Development of an ORC system to improve HD truck fuel efficiency

DEER 2011 CONFERENCE

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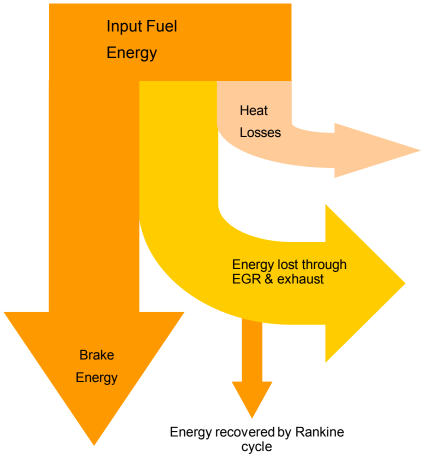
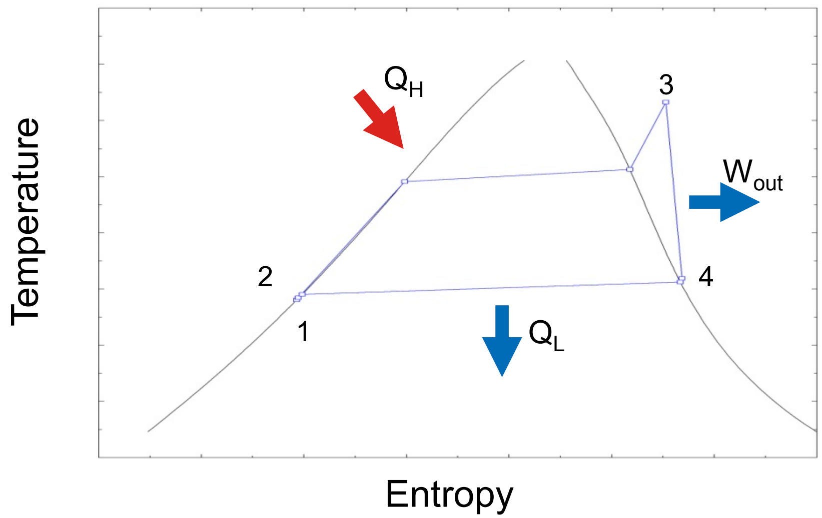
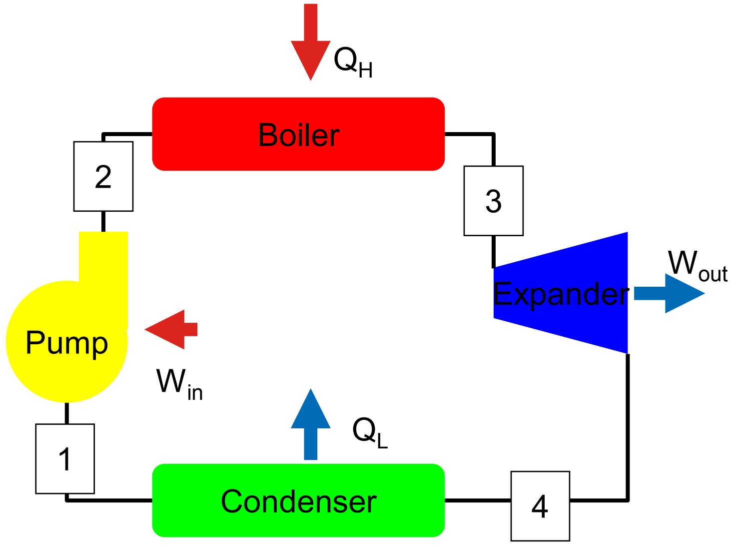


Contents

Organic Rankine Cycle Background

- The Organic Rankine Cycle (ORC) is one potential technology used to generate power from low temperature heat sources
  - Bottoming cycle from combustion engines
- ORC's are particularly suited to class 8 trucks due to:
  - High fuel consumption enabling return on investment of ORC hardware
  - Consistent periods of high duty cycle
  - Significant use of EGR for control of criteria emissions
  - Challenge rejecting waste heat through vehicle cooling pack





Organic Rankine Cycle
Objectives

- Key objectives for a successful ORC system for HD truck are:
  - Good control of emissions critical characteristics
  - Environmental responsibility and operational safety
  - Improve overall fuel economy by maximizing energy recovery from the ORC in key areas of the engine operating map.
  - Control of heat rejection required through the condenser to avoid increased aerodynamic drag or powertrain performance degradation

Organic Rankine Cycle
Project Outline

Concept Investigation	Design and Simulation	Procure and build	Testing & controls development

Concept Investigation

- Objective:
  - Establish concept ORC system
- Steady state simulation
- High level assessment of fuel economy benefits

Design and Simulation

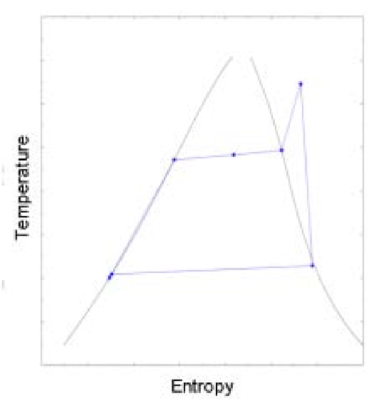
- Objective:
  - Detailed design & simulation of ORC
- Transient simulation
- Control strategy development
- Detailed design

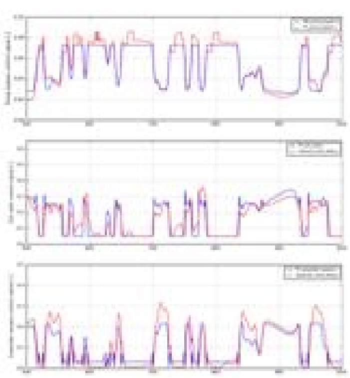
Procure and build

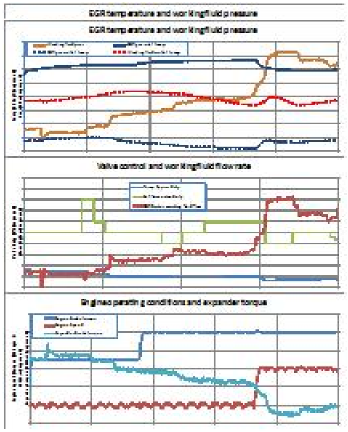
- Objective:
  - Procure & build system into test cell with engine
- Procure, build, instrument, install
- Implement controls into controller

Testing & controls development

- Objective:
  - Development of system and controls system
- Performance testing
- Control strategy development
- Calibration & testing

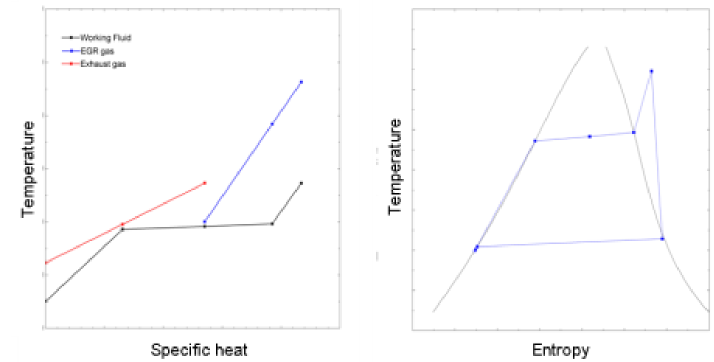




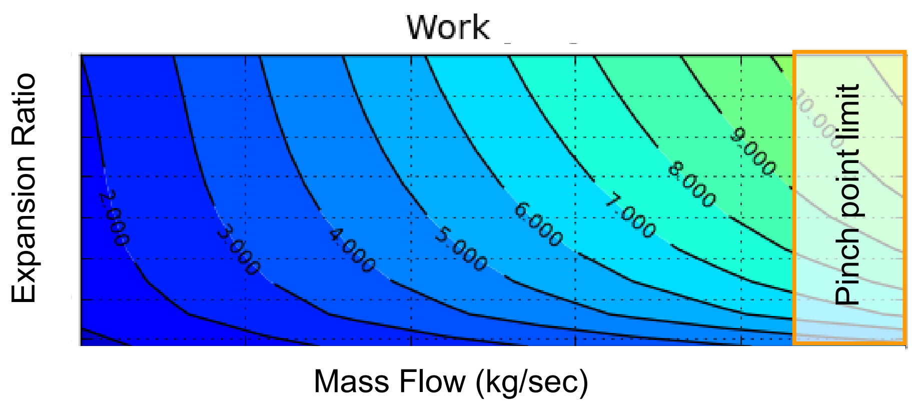


Concept Investigation
ORC Steady State Simulation

- Initial component sizing and efficiency investigations can be performed using basic thermodynamic equations with a solver such as EES®
- Ricardo approach includes simple models of heat exchangers to investigate pinch points within the 2 phase regime
  - Simulation of 1st and 2nd law of thermodynamics

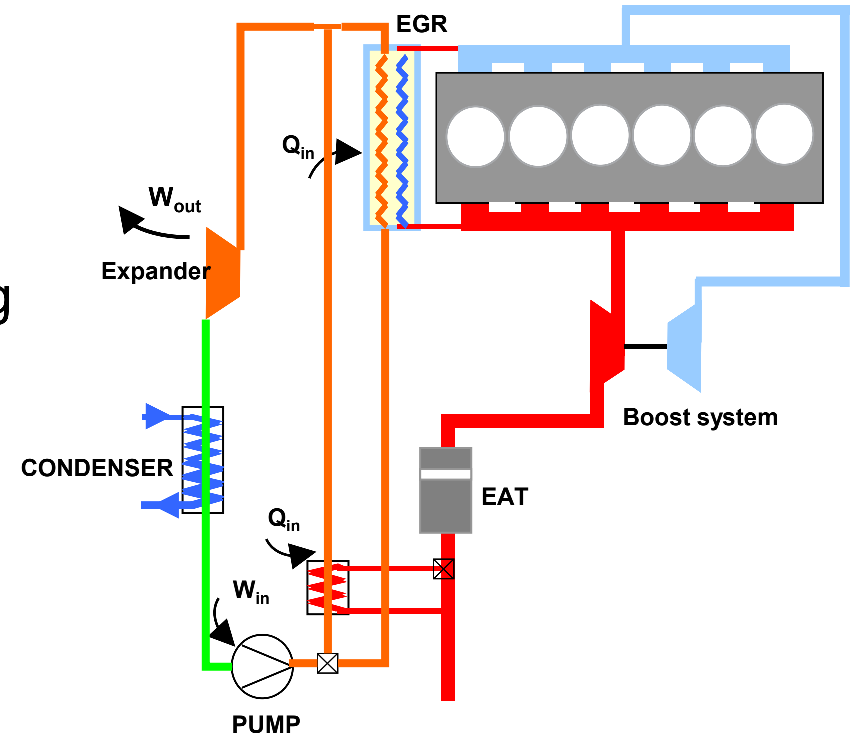


- Investigation of multiple parameters performed rapidly using neural net
  - Working fluid
  - System pressures and temps
  - Flow rate
  - Operating point
  - Component size
  - System layout



Concept Investigation
Selected Concept

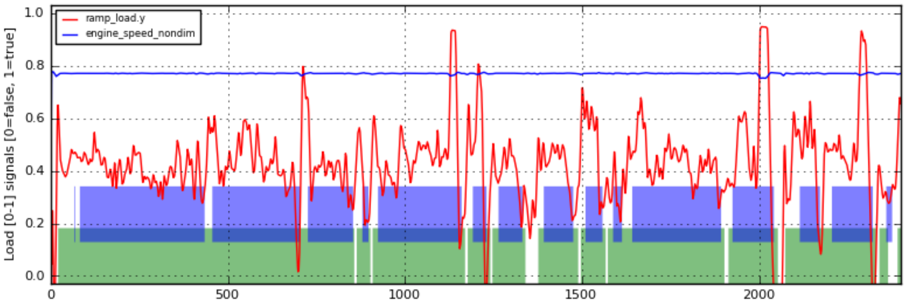
- Heat input from EGR and exhaust post exhaust after-treatment system (EATS)
- Heat sources in parallel
- Water / ethanol or pure ethanol working fluid
- Positive displacement expander with mechanical power delivery to drivetrain
- Indirect condenser (LT cooling circuit)

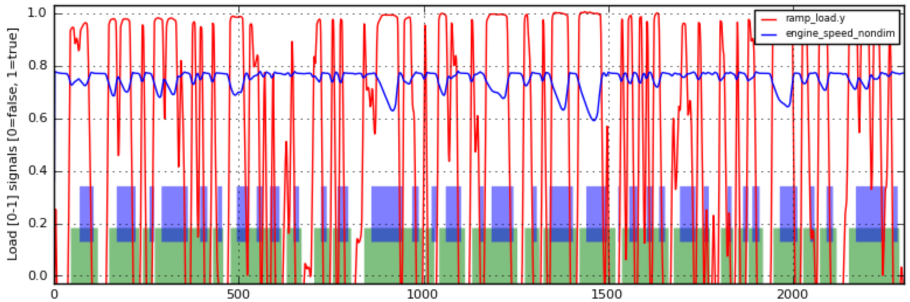


Heat Sources	Working Fluid	Layout	Expander	Cold Sink
EGR	~~Water~~	~~Option 1~~	Piston	LT circuit
~~Exh pre TC~~	~~Acetone~~	~~Option 3~~	~~Scroll~~	~~Air~~
~~Exh pre EATS~~	~~Isobutane~~	~~Option 4~~	~~Turbine~~	
Exh post EATS	~~R152a~~	~~Option 5~~		
~~Charge air cooler~~	~~Ethanol~~	Option 6		
~~Coolant~~	~~Water ammonia~~			
	~~R245fa~~			
	Water Ethanol			

Design and Simulation
Detailed Simulation Overview

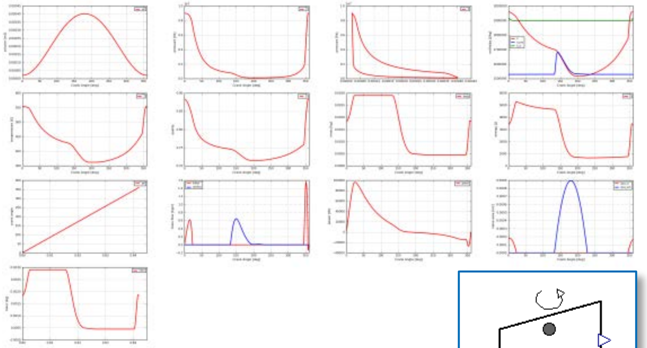
- Detailed simulation was performed to provide:
  - Fuel economy prediction during transient conditions
  - Establish control strategy for ORC system
- Ricardo wrote the ORC model using libraries in OpenModelica
  - Able to edit and run in Dymola®
  - Simulation faster than realtime enabled multiple iterations
- Simulation run over multiple drive cycles
  - Control strategy development and virtual calibration of control system
  - Assess vehicle implications (heat rejection, EGR temperature control)

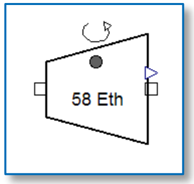


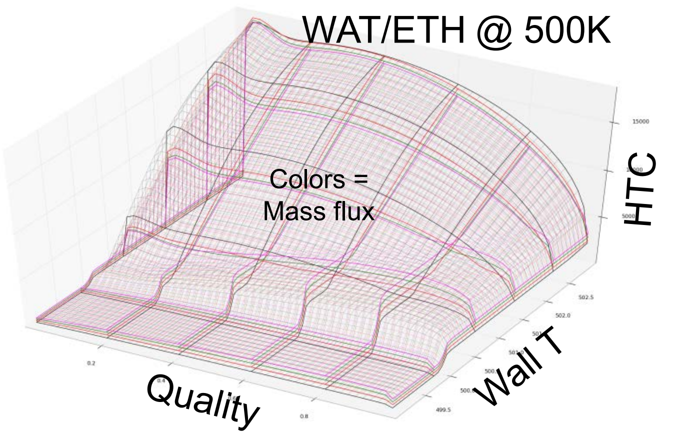


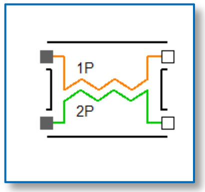
Design and Simulation
Selected Transient Model Details

- Detailed physics based model that accounts for affects such as:
  - Expander (piston type) modeled using crank angle resolved physics based model
    - For long duration transients a steady map based model constructed automatically by training a neural net to reproduce physics model results
  - Heat exchanger models including 2-phase flow and heat transfer effects
    - Nucleate boiling, convective boiling and condensation correlations
    - Validated against test data for complex HX layouts



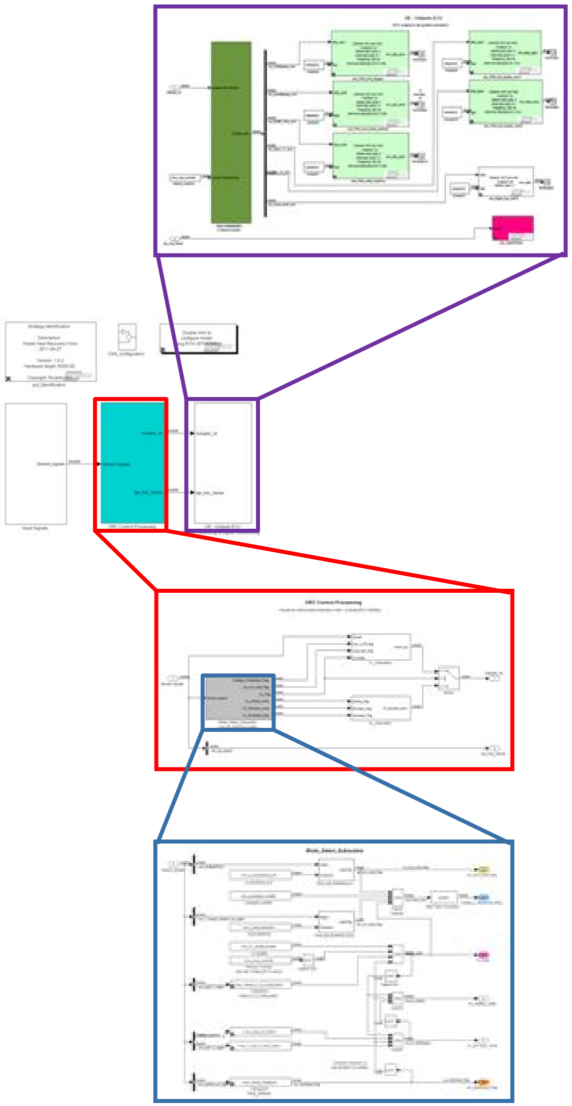




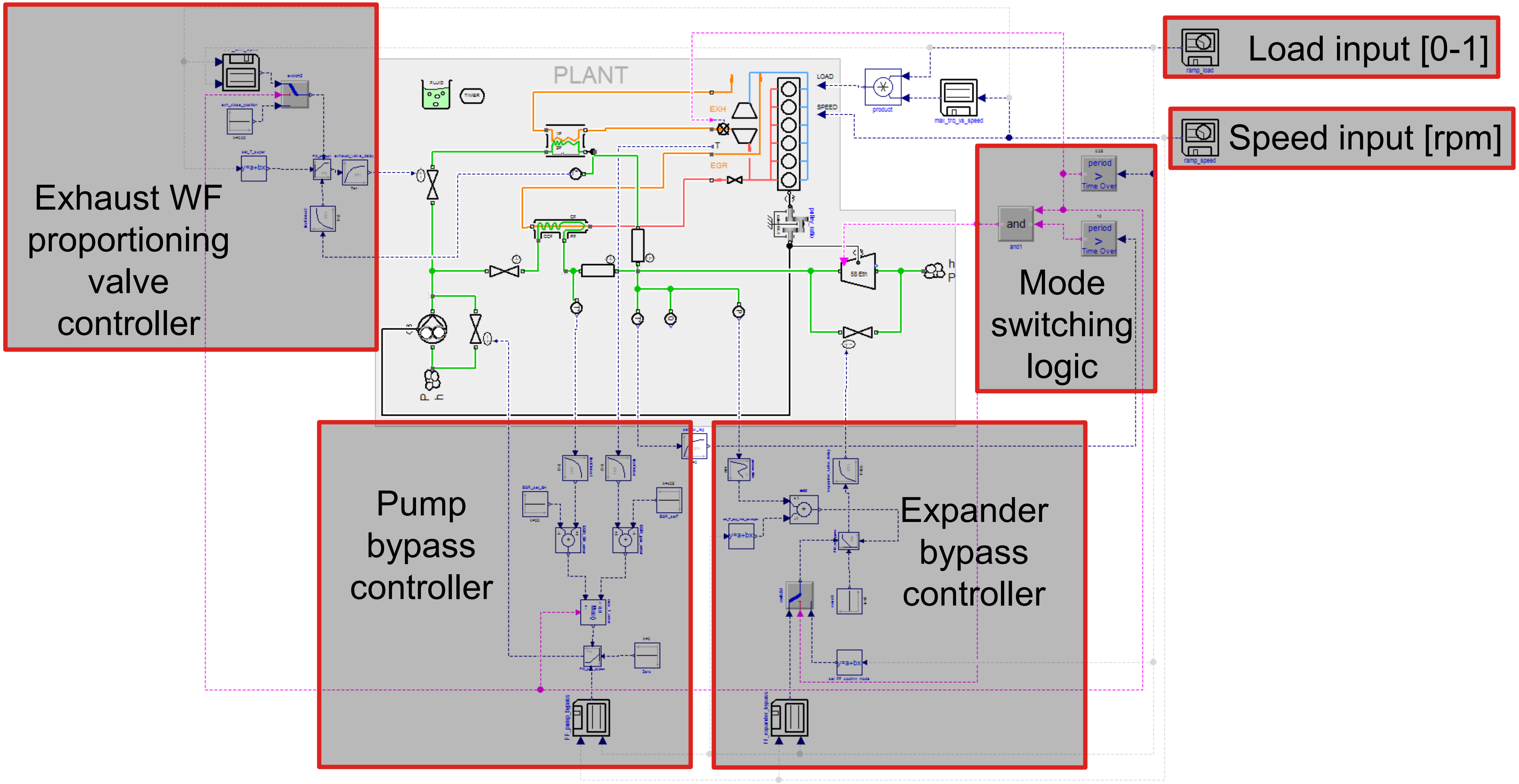


Design and Simulation
Transient Controls Approach

- Several control system approaches considered
  - Model based
    - Difficult to implement due to large number of variables affecting plant performance
  - Closed loop control
    - Unable to generate stable closed loop system
  - Feed-forward with closed loop correction
    - Selected approach
- Mode switching based on operating conditions
  - Warm-up / cool-down
  - EGR cooling only mode
  - Power generation mode

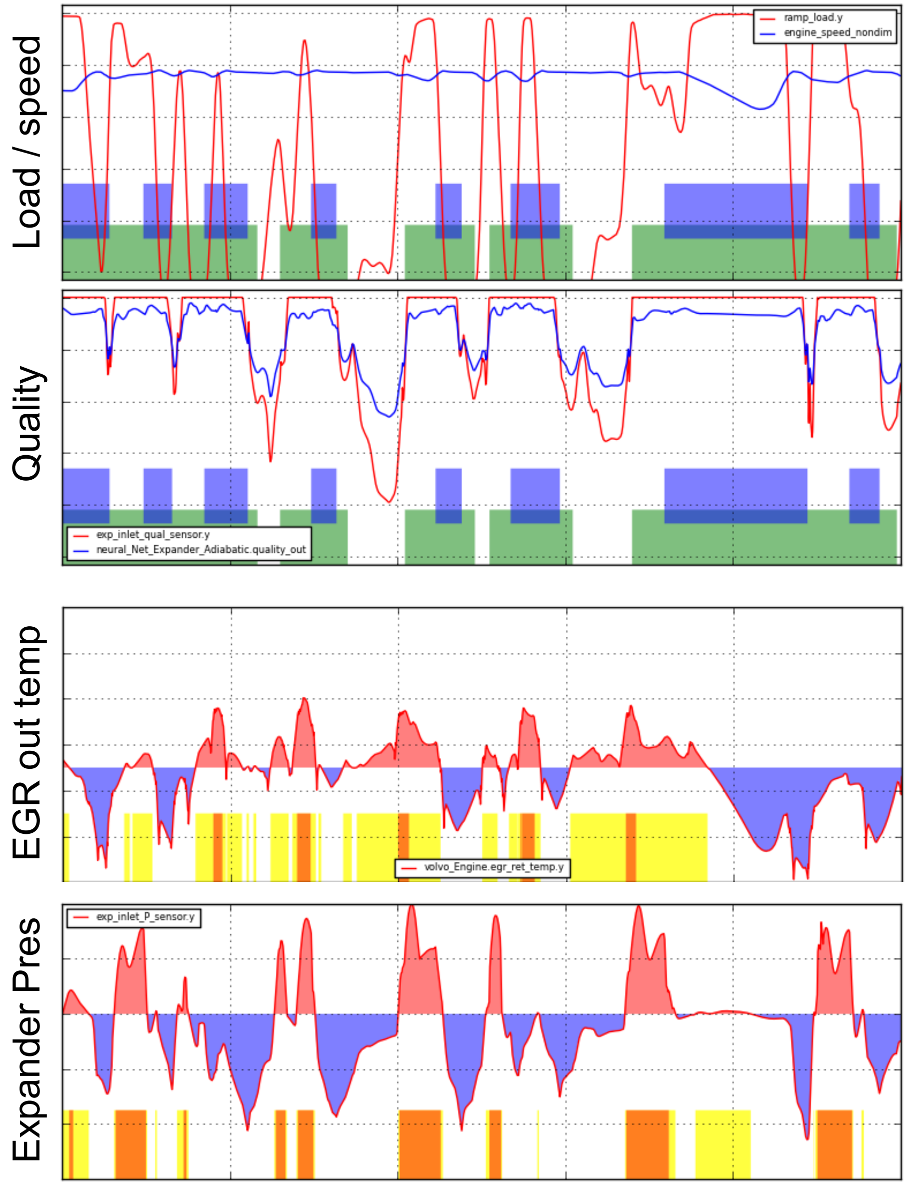


Design and Simulation
Plant Model and Control System



Design and Simulation
Transient Control System Performance

- Control performance assessed over highly transient cycles
- Control system switches between “Power Generation” and “EGR Cooling” mode when insufficient superheat is generated
- Control system maintains EGR gas temperature & system pressure within acceptable tolerance
- Initial calibration established using simulation environment

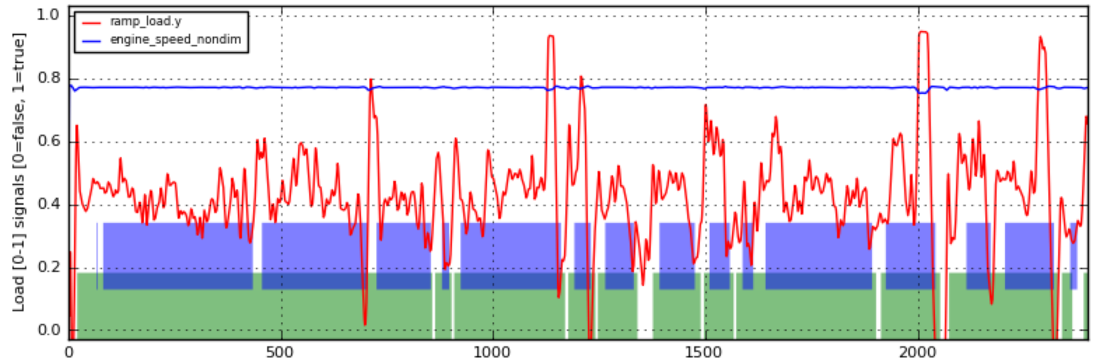


Power generation
Sufficient superheat

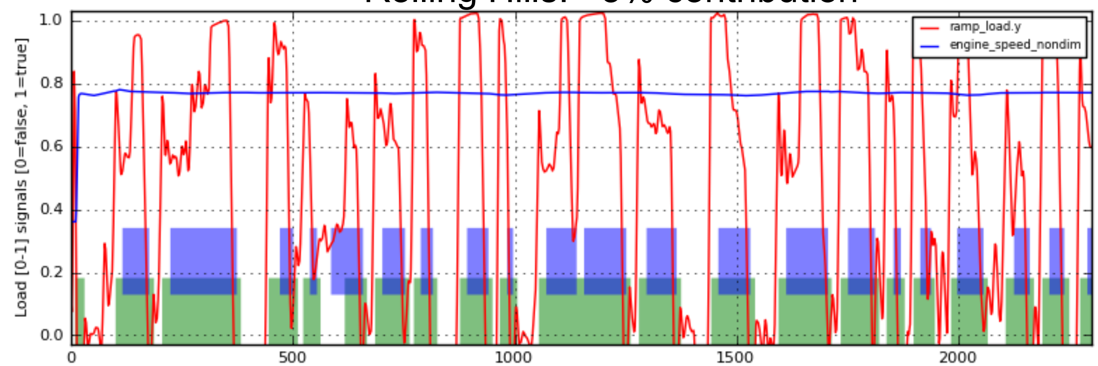
Design and Simulation
Transient Drive Cycle Results

- Net fuel economy benefit strongly dependent on drive cycle (>4% to <2.5%)
- Limiting factors for higher fuel economy benefit are:
  - Low heat input operation: Expander is bypassed resulting in drag torque
  - High heat input operation: Bypass boiler / expander
  - Pressure limitation of heat exchangers: Limits power at high load points (expander sized for cruise)

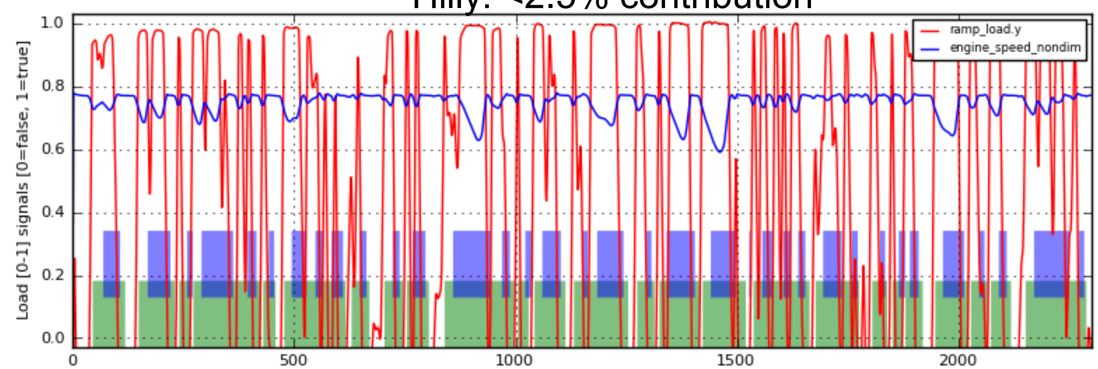
Flat: >4% contribution



Rolling Hills: <3% contribution



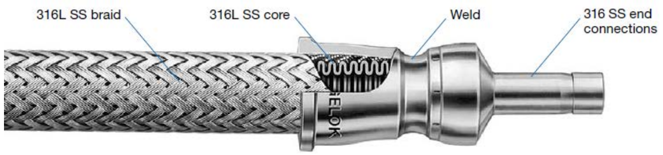
Hilly: <2.5% contribution



Engine torque duty
Engine speed duty
Power generation
Sufficient superheat

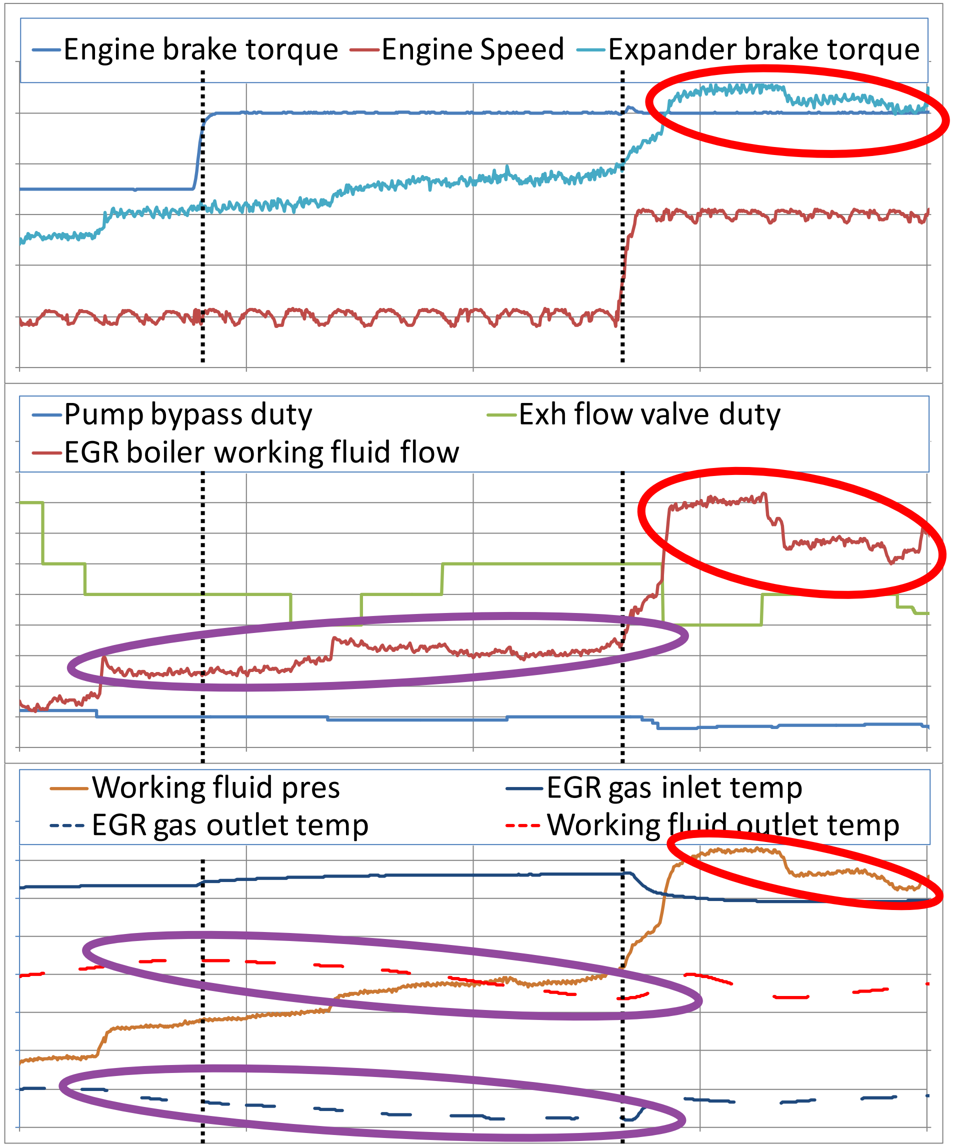
Procure and Build

- Prototype heat exchangers and expander (incl. pump & lube system)
- Control sensors from automotive production sources
- Industrial sources for all other components (valves, flexible pipes, sealing technology)
- Extensive instrumentation incorporated within design
  - Expander torque
  - Pressure
  - Temperature
  - Flow
- System installed & demonstrated in test cell with an engine including aftertreatment system

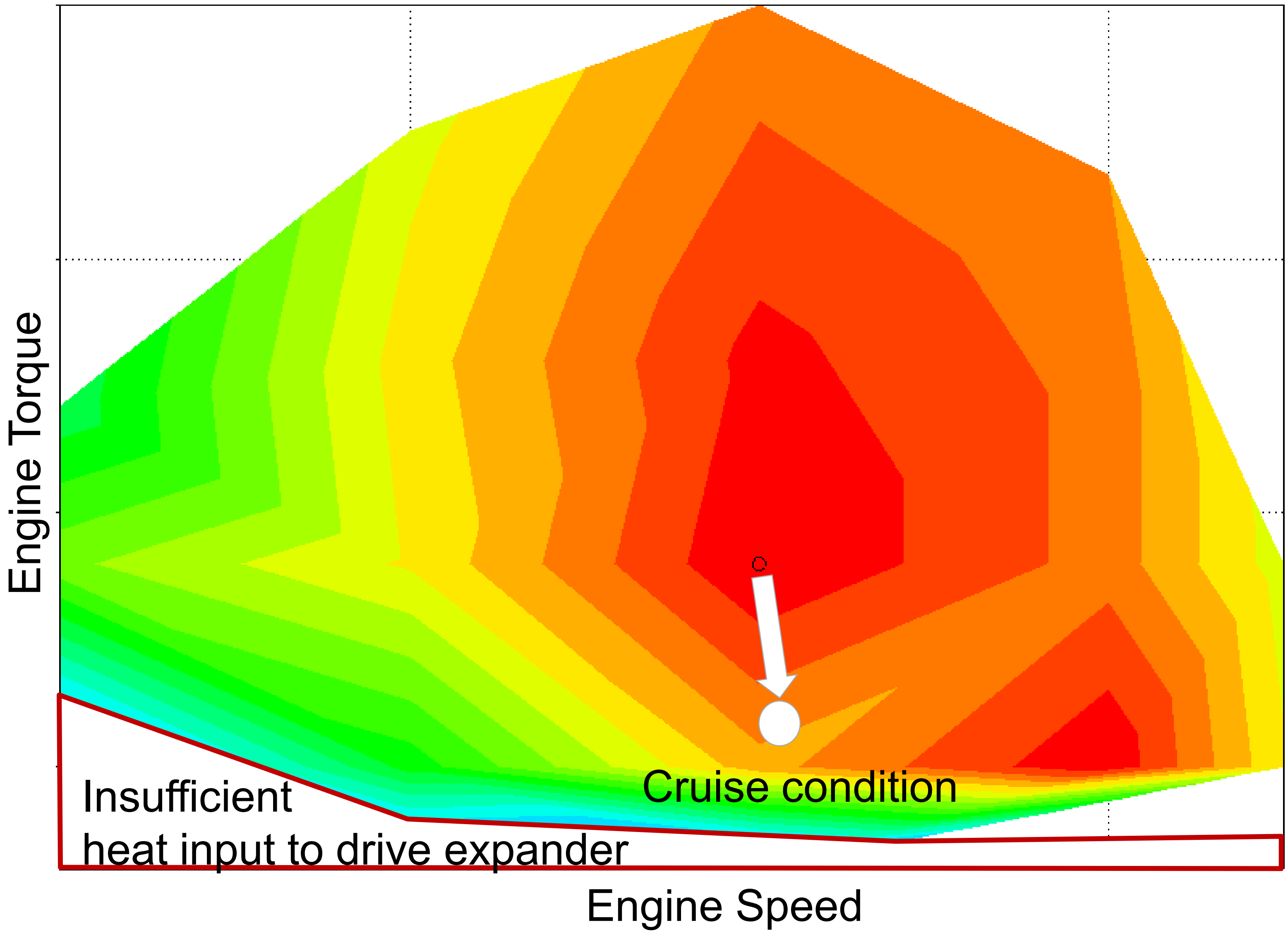


Testing & Controls Development
Changes in Speed and Load Test Results

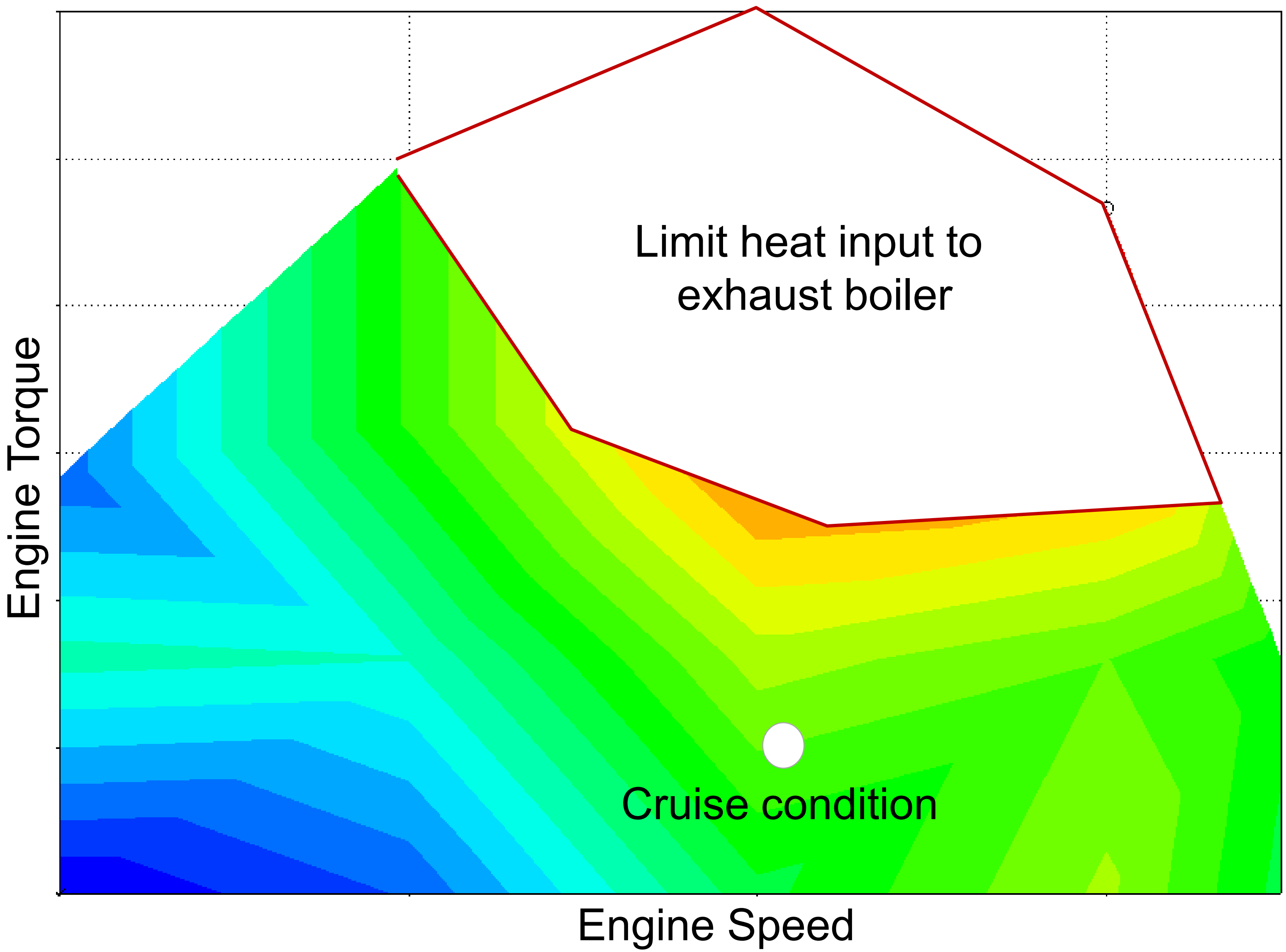
- Control of system is challenging
  - Thermal inertia
  - Flow restriction changes
  - Pump delivery with speed
  - Expander flow with speed, pressure and temperature
- Steady state for system is difficult to achieve
  - Variation in working fluid flow due to changing restriction
  - Thermal inertia of system



Testing & Controls Development
Fuel Economy Contribution from ORC System



Testing & Controls Development
Condenser Heat Rejection from ORC System



Current Project Status

- Completed:
  - Establish concept to achieve targets
  - Development of transient simulation and control strategy
  - Design, procure and build ORC system in test bed
  - Steady state manual operation of ORC system across speed / load range
- Activities underway
  - Controls development underway in test bed
  - Calibration of system under transient conditions
  - Comparison of test data to simulation results

Lessons Learnt

- Simulation
  - REFPROP® access and calculation too slow to enable transient simulation
    - Utilize map based fluid properties
- Controls
  - Long system time period (thermal inertia) creates challenging transient control
  - Gas outlet temperature is leading indicator of working fluid temperature
- Operation
  - Get out of the saturation dome as quickly as possible
  - Heat input management of exhaust stream is very effective control

Acknowledgements

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Considerations for Vehicle Application

- Applying ORC into a vehicle will require overcoming several other challenges:
  - Condenser heat rejection will be limited by the cooling pack
    - Current approach is to limit the heat input from the exhaust stream under high heat input conditions
- Drag during low heat input
  - Current system is mechanically linked to the crankshaft
    - Adds parasitic loss during periods with insufficient heat input due to expander drag
  - Addition of clutch would overcome issue
    - Cycle analysis required to show if investment is justified