/eWHR system is traded for better fuel economy.

Collaborations / Team

EATON
Powering Business Worldwide

- 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

SOUTHWEST RESEARCH INSTITUTE®

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

Remaining Challenges and Future Work

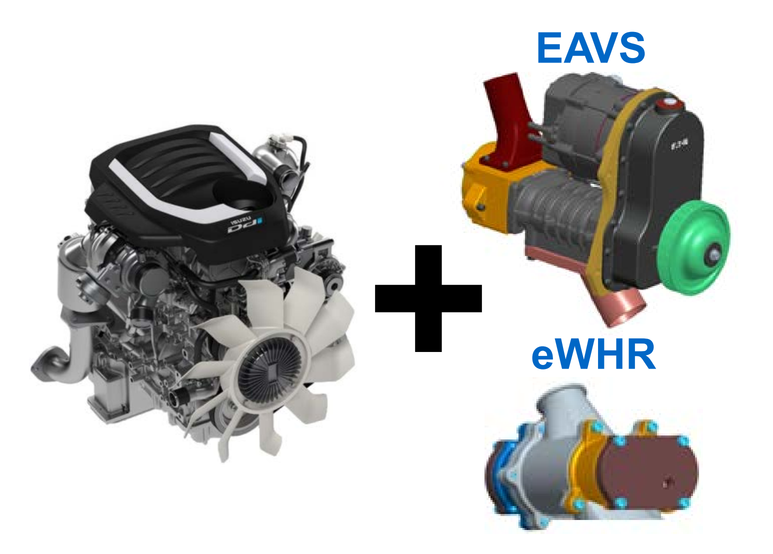
FY	Challenges	Future Work
2017	Functional Durability	SwRI Soot Fouling Study and Component level testing
	EAVS & eWHR System Controls Calibration	Dyno development and calibration with target engine. Implement controls from BP1 and calibrate.
	Emissions and Fuel Economy Optimization	Integrate components in target engine and develop/ calibrate control strategies on dynamometer
2018	Vehicle Integration	Further component durability testing and prepare mechanical/ electrical layout of demonstration vehicle
	System Benefit Demonstration	System Controls Refinement for Drivability, Fuel Economy and Emissions. Vehicle chassis dyno testing and demonstration.

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

EATON
Powering Business Worldwide

Summary

- Completed simulation analysis to identify right application for proposed technology
- Added critical partners for engine calibration and EGR analysis
- Completed eWHR thermal, structural and CFD optimization and designed/build prototypes
- Engine dyno testing and system controls development underway



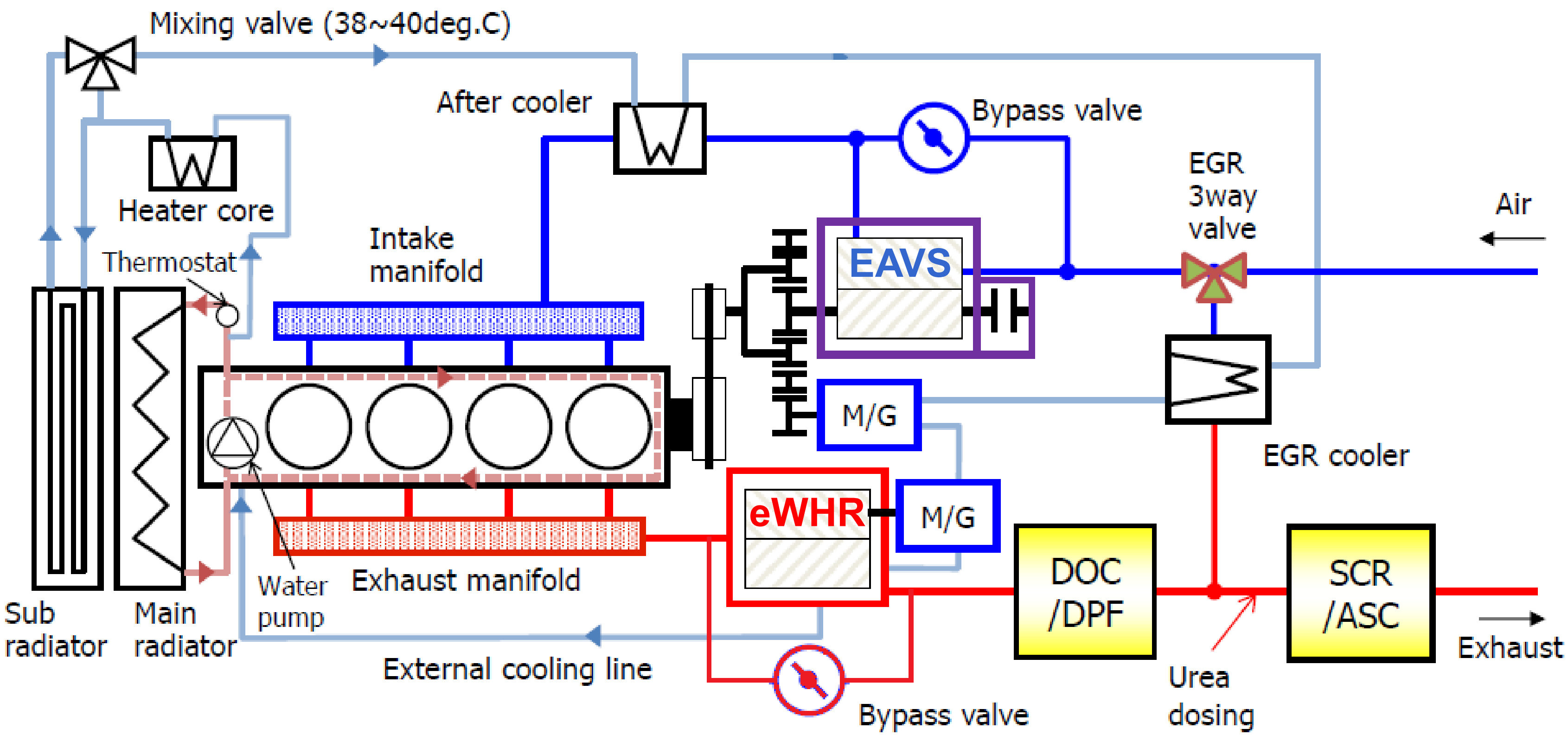
Type	Metric
Fuel economy	>20% fuel economy improvement over a turbocharged and downsized engine
Cost	<$50/% of fuel economy improvement net impact
Performance	Achieve peak engine torque at <1100rpm
Performance	300ms time to peak torque
Efficiency	>80% of required energy from regeneration (brake and waste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

EATON Powering Business Worldwide

Powering Business Worldwide

Technical Back-Up Slides

Technical Accomplishments and Progress
System Overview

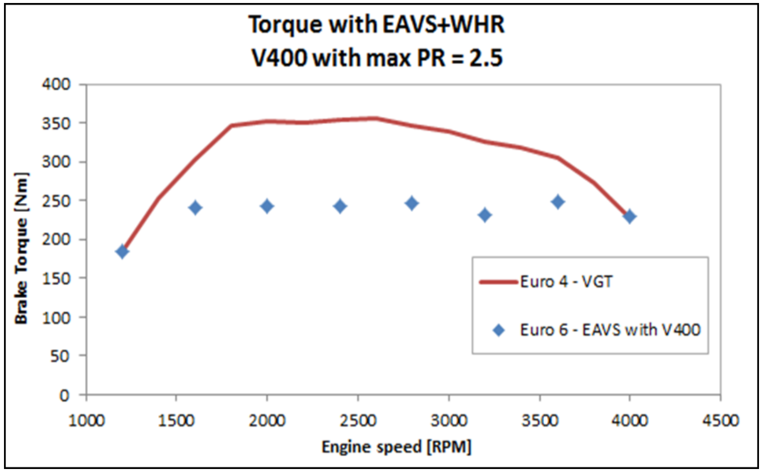


Low pressure loop EGR with electrified intake and exhaust engine air flow management using Roots devices

EAVS and eWHR Hardware Specifications

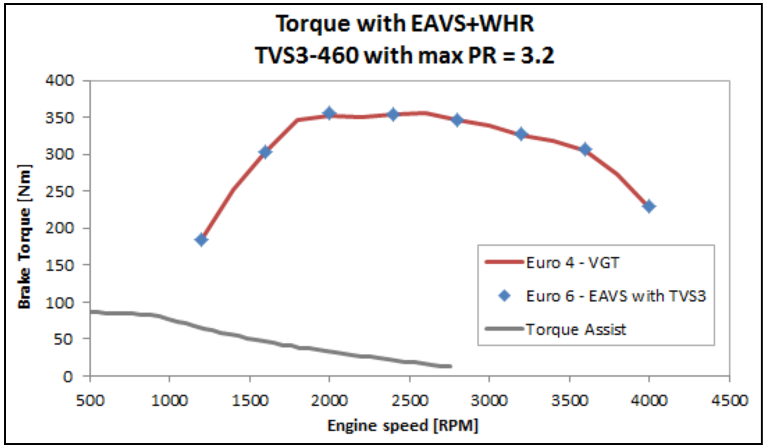
Mule 1

- Due to component availability the initial set of tests will be done with the following:
  - EAVS: Supercharger - V400 (2.5 Pressure ratio) / Motor - 9 kW
  - eWHR: Expander - 2.3 PR / Generator - 4 kW



Mule 2

- An upgraded set of hardware is planned for the second round of engine-dyno and vehicle tests, with the following hardware:
  - EAVS: Supercharger - R460 or equivalent (3.2 PR) / Motor - 9 kW
  - eWHR: Expander - 2.3 PR / Generator - 6 kW



EATON
Powering Business Worldwide