Final Technical Report

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Project Title: Integrated Boosting and Hybridization for Extreme Fuel Economy and Downsizing

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1 EXECUTIVE SUMMARY

The objective of this project was to develop, demonstrate, and evaluate commercialization of a highly efficient downsized engine by electrification of the air delivery and waste heat recovery system and optimizing energy usage to achieve significant fuel economy improvement at a commercially viable cost. The system consists of an Electrically Assisted Variable speed Supercharger (EAVS), driven by an electric motor and the engine through a planetary gear train, that provides engine boost pressure and provides the mild hybrid functions of engine start/stop, torque assist, and brake energy recovery. In the exhaust path of the engine is the electric Waste Heat Recovery (eWHR) system, a roots-based expander driven by another electric motor, that enables exhaust gas energy recovery along with controlled back pressure on the engine. The two electric motors are powered by a 48V rechargeable lithium-ion battery. Further, the EAVS system coupled to an EGR valve enables very precise high exhaust recirculation rates to control the NOx emissions.

Through two budget periods, the project team of Eaton, Isuzu, Southwest Research Institute and AVL designed and developed the EAVS and eWHR systems, integrated with an Isuzu diesel engine, and validated the target fuel economy performance and emissions by engine dynamometer testing and vehicle level simulations. GT Power model-based analyses results were used to size the EAVS and eWHR systems for the 1.9L Isuzu Spark engine. The two systems were built and the functional testing was carried out to verify the boosting performance of the superchargers. Following the baseline engine dynamometer testing, the two systems were integrated with the engine and the fuel economy performance and emissions were determined by combined steady state and transient testing over three drive cycles, namely, FTP75, NEDC and HWFET. The EAVS/eWHR system demonstrated 4% improvement in fuel economy for the NEDC cycle in engine dyno testing, correlating well with vehicle simulation results (5.3%). The simulation results indicated that the combination of hybrid functions and drivetrain optimization, fuel economy improvement of more than 20% was feasible with the system.

The commercialization study to evaluate the cost of the system and the scalability for different engine/vehicle classes was planned for the final budget period but not completed as the project was closed at the end of budget period two.

2 ACCOMPLISHMENTS

The projects targets and the results accomplished through Budget Periods 1 and 2 are provided in Table 1 below.

Table 1: Project Targets

Type	Target Description	Metric	Results
Fuel economy	For a mid-size diesel passenger vehicle with EAVS-WHR, show fuel economy over the same vehicle equipped with a downsized turbocharged engine: 7% FE from additional	>20% fuel economy improvement while meeting or exceeding EPA emission standards	The path to achieve 20% fuel economy improvement was demonstrated by combination of vehicle level simulation and engine dynamometer testing.

	downsizing, 4% FE from downspeeding, 3% FE from start/stop and 6% FE from energy recovery.		
Cost	Meet the system net cost per % of FE improvement that is appealing to OEMs	<$50/% of fuel economy improvement net impact	The system cost-benefit analysis was planned for BP3, and was not completed as the project was stopped after BP2.
Performance	Peak engine torque starting at low engine rpm	Achieve peak engine torque at <1100rpm	The right sized EAVS system was shown to achieve peak engine torque at ~1500rpm through simulation study.
Performance	Response time to peak torque	300ms time to peak torque	Step response of peak torque was not evaluated. However, transient response of EAVS system to boost pressure demand was found to have a lag of <300ms.
Efficiency	Most electrical energy generated without penalty in fuel consumption (i.e., not accessory load)	>80% of required energy from regeneration (brake and waste heat)	Engine dynamometer studies showed that the waste heat recovered energy from eWHR system could meet the boosting needs of the EAVS system over an FTP75 drive cycle.
Commercialization	Time to market after project completion	<5 years	Commercialization study was planned for BP3 and was not completed as the project was stopped after BP2.

3 PROJECT ACTIVITIES

The project was conducted over two (2) budget periods defined below:

- **Budget Period 1 (BP1): Model-based System Analysis and Individual Technology Risk Mitigation -** evaluating integration of the two technologies in a model-based environment where the architecture and the component sizes will be optimized.
- **Budget Period 2 (BP2): Design and Engine Dynamometer Testing of System and Optimize Controls -** designing and integrating the two technologies on a full engine dynamometer.

3.1 Hypothesis & Vehicle Selection

Hypothesis

Downsizing and downspeeding by definition improves fuel economy but also reduces vehicle performance, since peak power is lost. To make up for the lost performance, OEMs are employing on-demand performance boosters, such as electric motors, in parallel with the engine or engine boosting solutions such as turbochargers. Both of those solutions exhibit significant drawbacks; electrification solutions that directly put torque directly to the wheels require

complex, large, and expensive electronics, motors, and a battery. Traditional boosting solutions like turbochargers that depend on exhaust flow energy alone, lack performance as engines downsize and the exhaust flow energy is reduced—thus, their response time limits are reached.

Vehicle Selection

The vehicle platform and engine selected was the Chevy Cruze with a 1.4L turbo gasoline engine and a 1.2L engine for the Electrically Assisted Variable Speed Supercharger (EAVS)/ Waste Heat Recovery (WHR) technology demonstration. Based on simulation results of our model based analysis the team identified that a more suitable application for the proposed technology is diesel engines given the increase volumetric flow rates. The team selected the following vehicle for the program after communication with DoE:

- ✓ Baseline Vehicle: Isuzu D-Max with 2.5L Turbo diesel engine
- ✓ Target Vehicle: Isuzu D-Mac with 1.9L EAVS/WHR diesel engine

Specification and pictures of the selected vehicle are presented below.

parameter	Unit	Value
Gross vehicle weight	kg	confirming
Kerb weight	kg	1760
Overall length	mm	confirming
Overall width	mm	↑
Overall height	mm	↑
Drive train specifications		
1st	-	4.942
2nd	-	2.430
3rd	-	1.428
4th	-	1.000
5th	-	0.749
6th	-	0.634
Final (3)	-	3.909
Tire size (2)	-	245/70R16
Air resistance coefficient (2)	$N/(km/h)^2$	0.0791
Rolling resistance coefficient (2)	N	150.0

Figure 1: Selected vehicle specifications

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Figure 2: Selected vehicle pictures

The goal of the project for this given vehicle was to match the performance of the 2.5L Turbo engine with the 1.9L EAVS/WHR engine while improving on the fuel economy. The difference in peak torque is 50Nm between the two vehicles.

3.2 Model-Based Analysis

Significant effort was spent in developing a model based framework in order to evaluate various applications of the proposed technology as well as to optimize the component sizes and control algorithms for the selected architecture.

A description of the key components of the model is given below:

Engine Model

This engine model has been correlated to test data and adapted to simulate a 1.9L EAVS and WHR engine (Figure 3). The baseline model was provided by the OEM and is representative of the production engine.

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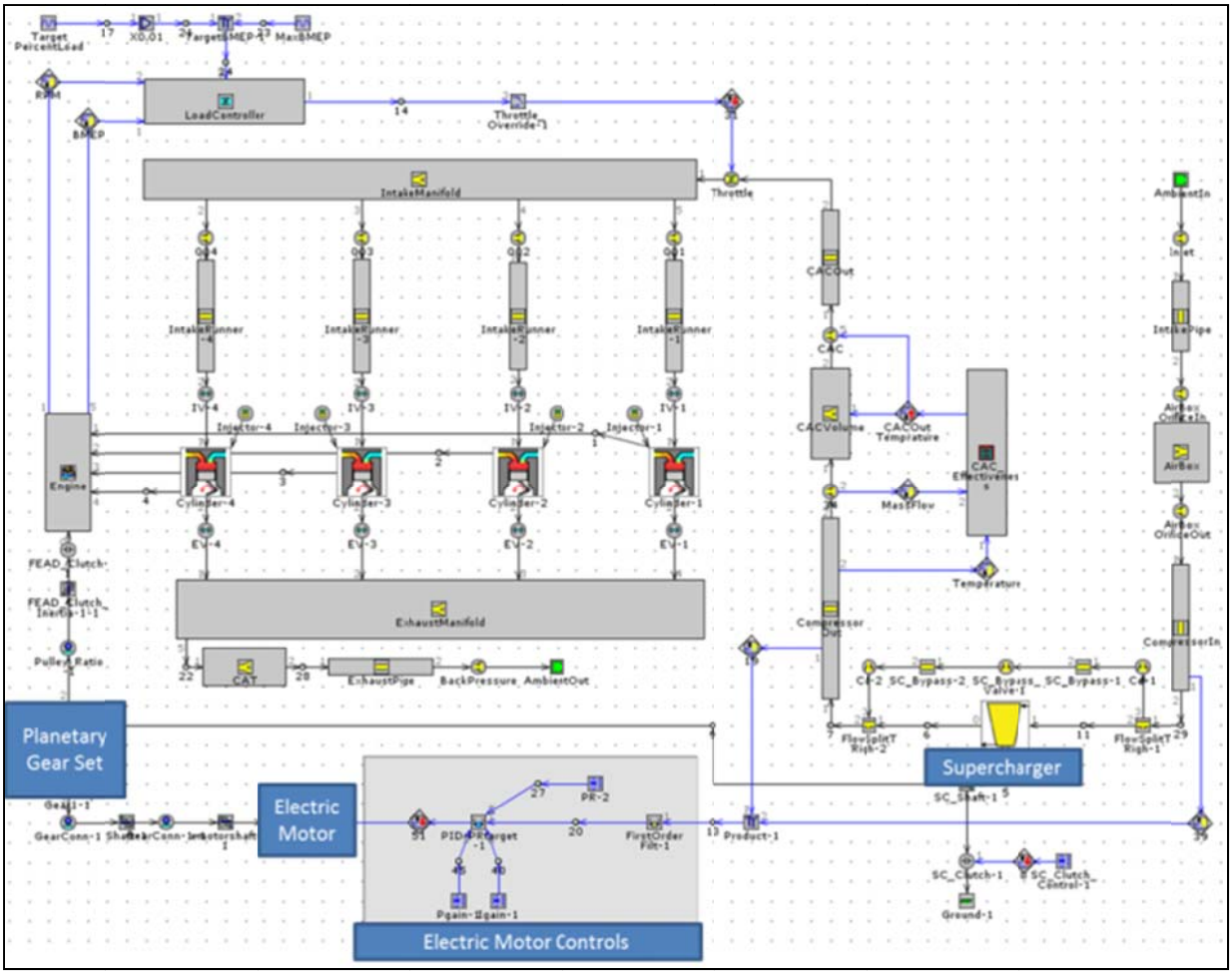

Figure 3: Schematic of GT-Suite Engine Model EAVS/WHR Models

The EAVS™ boosting system is integrated into the engine model by replacing the turbocharger with an Eaton TVS® supercharger. Additionally, a planetary gear set and electric motor are incorporated to couple the supercharger with the engine. Desired intake manifold pressure is achieved by modulating electric motor speed.

The WHR system was analyzed using the output of the GT-Power simulation. The mass flow rate, along with an estimated expansion ratio, was used to calculate the power recovered from the exhaust. The backpressure was then imposed on the engine, and the recovered energy was simulated as available battery energy for operation of the EAVS system.

Vehicle/Driver Model

The vehicle configuration used in this simulation is representative of the target vehicle. The model was created from in-house vehicle test data and publicly available vehicle characteristics. Gear efficiencies, driveline efficiencies, and all other vehicle parameters were obtained from the OEM.

Controller Model

The vehicle model contains a state of charge model simulating a battery. The energy balance is being accounted for by monitoring the electric motor power consumption and generation during boosting as well, as the power it generates during braking. The EAVS boost system operation provides further insight into how the EAVS boost system can either consume or generate electricity, while using the supercharger to increase the intake manifold charge density. The electric motor combined with the planetary gear set allows the system to operate both above and below the fixed ratio boosting line, correspondingly using or generating electricity. In the region above the fixed ratio boosting line, the electric motor is consuming electricity to spin the supercharger faster to make more boost than would be possible at the fixed ratio. Below this line, the motor is generating electricity by slowing the supercharger down to make less boost than would be created if operating at the fixed ratio boosting line.

WHR Recovery Study

The average power recovered over the FTP75 drive cycle is shown in Figure 4 using the different engine models developed. Note that the power was recovered by applying a fixed backpressure throughout the duty cycle. Further optimization of the backpressure level need to be performed in order to ensure that the maximum power is recovered for each engine operating point. The study was performed in order to compare the WHR device operation when paired with different engines. With significant levels of high pressure Exhaust Gas Recirculation (EGR) required to meet U.S. emission standards the backpressure levels will be significantly higher that what was simulated here, thus the energy recovery will increase.

Results indicate power recovery under higher volumetric rates is improved significantly thus the diesel application has been chosen as right application for this technology. The sizing results for the expander size are presented in the next paragraph.

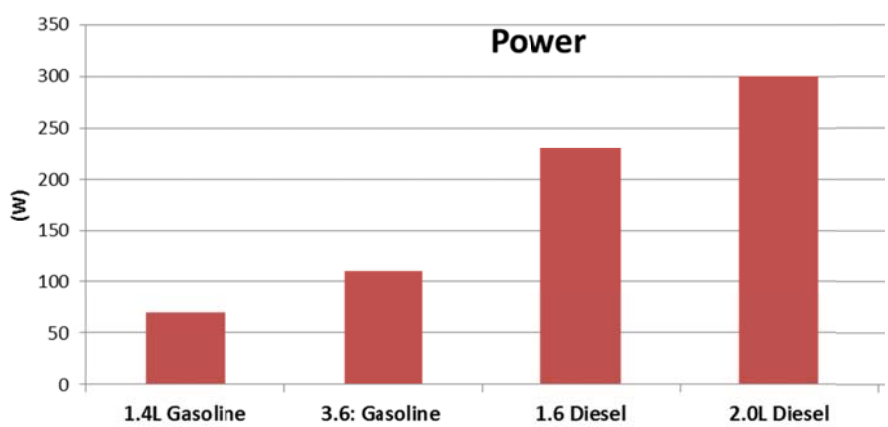

Figure 4: Average power recovered during FTP75 at a fixed backpressure

Unit Sizing Results

Expander sizing for the project application is critical for optimal performance. GT Power simulation results outlined in Figure 5 show that exhaust mass flow rates vary by selected drive cycle and engine displacement. To maximize efficiency and power generation of the expander

with reduced levels of engine backpressure during the application drive cycles the expander displacement will be in the V150 to V250 range.

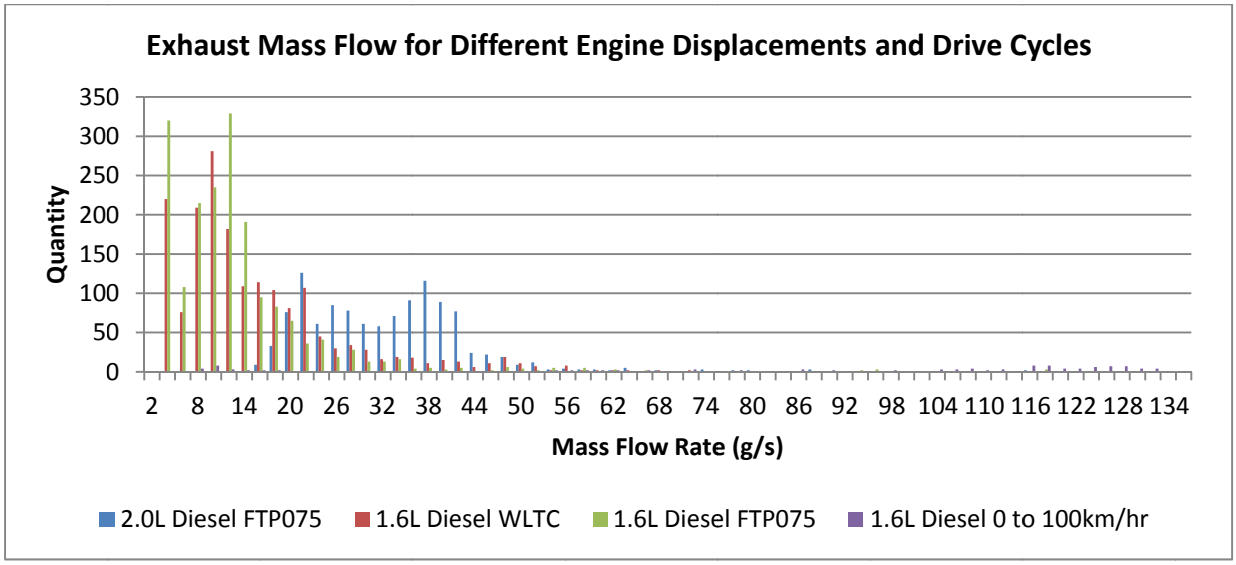

Figure 5: Simulation data for Exhaust Mass Flow Rates

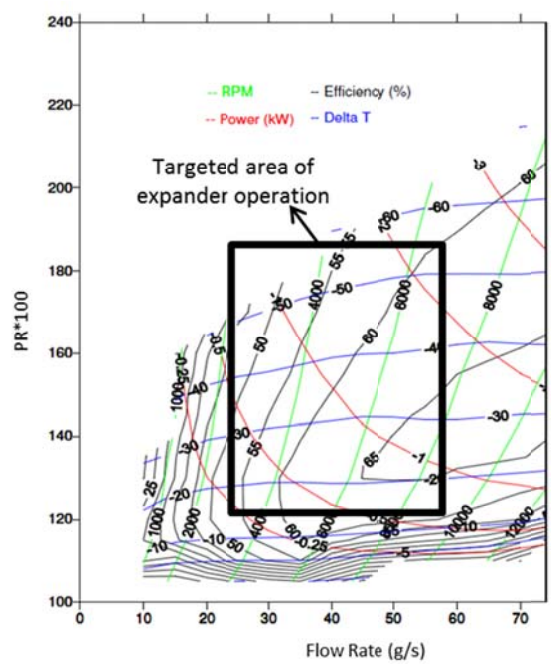

Figure 6: Example V250 Expander Map

3.3 WHR Preliminary Testing and Design Requirements

Outputs from the analytical activities resulted in the following design optimizations:

1) Housing structure
2) Housing outlet port geometry
3) Bearing plate and rotor material selection

4) Rotor coating that will abrade and handle operating environment
5) Front and rear bearings
6) Static flange seals and bolt patterns at all mating surfaces

Eaton engaged suppliers to develop the rotor coating, bearings, static flange seals and generator. The design used an available generator for the dyno operation but since the generator is oversized for this application, further optimization was required.

Extensive computational fluid dynamics (CFD) studies were completed to identify the optimal exhaust manifold design to achieve maximum expander output shaft torque. The exhaust manifold was a point of focus since conversion of the kinetic energy from the exhaust valve opening event into expander rotational torque is critical. 10 to 15% improvement in expander output shaft torque was simulated with the optimal exhaust manifold design compared to the baseline exhaust manifold design. The identified optimal exhaust manifold design was utilized as starting point for packaging in the project vehicle. (Figure 7 and Figure 8)

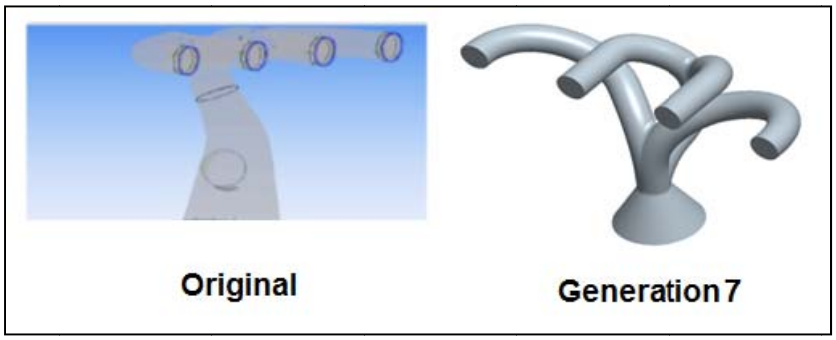

Figure 7: 3D Models of the Exhaust Manifold

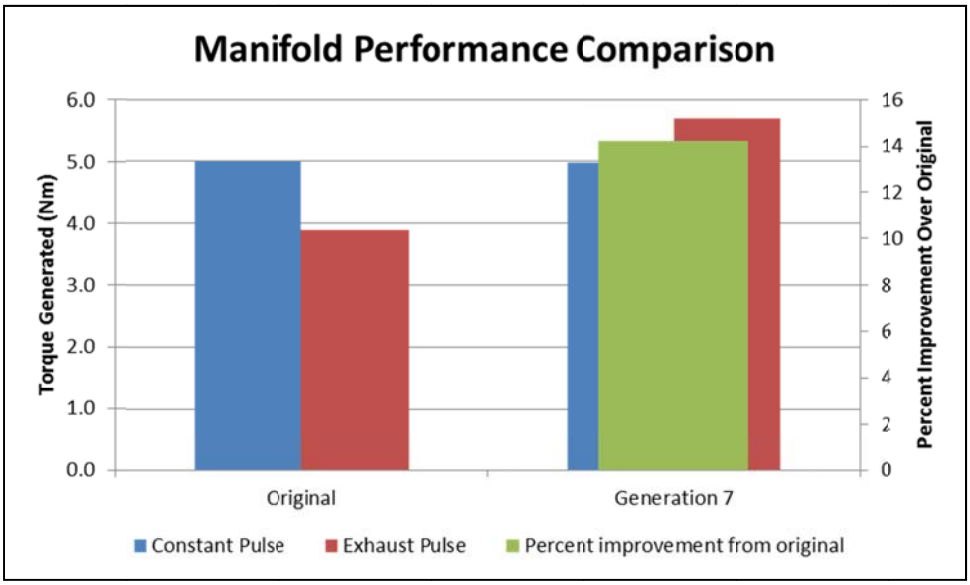

Figure 8: Torque Generated by the Expander with different manifold designs

Expander Build and Testing

Following the analytical study the expander was built and integrated on the dyno with a representative diesel engine. Figure 9, shows the dyno setup that has been completed with a full instrumented WHR expander attached to a torque and speed sensor in order to measure the amount of power generated as well as flow measurements, exhaust/intake pressures and temperatures.

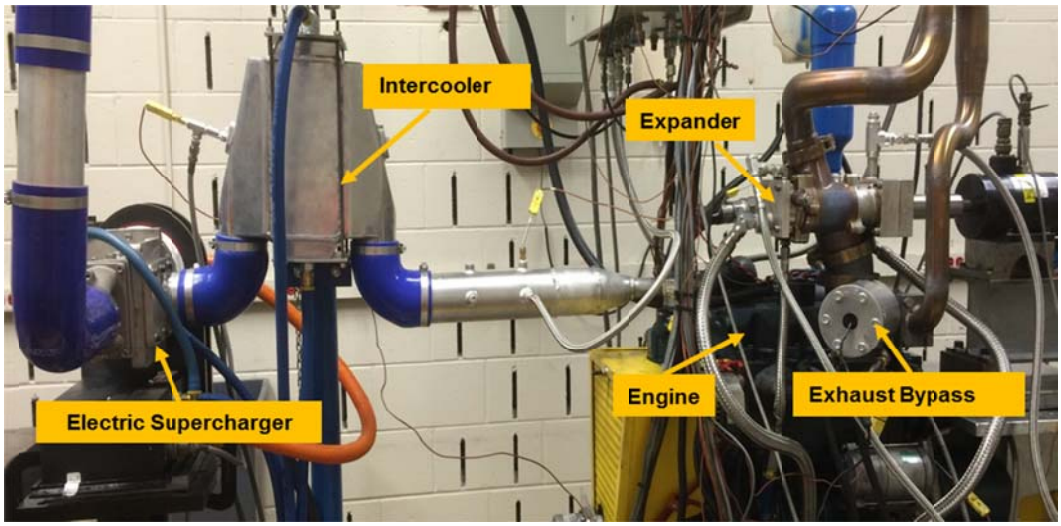

Figure 9: Expander Dynamometer Setup

Functional testing was completed with a V250 roots expander on a 2.4L Kubota diesel engine with a R410 electrically driven supercharger supplying air flow to the engine intake. At various engine operating points the expander generated power while being subjected to exhaust temperatures in the 700°C range. The expander produced a maximum power of 2.5kW at a relatively low mass flow rate – higher operating flow rates and backpressures will generate significantly more power.

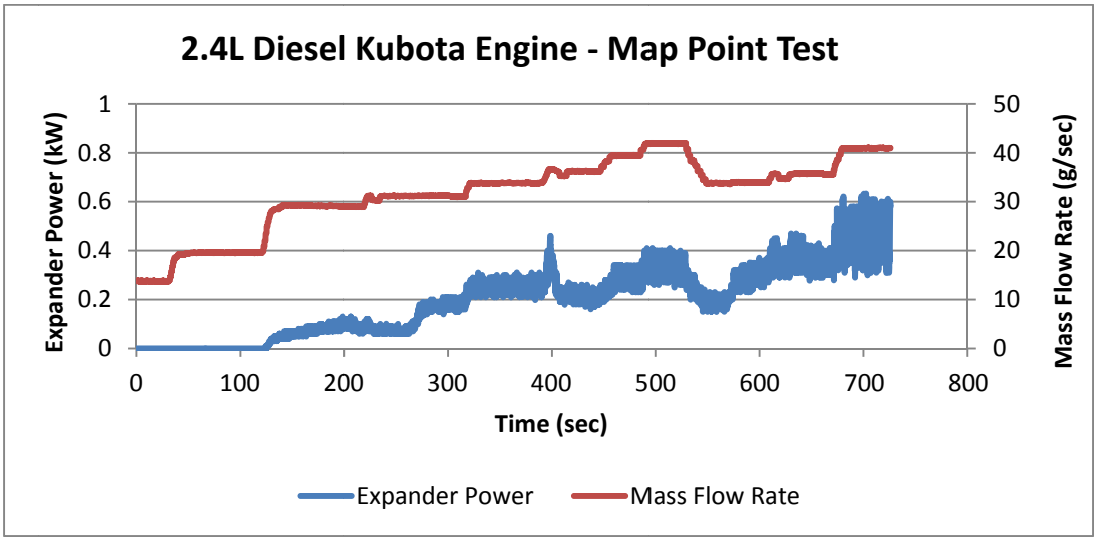

Figure 10: Expander power generated and Mass Flow Rate of the Exhaust

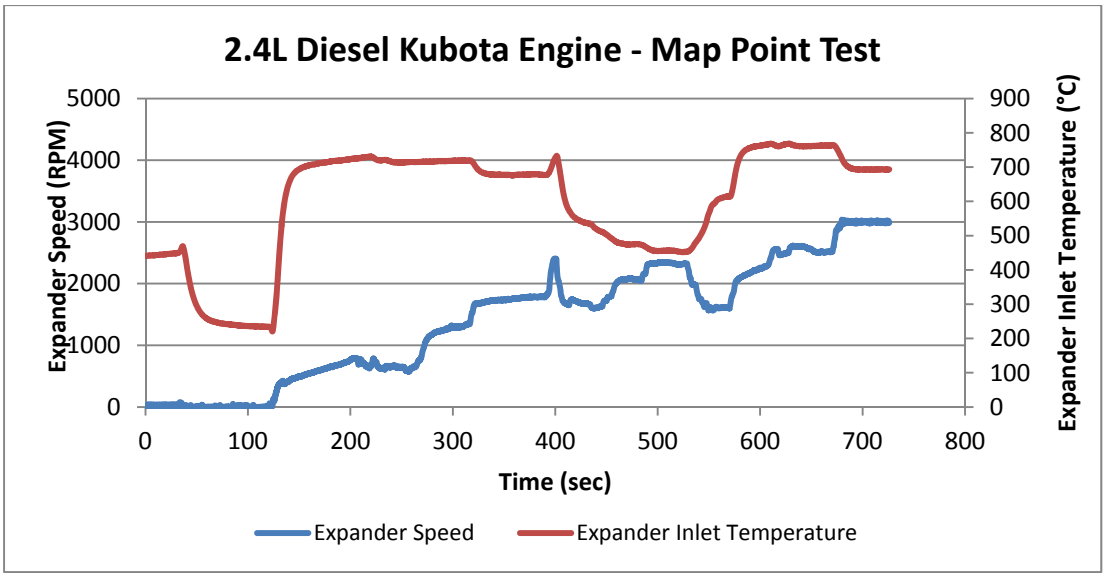

Figure 11: Expander Speed and Exhaust Inlet temperature

3.4 Baseline Engine Testing

The Isuzu Spark vehicle was received at the Eaton facility in Southfield, Michigan on January 17, 2017. The engine was subsequently removed from the vehicle and installed in the engine dyno test cell. Figure 12 shows the engine dyno test setup. Figure 13 shows the schematic of the dyno test setup with the key sensors for combustion and emission analysis. The baseline engine testing focused on characterizing the baseline engine power map and obtaining repeatable engine performance for three transient drive cycles, as shown in Table 2. Figure 14 shows the steady state engine power map. Figure 15 shows transient drive cycle test data for New European Driving Cycle (NEDC). The data was collected over 8 test runs and all the key variables including engine speed, torque, and fuel flow show very good repeatability.

Figure 12: Isuzu engine unmount from vehicle, mount on dyno

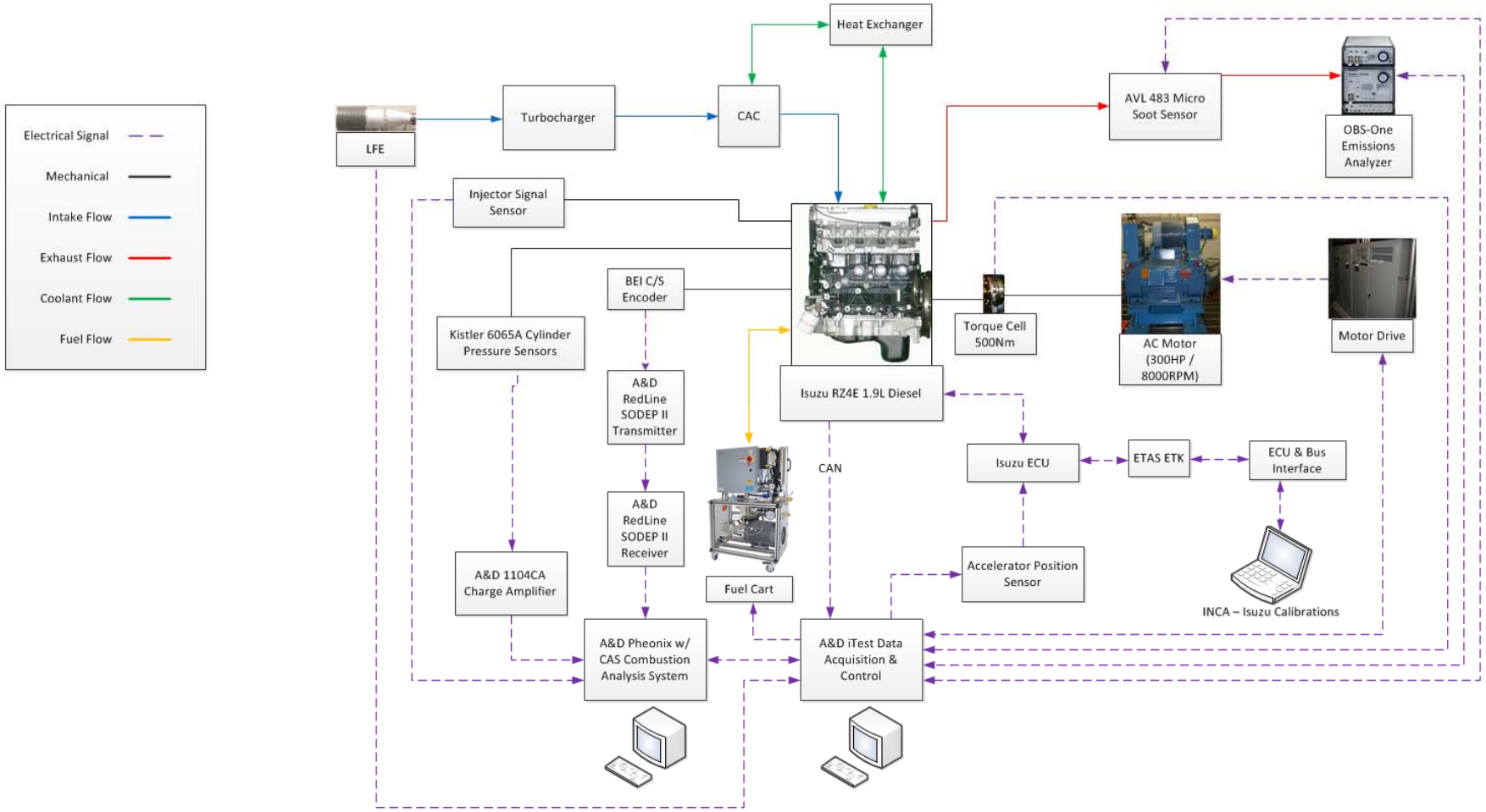

Figure 13: Engine Dyno Test Setup Schematic for Baseline Engine Testing

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Table 2: Engine Dyno Test Plan, including baseline and with EAVS/eWHR technologies

Hardware	Objective	Cycle	Test Runs
Baseline RZ4E 1.9L Isuzu engine w/ turbo	Power mapping	Power map	1
	Repeatability analysis, steady state testing	Steady state torque map	10
	Performance baseline testing	US06 FTP75 NEDC	8 8 8
RZ4E + EAVS + eWHR	Power mapping	Power map	1
	Repeatability analysis / steady state testing	Steady state torque map	10
	Performance testing	US06 FTP75 NEDC	3 3 3

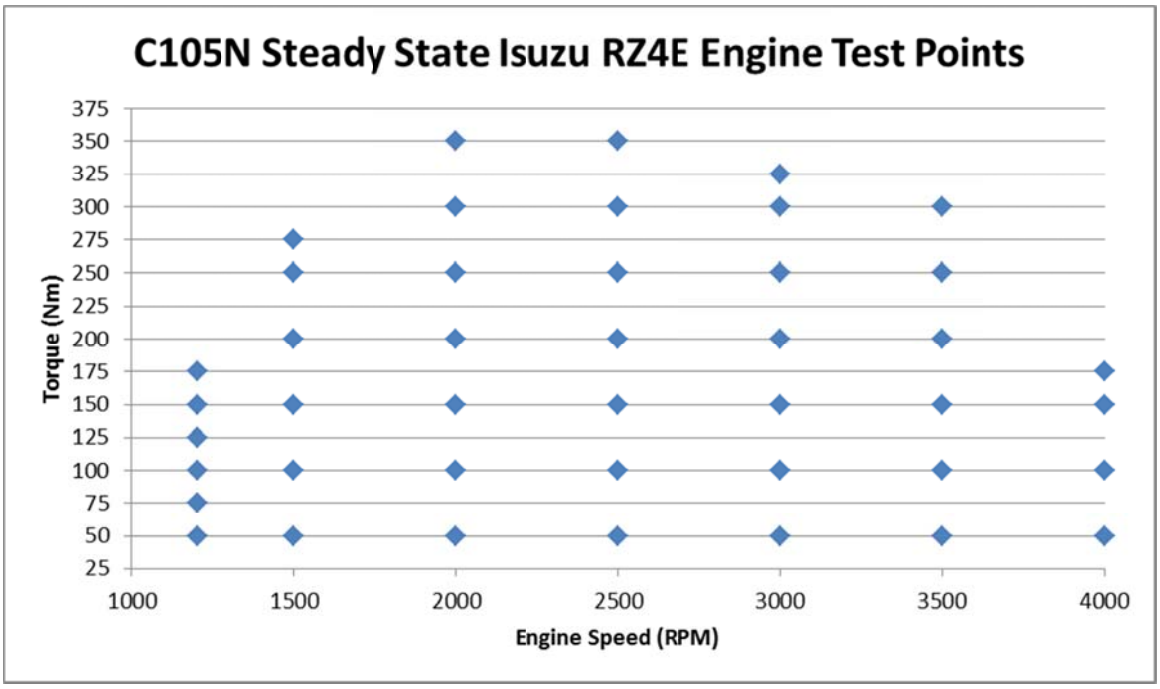


Figure 14: Engine steady state power map test points

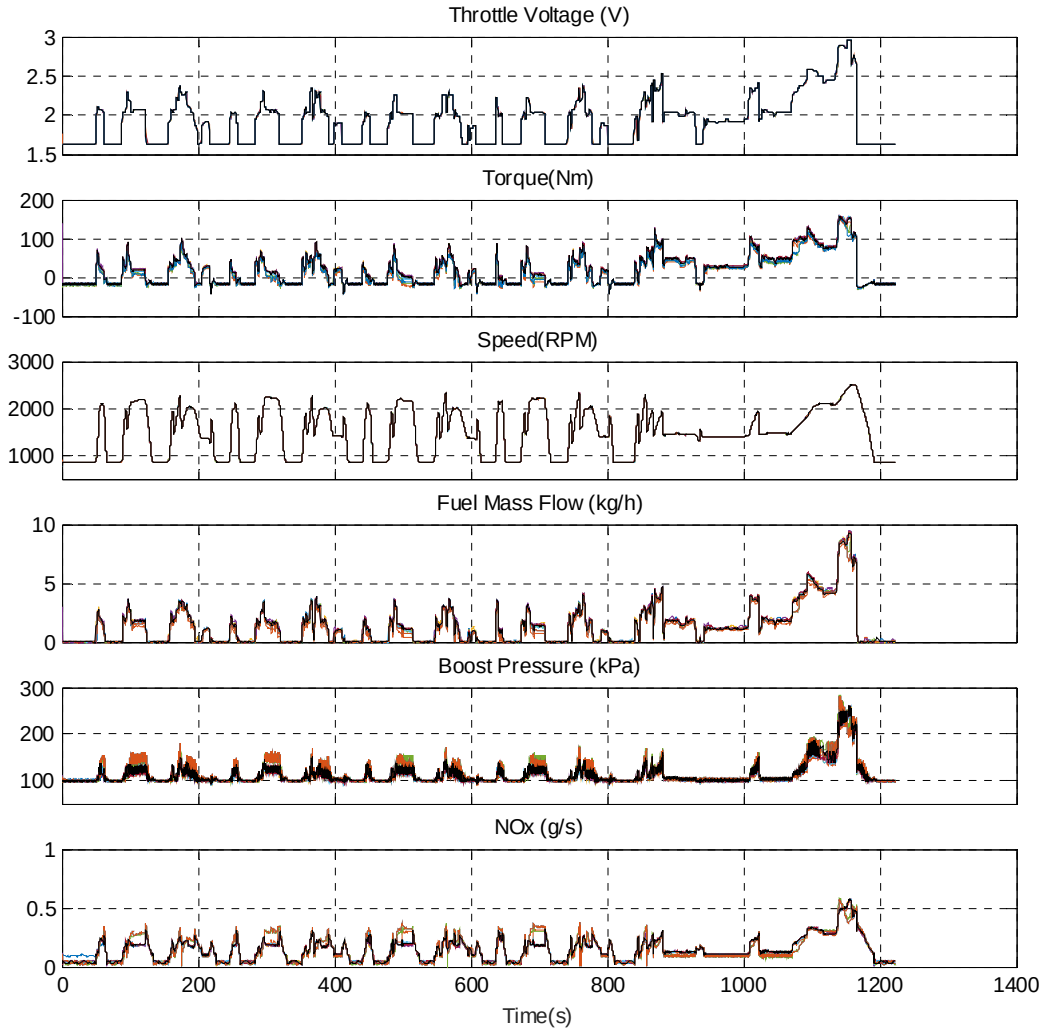


Figure 15: NEDC Transient Drive Cycle Test Data

3.5 EAVS Design Study

Eaton had previously developed an EAVS system for a gasoline engine using a V400 supercharger. Initial results from a design of experiment indicated that the EAVS unit with Eaton's V400 supercharger will likely fall short of the required Air Fuel Ratio (AFR) and EGR requirements of the Isuzu engine. Simulations with the Eaton's TVS3-460 supercharger showed promising results. The design parameters for the high pressure ratio EAVS were finalized through an iterative approach using GT Power simulations; this resulted in the following design parameters: 3.2 pressure ratio, 460cc displacement, motor to ring gear ratio of 0.255, and EAVS to crank pulley ratio 1.06. A comparison of the new design parameters and the current EAVS is provided in Table 3, and the resulting engine torque map is shown in Figure 16. However, due to project timing and budget, the development of the high pressure EAVS system was not pursued, and the V400 design was implemented with the Isuzu engine. Figure 17 shows the EAVS unit using the V400 supercharger.

Table 3: EAVS Design Parameter Comparison

Design Parameter	EAVS with V400	EAVS with R460
Pressure Ratio	2.5	3.2
Displacement (cc)	400	460
Motor/Ring Gear Ratio	0.441	0.255
EAVS/Crank Pulley Ratio	1.15	1.06

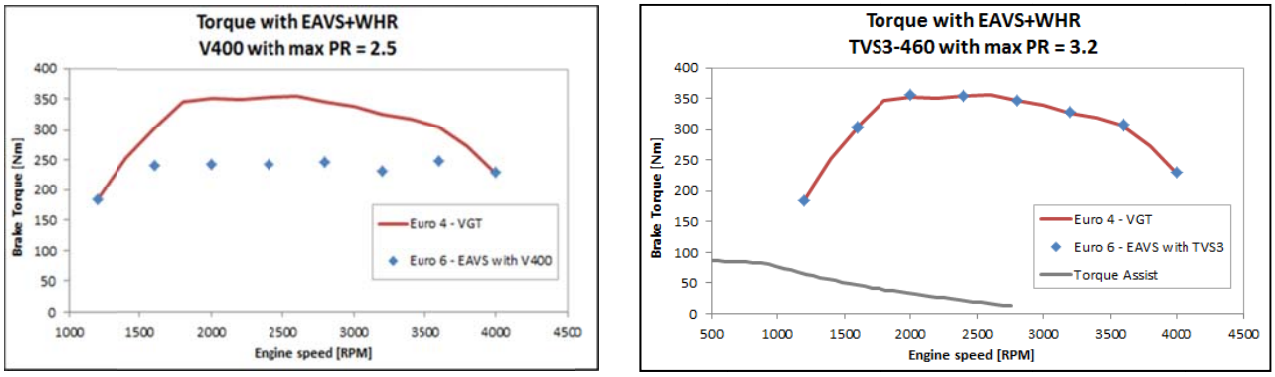


Figure 16: Comparison of Engine performance with V400 and R460 Supercharger Designs

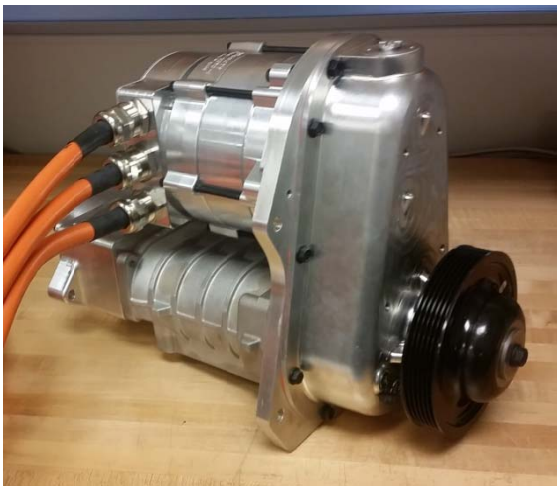


Figure 17: EAVS V400 Supercharger

3.6 eWHR Design and Build

A preliminary expander was built and tested on a Kubota diesel engine during the first budget period; a CFD analysis was completed to optimize the rotor & porting geometry in the second budget period. This was used as a starting point for further optimization of the WHR expander.

Figure 18: Preliminary WHR expander

Expander Analytical Studies and Design

Finite Element Analysis (FEA) and CFD analysis were completed to improve upon the expander design, for increased efficiency and durability. Firstly, steady state FEA thermal analysis was completed to determine component temperatures when the exhaust gas was at its operating temperature of 700ºC. This was input into a structural FEA to understand stress concentrations and deformation. Through a series of design iterations and this FEA analysis, the final housing design was selected. Changes from the first iteration included the addition of ribbing on the housing, heat sinks, and a ceramic plasma spray coating on the interior of the housing.

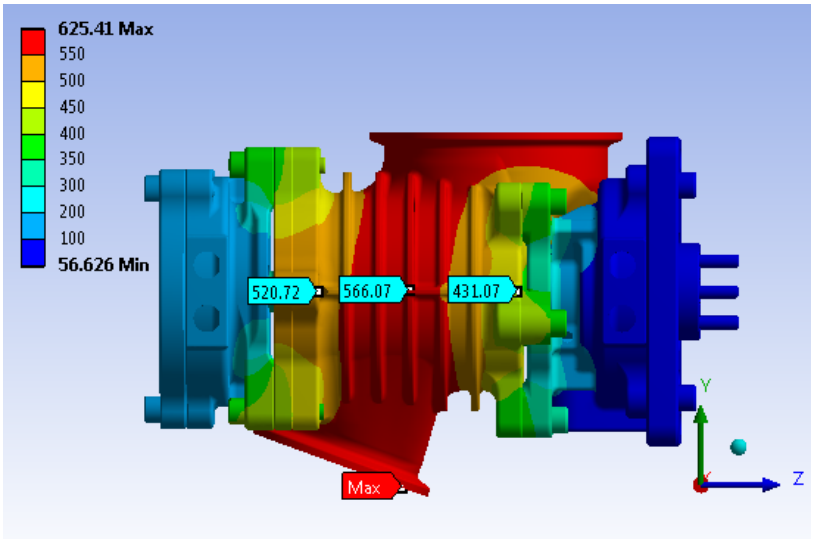


Figure 19: Sample results from thermal FEA

Once the final design was selected, a thermal tolerance stack was completed. This was to ensure the expander components would have the required dimensions while operating in the exhaust stream. The operating temperature of each component, thermal expansion coefficient of each material, and desired clearances/interferences were taken into consideration. This was necessary such that press fits would stay in place and rotors would not bind during repeated thermal cycling from room temperature to operating temperature (700℃ exhaust). The final expander hardware is shown below (Figure 20).

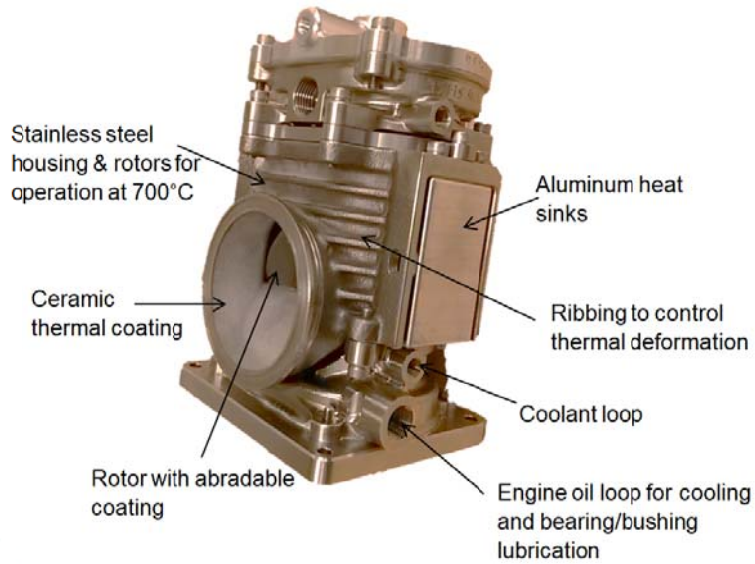
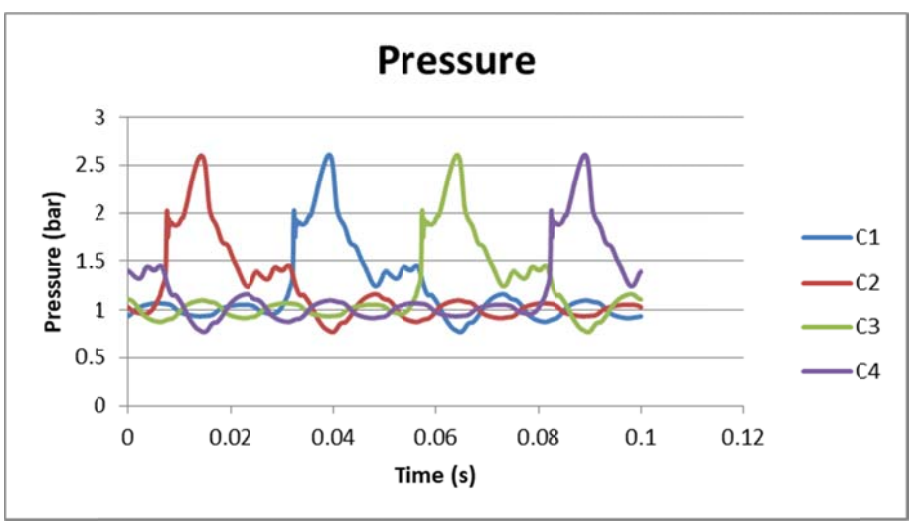


Figure 20: Waste heat recovery expander final hardware

Exhaust Manifold Optimization

The exhaust manifold design impacts how much of the exhaust pulse energy can be recovered, therefore impacting the performance of the WHR expander. During budget period 1 a series of exhaust manifold flow paths designs were compared using CFD analysis. The best design was chosen based on the manifold that resulted in the highest expander output shaft torque. Using the optimized manifold flow path, several designs that were feasible from a packaging and manufacturing standpoint were developed. These 3D models were used in CFD analysis coupled to the optimized expander from budget period 1. Engine pulse maps determined using GT Power were input into the CFD software (Figure 21). Outputs were flow rate through the expander, expander speed, torque, and pressure ratio. These outputs were used to calculate volumetric efficiency, isentropic efficiency, and mechanical efficiency. The manifold that provided the highest efficiencies was chosen for fabrication and testing. The final manifold design is shown in Figure 22.



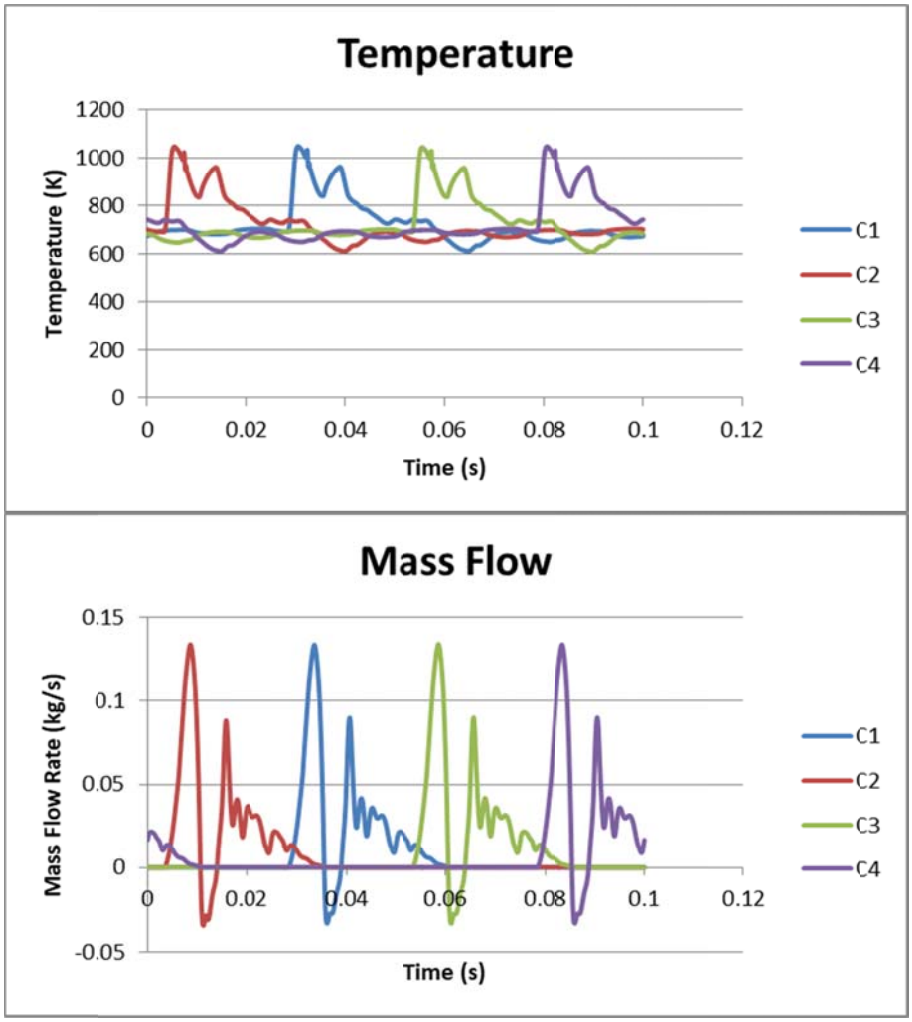


Figure 21: Sample of engine pulse data for each cylinder

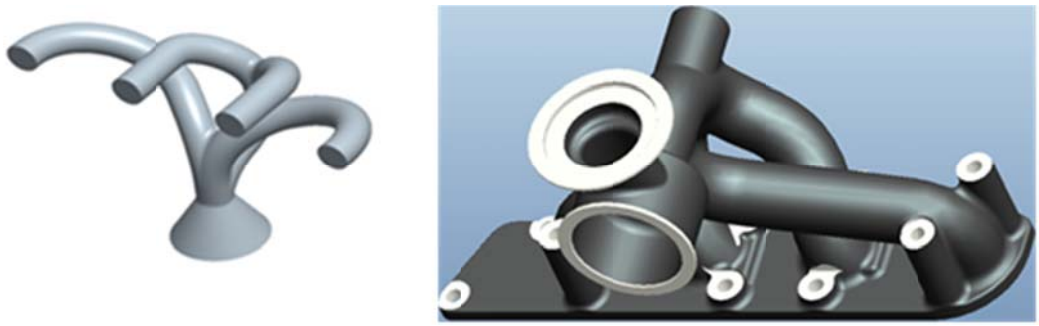


Figure 22: BP 1 optimized design (left) and final exhaust manifold design (right)

Generator Specification

A generator was designed to be coupled to the WHR expander via direct drive, in order to use the exhaust energy to charge a battery. The specifications for the motor were chosen based on preliminary test results from budget period 1 and projections of improved expander

performance/efficiency. A map of expander power, speed, and torque from preliminary testing is shown below (Figure 23) along with the expected operating range of the budget period 2 expander. Based on this information the generator was specified to have a maximum speed of 12k RPM, max torque of 4.5Nm and 4kW peak power. The custom motor that was built to this specification is shown below in Figure 24.

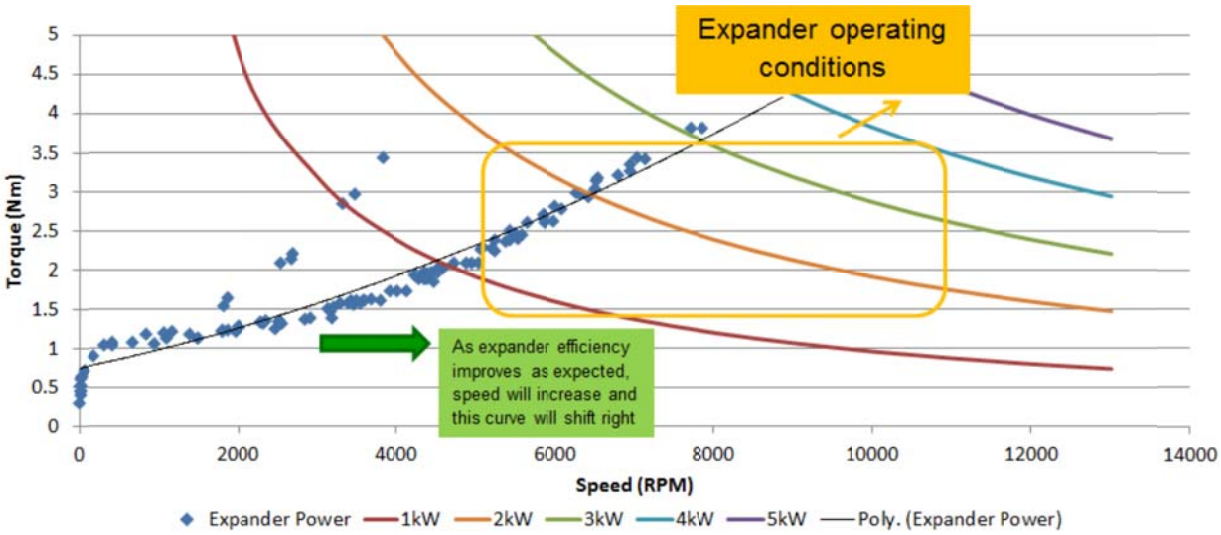


Figure 23: BP1 expander operating data and projected operating range of BP2 expander

Figure 24: Custom WHR motor built to Eaton's specification

Bench Testing

Testing was completed on the WHR expander and generator to determine performance and efficiency maps. First the generator was tested by coupling its input shaft to the dynamometer. Then the dyno was set to 1000RPM and the generator was swept through its torque range. The generated energy was stored and measured using a battery emulator. This process was repeated at speeds up to 12000RPM. Generator efficiency is shown below (Figure 25).

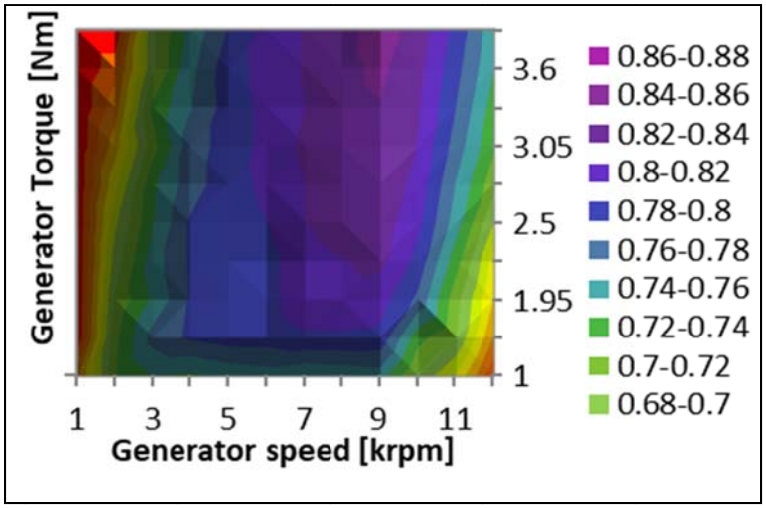


Figure 25: Generator efficiency map

The expander was then bench tested. A supercharger was coupled to the dyno and its outlet was connected to the expander inlet. The spinning supercharger was used to force fresh air through the supercharger, simulating the exhaust stream. The generator was coupled via direct drive to the expander rotor shaft. The test setup is shown below in Figure 26. The dyno was set at various speeds, which in turn set the air mass flow rate. With the generator in torque control mode, torque sweeps were completed for each flow rate. The following parameters were measured in order to calculate the expander efficiency: air mass flow rate, expander inlet and outlet pressure, expander inlet and outlet temperature, speed, torque, and generated power. The expander efficiency map is shown in Figure 27.

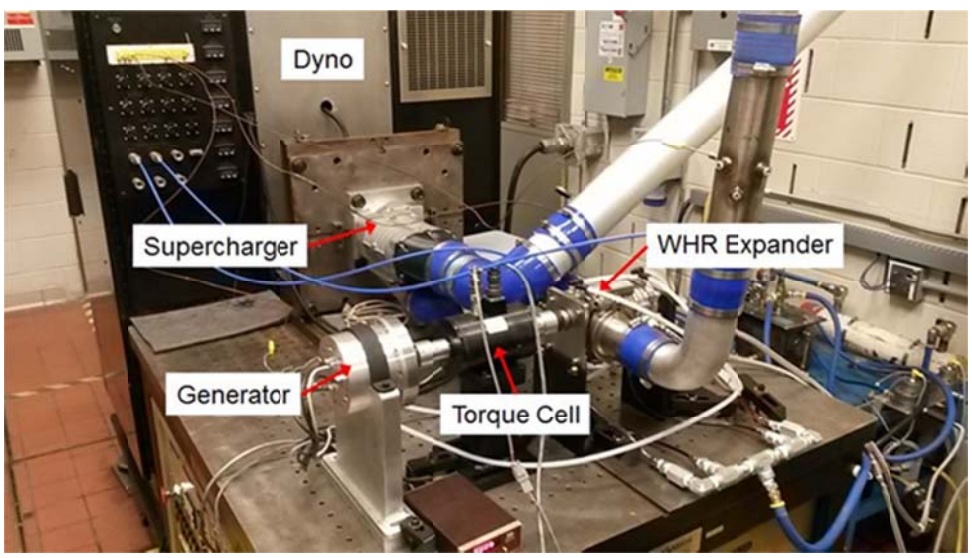


Figure 26: Test setup for WHR expander characterization testing

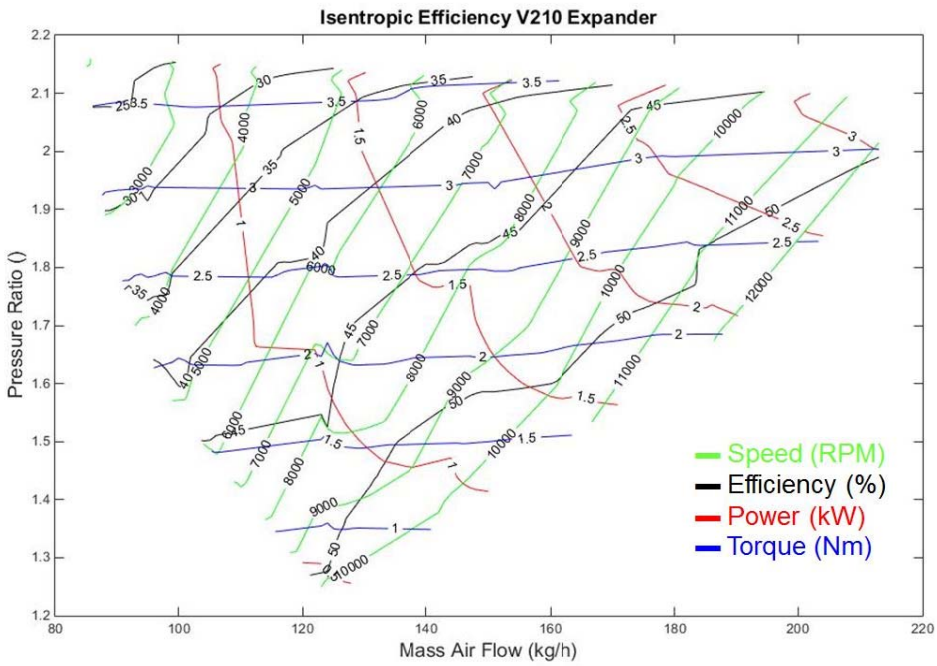


Figure 27: Expander Performance Map

3.7 Steady State Engine Calibration with EAVS EGR and eWHR Systems

The EAVS and eWHR systems were integrated with the baseline engine after unmounting the turbocharger. The EAVS and EGR setup in the engine intake path are shown in Figure 28, while the eWHR system setup along with DOC and DPF in the exhaust path are shown in Figure 29.

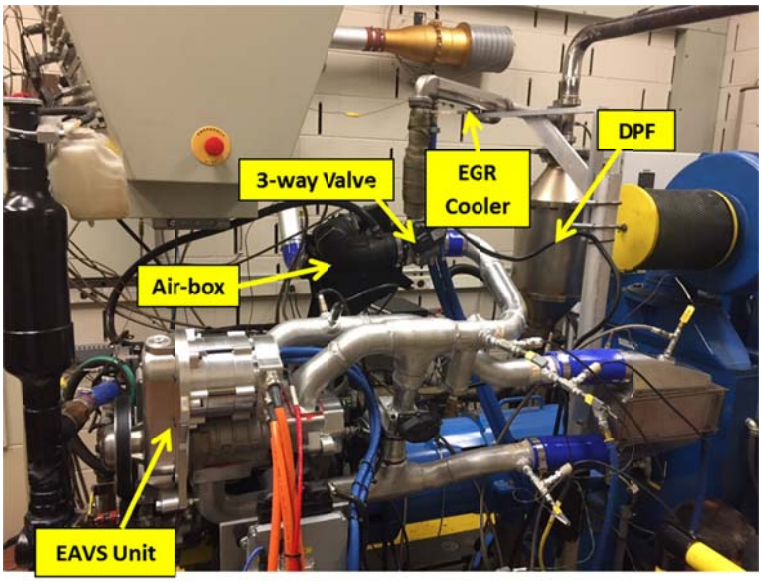


Figure 28: Dyno setup with EAVS and EGR valve installation

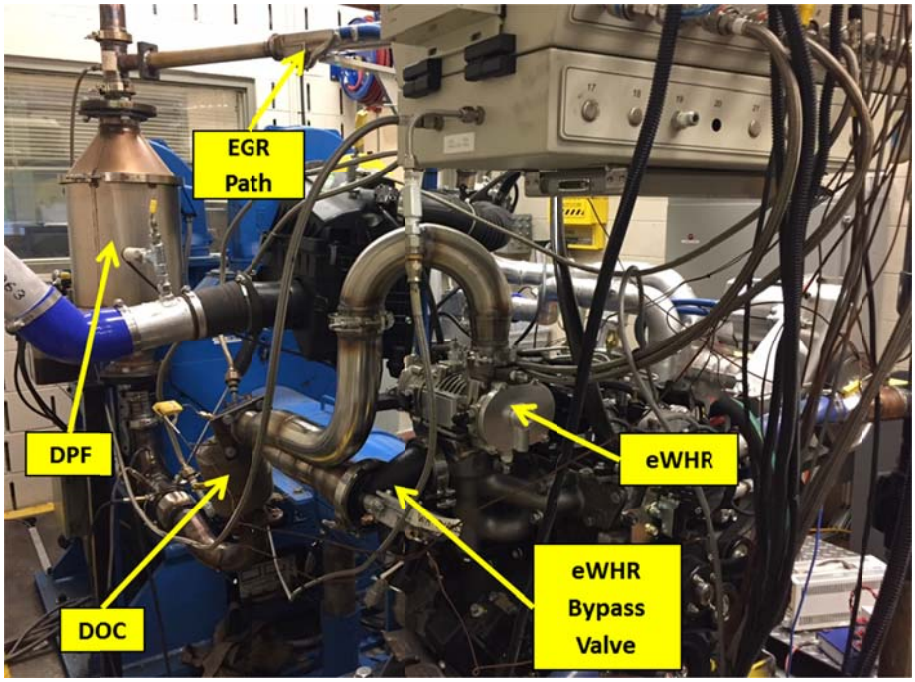


Figure 29: Engine dyno test setup with eWHR system installed in exhaust path

Measurement Setup

The engine dynamometer system includes several key measurement instrument systems required to achieve the project objectives. These instruments were acquired and installed in the engine dynamometer lab, and then integrated with the A&D iTest dynamometer control and acquisition system. A schematic of the engine dynamometer setup can be seen in Figure 30 below. These key instruments implemented include the A&D Phoenix Combustion Analysis System for monitoring cylinder pressure and combustion characteristics, ETAS INCA system for engine calibration and ECU data logging, Horiba MEXA720 NOx Sensor for measuring NOx emissions, AVL415S Smoke Meter for measuring particulate emissions, Re-Sol fuel cart for fuel conditioning and metering, and a Meriam Laminar Flow Element for measuring engine intake mass air flow. Instrument systems such as the A&D Phoenix and ETAS INCA are very expensive and complex, and the implementation and integration required significant time and onsite support from A&D and the instrument suppliers. One of the lessons learned from the measurement systems procurement and implementation process is that the project partners should agree on instrumentation requirements and responsibility as early as possible in order to facilitate timelier instrument procurement and better project cost forecasting.

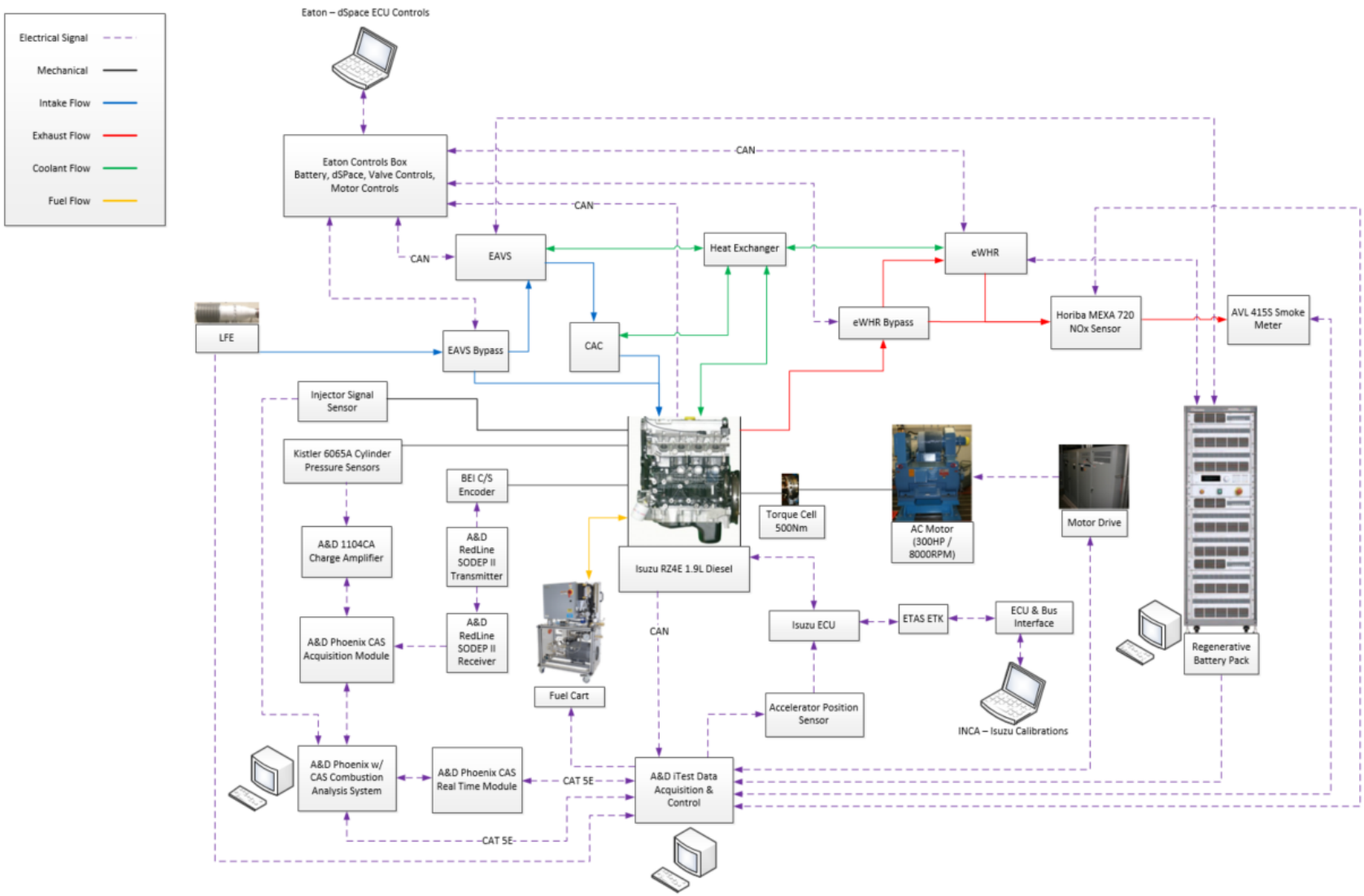


Figure 30: Schematic of the engine dynamometer setup for EAVS/eWHR System Testing

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Engine Calibration with EAVS, EGR and eWHR Systems

The EAVS system controls were integrated with the Isuzu engine controls on the engine dyno to be able to generate and maintain desired boost pressure ratio and EGR settings. The key engine operating points for which the EAVS and EGR systems were calibrated were identified from the baseline engine operation over three transient duty cycles, namely, US06, FTP75, and NEDC. The operating points are show in Table 4.

Table 4: Engine Operating Points for EAVS and EGR Calibration

Engine Torque [Nm]			250				
		200	200	200			
		150	150	150	150		
	100	100	100	100	100	100	
	50	50	50	50	50	50	50
Engine Speed [rpm]	1200	1600	2000	2400	2800	3200	3600

The response of the engine brake torque to the variation in boost pressure ratio and EGR valve position for engine operating point of 2400 rpm and 100 Nm is shown in Figure 31. Increasing the boost pressure ratio from nominal of 1.72 to 1.84 leads to drop in brake torque, this is due to the increasing EAVS load reflected on the engine via the planetary gearbox. Also, increasing EGR by opening the 3-way EGR valve reduces the torque output due to reduction in fresh charge.

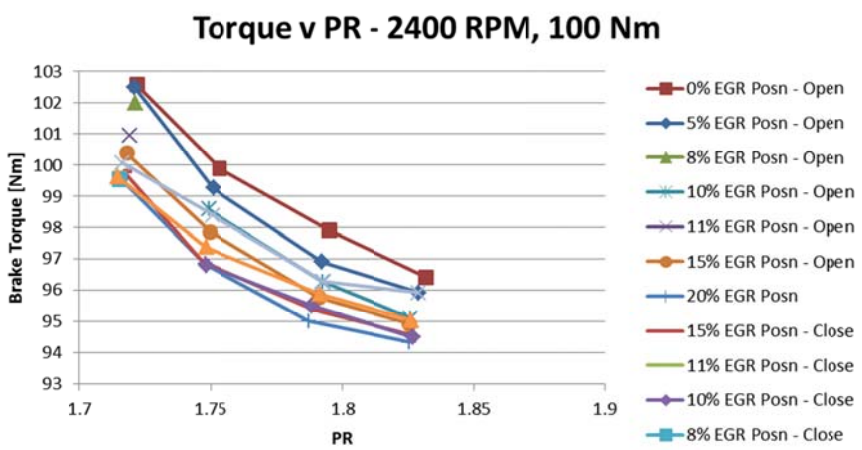

Figure 31: Engine with EAVS, Torque vs Boosting Pressure Ratio (PR)

The variation of engine NOx emission with EGR valve position is shown in Figure 32. As expected, increasing EGR lowers the NOx level, with any position greater than 5% improving the NOx below the baseline emission level (shown by the solid black square on the plot). Thus, the combined trends of engine brake torque and NOx from the two figures lead to the window of operation at 2400 rpm and 100 Nm as boost PR < 1.75 and EGR valve position > 5%. As these experiments were conducted without the eWHR unit in the exhaust loop, there was no backpressure on the engine. The operating window for boost pressure and EGR setting will

change with increasing backpressure. Calibration of the system with eWHR system installed will be the final system set points chosen for transient engine operation.

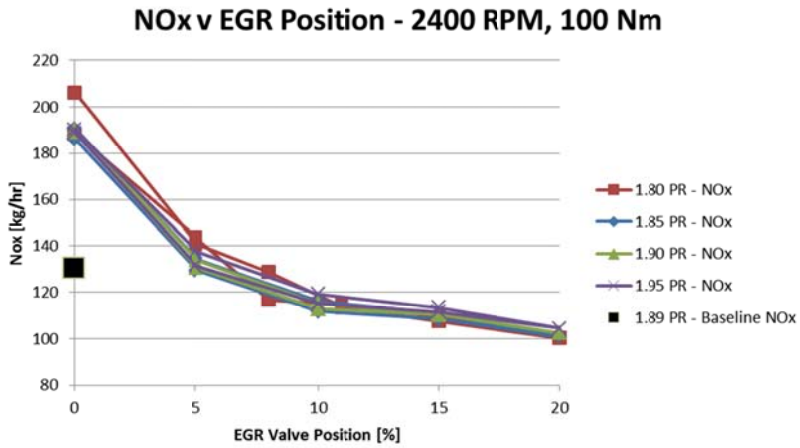

Figure 32: Engine with EAVS, NOx vs EGR Valve Position

The calibration of the combined EAVS and eWHR system was repeated for different back pressures from the eWHR system and the target engine boost pressure to achieve the engine brake torque while maximizing the recovered energy was determined.

3.8 Control System Development for Transient Engine Operation

The system schematic is shown in Figure 33. System controls are shared between Eaton and Isuzu (Figure 34). Eaton controlled air flow while Isuzu controlled fuel flow to achieve ideal AFR and EGR rates in order to increase fuel economy while maintaining engine output power.

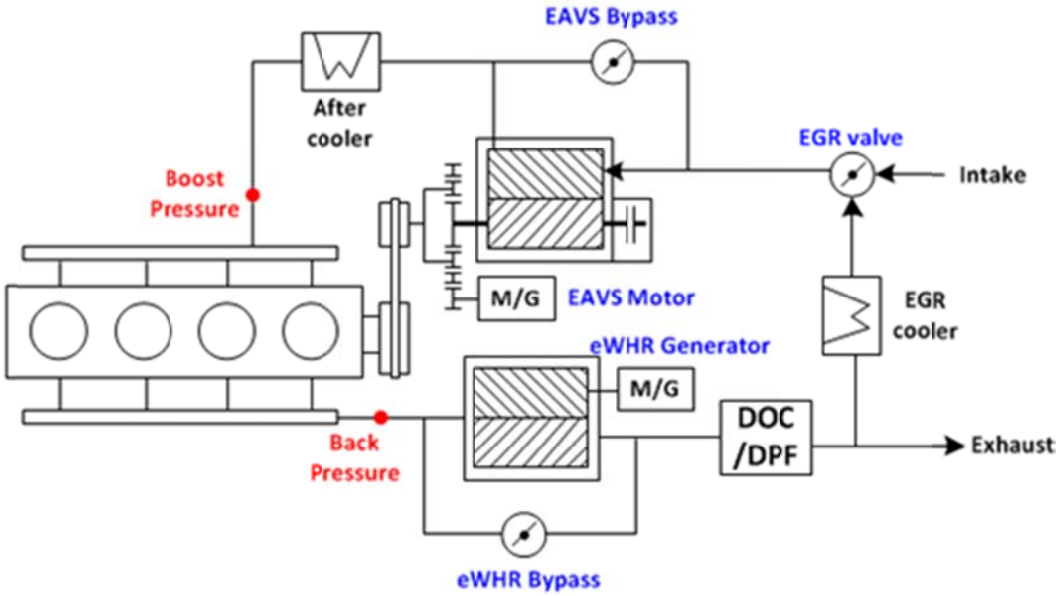

Figure 33: System Schematic

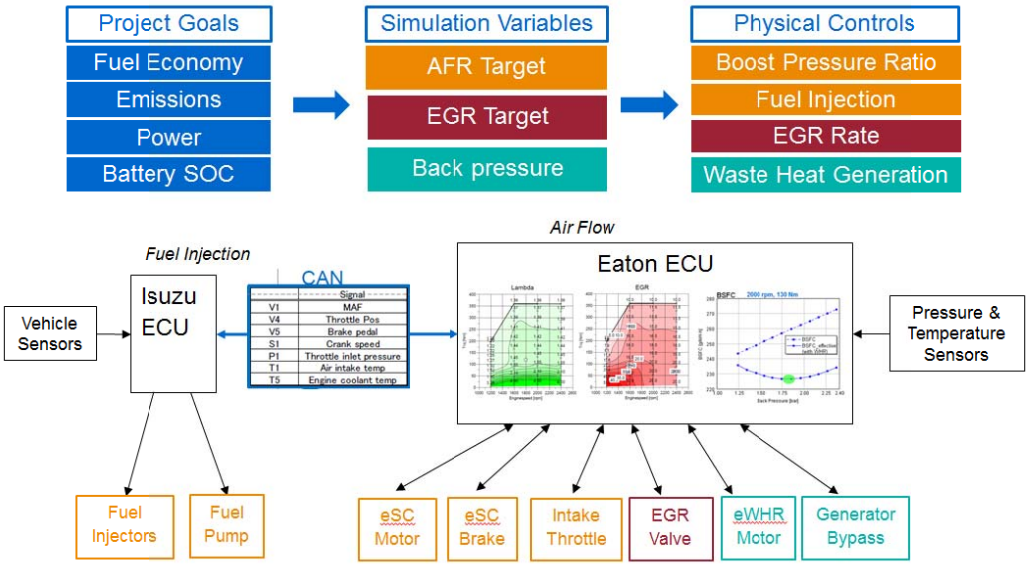

Figure 34: System Control Coordinated between Eaton and Isuzu ECUS

EAVS Controls

The EAVS system is responsible for ensuring the target AFR desired by the engine at all speed-torque operating points. The target AFR is achieved by maintaining a desired boost ratio (ratio of charge air pressure to ambient air pressure) which can be controlled by the supercharger speed. The desired boost ratio at speed-torque operating points chosen in the project is shown in Figure 35. The V400 supercharger is limited to 2.5 boost ratios. The supercharger speed is controlled by the EAVS motor via a feedback loop PID controller.

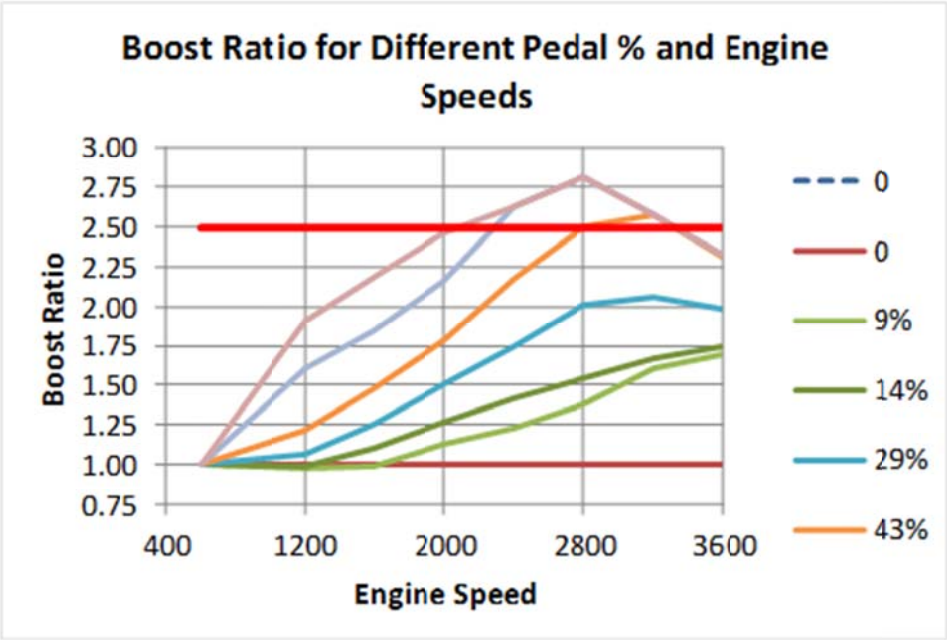

Figure 35: Boost Ratio for Different Pedal % and Engine Speeds

The EGR valve regulates the exhaust gas recirculation to achieve a desired EGR level to control the NOx in emissions. It was calibrated in steady state engine testing. The EGR valve position to achieve a target EGR value is shown in Figure 36.

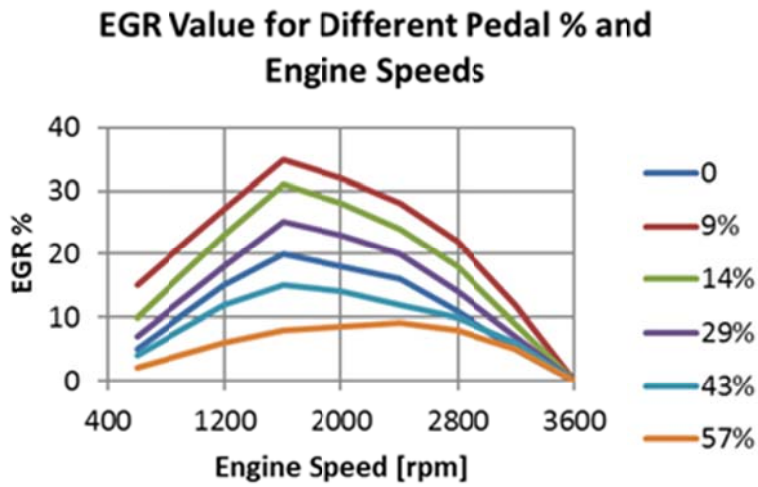

Figure 36: EGR Value for Different Pedal % and Engine Speeds

eWHR Controls

The WHR system applies a desired back pressure to the engine which will result in maximizing the exhaust energy recovery while ensuring the engine fuel economy is not compromised. The back pressure is controlled by a combination of the expander speed and the bypass valve position.

Figure 37 shows the optimal back pressure ratio operating line for the WHR system overlaid on the expander and generator efficiency maps. The target line specifies the generator torque-speed operation to maximize the recovered energy.

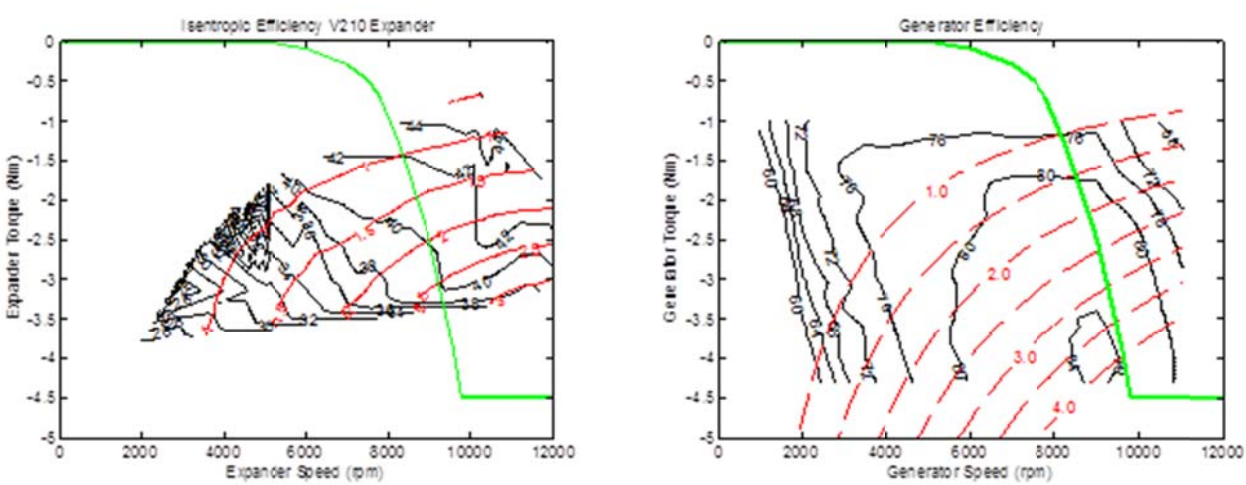

Figure 37: Waste heat recovery system optimal operation

The electrical hardware to interface between the Isuzu engine and the EAVS, eWHR and EGR valve was wired and tested. Figure 38 shows the assembled system.

Figure 38: Control Hardware

3.9 Transient Dyno Testing and Results

The transient testing included running the engine with EAVS and eWHR systems for three duty cycles, namely, FTP75, HWFET and NEDC, and comparing the fuel consumption and NOx emissions with the baseline engine. The engine dynamometer was programmed to control the engine speed while the accelerator pedal signal was sent to the Isuzu ECU and the Eaton controller. The EAVS system generated the transient boost pressures required to produce the engine torque for meeting the drive cycle requirements. The eWHR system was controlled to recover energy from exhaust gases by applying the right amount of back pressure on the engine.

Figure 39 shows the FTP75 drive cycle engine speed and accelerator pedal signals from the transient testing. Figure 40 shows the response of the EAVS system in detail. The EAVS is able to track the desired pressure ratio signal from the controller with a lag of <300ms. Figure 41 shows the response of the eWHR system, and compares the back pressure applied by the eWHR system to the boost pressure generated by the EAVS system. Whenever the desired boost pressure ratio exceeds 2, the eWHR system eases up on the back pressure to enable the engine to build the brake torque rapidly. This is accomplished by opening the eWHR bypass valve. Thus the coordination between EAVS and eWHR systems is critical to achieve the vehicle performance and improve fuel economy.

Figure 42 shows the details of the electrical energy consumed/produced by the system. The EAVS system consumes large electrical power during aggressive boosting conditions. The eWHR system replenishes the battery by generating steady power during cruising conditions. Thus, over the complete FTP75 cycle, the combined EAVS and eWHR systems result in net zero battery energy.

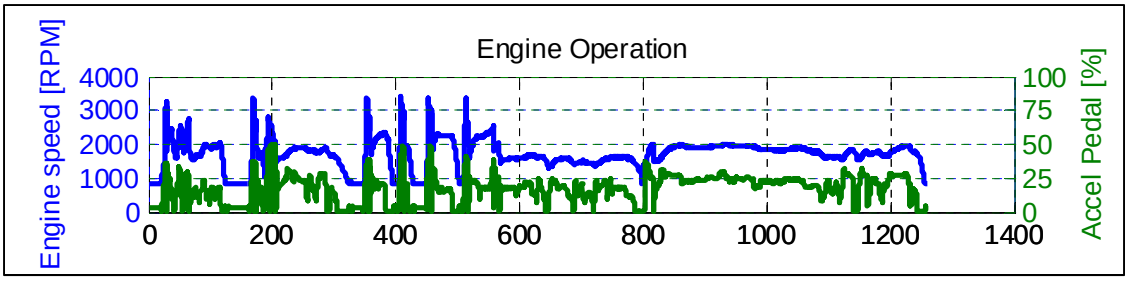

Figure 39: Engine Speed and Accelerator pedal signal for FTP 75 test

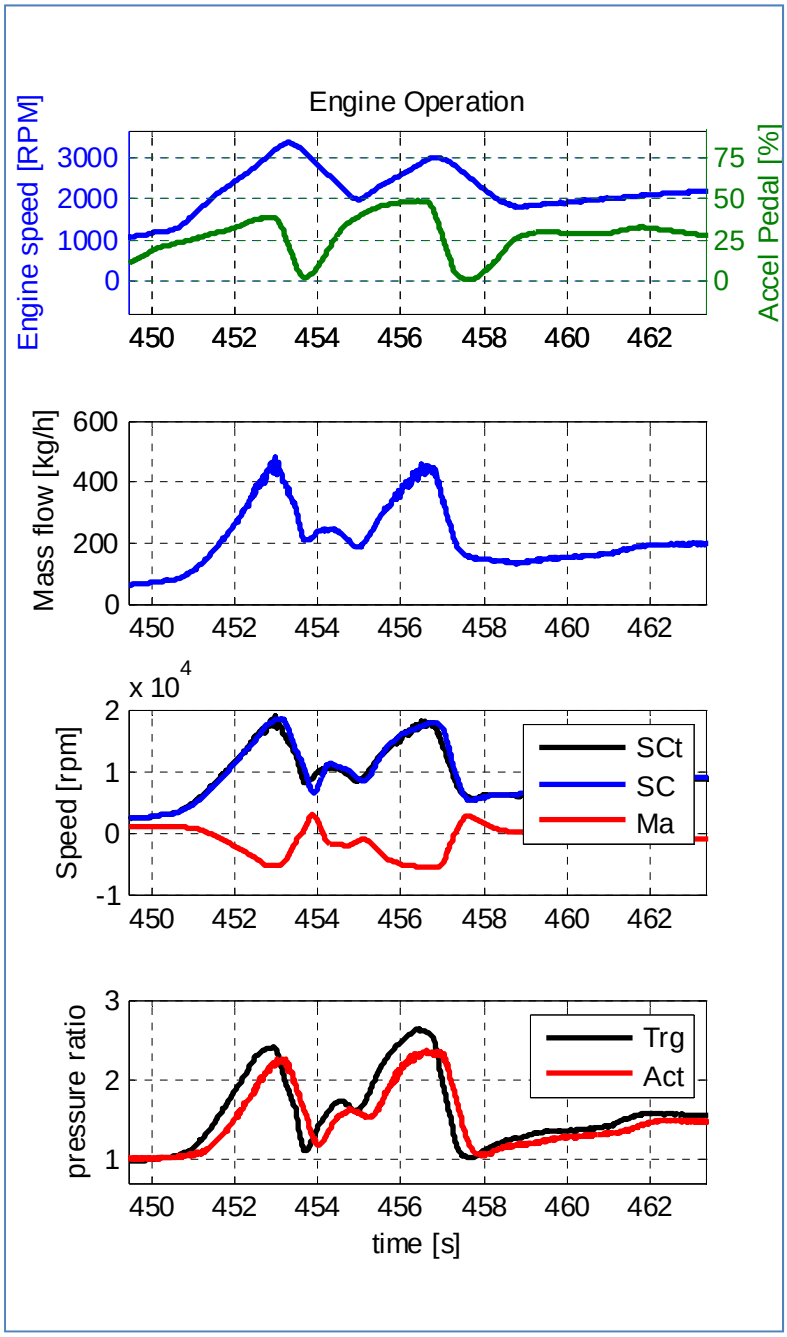

Figure 40: EAVS system response details.

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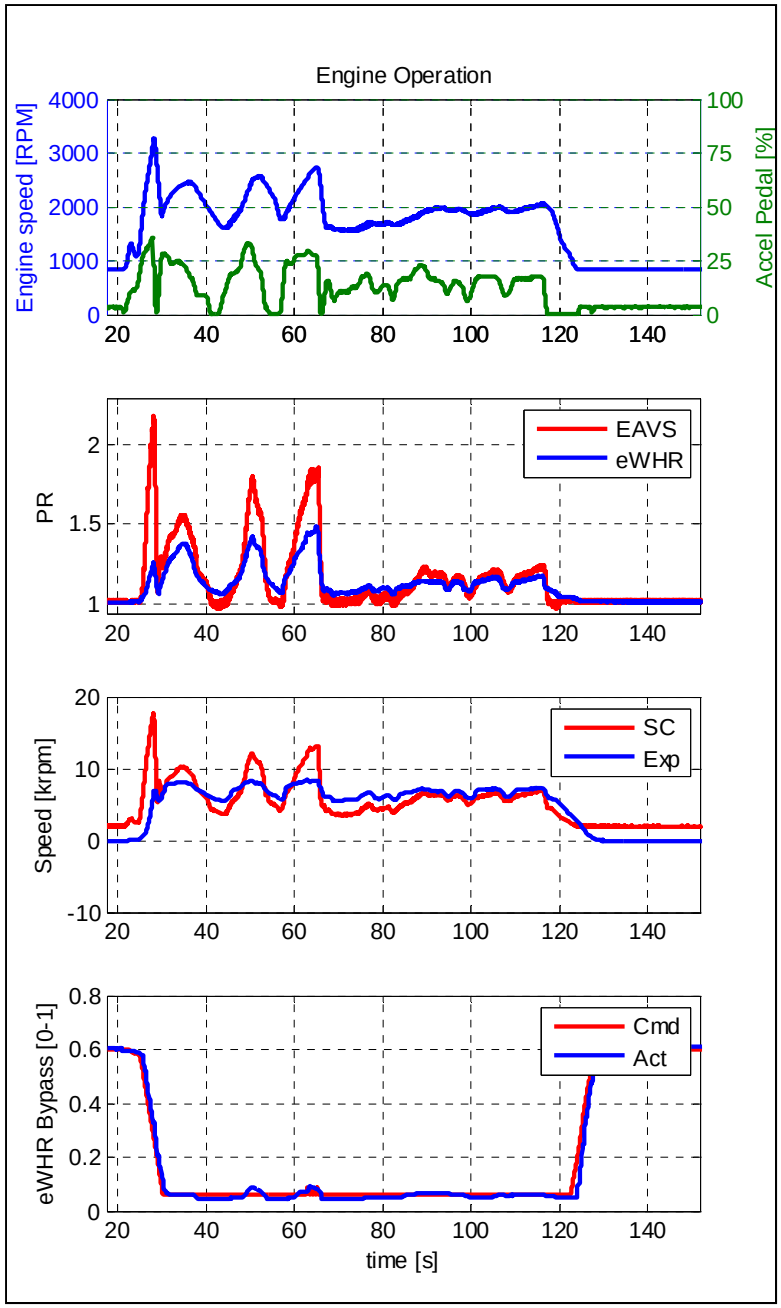

Figure 41: eWHR system response details

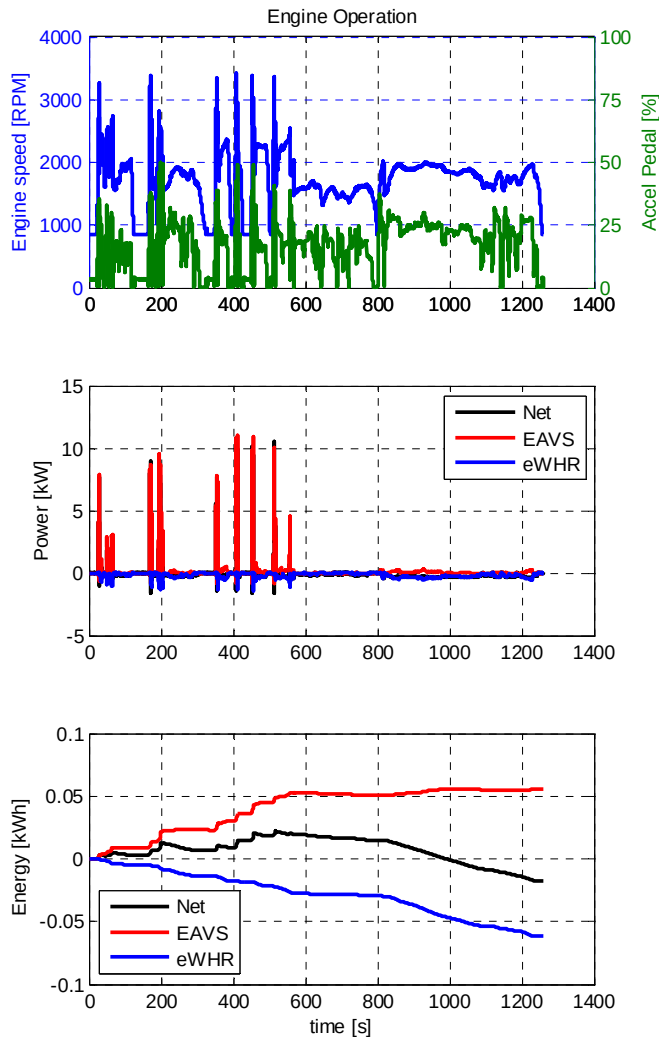

Figure 42: Electrical power and energy consumed by EAVS and recovered by eWHR system for FTP75 drive cycle

The fuel economy of the engine with EAVS and eWHR systems was compared with the baseline turbocharged engine and results are shown in Table 5.

Table 5: Fuel economy of the engine with EAVS and eWHR systems

Drive Cycle	Fuel Economy [kWh/kg]				
	Baseline	EAVS + eWHR		EAVS + eWHR w/ SS	
FTP75	3.837	3.749	-2.3%	3.786	-1.3%
HWFET	2.923	2.877	-1.6%	2.980	2.0%
NEDC	3.344	3.303	-1.2%	3.479	4.0%
US06	4.049	-	-	-	-

The fuel economy predicted from simulation study are shown in Table 6.

Table 6: Fuel economy from simulation

Architectures – NEDC	km/lt	%
VGT – Baseline (17.5km/lt measured)	17.88	0.00%
EAVS/eWHR - Boost+No TA	17.58	-1.68%
EAVS/eWHR - Boost+TA	18.88	5.59%
EAVS/eWHR - Boost+TA+S/S	**19.82**	**10.85%**
EAVS/eWHR - Boost+S/S	**18.52**	**5.35%**

The vehicle level simulation of the Isuzu engine with EAVS and eWHR systems predicted a change in fuel economy when the system is not performing any hybrid functions of -1.68%. The engine dyno testing with boosting function only showed fuel economy change of -1.2% over baseline. Further, when engine start/stop (anti-idling) feature was enabled, the fuel economy change was +5.35% in simulation study and +4.0% over baseline in the engine dyno testing. The good correlation between the engine dyno testing and simulation study indicates that it is possible to achieve the target fuel economy improvement of +20% over baseline using EAVS/eWHR system in full performance + hybrid mode.

4 TECHNOLOGY TRANSFER

No products were developed under the award.

The project was presented at the 2016 and 2017 DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meetings.

1. Integrated Boosting and Hybridization for Extreme Fuel Economy and Downsizing, Project ID: ACS112, 2017 DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meetings, PI Chinmaya Patil, June 9, 2017.
2. Integrated Boosting and Hybridization for Extreme Fuel Economy and Downsizing, Project ID: VSS162, 2017 DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meetings, PI Vasilios Tsourapas, June 9, 2016.

5 COMPUTER MODELING

No computer models were developed through the award.