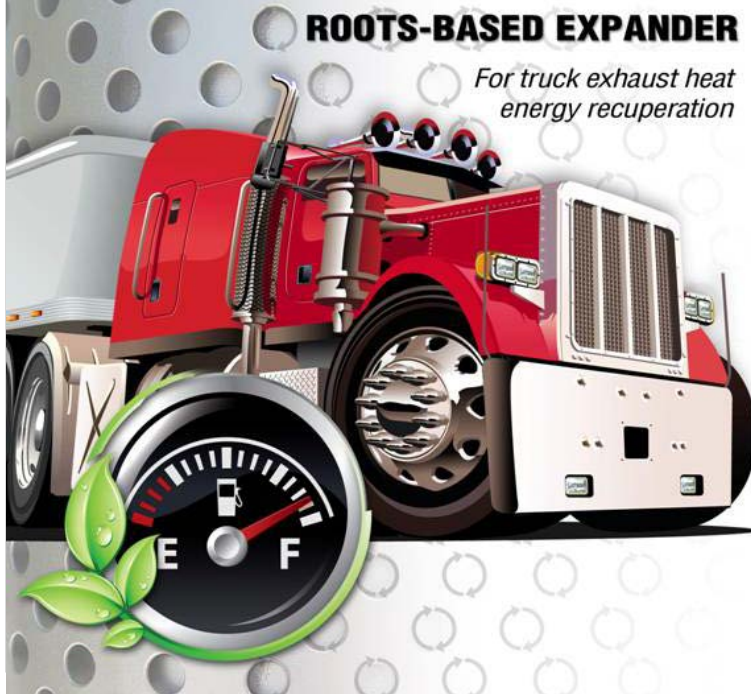




2013 DOE Vehicle Technologies Program Review

Heavy Duty Roots Expander Heat Energy Recovery (HD-REHER)

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Eaton Corporation

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Project ID # ACE088



Powering Business Worldwide

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Overview

Timeline

- Project Start Date: 04/01/2012
- Project End Date: 03/31/2013
- Phase 1 Percent Complete: 100%

Budget Period	Start Date	End Date	% Complete
Phase 1	04/01/2012	03/31/2013	100
Phase 2	04/01/2013	03/31/2014	
Phase 3	04/01/2014	03/31/2015	

Budget

- Total Project Funding: \$3,357,479
 - DOE Share: \$2,500,000
 - Contractor Share: \$857,479
- Funding received in FY12: \$900,203
- Funding for FY13: \$724,598

Barriers

- Improve Heavy Duty engine efficiency (improvement $\geq 5\%$) through WHR systems
- Engine efficiency improvement without NOx and PM penalty
- Highly durable waste heat recovery system
- Cost effective Organic Rankine Cycle (ORC) system by Roots expander

Partners

- Project lead: Eaton Corporation
- Collaborations:
 - AVL Powertrain Engineering
 - John Deere
 - Electricore, Inc

Relevance

Objectives of This Study

Program Objectives

- Demonstrate heavy-duty diesel engine fuel economy improvement through “Roots Expander Organic Rankine Cycle Waste Heat Recovery Systems”:
 - 5% (baseline objective) if only energy from the EGR loop is recovered
 - 8% (target objective) if exhaust energy from downstream of the turbine is also used for recovery
- Demonstrate that other pollutants, such as NOx, HC, CO and PM will not increase as part of the overall engine/WHR/exhaust after treatment optimization
- Demonstrate a plan for cost reduction by incorporation of a Roots type expander

Phase 1 Objectives

- Analyze exhaust heat energy availability in a heavy duty diesel engine through experiments
- Quantify the Roots based Rankine cycle system fuel economy improvement from simulation and baseline experimental data
- Design a Roots expander system for Rankine cycle based on available exhaust energy to achieve 5% fuel economy improvement

Milestones

Month/Year	Milestone	Status
July 2012	Baseline engine characterization (EGR, injection timing, AFR and back pressure)	Completed
Sep 2012	Energy flow and trade-off analysis and concept definition	Completed
Nov 2012	WHR architectures evaluation through simulation (achieved ~6% FE)	Completed
Jan 2013	Single stage Roots expander design and components selection	Completed
Mar 2013	Single stage Roots expander prototyping	On schedule
April 2014	Go/ No Go Review	Planned
FY 14	Expander development, prototyping and testing	Planned
FY 14 - 15	Heat exchangers and other ORC hardware integration and testing	Planned

Approach/Strategy

- Using baseline 13.5 liter John Deere HD diesel engine, characterize and quantify the potential waste energy sources for construction of thermodynamic analysis models – **July 2012 (Complete)**
- Evaluate different Roots expander ORC WHR system architectures theoretically and finalize optimized system (assess heat exchanger layouts on system performance, leading to specifications of Roots expander and other required WHR system components) – **Nov 2012 (Complete)**
- Develop and test expander (utilize CFD analysis, bench testing, calibration, and validation to maximize efficiency and durability) – **2013 and 2014 (In Progress)**
- Test Roots expander ORC system on engine and compare to baseline engine performance - **2014 and 2015 (Planned)**

Technical Accomplishments and Progress

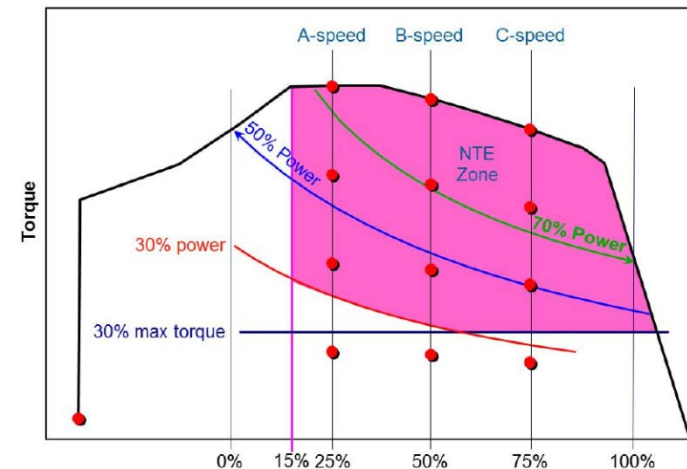
- Baseline engine calibration and experimental data collection of EGR, injection timing, AFR sweeps and exhaust restriction sensitivity on performance
- 1-D simulation validated against experimental data predicting the enthalpy availability
- Analytical investigation completed to predict the Roots based Rankine cycle performance (Ethanol – Working fluid)
- Evaluated four different Roots expander ORC WHR architectures and achieved ~6% fuel economy improvement (Analytically)
- Developed Roots expander concept design based on simulation and analytical results
- Completed, single stage expander design including auxiliary components and material selection process - prototyping is in progress
- Multistage Roots expander rotor critical speed analysis is complete and a detailed system design is in progress

Technical Accomplishments and Progress

Engine Specifications and Testing

John Deere 13.5L (I-6); 448 kW @ 2100 rpm - designed to run #2 diesel

Properties	Value
Charging System	2 stage LP fixed, HP VGT
Fuel Injection System	Electronic Unit Injector
Bore	132 mm
Stroke	165 mm
Compression Ratio	16.5:1
Connecting Rod Length	265 mm
Valve Configuration	2 Intake ; 2 Exhaust



USEPA 13 mode Supplemental Emission Test (SET) Cycle

Technical Accomplishments and Progress

Impacts of WHR System

	13 Mode Engine Out SET Values (g/kW-h)			
Configuration	NOx	HC	CO	PM
Baseline w/std exhaust restriction (15 kPa)	1.428	0.114	0.426	0.181
Base w/Inc. restriction (30 kPa)	1.269	0.099	0.638	0.235

	EGR Cooler		Exhaust
Configuration	Q _{rej} (kW)	bsfc Projection (%)	Wtd Q _{rej} (kW)
Baseline w/std exhaust restriction	79.0	4.5	173.3
Base w/Inc. restriction	75.2	4.3	183.6

- In general, increasing the exhaust restriction resulted lower NOx, lower HC
- Increase in PM level is within the acceptable allowed range (with DPF)
- The slight reduction in EGR heat rejection observed with increased back pressure due to the normal response of the engine controller
- Preliminary estimates of the potential bsfc projection is $\geq 4\%$ using EGR heat rejection as the sole source for an ORC WHR system

Technical Accomplishments and Progress

Energy Balance Analysis

Load points	A25	A50	A75	A100	B25	B50	B75	B100	C25	C50	C75	C100
Engine speed [rpm]	1307	1307	1307	1307	1609	1609	1609	1609	1910	1910	1910	1910
Brake power [bkW]	89	178	266	355	112	224	337	449	118	235	352	468
BMEP [bar]	6.0	12.0	18.1	24.1	6.2	12.4	18.5	24.7	5.5	10.9	16.3	21.7
Engine torque [Nm]	650	1297	1947	2595	666	1332	1997	2663	588	1174	1760	2339
Parameters affecting waste heat conditions												
EGR rate [%]	33.5	27.4	26.1	25.1	37.0	33.4	31.5	25.9	39.9	36.7	33.8	28.2

EGR rates were increased from production calibration to help WHR potential

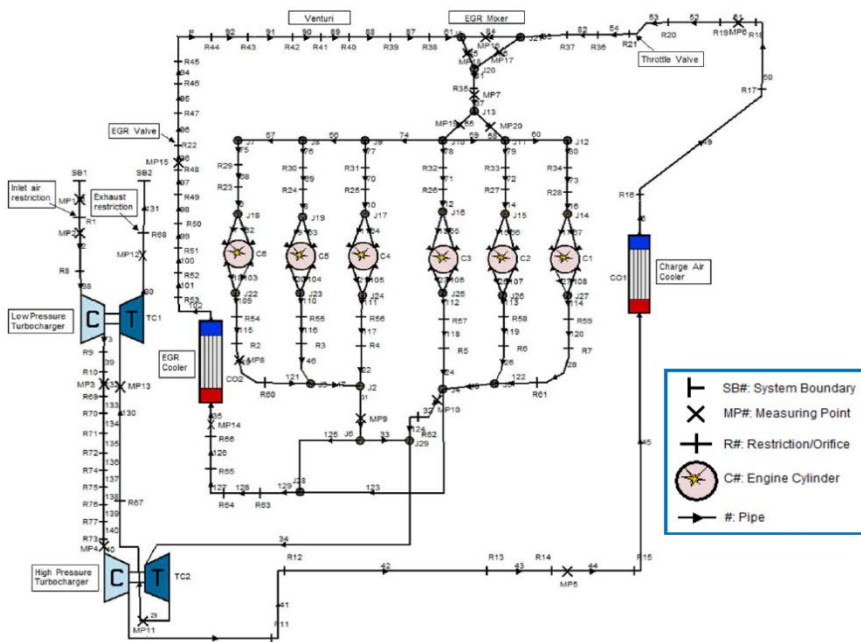
EGR cooler heat rejection/Fuel Energy [%]	9.8	9.0	9.9	9.9	12.0	12.6	12.8	10.6	13.6	14.1	13.2	11.6
Net exhaust energy/Fuel energy [%]	21.5	21.7	21.3	21.5	21.1	20.7	20.5	22.0	21.4	20.7	20.5	22.1
Exergy (available energy) of EGR before EGR cooler and exhaust after turbine												
Exergy in EGR before EGR cooler [kW]	9	18	31	43	15	33	53	61	20	43	61	71
Exergy in exhaust after turbine [kW]	13	28	42	59	17	34	51	77	18	35	52	81
Total exergy available for WHR (kW)	22	46	73	102	32	67	104	138	38	78	113	152

- Exergy levels - vary from 22 kW (A25) to 152 kW (C100)
- Shows high Exergy levels for most load points
- Exergy level of EGR is highly considerable for WHR system which reduces engine system cooling load

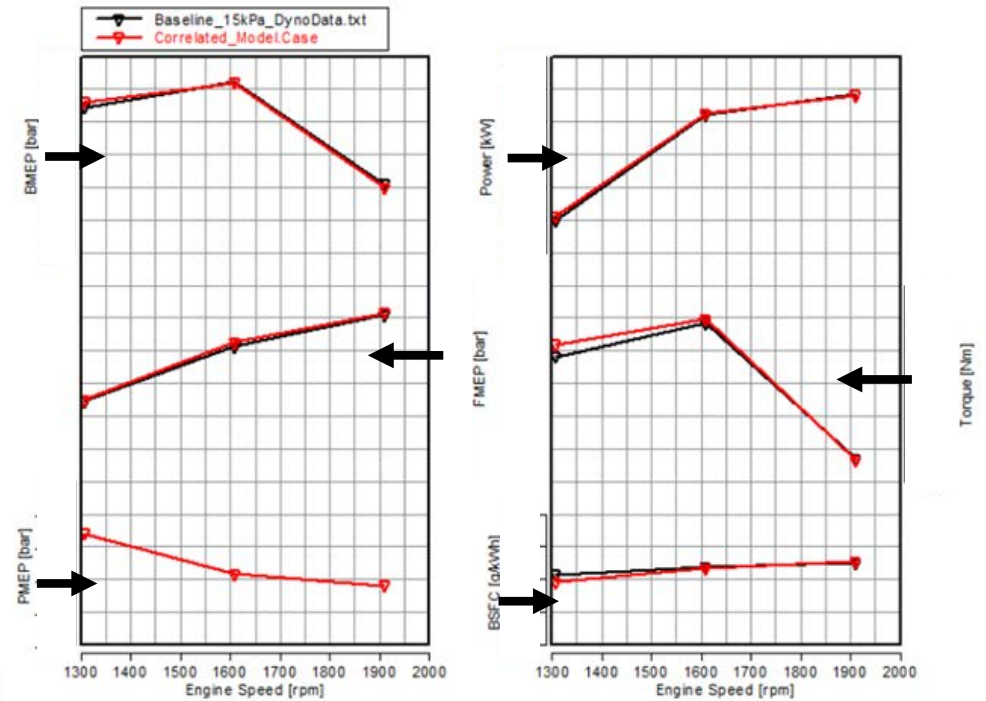
Technical Accomplishments and Progress

1-D Simulation

The simulation model closely predicts the measured engine performance parameters within 3% deviation



Schematic of Simulation model



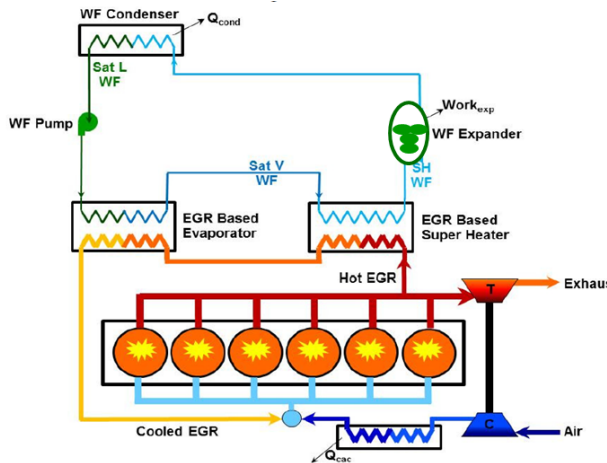
- System modeling will help optimize the size of the ORC hardware
- 1-D thermodynamic model will be used to optimize the effectiveness of the ORC system

Technical Accomplishments and Progress

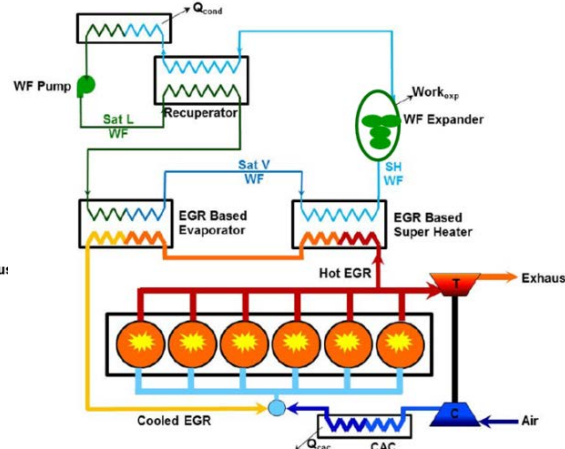
ORC WHR Architecture Study

Four ORC WHR system architectures were defined for evaluation:

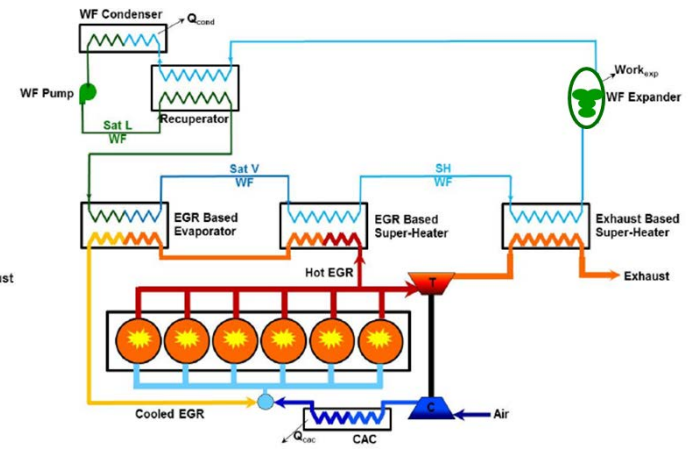
1. A simple Rankine cycle WHR system using EGR gas as the only heat source – **2% bsfc improvement**
2. Recuperation was combined with first architecture (EGR + Recuperation) – **3% bsfc**
3. Post turbine low pressure exhaust energy with second architecture (EGR + Recuperation + 25% Post turbine) – **5% bsfc**
4. Multistage Roots expander ORC system (EGR + Recuperation + 25% Post turbine) – **6% bsfc**



Architecture 1 (Simple EGR WHR)



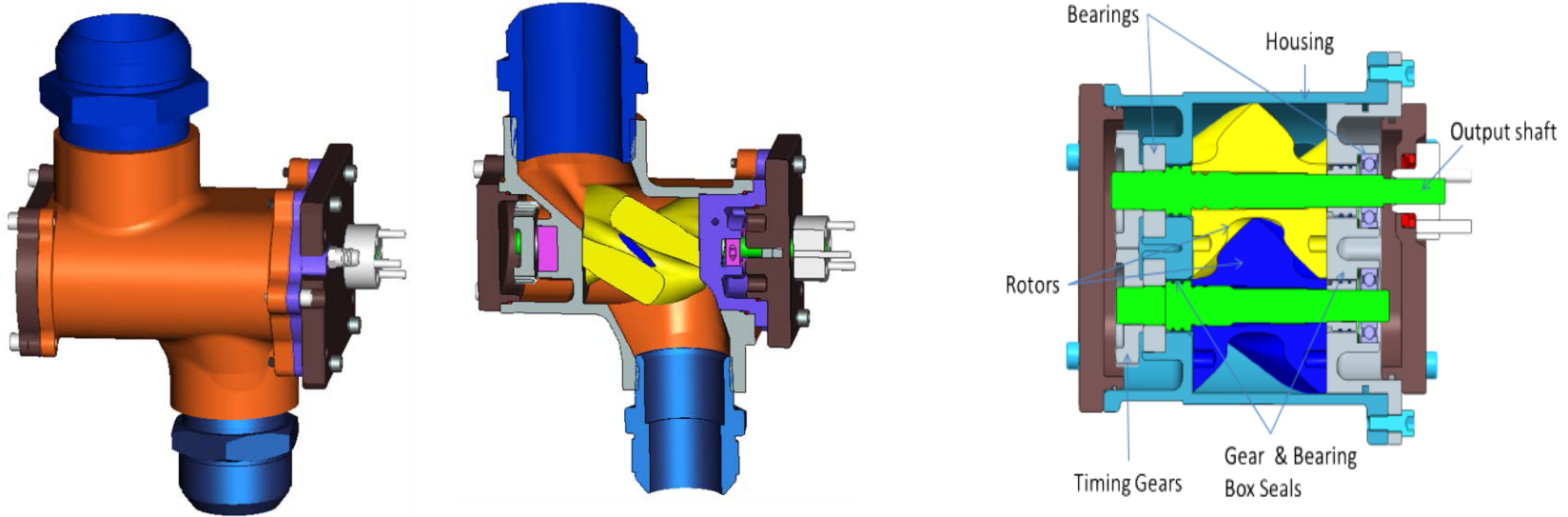
Architecture 2 (Simple EGR + Recuperation)



Architecture 3 - Rankine Cycle With Both EGR and Post Turbocharger Turbine Exhaust Based Recovery

Technical Accomplishments and Progress

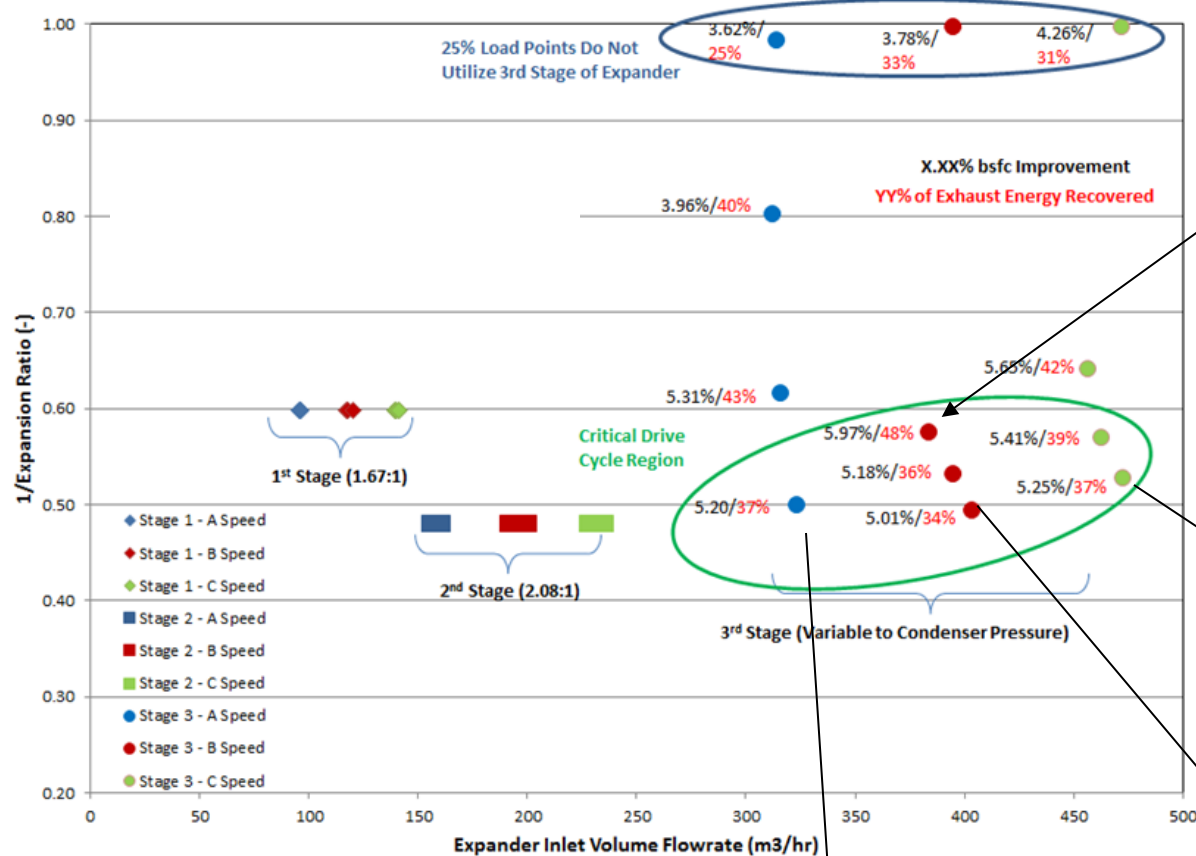
Single Stage Expander



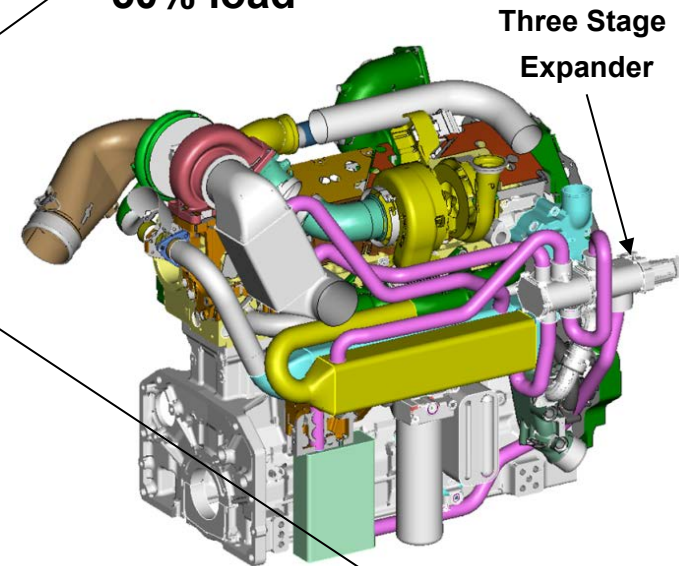
- Expander has been designed such that it can be reduced in size allowing for evaluation of the smaller expanders
- Stainless steel has been identified as the rotors and housing material
- A lubrication separator will be used to separate the oil from the ethanol
- Single stage expander will be tested on the ethanol
- Single stage expander components (bearing, seals, coating materials, expander cooling circuit) were clearly defined and procurement/prototyping is in progress

Technical Accomplishments and Progress

Three Stage Root Expander



- ~6% BSFC improvement
- 45% exhaust recovery
- 50% load



Roots Expander WHR System
Packaged on HD Diesel Engine

Base Engine Inputs		On-Highway System											
	Mode	A25	A50	A75	A100	B25	B50	B75	B100	C25	C50	C75	C100
	Speed (rpm)	1307	1307	1307	1307	1609	1609	1609	1609	1910	1910	1910	1910
	Torque (N-m)	650	1297	1946	2595	666	1332	1997	2649	587	1174	1760	2331
	Power (KW)	88.9	177.6	266.4	355.2	112.3	224.5	336.5	446.3	117.4	234.8	352.1	466.3

Technical Accomplishments and Progress

Expander Components

Seals:

- Dynamic seal - Dual lip, spring energized, and Teflon® seal – preventing ethanol escape or air ingress
- Static Seal - Two different seals will be used based on temperatures (Synthetic fluoropolymer)

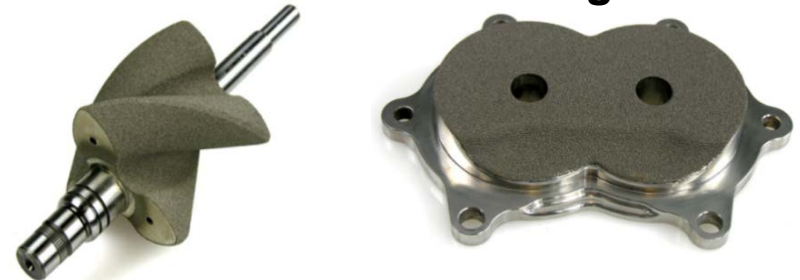
Bearings:

- Off-the-shelf bearings are not sufficient for the temperature of this application (higher temperatures reduce life)
- Different heat treatment (X29) has been selected for high temperature operation

Ethanol/Oil Separator:

- Oil will be used to cool and lubricate the gears, bearings, bearing plate, and pump
- This eliminates the added complexity of an additional oil pump and cooler, but it does require an ethanol/oil separator

Expander Material and Coating:



- Rotors, housing, and end plates are 316 Austenitic Stainless Steel with abradable coating material
- The abradable coating will support minimal clearance

Collaborations and Coordination



- AVL for baseline engine testing, system modeling, waste heat recovery hardware specification, engine integration and engine final testing



- John Deere brings engine expertise to develop system requirements and specifications, provides test engine and auxiliary systems



- Electricore helps with administrative program management

Outside Vehicle Technologies Program Eaton is working with:



- Modine for WHR heat exchangers



- NSK Bearings for high temperature application bearings



- St. Louis Metalizing company for abradable coatings



- Zatkoff and Eclipse Engineering Inc. for expander seals



Proposed Future Work

- Remainder FY 2013
 - Single stage expander will be tested on an ethanol test stand at Eaton Facility
 - Go/No Go Review (April 2013)
 - Multistage expander design will be completed
- FY 2014
 - Multistage expander will be prototyped
 - Multistage expander will be tested on the ethanol test stand
 - Roots expander hardware for the ORC system will be ready for engine testing
 - Heat exchangers development for the 13.5L engine ORC system
 - Go/No Go Review (April 2014)
- FY 2015
 - Roots expander ORC WHR system will be integrated in a 13.5 L John Deere diesel engine
 - Roots expander ORC system will be evaluated and compared to baseline performance

Summary

- The baseline John Deere engine provides an excellent platform for WHR demonstration and exhibits very good EGR tolerance
- Minor impact on base engine bsfc and EGR heat rejection as a result of increased exhaust restriction
- Developed and calibrated the thermodynamic model to optimize WHR system using data from 13 mode tests
- Ethanol was selected as the working fluid
- Highest bsfc ($\sim 6\%$ bsfc) improvement is achieved utilizing a three-stage Roots expander with EGR and post turbine low pressure exhaust heat with recuperation
- A relatively simple coupling of the WHR system expander to the engine crankshaft appears feasible (variable speed coupling can be avoided)
- Clearly identified Roots expander components (bearings, seals) and rotor as well as housing materials based on operating conditions
- Single stage expander prototyping is in progress
- The preliminary Multistage Roots expander system (inline) design analysis is in progress

Technical Back-Up Slides

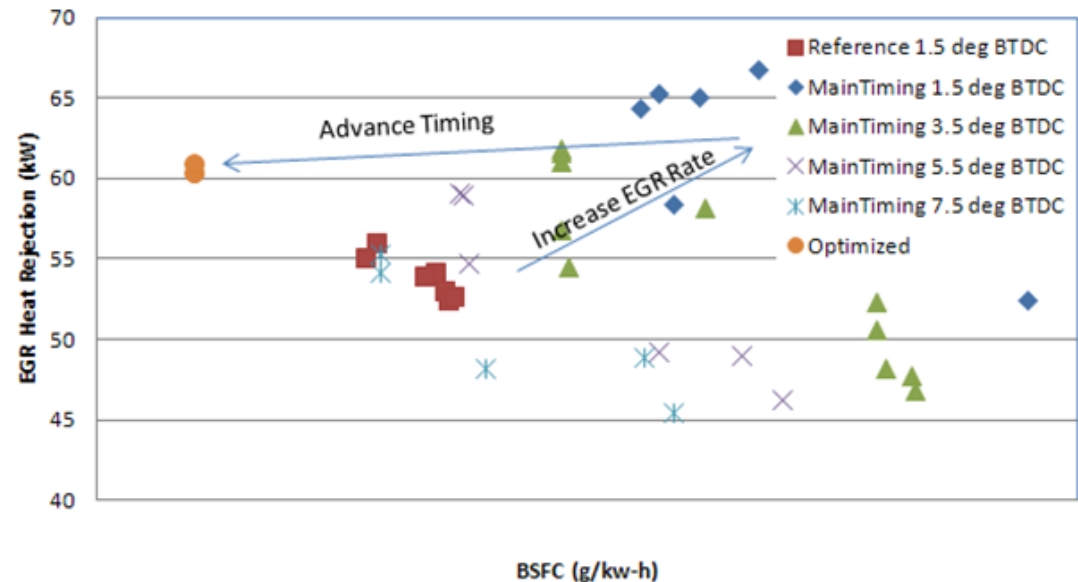
13 Mode Test Points WFs & Optimization Path

Mode	Speed	Load	Speed (rpm)	Torque (N-m)	SET WF	In Use WF
1	idle	Idle	802	*	15%	0%
2	A	100%	1307	2595	8%	10%
3	B	50%	1609	1332	10%	10%
4	B	75%	1609	1997	10%	20%
5	A	50%	1307	1297	5%	20%
6	A	75%	1307	1945	5%	20%
7	A	25%	1307	650	5%	0%
8	B	100%	1609	2663	9%	10%
9	B	25%	1609	666	10%	0%
10	C	100%	1910	2339	8%	10%
11	C	25%	1910	588	5%	0%
12	C	75%	1910	1760	5%	0%
13	C	50%	1910	1173	5%	0%

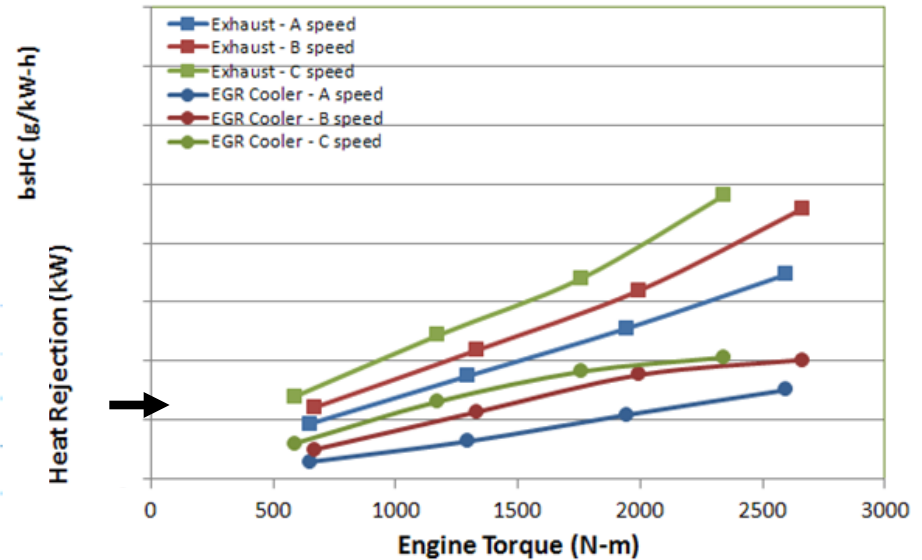
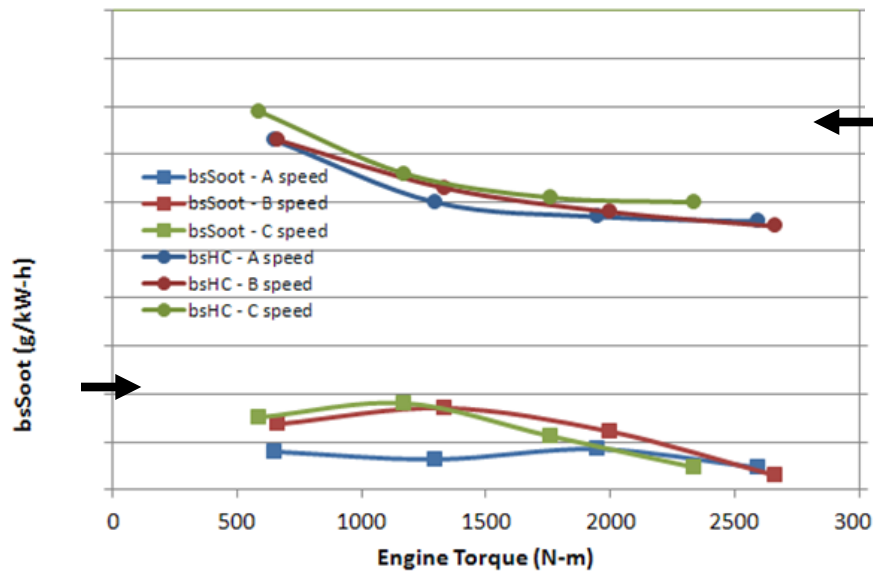
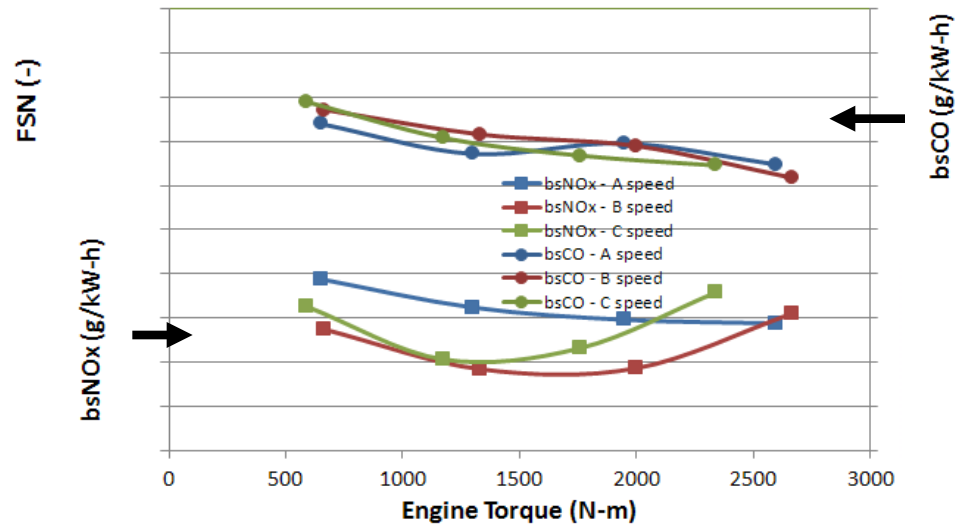
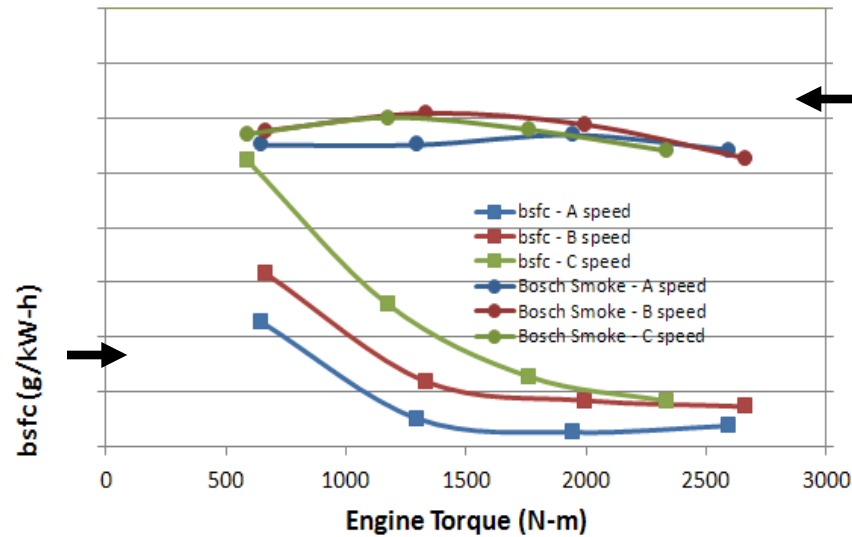
13 mode engine out SET points and corresponding Weighing Factors (WF)

Average based on working estimate drive cycle weighting values, wtd. cycle power = 350.6 kW

Example of optimization path (B50)



Engine Baseline



Working Fluid Selection

- High thermal stability (to allow for sufficiently high superheating temperature)
- Appropriate evaporation temperature (for use as an EGR cooling media)
- Condensation pressure close to or higher than the ambient pressure (to minimize ambient air entering the WHR system during normal system operation)
- Large pressure ratio potential over the expander (to increase work extraction and Rankine Cycle efficiency)
- Relatively low evaporation pressure (to lessen overall working pressures and system mass required to contain system pressure)
- R245fa (C₃H₃F₅), water and ethanol were selected as candidates from a literature study
- Water was eliminated from the candidate list due to having a low condensation pressure (0.3 bar) (sealing concerns), a high freezing point and a significantly higher than desired volume flow rate
- Ethanol has advantages over R245fa in the system pressure and the size of the recuperator required. The system pressure has significant impact to the cost of the WHR system
- **Ethanol has been selected as Roots Expander ORC system working fluid**