Model Predictive Control of an Automotive Organic Rankine Cycle System

Xiaobing Liu, Adamu Yebi, Paul Anschel, John Shutty,
Bin Xu, Mark Hoffman, Simona Onori

ORC 2017
13 - 15 September
MILANO, Italy

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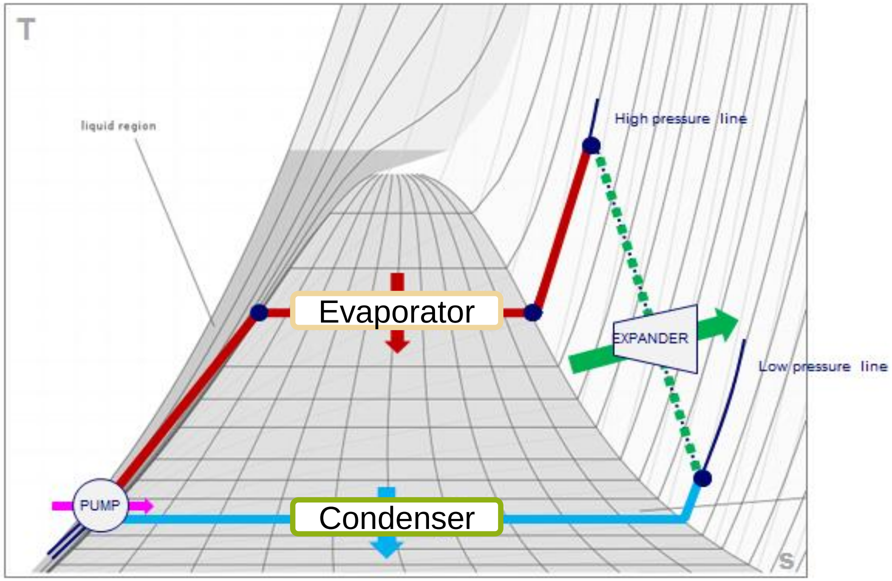
Presentation Outline

- System Description, Layout, and Test Rig Setup
- Control Development Challenges
- PID Based ORC Control
- Model Predictive Control (MPC)
- Summary

Introduction

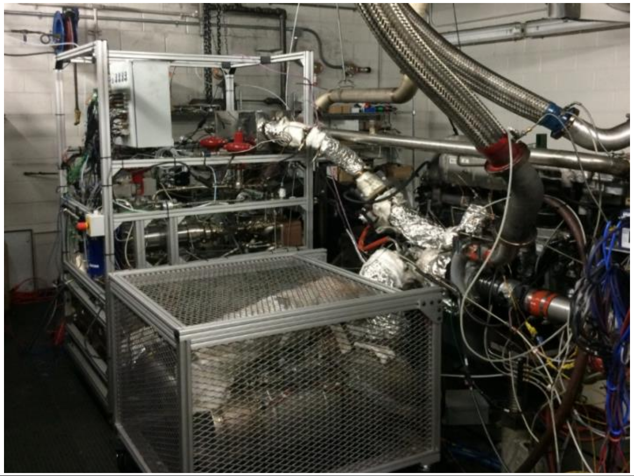
- Organic Rankine Cycle (ORC) is a promising waste heat recovery technology providing 3-5% fuel economy improvement for Heavy-Duty On-Highway trucks

- A typical ORC cycle

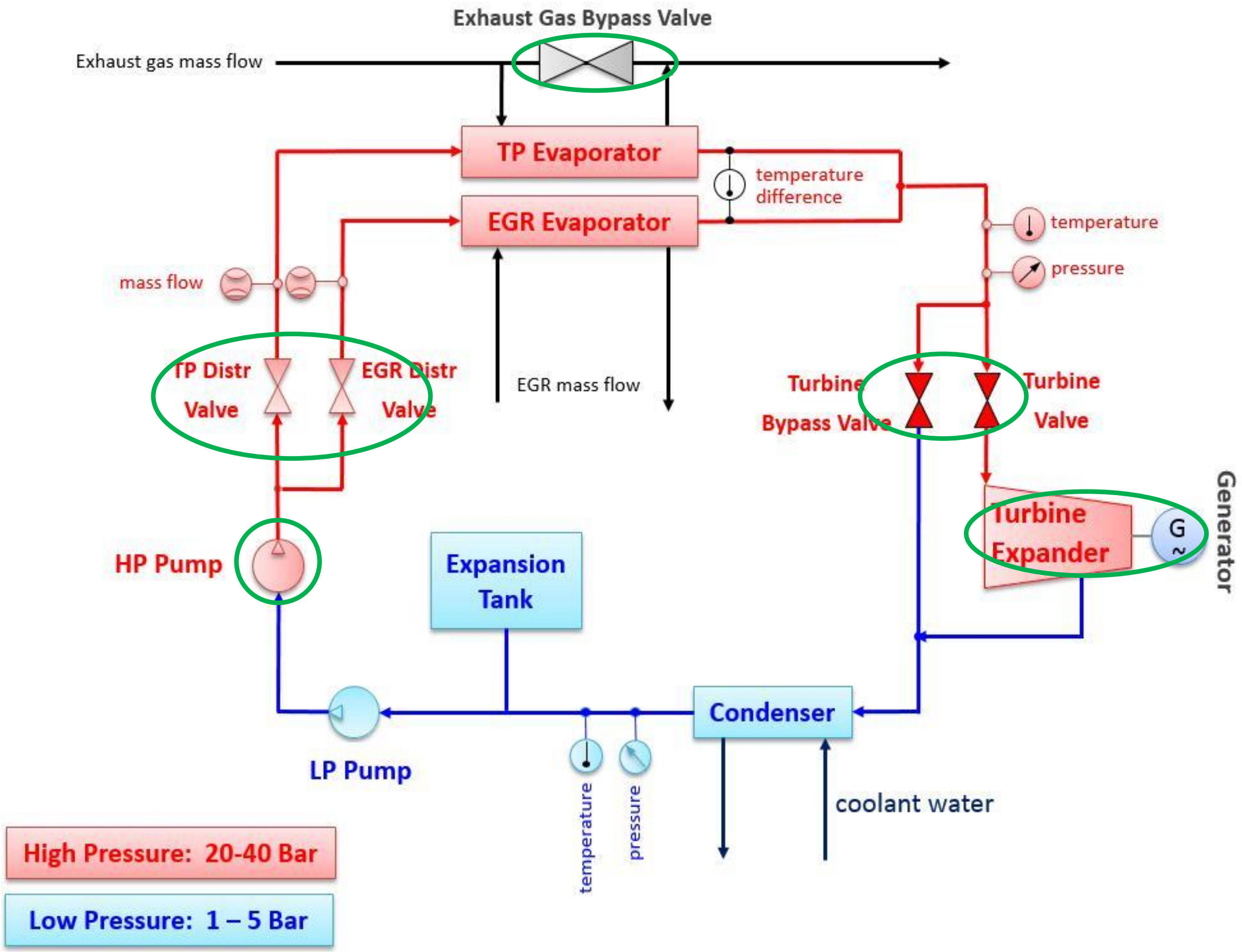


ORC Test System

- An ORC test rig was built
- Motivation
  - System integration and control development
  - ORC component performance and durability testing
  - Fuel economy benefit measurement
- Features
  - Coupled with a 13L HD diesel engine w/ HP EGR & VTG
  - Tailpipe and EGR evaporators in parallel
  - Turbine expander with 48V integrated generator
  - Ethanol as working fluid



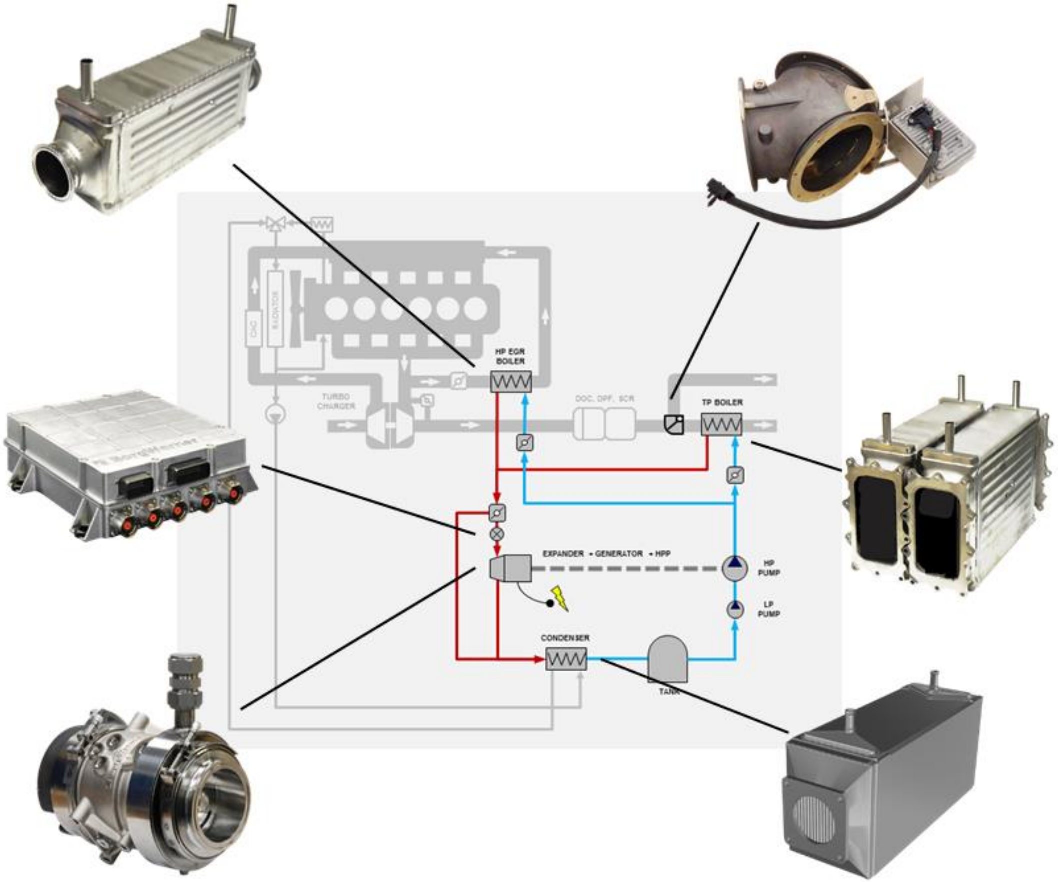
ORC System Layout



System Development – Hardware

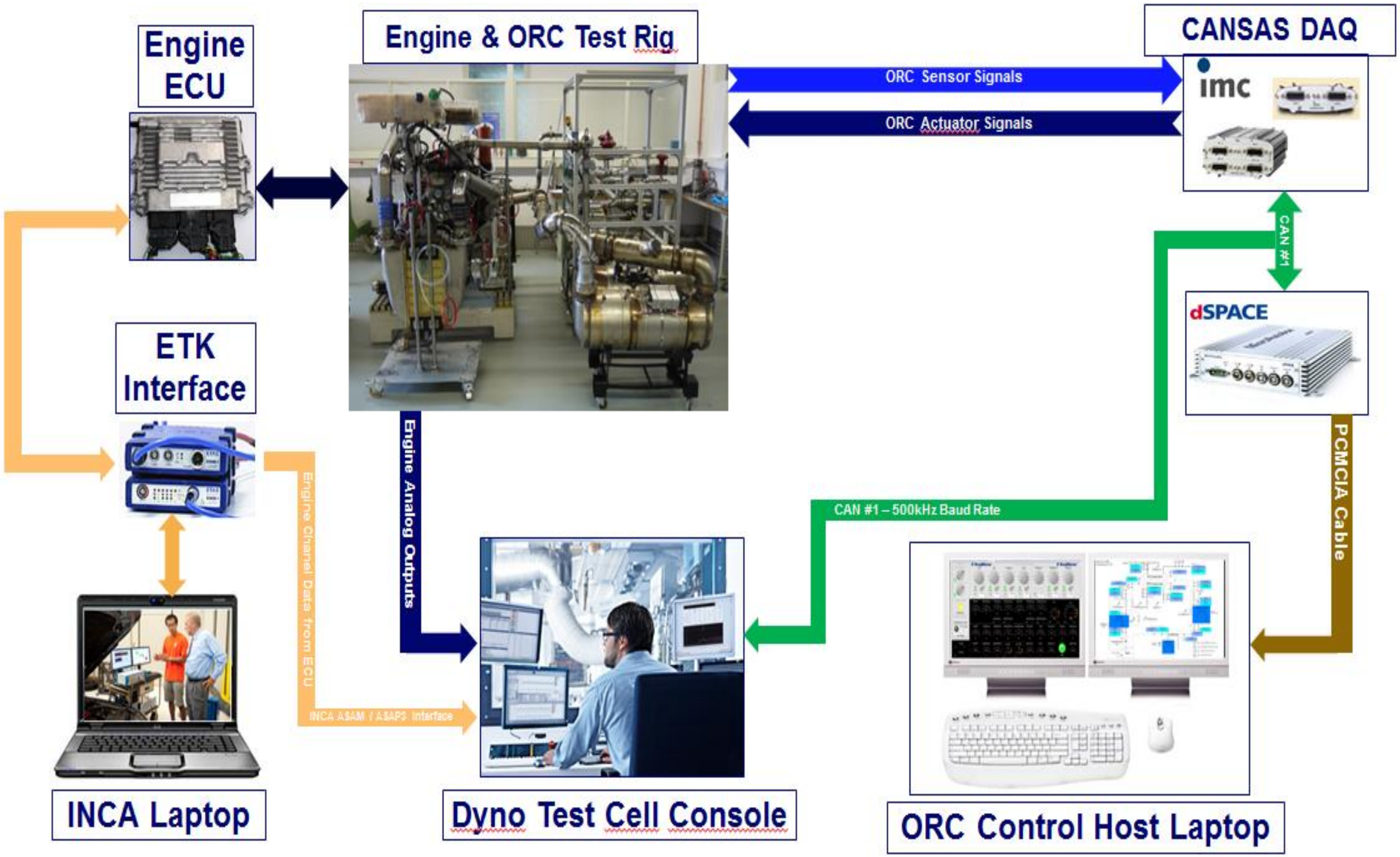
PRODUCT RANGE

- EGR evaporator
- Exhaust tailpipe evaporator
- eTurbine expander
- eTurbine Controller
- Exhaust bypass valve
- Condenser



BorgWarner offers a wide range of components for the ORC system

ORC Test Rig / Dyno Controls Setup



ORC Control Challenges

- Complex MIMO nonlinear system
- Wide operation range (T, P, 2-phase, expander speed)
- Very challenging ORC control in transient cycles
  - Fast disturbances (engine exhaust flow/T) while slow WF temperature response
  - Different time constants for EGR and TP evaporators
    - After-treatment system on TP path as a thermal buffer
  - Limited information in literature on ORC transient control
- An optimal control problem with safety limitations
  - Temperature limit due to dissociation/ flammability of working fluid
  - Pressure limit due to structural integrity of key components
  - Vapor phase limit on turbine expander operation

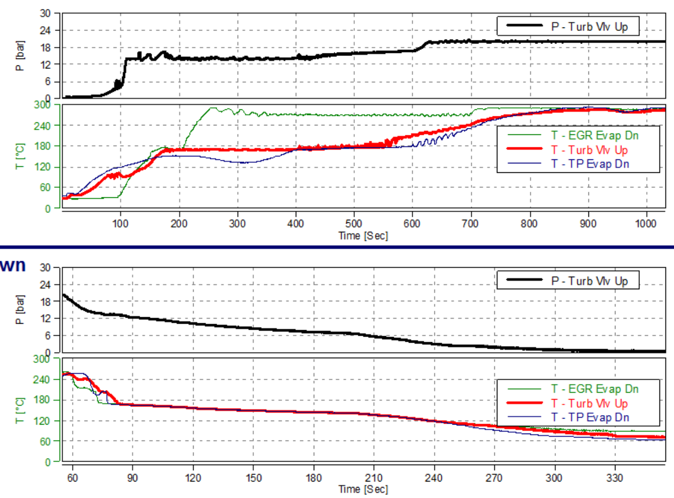
PID Based Controller

- A PID based ORC controller was developed and enabled steady state and slow transient operation of the test rig

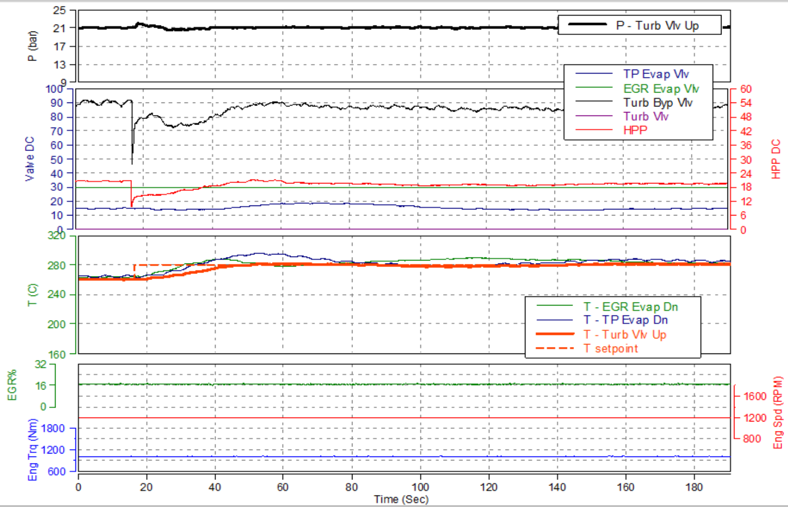
ORC Control Plot – Startup & Shut down

Startup

Shut down

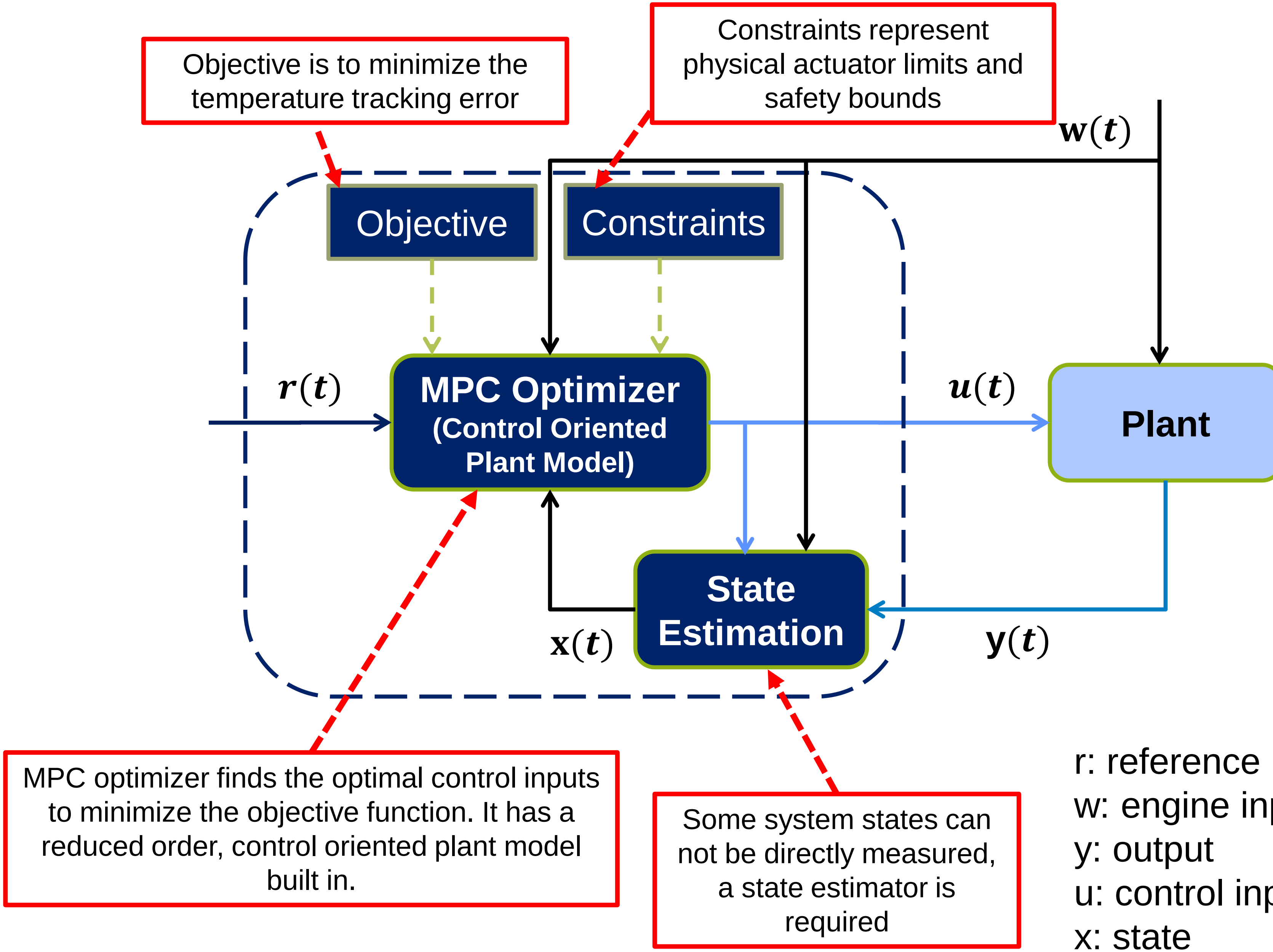


ORC Control Plot – T_{sp} Step



- The PID controller worked well in steady-state and slow transient operations, but had difficulties in fast transient conditions due to poor disturbance rejection and undesired coupling between PID control loops
- Therefore Model Predictive control (MPC) approach was adopted in the second phase of the project

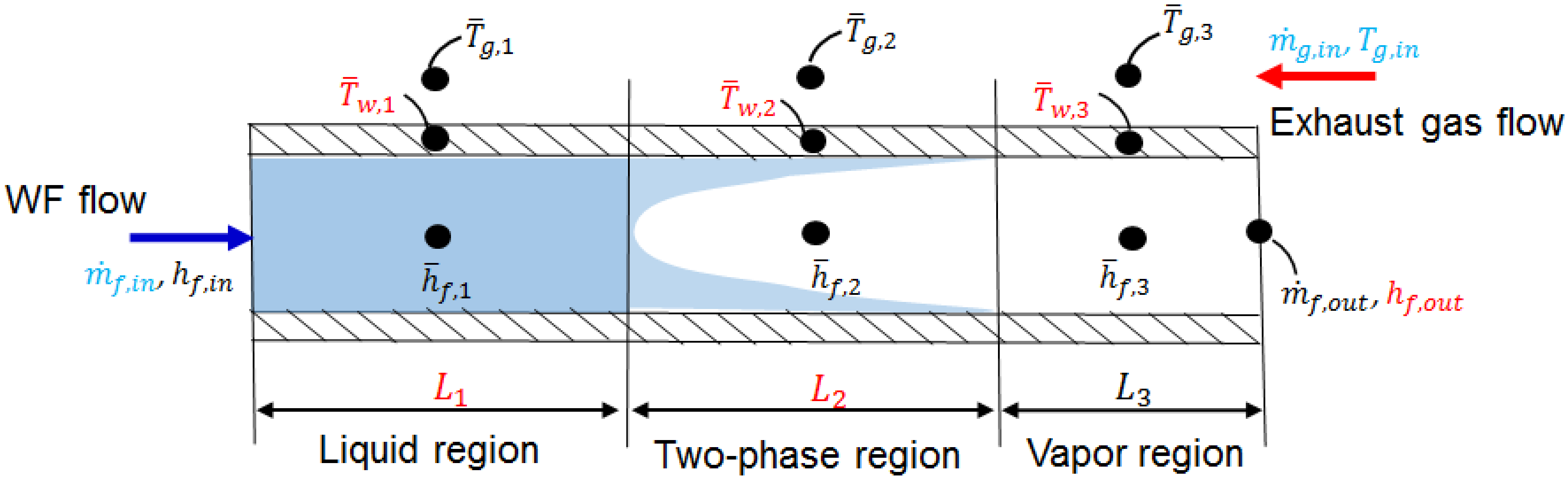
MPC Control Structure



r: reference point
w: engine input
y: output
u: control input
x: state

Evaporator Control Oriented Model

- Moving boundary model (MBM): 3 regions



- 6 states: x=[L_1, L_2, $h_{f,out}$, T_{w1}, T_{w2}, T_{w3}] *h*: enthalpy; T_{wi}: *wall T*
- Inputs: $\dot{m}_{f,in}$; Outputs: $h_{f,out}$; Disturbances: $\dot{m}_{g,in}$, $T_{g,in}$, $h_{f,in}$
- The MBM model was correlated with test rig data

Ref: A. Yebi, “Nonlinear Model Predictive Control Strategies for a Parallel Evaporator Diesel Engine Waste Heat Recovery System,” DSCC 2016-9801
J. Jensen, "Dynamic Modeling of Thermo-Fluid Systems with Focus on Evaporators for Refrigeration," 2003.

MPC Implementation on an Embedded Platform

- Embedded Control Hardware Specification
  - dSpace Micro Autobox Gen II
    - IBM PowerPC 900MHz, 16MB RAM

- MPC Real-time Implementation
  - Execution time reduction to meet real-time constraint
  - Memory consumption reduction to fit into embedded platform

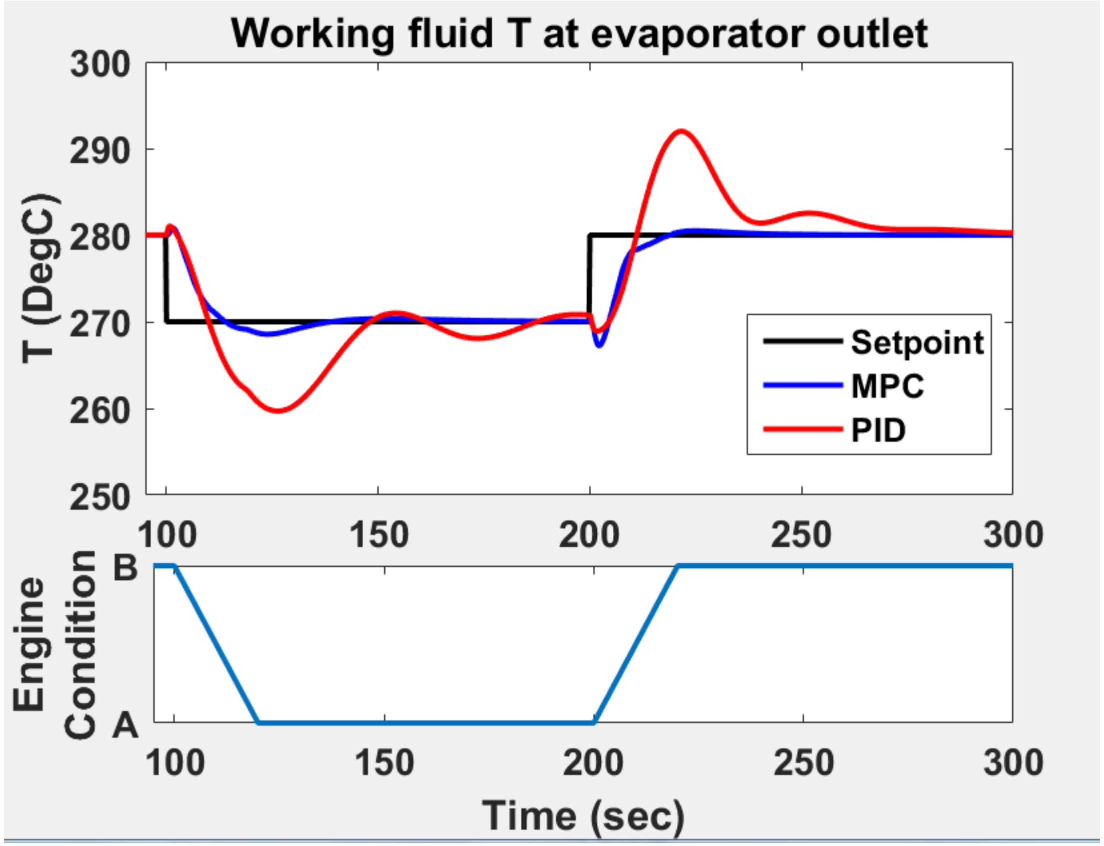
- Two variants of MPC
  - Adaptive Linear MPC (LMPC)

    Mathworks MPC Toolbox
  - Nonlinear MPC (NPMC)

    ACADO Toolkit from Univ. of Leuven

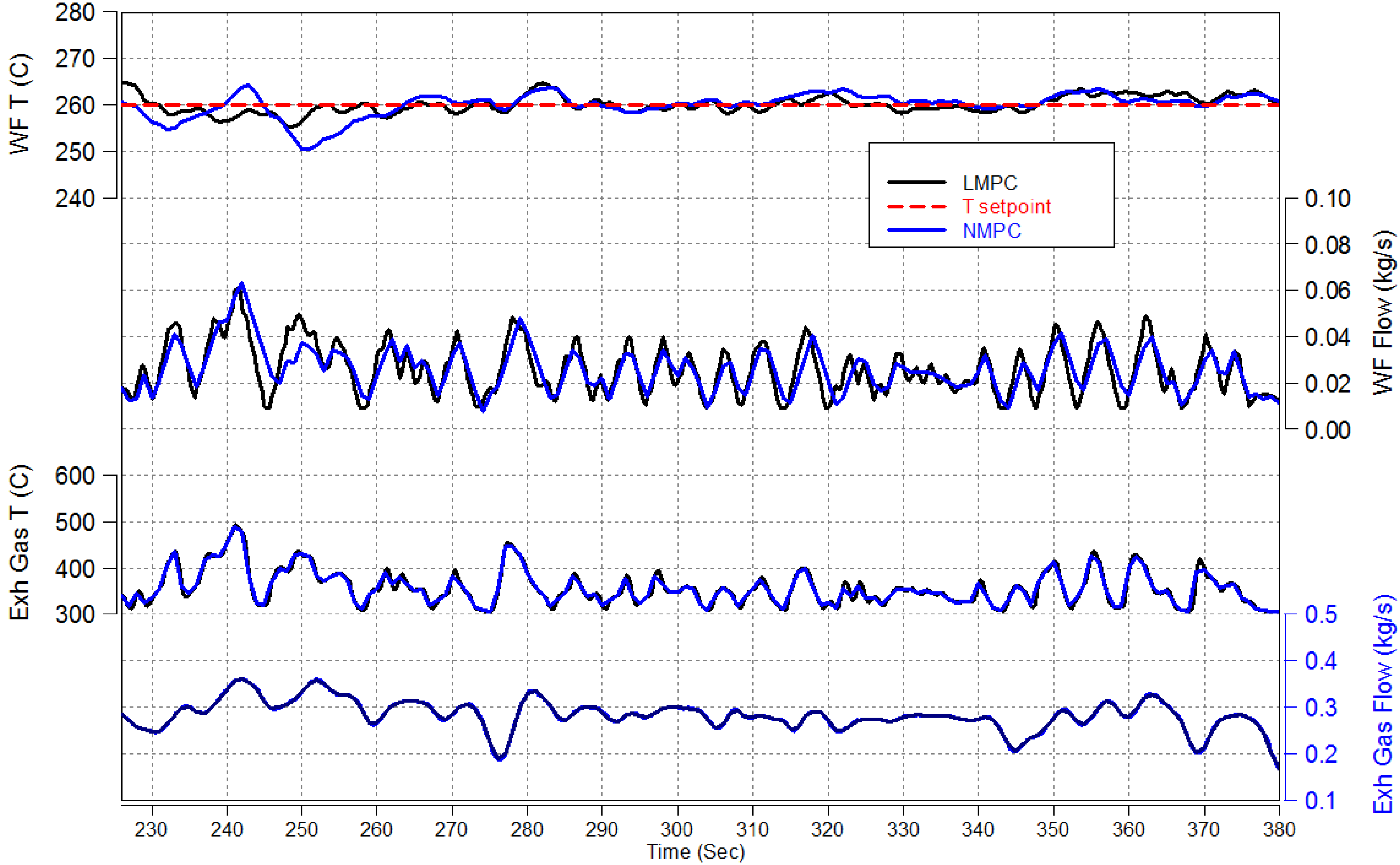
Comparison of PID and MPC – Simulation

- Engine conditions:
  - B (1575RPM, 1540Nm) to A (1200 RPM, 1000Nm) to B
- Step working fluid T setpoint



MPC has better temperature regulation and disturbance rejection, with fast response and minimal overshoot

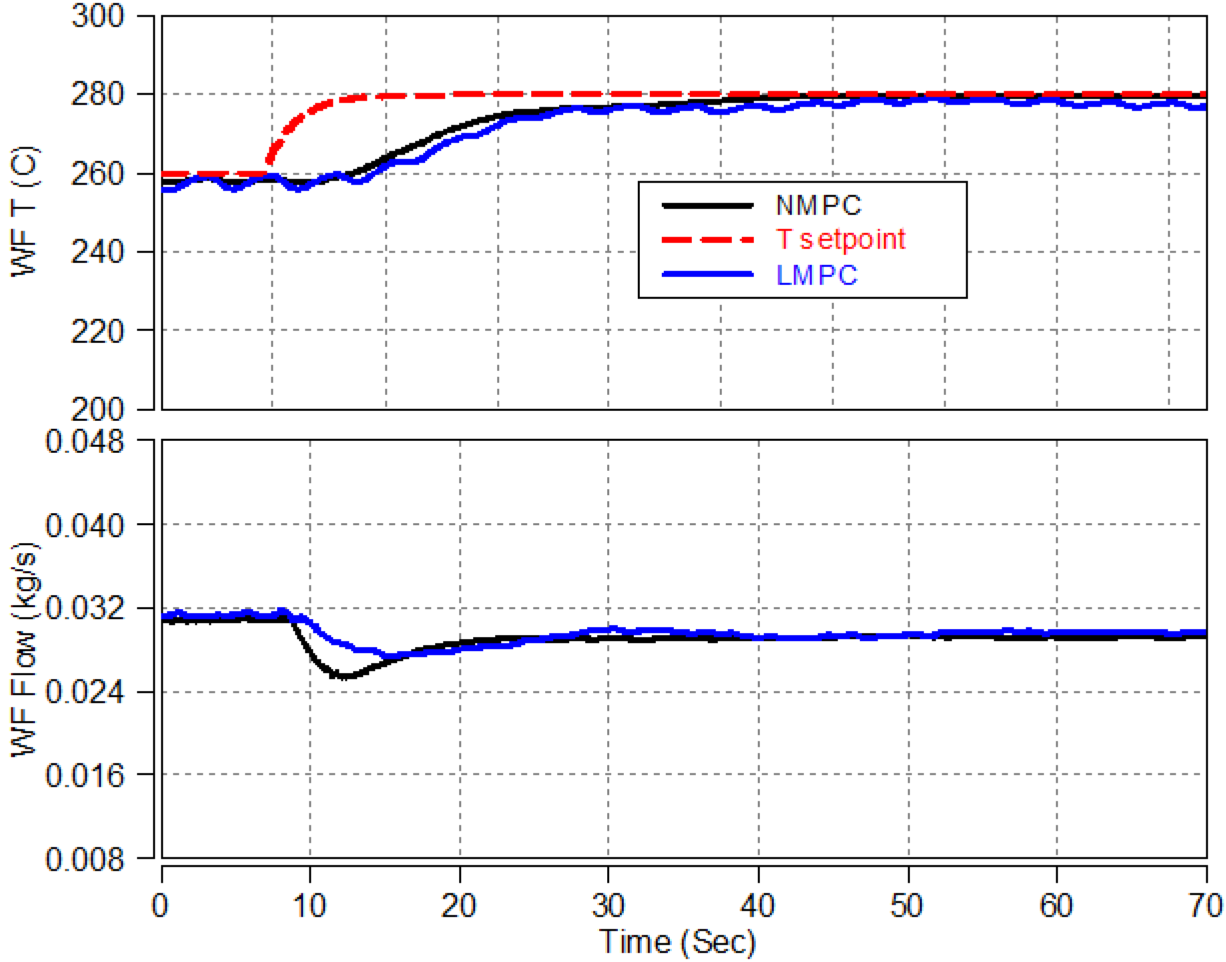
MPC Simulation over a Transient Cycle



LMPC and NMPC produce comparable results

The working fluid temperature is well regulated within $\pm 10℃$

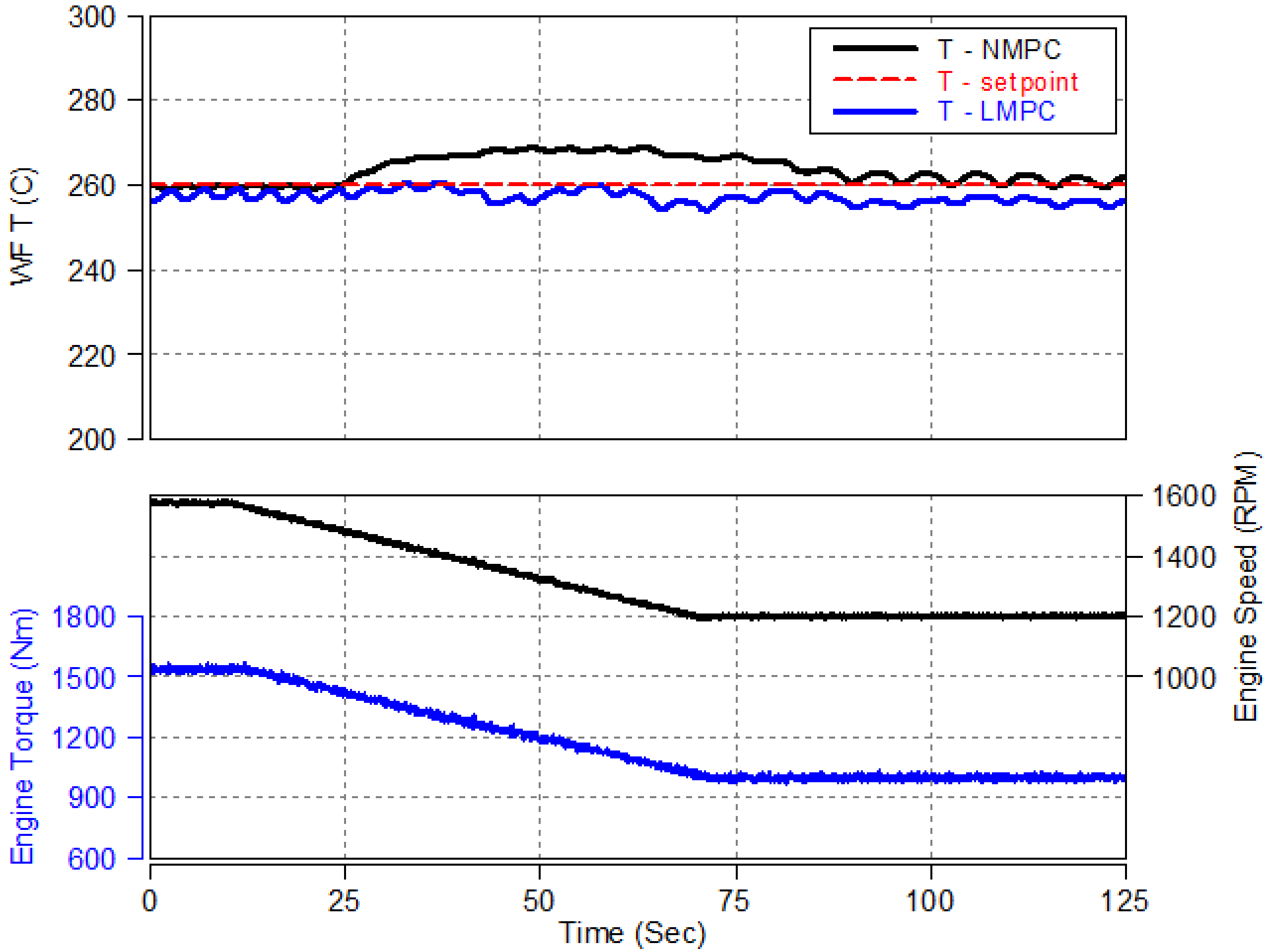
MPC Controller Test Result – T Step



Fast T step response with no overshoot

Small steady state error

MPC Controller Test Result – Engine Speed/Load Ramp



WF Temperature is well regulated

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Summary

- An ORC test system, which recovers waste heat from engine tailpipe exhaust and EGR, was implemented
- A PID based controller was developed enabling steady state and slow transient operation of the ORC system
- Two MPC controllers (LMPC & NMPC) were developed which provided better temperature control and improved disturbance rejection in simulation
- MPC controllers were implemented on a real-time embedded platform and initial test results were satisfactory

Thank you!

ORC Publications

- Publications
  - Liu, X., Yebi, A., Anschel P., Shutty, J., “Model Predictive Control of an Automotive Organic Rankine Cycle System,” to be presented at IV International Seminar on ORC Power Systems, ORC2017, Milano, Italy.
  - Liu, X., Yebi, A., Anschel P., Shutty, J., “Real-time Embedded Implementation of Model Predictive Control of an Organic Rankine Cycle System,” SAE Thermal Management Systems Symposium, Mesa, Arizona, 2016.
  - Anschel P., “A System-Level Approach to the Development of Optimized ORC Waste Heat Recovery Components for Heavy Duty Truck,” Engine ORC Consortium, Belfast, Northern Ireland, 2016.
  - Yebi, A., Xu, B., Liu, X. , Shutty, J., Anschel, P., Onori, S., et al., "Nonlinear Model Predictive Control Strategies for A Parallel Evaporator Diesel Engine Waste Heat Recovery System " in ASME Dynamic System and Control Conference, Minneapolis, Minnesota, 2016.
  - Xu, B., Liu, X., Shutty, J., Anschel, P. et al., "Physics-Based Modeling and Transient Validation of an Organic Rankine Cycle Waste Heat Recovery System for a Heavy-Duty Diesel Engine," SAE Technical Paper 2016-01-0199, 2016, doi:10.4271/2016- 01-0199.
  - Xu, B., Yebi, A., Liu, X. , Shutty, J., Anschel, P., Onori, S., et al., "Power Maximization of A Heavy Duty Diesel Organic Rankine Cycle Waste Heat Recovery System Utilizing Mechanically Coupled And Fully Electrified Turbine Expanders " in ASME Internal Combustion Fall Technical Conference, Greenville, South Carolina, 2016.

MPC vs PID Controller

- MPC has better performance over PID in transient conditions
  - Built-in plant model for response prediction
  - Optimizer to find optimal control inputs
  - Potential synergy with future GPS-based road load prediction system

  but requires more CPU computation time, memory consumption, and modeling effort.

- Looking into ORC control options on vehicle
  - Advanced PID with better feed forward model

  or

  - Linear MPC

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