High Efficiency Engine Systems Development and Evaluation

Presented by **Tom Briggs**

Kukwon Cho, Scott Curran, Dean Edwards, Eric Nafziger, Robert Wagner
Oak Ridge National Laboratory

Gurpreet Singh, Ken Howden, Steve Goguen, Kellen Schefter
Vehicle Technologies
U.S. Department of Energy

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ACE017

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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Project overview

This project supports DOE Vehicle Technology efficiency and emissions objectives through experiments and modeling, and also supports ACEC Tech Team goal setting activities for 2011 and beyond.

Timeline

- **Consistent with VT MYPP**
- **Evolves to address OVT efficiency/emissions goals**

Barriers

- **Efficiency/combustion**
- **Engine-system management**
- ➡ **VT performance milestones**

Budget

- **FY 2010 – $750k**
- **FY 2011 – $400k (no major hardware additions this FY)**

Partners / Interactions

- **Regular status reports to DOE and ACEC Tech Team**
- **Barber-Nichols on bottoming cycle development**
- **BorgWarner on advanced turbocharging and EGR systems**
- **One-on-one interactions on hardware development (*e.g.,* Cummins) and software issues (*e.g.*, Gamma Technologies)**

Relevance & Milestones

Objectives are to demonstrate Vehicle Technologies fuel efficiency performance goals and to support the setting of new goals for future technologies

Characteristics	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010
Peak Brake Thermal Efficiency (HC Fuel)	39%	41%	42%	43%	44%	45%
Part–Load Brake Thermal Efficiency (2 bar BMEP @ 1500 rpm)	27%	27%	27%	27%	29%	31%
Emissions	Tier 2 Bin 5	Tier 2 Bin 5	Tier 2 Bin 5	Tier 2 Bin 5	Tier 2 Bin 5	Tier 2 Bin 5
Thermal efficiency penalty due to emission control devices	<2%	< 2%	< 2%	< 2%	< 1%	< 1%

- **FY 2010 Q4 * – Met**

  Demonstrated 45% peak BTE on a multi-cylinder engine – a 15% improvement from 2005

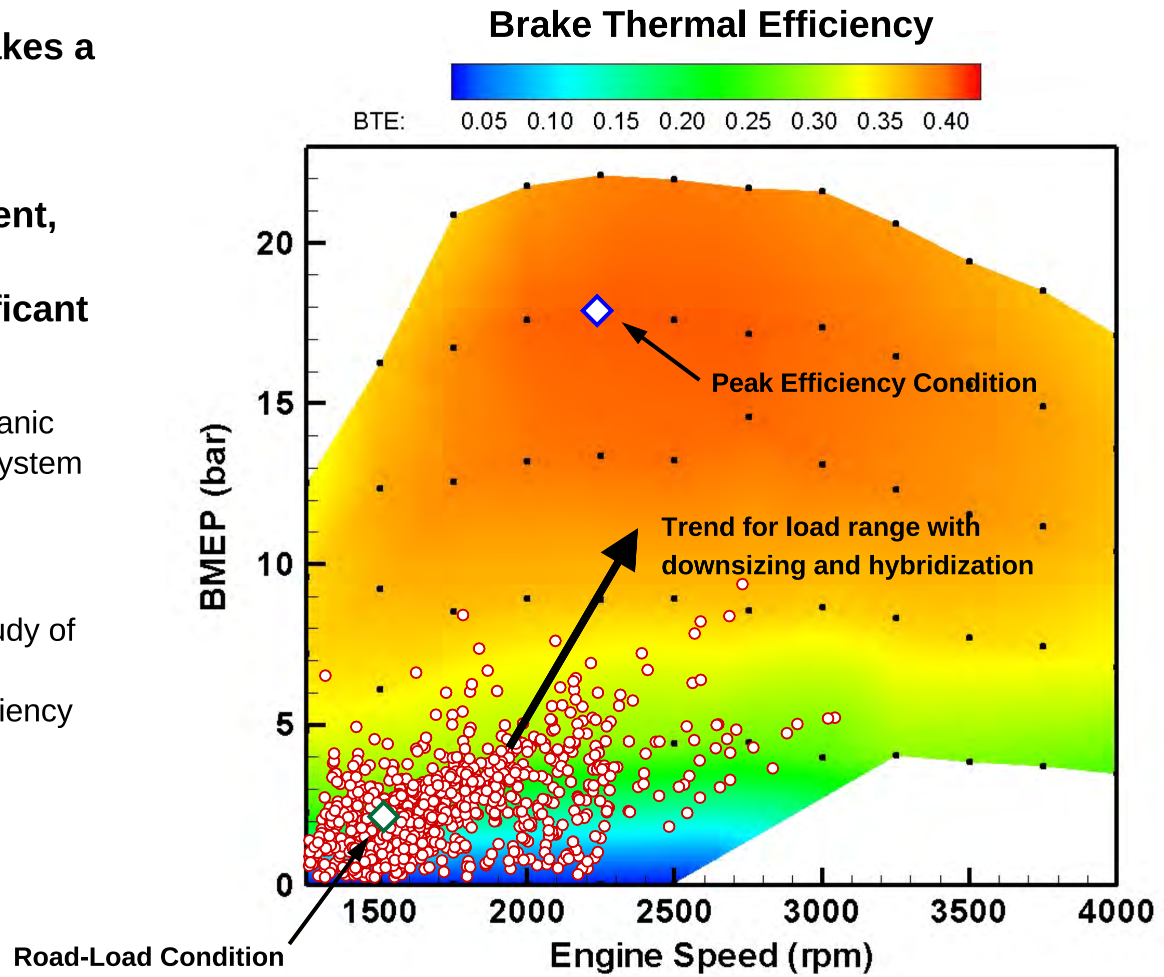
- **FY 2011 Q3 – In Progress**

  Quantify loss mechanisms and efficiency opportunities in state of the art engines using a 2nd Law thermodynamic analysis

* This was a Joule milestone which is used to track important accomplishments and progress towards Vehicle Technologies program goals.

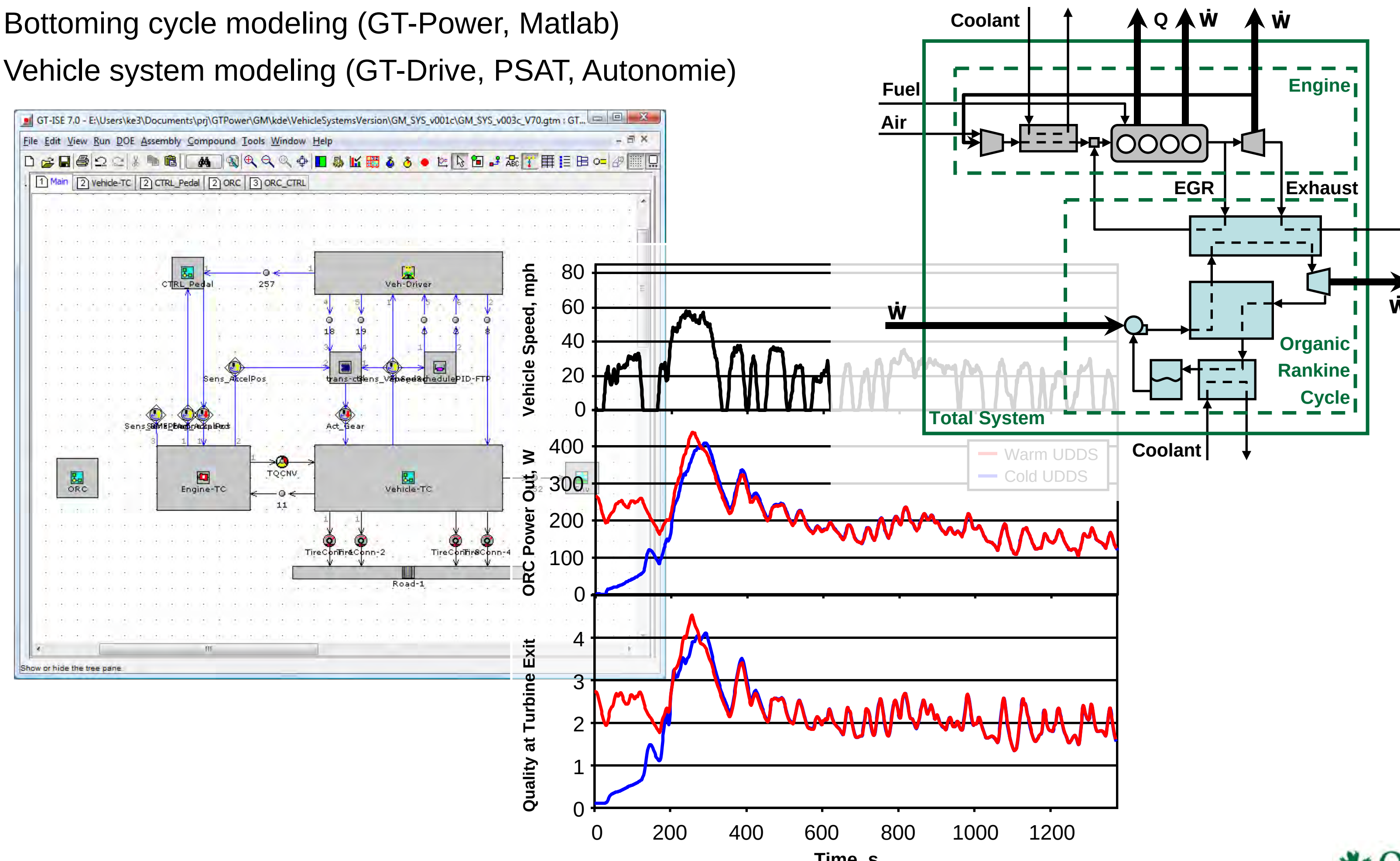
Approach: efficiency increases need to match the drive cycle

- **Peak efficiencies can be high, but don't impact real-world fuel use with current powertrain strategies**
- **Improving road-load efficiency makes a disproportionate increase in fuel economy**
- **ORNL is using modeling, experiment, and analysis to target efficiency improvements at conditions significant to current and future platforms**
  - Experiment: demonstration of an organic Rankine cycle waste heat recovery system
  - Modeling: simulation of an ORC and turbocompounding over drive cycles
  - Analysis: detailed thermodynamic study of advanced engines and combustion approaches to quantify potential efficiency gains



Modeling approach for engine systems

- **Simulation of the engine and vehicle provide readily understood guidance for technology implementation**
  - » Engine system modeling (GT-Power)
  - » Bottoming cycle modeling (GT-Power, Matlab)
  - » Vehicle system modeling (GT-Drive, PSAT, Autonomie)



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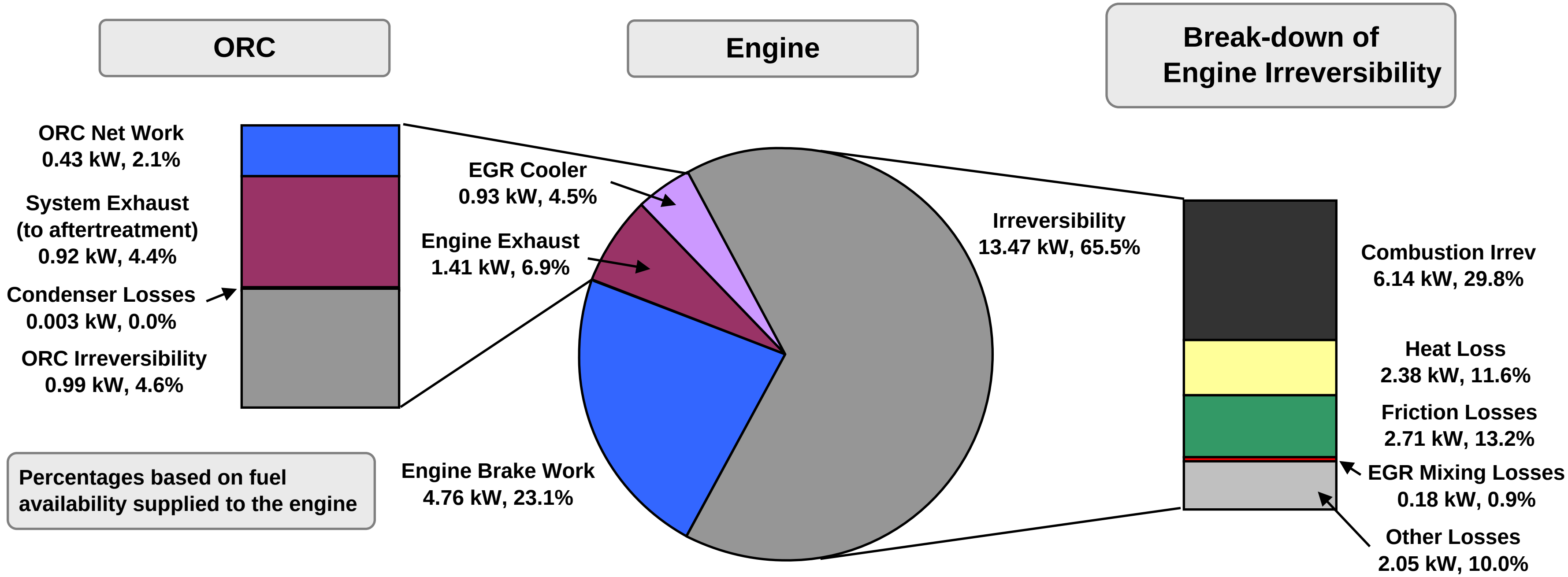
Thermodynamic analysis to quantify efficiency potentials

Example of fuel availability breakdown and recovery opportunities at 1500 rpm, 2 bar BMEP



Percentages based on fuel availability supplied to the engine

Comprehensive approach to system efficiency opportunities and challenges builds upon on-going activities at ORNL and elsewhere

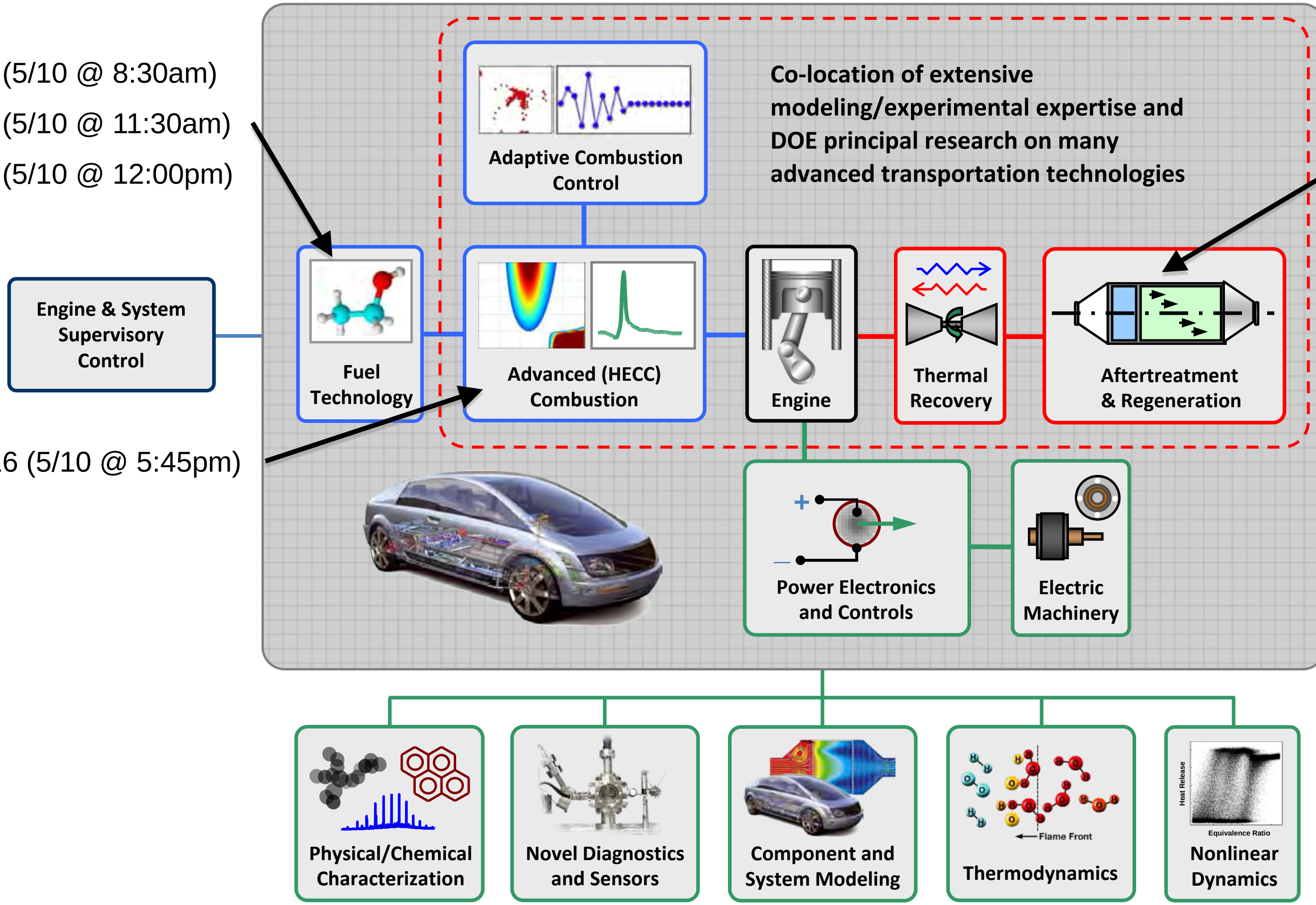
FT001 (5/10 @ 8:30am)

FT007 (5/10 @ 11:30am)

FT008 (5/10 @ 12:00pm)

ACE016 (5/10 @ 5:45pm)

ACE031 (5/12 @ 9:00am)

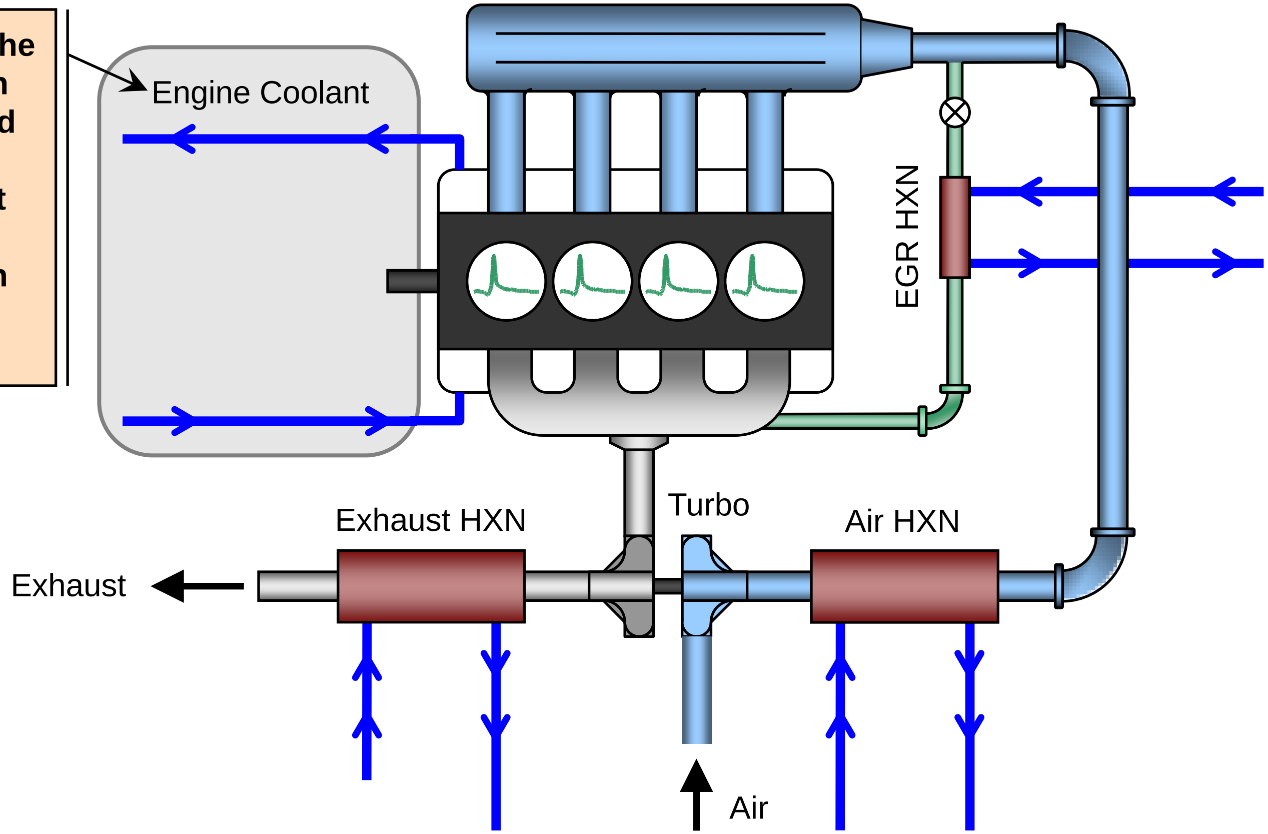


Technical Accomplishments Summary

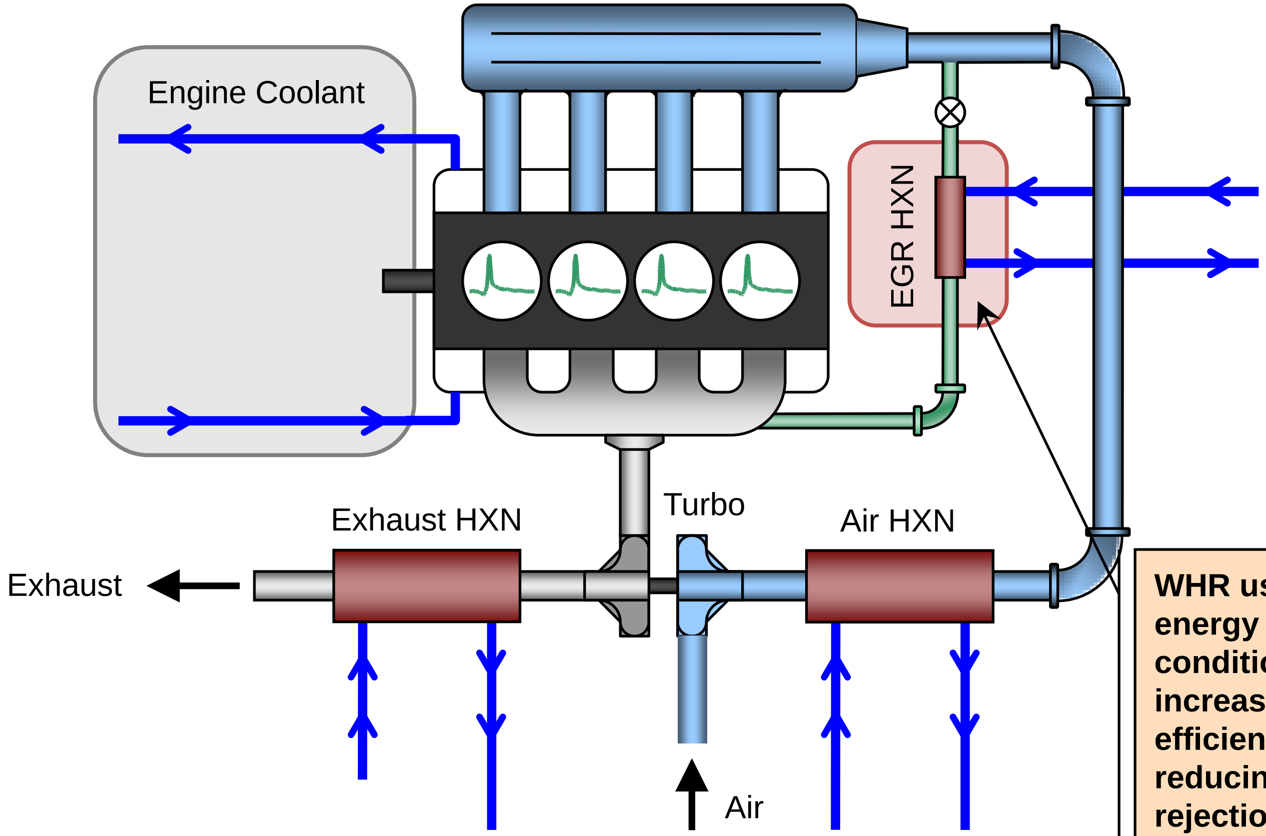
- Demonstrated 45% combined peak brake thermal efficiency on a light duty diesel engine (DOE Joule milestone)
- Designed and fabricated an organic Rankine cycle (ORC) for converting thermal exhaust energy to electricity
- Developed transient capable ORC model and coupled to GT-Power engine model
- Modeled the efficiency benefit of implementing an ORC under road-load conditions and across FTO drive cycles
- Modeled turbo-compounding in addition to ORC – adds an additional 1% point increase to engine efficiency (not detailed in this talk)

Waste heat recovery is possible with multiple streams on the engine

Heat recovery from the coolant has not been extensively examined in recent work, but remains a significant portion of overall engine heat rejection and will be of increasing interest

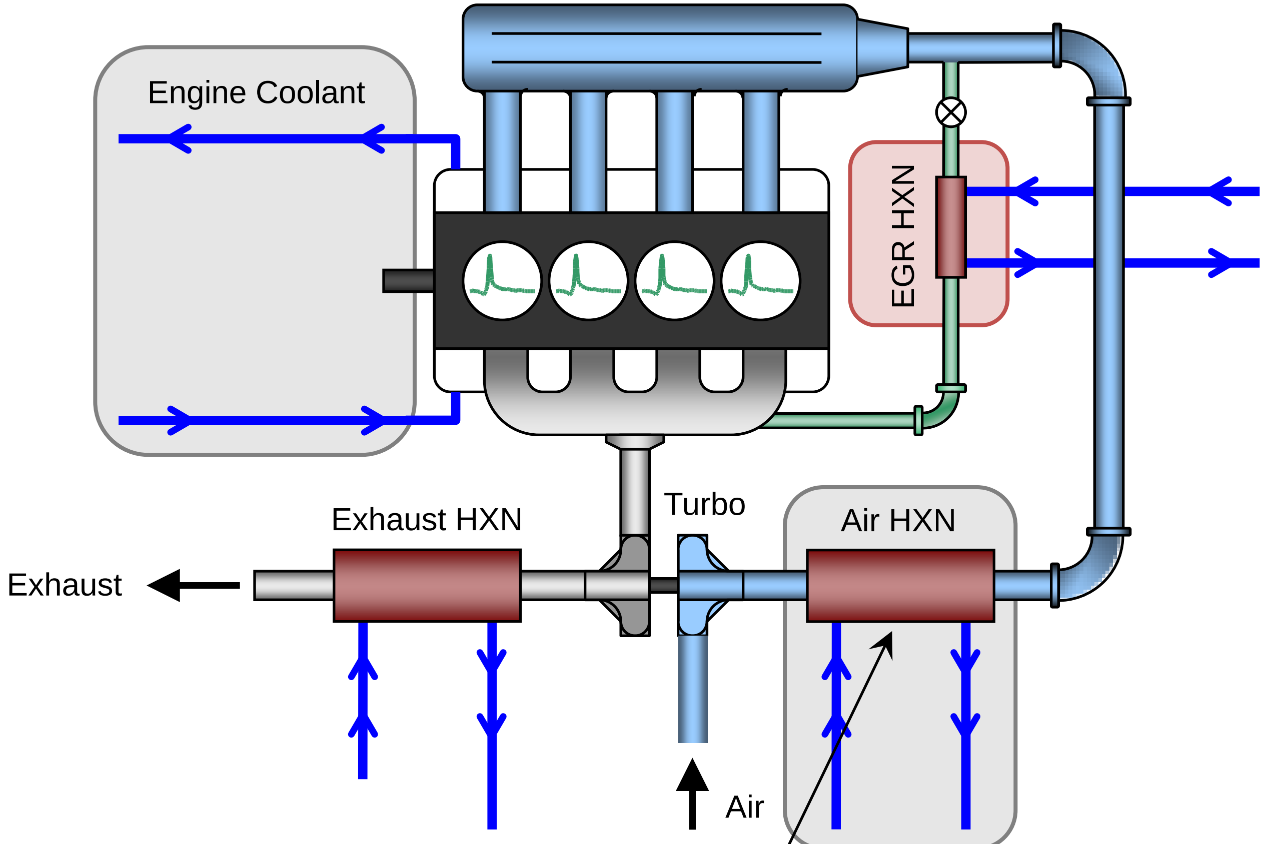


Waste heat recovery is possible with multiple streams on the engine



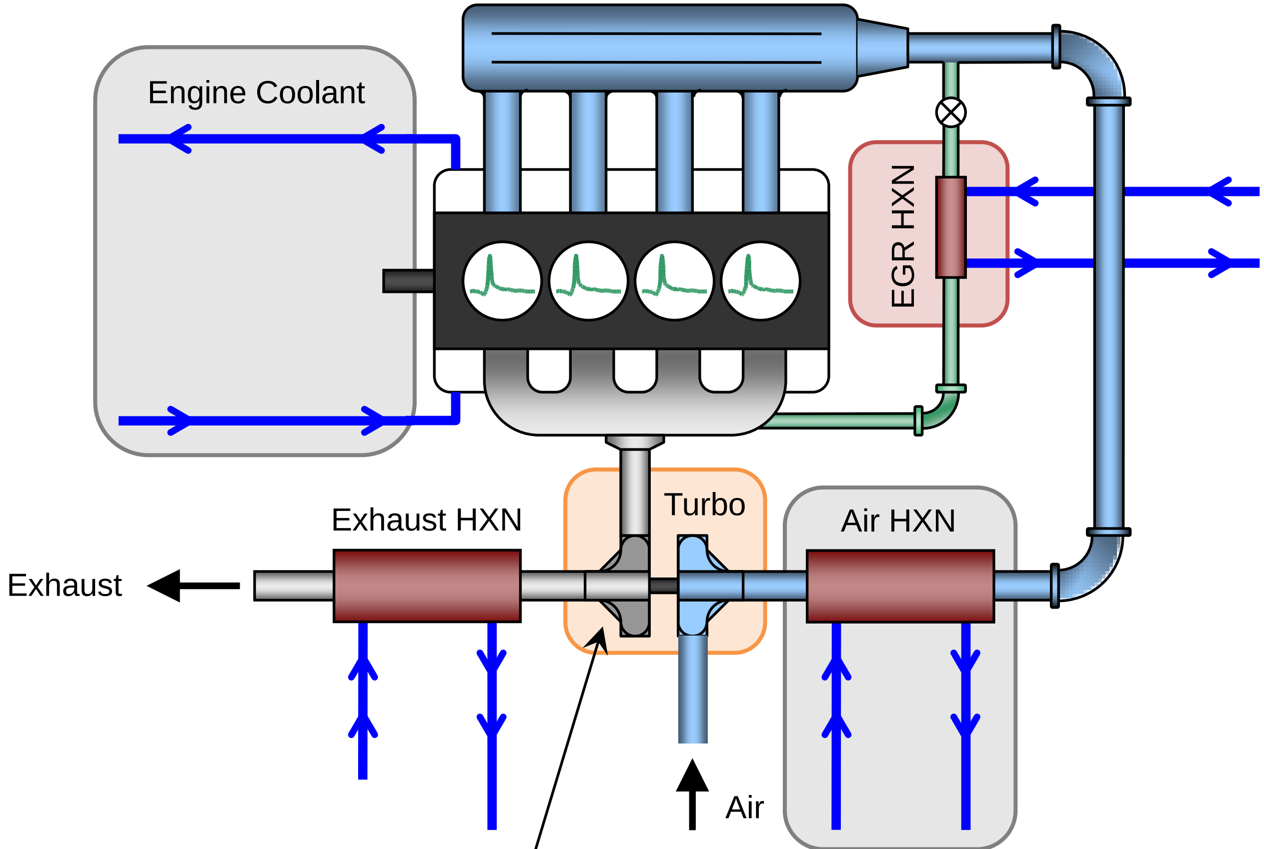
WHR using EGR energy at road-load conditions can increase vehicle efficiency while reducing heat rejection to the engine coolant – addressed through modeling in the present work

Waste heat recovery is possible with multiple streams on the engine



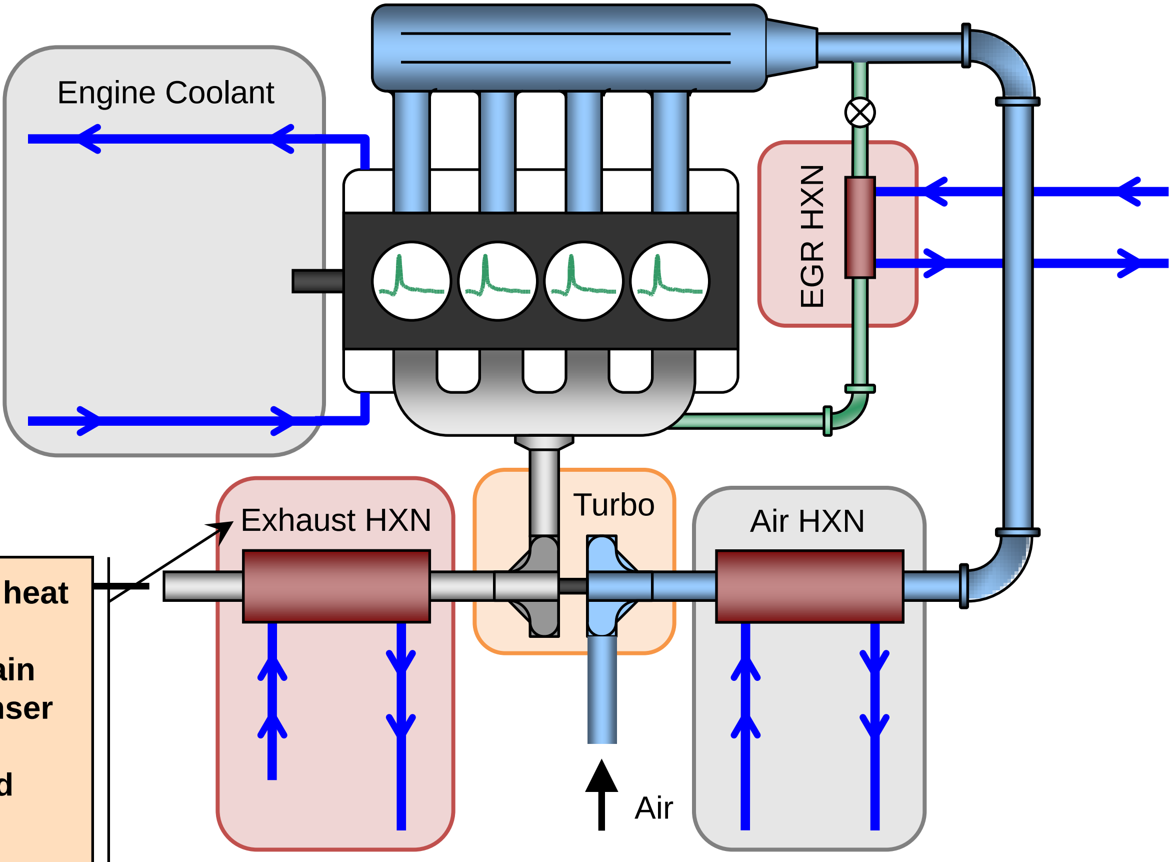
Intercooling does not offer much potential WHR energy input, but may be useful to consider as part of an overall heat rejection optimization

Waste heat recovery is possible with multiple streams on the engine



Turbo-compounding has been studied via modeling in conjunction with exhaust and EGR heat recovery – addressed through modeling in the present work

Waste heat recovery is possible with multiple streams on the engine



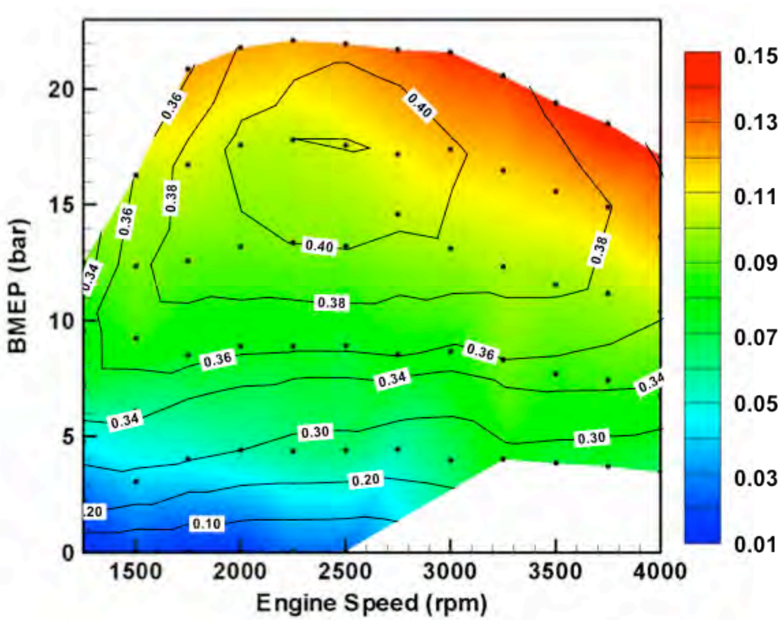
Recovery of waste exhaust heat can provide a substantial increase in overall powertrain efficiency, provided condenser heat rejection can be accommodated – addressed through modeling and experiments in the present work

A second-law analysis shows the potential of WHR

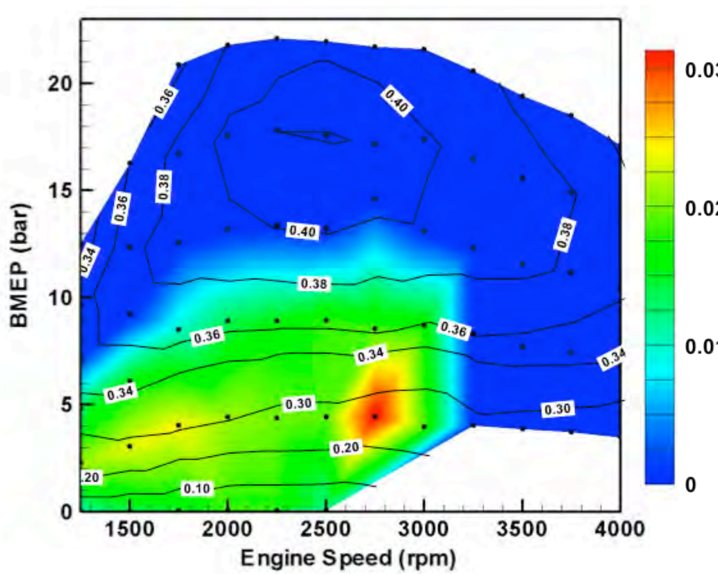
- **Exhaust availability is low over much of drive cycle operating range, but is high near the engine's peak efficiency point**
- **EGR availability is moderate over the drive cycle range, but cuts out at high loads**
- **This analysis guided the experimental and modeling efforts to maximize the system benefit for the intended purpose**

Working Definition: ***Availability*** *(a.k.a. exergy) is a measure of a system's potential to do useful work due to physical (P, T, etc.) and chemical differences between the system and the ambient environment.*

Exhaust availability



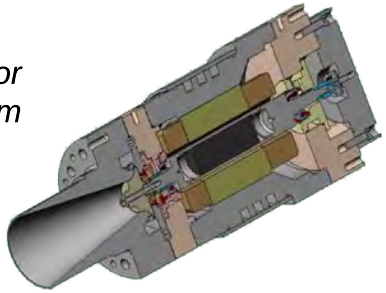
EGR availability

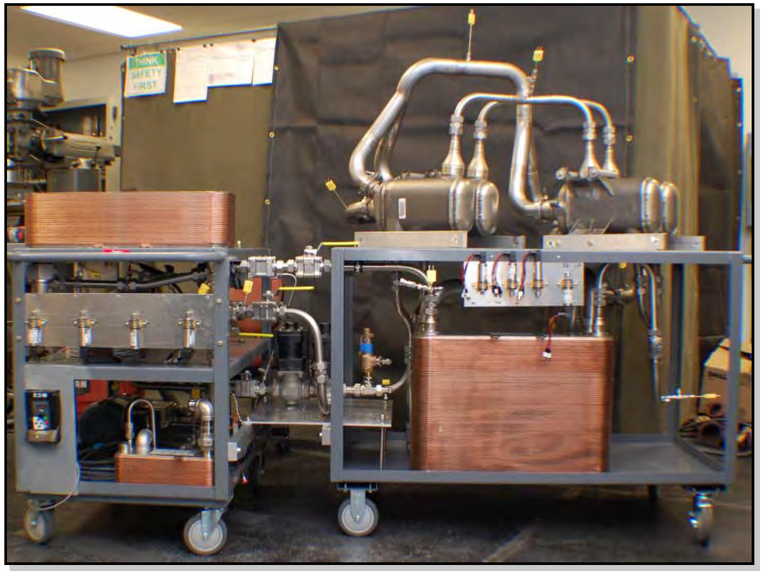


Light duty waste heat recovery has been demonstrated using an organic Rankine cycle

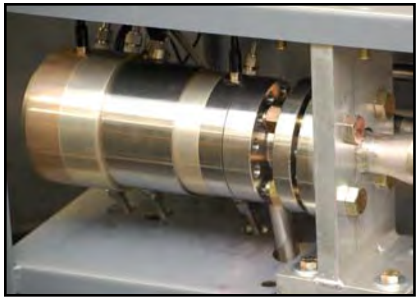
- **Recuperated Rankine cycle**
  - Designed to increase engine's peak efficiency (2250 rpm, 18 bar BMEP)
  - Heat input from engine exhaust (no EGR flow at selected engine condition)
  - R245fa working fluid
- **Not designed for underhood packaging**
  - Industrial heat exchangers
  - Laid out for plumbing access
- **Integrated turbine/generator expander designed by Barber Nichols**
  - Direct generation of electricity from WHR system

Turbine/generator system





ORC before installation on the engine.



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ORC performance for peak BTE condition (2250 rpm, 18 bar BMEP)

ORC Performance

- **Turbine inlet pressure: 310 psig**
- **Condenser pressure: 8 psig**
- **Cycle efficiency: 13%**
- **Cycle power:**
  - » Gross generator power: 4.3 kWe
  - » Pump power: 0.3 kWe
  - » Net power from cycle: 4.0 kWe

Engine-ORC System Performance

- **Engine performance:**
  - » Engine power: 66 kW
  - » Fuel rate: 12.97 kg/hr
  - » Engine-out efficiency: 42.5%
- **Combined cycle performance:**
  - » Total power: 70 kW
  - » Combined efficiency: 45.0%

Run	A	B	C	D	Average
Engine power [kW]	66.1	66.0	65.9	66.1	66.0
ORC power [kW]	3.82	3.90	4.03	3.96	3.93
Fuel flow [kg/hr]	12.96	12.97	12.96	12.99	12.97
Engine efficiency [%]	42.6	42.5	42.4	42.4	42.5
Combined efficiency [%]	45.0	45.0	45.0	45.0	45.0

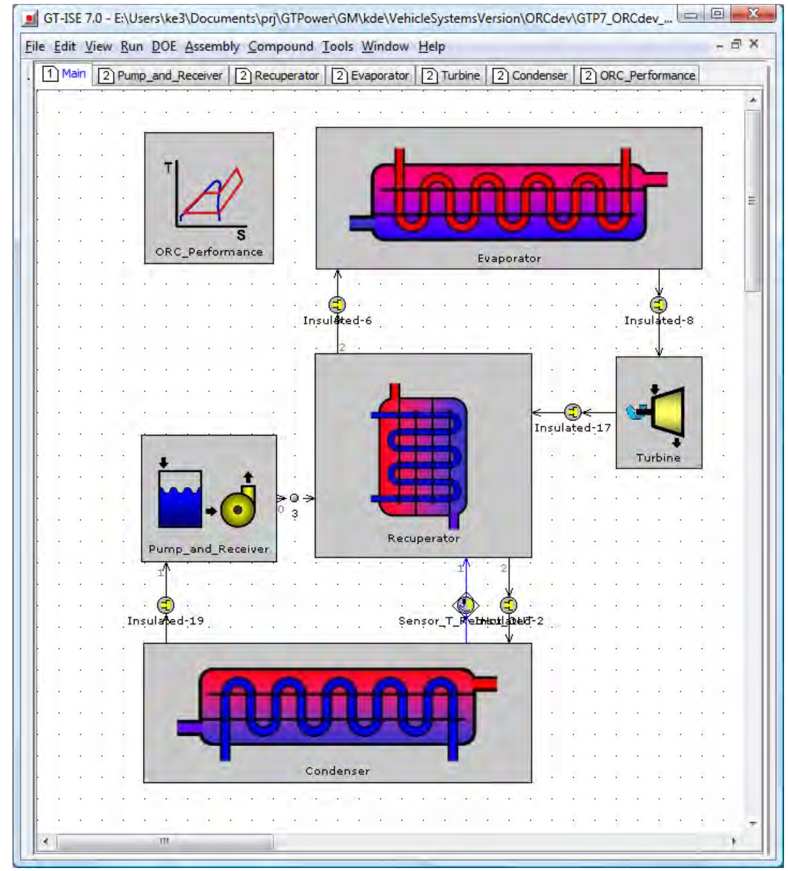
Experimental system not used for road-load operation

- **Experimental setup not well suited for road-load operation due to oversized components**
  - » Expander turbine design is inefficient for low thermal input of road-load conditions
  - » Component limitations required excessive working fluid loading; system cannot respond to light load heat input with reasonable timescales
- **Modeling has been used to examine road-load and transient operation**
  - » Results indicate that optimally sized components provide good road-load and transient performance

The peak efficiency point was examined experimentally in order to address a key DOE objective of bounding maximum engine-system efficiency

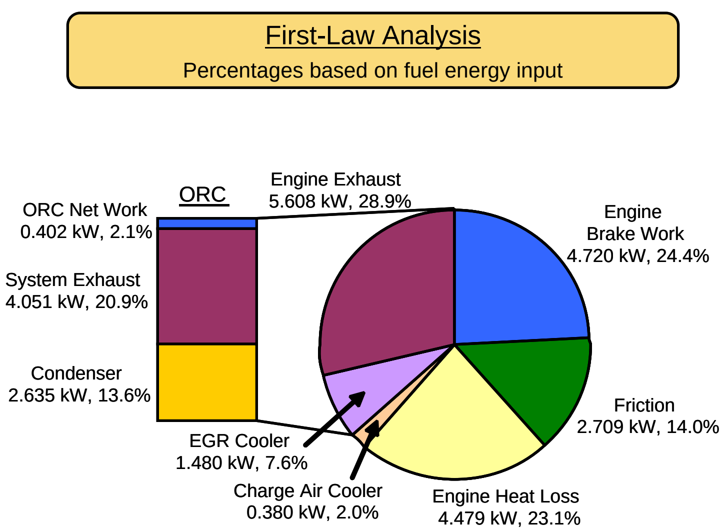
WHR modeling was used to examine a broader range of operation

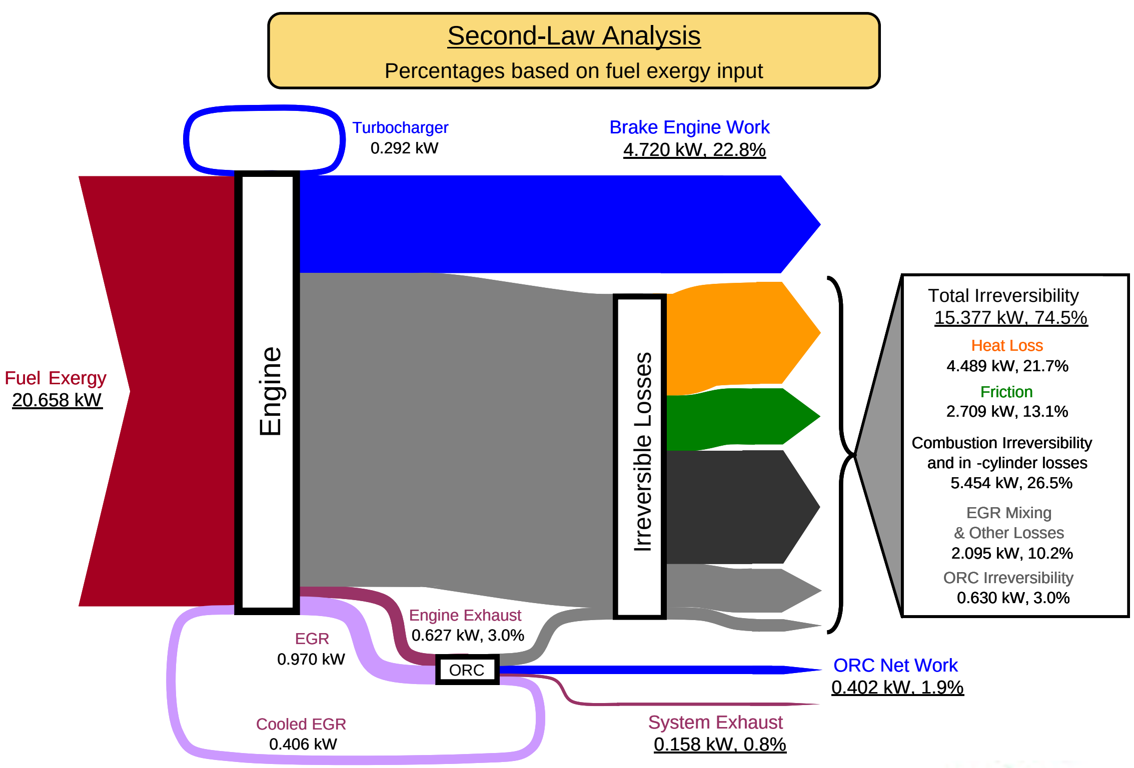
- **Model created in GT-SUITE V7.0**
  - » Enables two-phase fluid properties
  - » WHR system coupled to GM 1.9-L engine model
- **Heat recovery from exhaust and EGR cooler**
  - » High availability flows across engine map
- **R245fa working fluid**
- **Primary objectives:**
  - » Explore effects of component efficiencies on system performance
  - » Investigate potential for WHR over typical road loads
  - » Evaluate transient behavior of WHR system over standard driving cycles



Part-load ORC system performance simulation (1500 rpm, 2 bar BMEP)

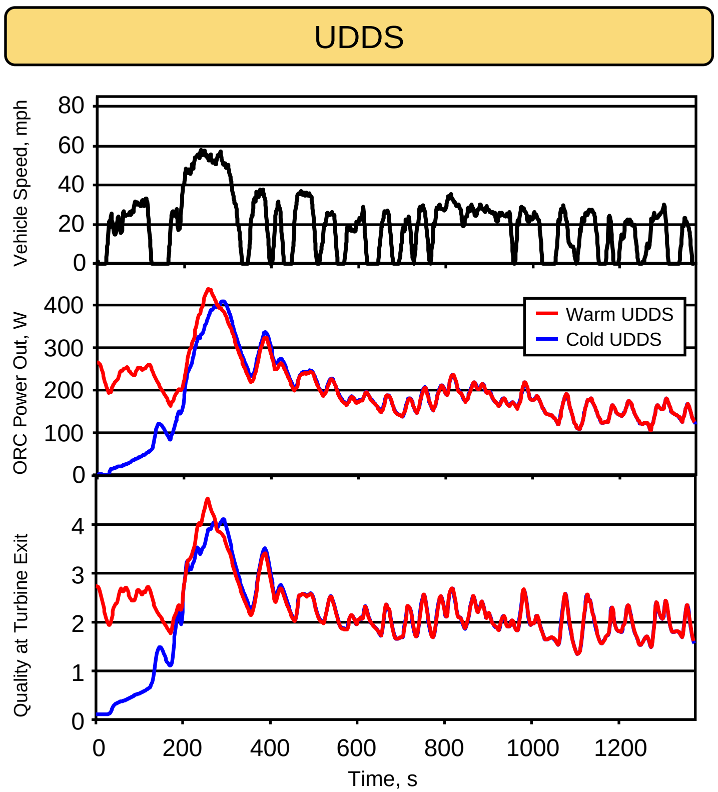
- **First-law efficiency of ORC = 13.5% with 400 W of net power output recovered**
- **EGR may need additional cooling (140 °C leaving evaporator)**
- **Exhaust temperature reduced from 200 °C leaving turbocharger to 110 °C leaving evaporator**
- ***Brake thermal efficiency increased by 2.1% points***

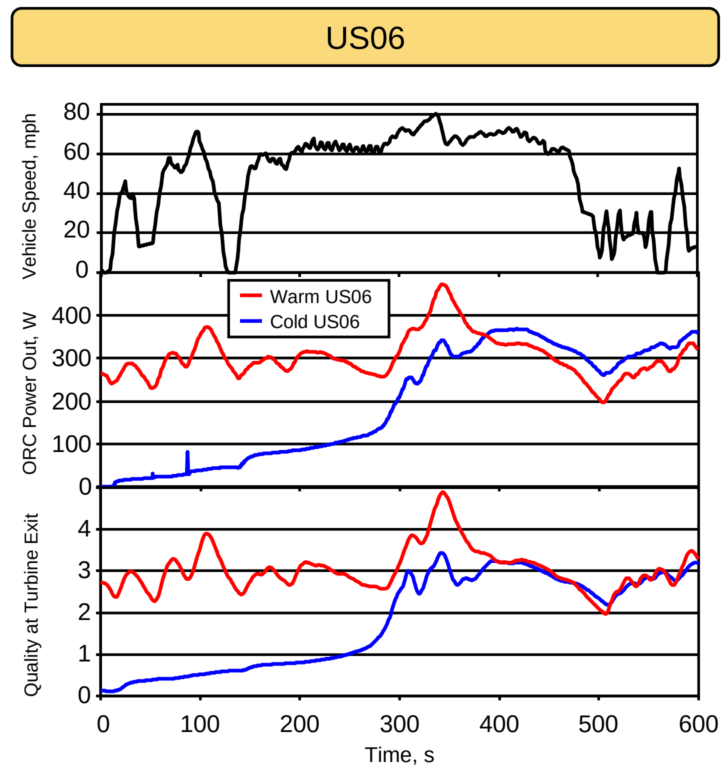




Simulated engine/ORC transient performance

- **ORC model paired with map-based engine model and mid-sized passenger vehicle model**
- **Performance evaluated over 'cold' and 'warm' UDDS and US06 driving schedules**
  - » 'Warm' – ORC allowed to warm-up for 1000 s with engine at road-load conditions
  - » 'Cold' – ORC refrigerant uniformly at 25 °C at beginning of test
- **ORC time-averaged power output: 200 W for warm UDDS, 300 W for warm US06**
  - » This is a significant fraction of the alternator load on a vehicle
- **System exhaust temperature: 145 °C for warm UDDS, 190 °C for warm US06**





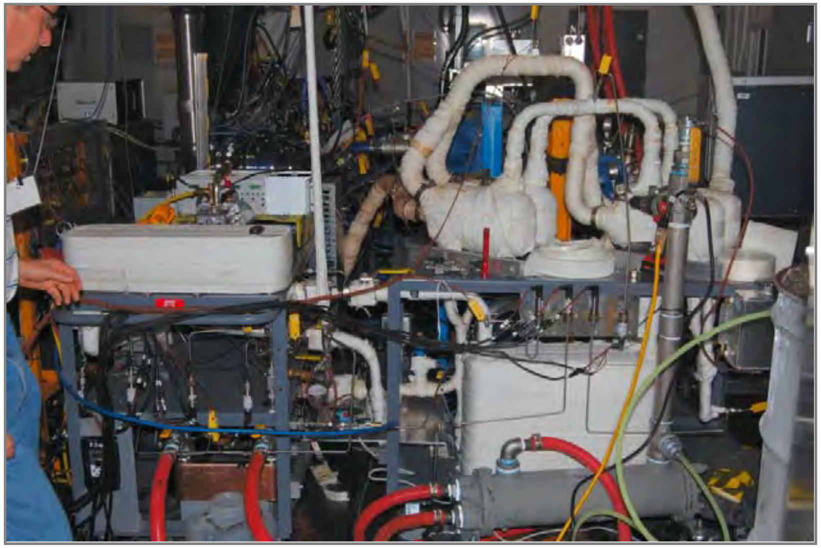
Collaborations and Interactions

- **Industry Tech Teams and DOE Working Groups**
  - » Regular status updates to ACEC Tech Team on status of Vehicle Technologies milestones
  - » Expander/generator construction and input on ORC design and implementation
- **BorgWarner**
  - » Technical input for improving turbocharging efficiency
  - » Guidance on optimizing EGR systems
- **Gamma Technologies**
  - » Many one-on-one interactions for added GT-Power features to enable this level of thermodynamic analysis and bottoming cycle modeling
- **General Motors**
  - » Support of GM 1.9-L engines and open controllers
- **Other ORNL-DOE Activities**
  - » Fuels, emissions, and vehicle systems modeling activities

Next Steps FY 2011

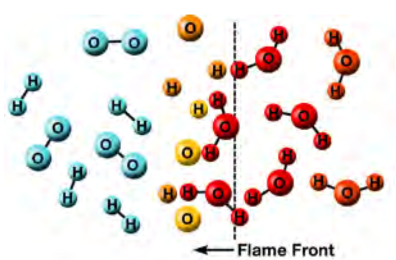
- **Perform 2nd law thermodynamic analysis of state-of-the-art engines to support ACEC Tech Team goal setting and roadmaps**
- **Perform detailed analysis of advanced combustion approaches (RCCI, PPC) to quantify drive-cycle benefits of full- and mixed-mode implementation**
- **Simulation study of potential of turbo-compounding & supercharging for efficiency benefit and potential for enabling advanced efficient combustion modes**

ORC installed on GM 1.9-L engine in FEERC Cell 2. Size would be dramatically reduced with purpose designed heat exchangers.



Future FY 2012

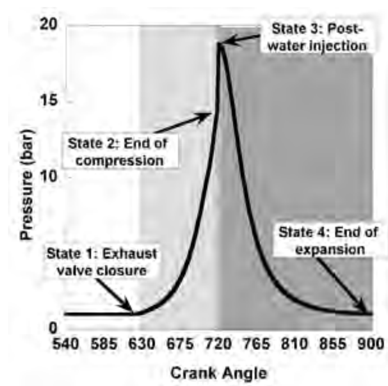
- **Continue to serve in role of demonstrating Vehicle Technologies efficiency and emissions milestones**
  - » Assess state-of-the-art engines and combustion approaches using second-law analysis to quantify efficiency improvement potential of advanced technologies
  - » Support ACEC Tech Team and DOE VT goal-setting for future research programs
  - » Evaluate advanced combustion concepts for their integration into the full engine system (leveraged with other ORNL projects)
- **Leverage with fundamental expertise and on-going activities to better understand systems integration issues and fuel economy potential**



Fundamental approaches to combustion

$$\left.\frac{dS}{dt}\right|_{CV} = \underbrace{\sum_{in} \dot{m}s - \sum_{out} \dot{m}s}_{\text{Path Independent}} + \underbrace{\int \frac{\partial \dot{Q}}{T_w} + \frac{\dot{I}}{T_o}}_{\text{Path Dependent}}$$

Characterize state-of-the-art and define efficiency potential of next generation of engines



Advance concepts for maximum useful fuel utilization

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Summary

Met FY 2010 Joule Milestones. On track for FY 2011 Milestone.

- **Relevance**
  - » Demonstration of Vehicle Technologies fuel efficiency milestones
- **Approach**
  - » Comprehensive approach including Modeling + Experiments + Analysis + Collaboration
- **Technical Accomplishments**
  - » Demonstrated 45% combined peak BTE (Q4 2010 Joule milestone)
  - » Modeled and demonstrated potential for efficiency improvements at road-load points
  - » Drive-cycle modeling suggests a potential fuel economy benefit of 2-5% using WHR
  - » Modeling shows an additional 1% BTE point improvement possible with turbo-compounding+ORC
- **Collaborations**
  - » Regular communication to DOE, industry, and others through technical meetings and one-on-one interactions
  - » Barber-Nichols, Gamma Technologies, BorgWarner
  - » General Motors on support of GM 1.9-L diesel engines
- **Future**
  - » **Continue to serve role of demonstrating Vehicle Technologies efficiency and emissions milestones**
  - » Support Vehicle Technologies and ACEC Tech Team in characterization of current state-of-the-art and defining future efficiency/emissions targets
  - » Develop and assess advanced efficiency technologies on multi-cylinder engines

Tom Briggs • 865-946-1528 • briggste@ornl.gov