Modeling and Model-based Control of Automotive Air Paths

Robin Holmbom

LINKÖPING UNIVERSITY

Background

Defense of dissertation planned for 2022-01-28

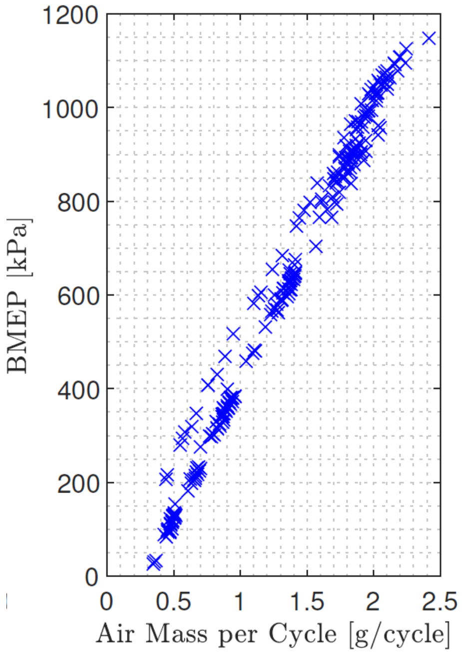
- The strive towards cleaner engines increses the number of configurations
  - Low-Pressure EGR
  - EGR
  - Variable Cam Systems
  - Turbocharger, single, double, …
  - …
- As more configurations are introduced the cross-couplings within the automotive air path increases

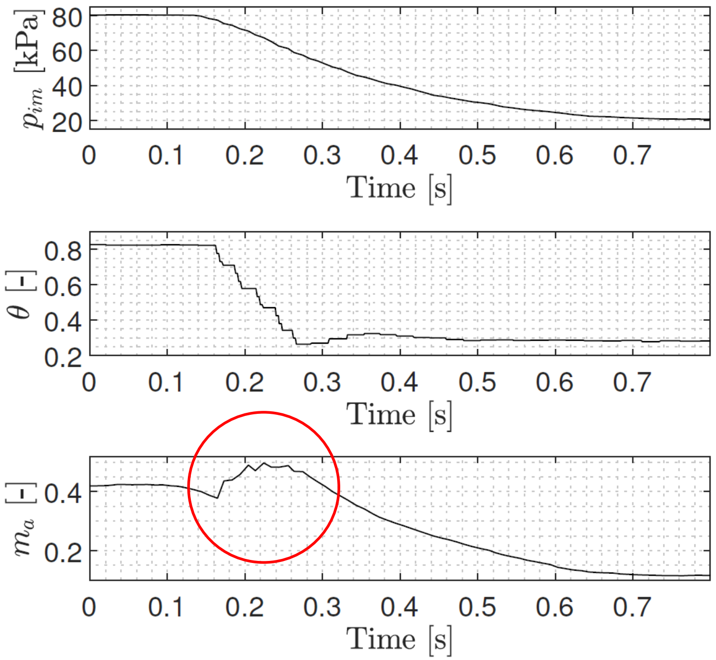
SI-engine with three-way-catalyst (λ=1)

$$\lambda = 1 \Rightarrow m_a \propto T_q$$

- Model-based methodology with a control-oriented focus.

- MPC as reference governor.





Paper I - Investigation of Performance Differences and Control Synthesis for Servo-Controlled and Vacuum-Actuated Wastegates

Actuator focus

Paper II - Analysis and Development of Compact Models for Mass Flows through Butterfly Throttle Valves

Modeling of mass flow (poppet valves, throttle, egr, wastegate, etc)

Paper III - Development of a Control-Oriented Cylinder Air-Charge Model for Gasoline Engines with Dual Independent Cam Phasing

Modeling of mass flow

Paper IV - Throttle Control using NMPC with Soft Intake Temperature Constraint for Knock Mitigation

MPC Control, simulation

Paper V - Real-Time Implementation of an Intake Manifold Pressure Controller with Dependence on Intake Cam Phaser using Nonlinear Model Predictive Control

MPC Control, in real-time evaluated in engine test cell

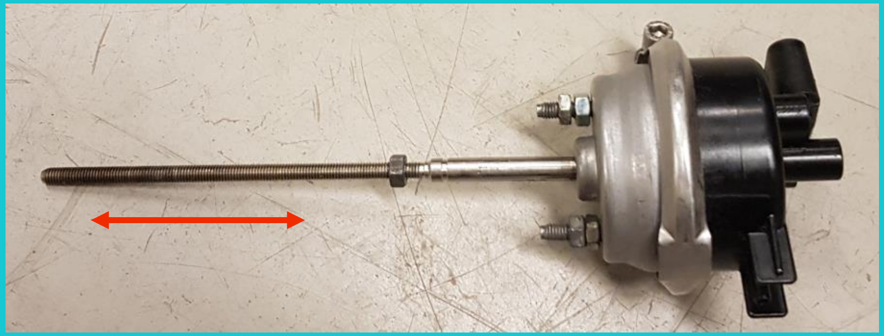
Paper I - Investigation of Performance Differences and Control Synthesis for Servo-Controlled and Vacuum-Actuated Wastegates

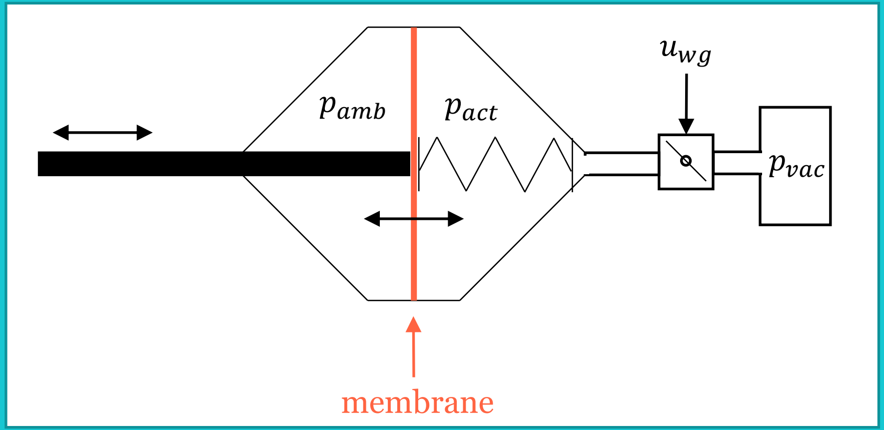
Robin Holmbom, Bohan Liang, Lars Eriksson

- Performance differences

- Control Synthesis
    - Vacuum-actuated
    - Servo-controlled

Vacuum-actuated, 100 Hz



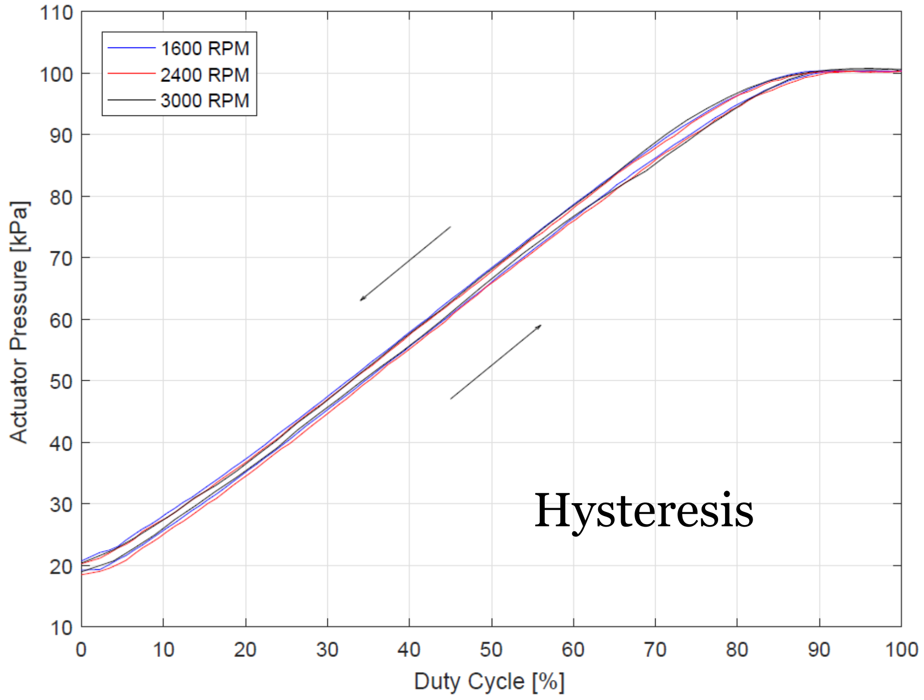


Electric-Servo, 1000 Hz

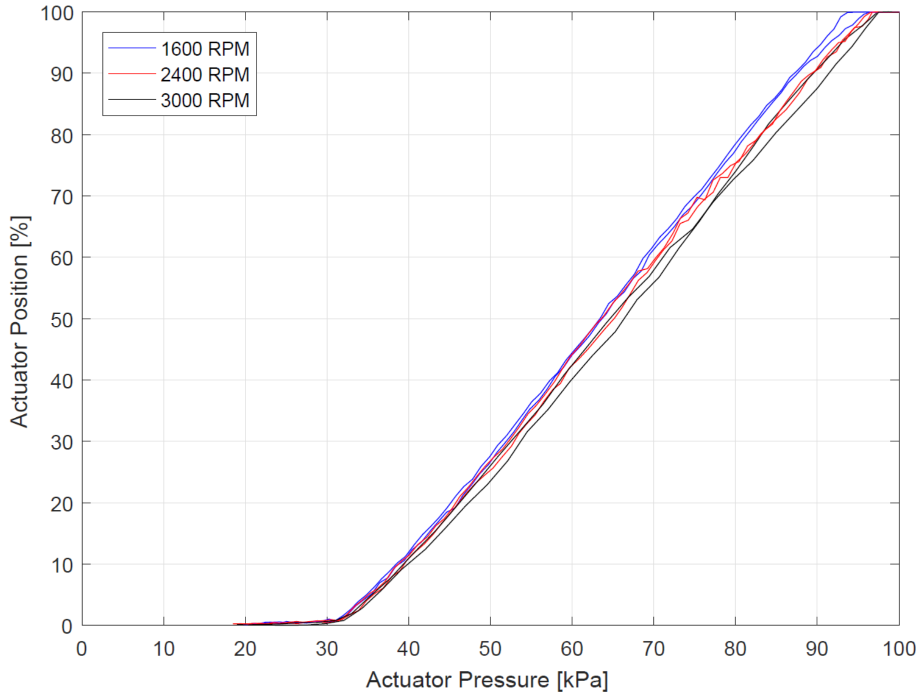
Vacuum-actuated

$$u_{wg}(s) \longrightarrow \boxed{G_{\text{EPC}}(s)} \xrightarrow{p_{act}(s)} \boxed{G_{wg}(s)} \xrightarrow{x_{wg}(s)}$$

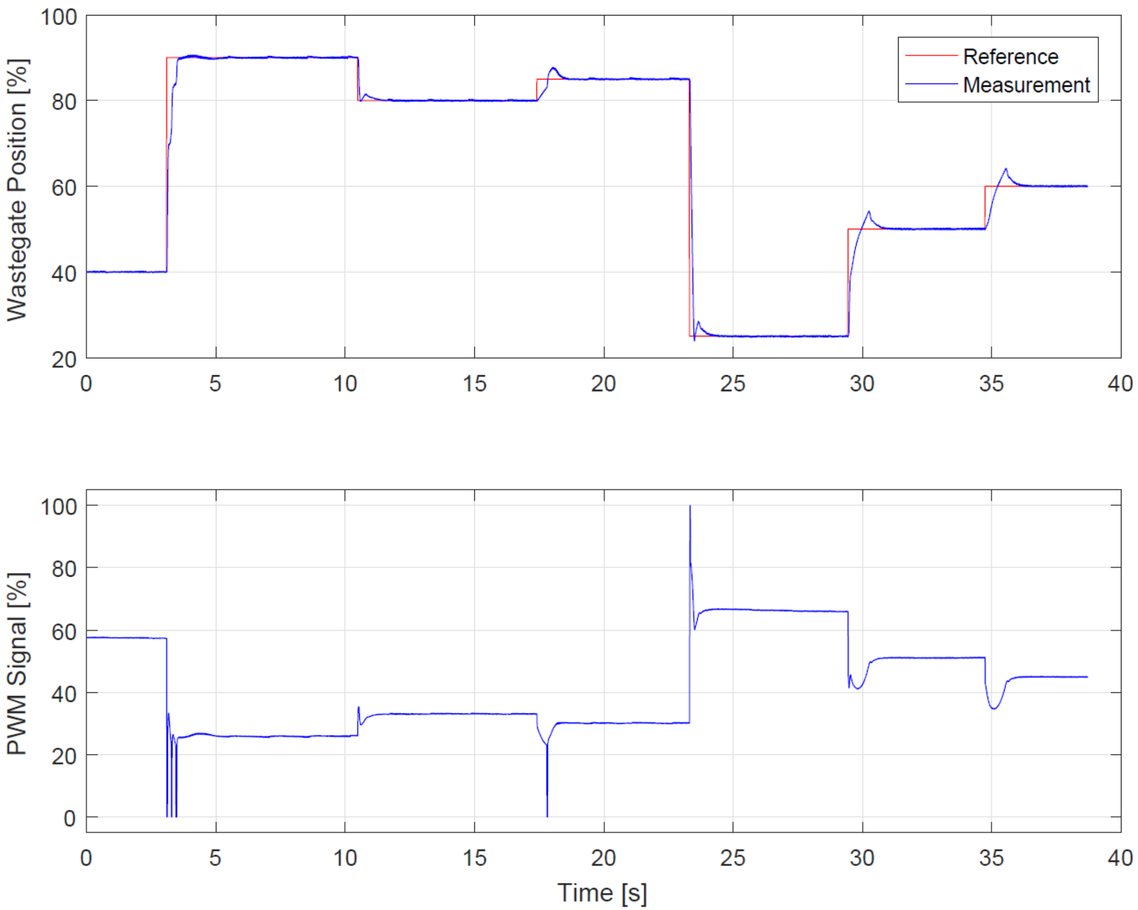
G_{EPC}



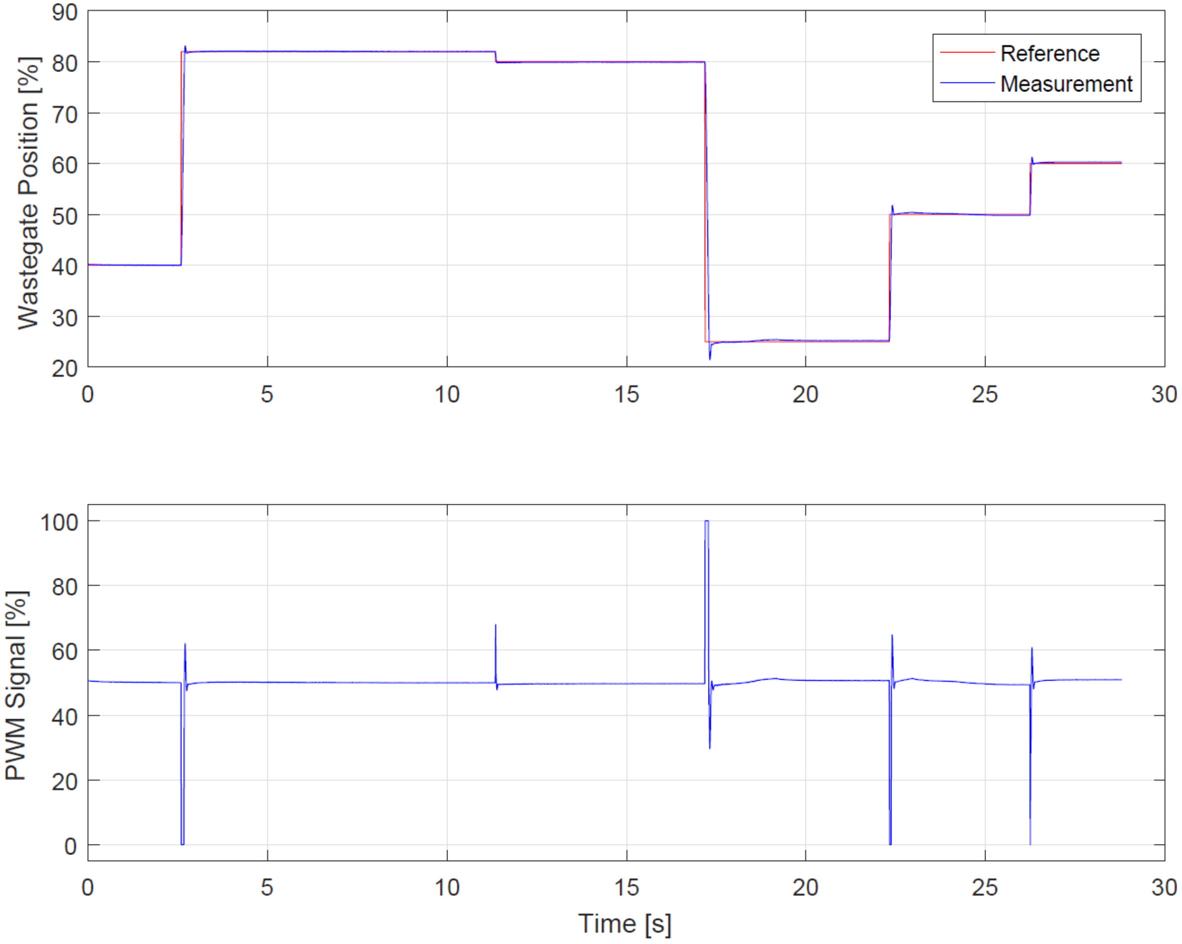
G_{wg}



Vacuum-actuated



Electric-servo



Conclusions

Electric-servo:

- Linear System
- Linear control theory works well
- Being a linear system, it behaves in the same way for both directions

Vacuum actuated:

- Nonlinear effects, hysteresis, different behaviors for opening and closing.
- Further modeling needed to improve results.

- Electric-servo is preferred
- Reference supervision perspective: Easier to model closed loop system of electric servo actuator.

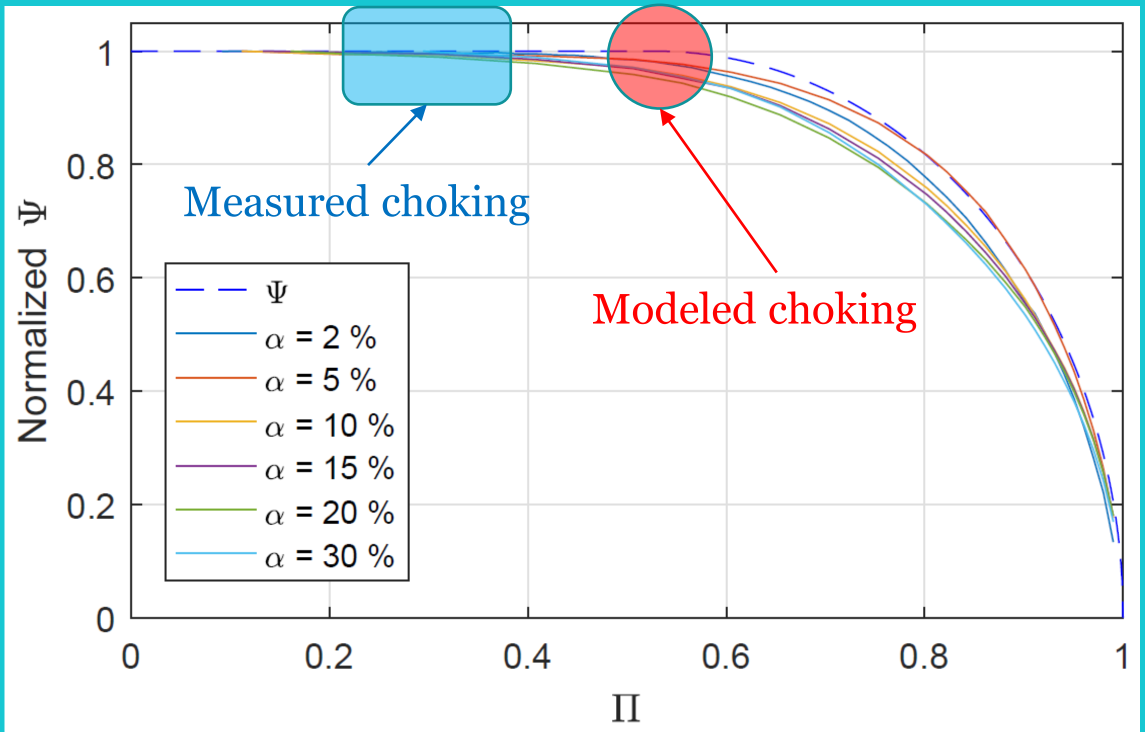
Paper II - Analysis and Development of Compact Models for Mass Flows through Butterfly Throttle Valves

Robin Holmbom, Lars Eriksson

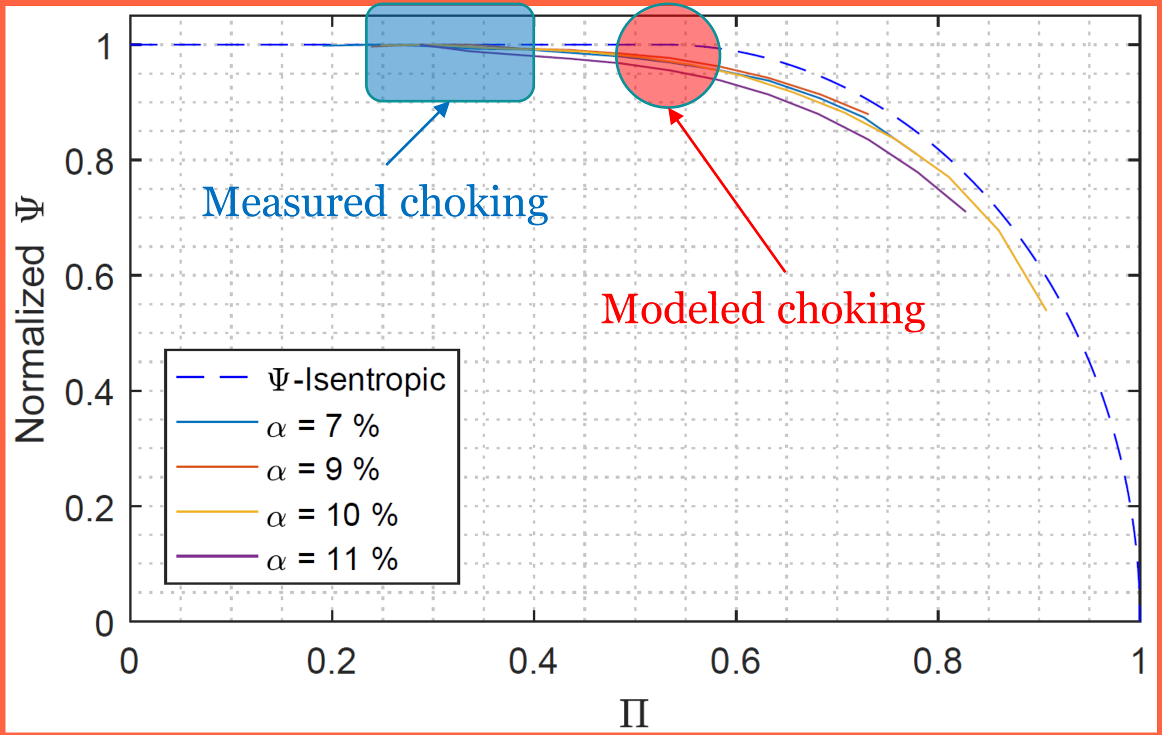
LINKÖPING UNIVERSITY

Different Compact Models of Compressible Flow investigated

Part-load maps (2 engines)



Throttle in Flow Bench



$$\dot{m} = \frac{p_u}{\sqrt{RT_u}} A_{th} C_d \Psi(\Pi)$$

Original (Isentropic)

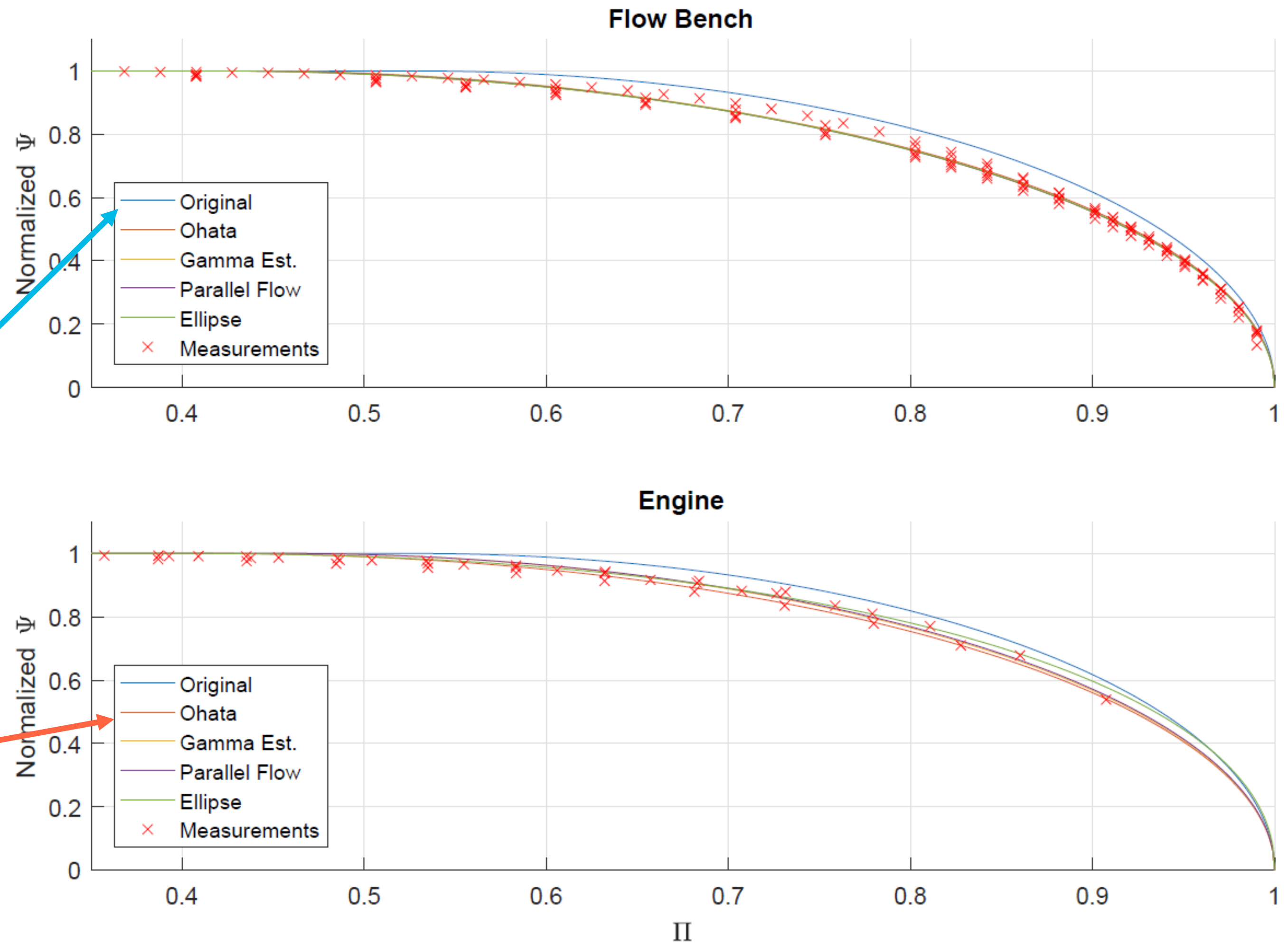
$$\Pi = \begin{cases} \frac{p_d}{p_u}, & \text{if } \frac{p_d}{p_u} \geq \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \\ \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}, & \text{otherwise} \end{cases}$$

$$\Psi_o(\Pi) = \sqrt{\frac{2\gamma}{\gamma-1}\left(\Pi^{\frac{2}{\gamma}} - \Pi^{\frac{\gamma+1}{\gamma}}\right)}$$

Ohata (Conservation of mass, energy, and momentum)

$$\Psi_{cv}(\Pi) = \sqrt{\frac{\gamma+1}{2\gamma}(1-\Pi)\left(\Pi + \frac{\gamma-1}{\gamma+1}\right)}$$

$$\Pi = \begin{cases} \frac{p_d}{p_u}, & \text{if } \frac{p_d}{p_u} \geq \frac{1}{\gamma+1} \\ \frac{1}{\gamma+1}, & \text{otherwise} \end{cases}$$



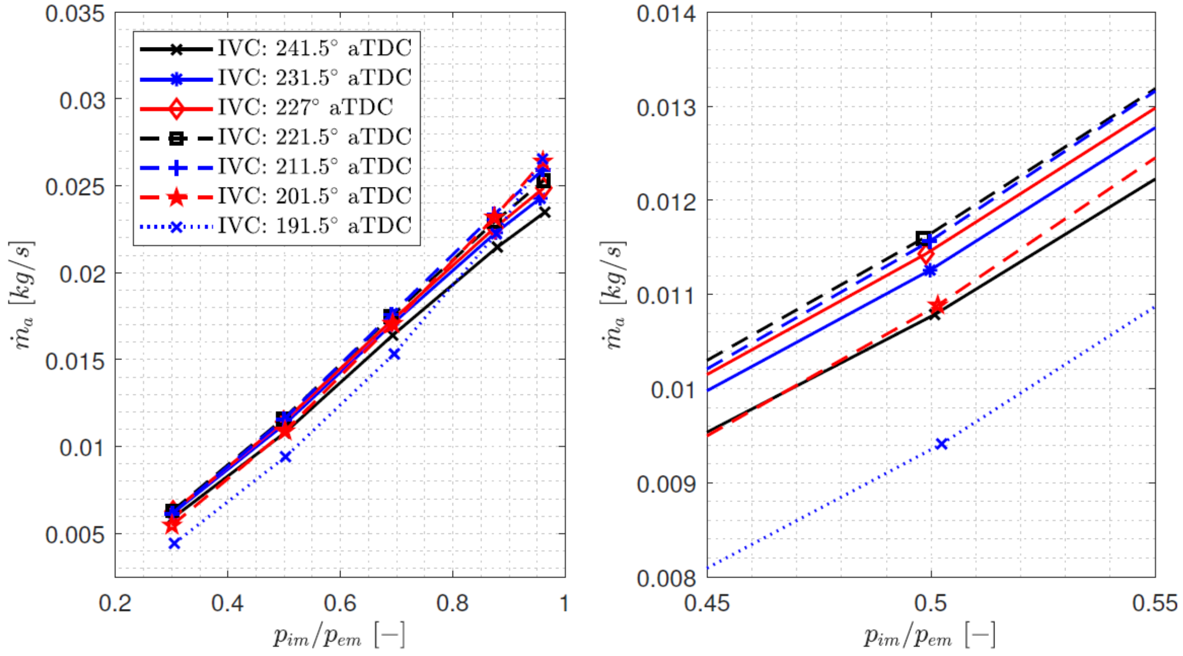
Conclusions

- Ohata’s model based on conservation of energy, mass, and momentum, coincide with models using more parameters.
- Standard Isentropic Model does not seem to capture the correct pressure ratio of choking.
- Effective area estimation compensates for some of the differences in the ψ-functions.

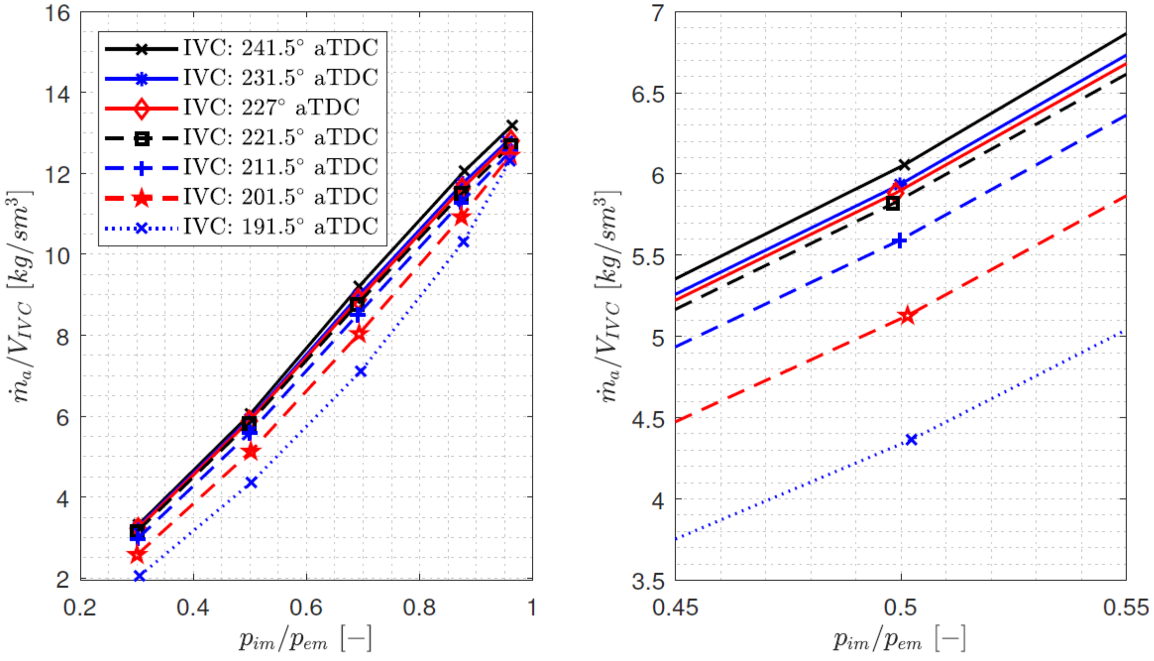
Paper III - Development of a Control-Oriented Cylinder Air-Charge Model for Gasoline Engines with Dual Independent Cam Phasing

Robin Holmbom, Lars Eriksson

- Normalizing air mass flow with cylinder volume at IVC brings structure
  - Ordered according to overlap, for fix exhaust cam.



$$\dot{m}_{a,1} = \frac{N n_{cyl} p_{im} V_d}{n_r R T_{im}}$$



$$\dot{m}_{a,2} = \frac{N n_{cyl} p_{im} V_{IVC}}{n_r R T_{im}}$$

$$\dot{m}_a = \frac{N n_{cyl} p_{IVC}}{n_r R T_a} V_a = \frac{N n_{cyl} p_{IVC}}{n_r R T_a} (V_{IVC} - V_r)$$

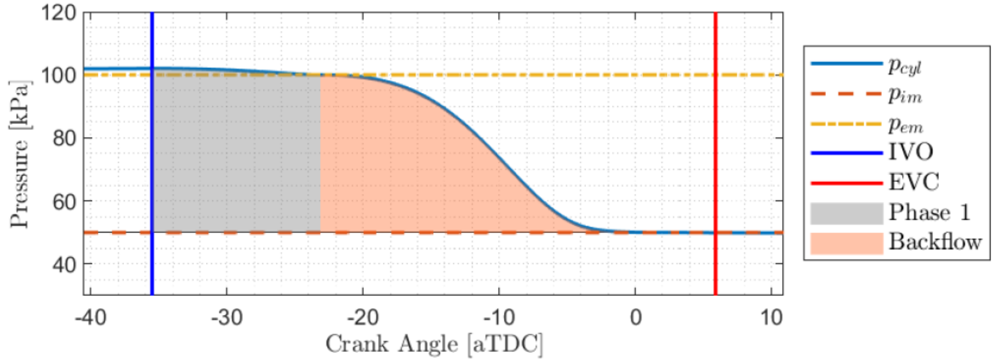
Trapped residuals Backflow

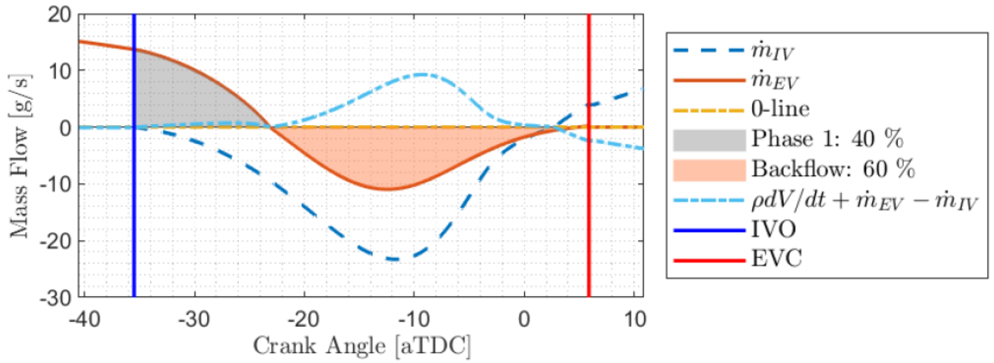
$$V_{exp} = \boxed{V_{tr}} + \boxed{V_{bf}}$$

$$V_r = V_{exp} \left(\frac{p_{em}}{p_{IVC}} \right)^{\frac{1}{\gamma}}$$

$$m_r = \boxed{m_{IVO}} + \boxed{\int_{IVO}^{EVC} -\dot{m}_{EV} \, dt}$$

Simulation



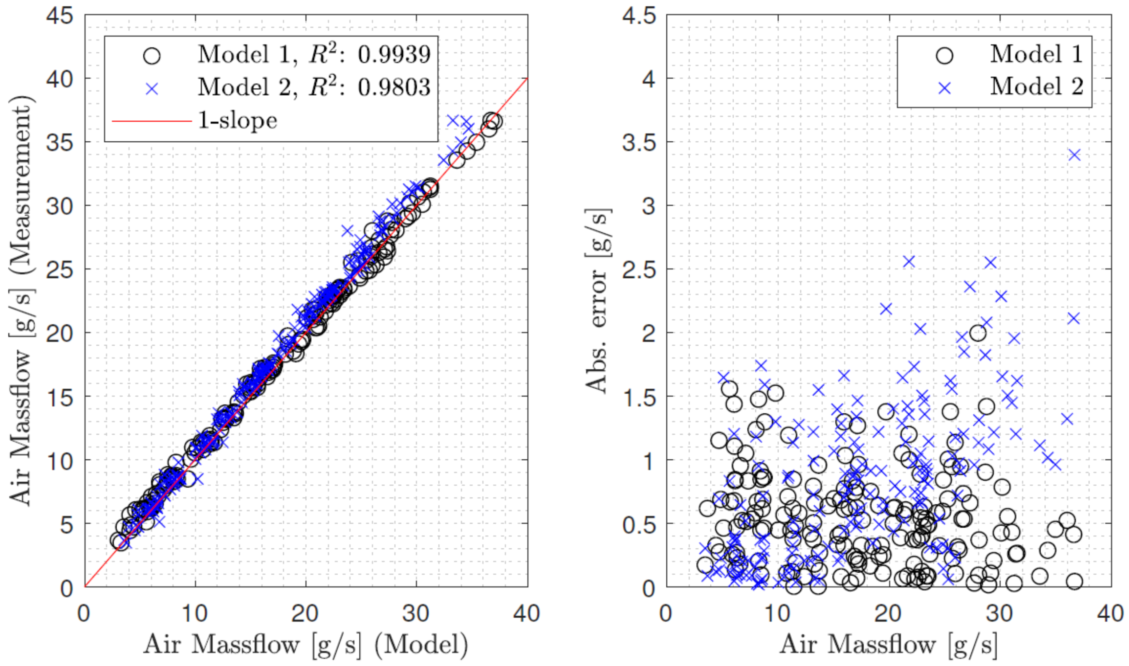


Net Backflow: 20 %

Overlap: 41.4 CAD

$\frac{p_{im}}{p_{em}} = 0.5$

Conclusions



- Each cam's valve events have an effect on the air flow of fresh air.
- First phase behavior inhibit backflow during overlap period.
- V_{IVC} should be used instead of V_d in the speed-density formulation
- Model proposed:

$$\dot{m}_a = \frac{N n_{cyl} p_{im} V_{IVC}}{n_r R T_{im}} \eta_{vol}(c)$$

$$\eta_{vol}(c) = \left(c_1 - \frac{V_{r,\cdot}(c_2, c_3)}{V_{IVC}} \right)$$

$$V_r(c_2, c_3) = \left(\frac{p_{em}}{p_{im}} \right)^{\frac{1}{\gamma}} \left[c_2 V_{tr} + c_3 \left(\frac{p_{em}}{p_{im}} \right)^{\frac{\gamma-1}{2\gamma}} \sqrt{R T_{im}} \Psi_{cv} \frac{\text{OF}}{N} \right]$$

$$V_{tr} = \begin{cases} V_{EVC}, & \text{if } IVO \geq EVC \\ V_{TDC}, & \text{if } IVO \leq 0 < EVC \\ V_{IVO}, & \text{if } 0 < IVO < EVC \end{cases}$$

where c_1, c_2, and c_3 are parameters to be estimated.

Paper IV - Throttle Control using NMPC with Soft Intake Temperature Constraint for Knock Mitigation

Robin Holmbom, Lars Eriksson

LINKÖPING UNIVERSITY

MPC as reference governor

$$\dot{p}_{im} = \frac{RT_{im}}{V_{im}}(\dot{m}_{thr} - \dot{m}_{cyl}) + \frac{p_{im}}{T_{im}}\dot{T}_{im}$$

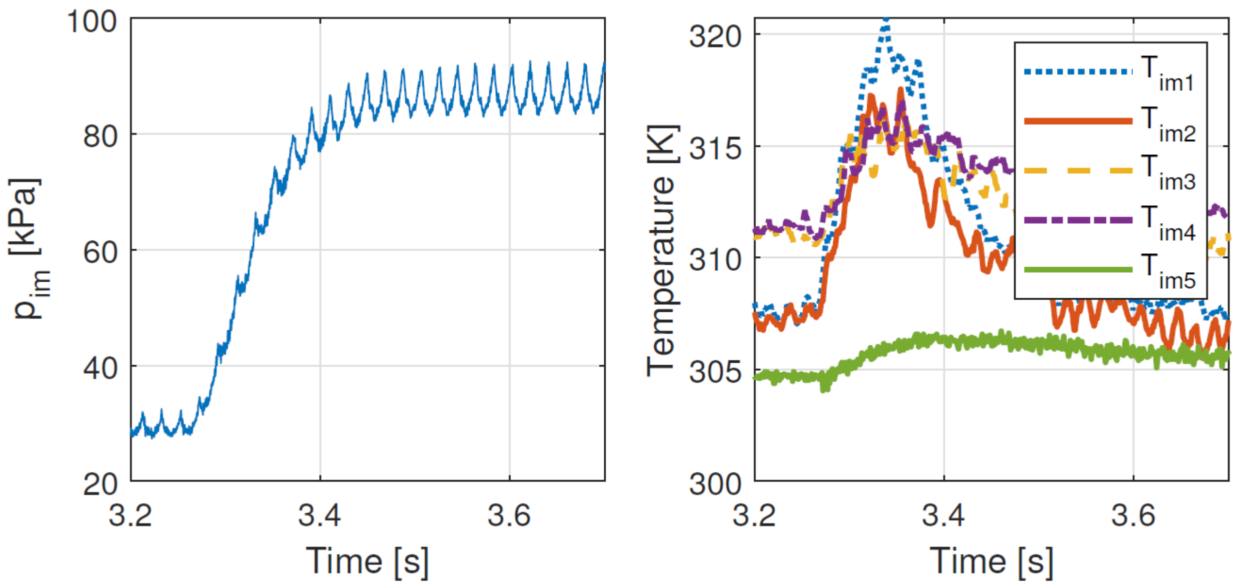
$$\dot{T}_{im} = \frac{RT_{im}}{p_{im}V_{im}c_v}\left[\dot{m}_{thr}c_v(T_{ic} - T_{im}) + R\left(T_{ic}\dot{m}_{thr} - T_{im}\dot{m}_{cyl}\right) - \dot{Q}\right]$$

$$\dot{\alpha} = \frac{1}{\tau}(\alpha_{ref} - \alpha)$$

$$x = \begin{bmatrix} p_{im} \\ T_{im} \\ \alpha \end{bmatrix} \qquad u = \alpha_{ref}$$

p_{im} - Intake Manifold Pressure
T_{im} - Intake Manifold Temperature
α - Throttle Position
α_{ref} - Throttle Position Reference

Measurements



Optimal Control Problem

$$z = p_{im} - p_{im,ref}$$

$$\arg\min_{u} \sum_{k=0}^{N_p-1} \left(z^T[k] Q_1 z[k] + u[k]^T Q_2 u[k] \right) dt$$

$$\begin{aligned}
\text{s.t} \quad & u[k] = [\delta\alpha_{ref}[k],\ u_{slack}[k]]^T \\
& 0 \le T_{im} \le T_{im,max} + \boxed{u_{slack} T_{soft}} \\
& 0 \le u_{slack} \le 1 \\
& 0 \le \alpha_{ref} \le 1 \\
& \boxed{u_{slack}[0] = u_{slack}[1] = \cdots = u_{slack}[N_p - 1]}
\end{aligned}$$

Max Peak Temperature

Baseline setting

Prediction Horizon

$$Q_1 = 1 \times 10^{-10} \qquad Q_2 = \begin{bmatrix} 0.1 & 0 \\ 0 & 10 \end{bmatrix} \qquad N = 15$$

$$T_{im,max} = 330 \text{ K} \qquad T_{soft} = 50 \text{ K} \qquad T_s = 10 \text{ ms}$$

$$T_{ic} = 308 \text{ K}$$

100 Hz

Temperature feedback:

$$\dot{T}_{im,s} = \frac{1}{\tau_{sensor}} (T_{im} - T_{im,s})$$

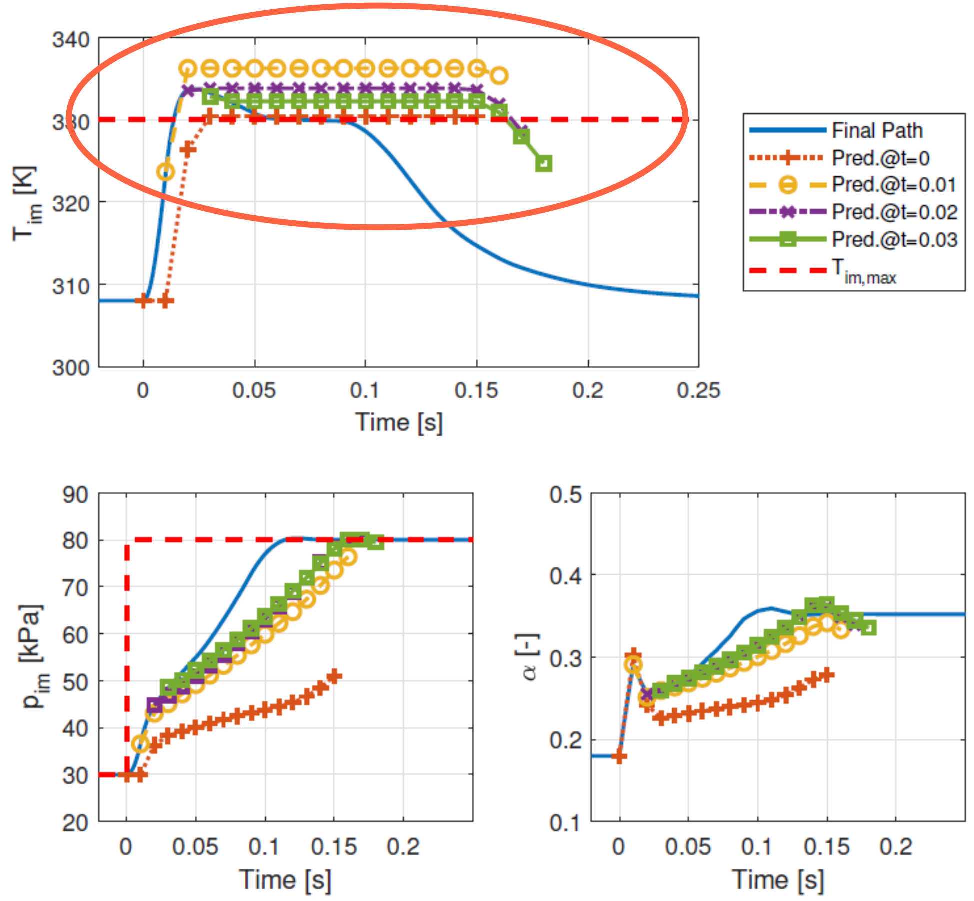
$$\tau_{sensor} = 5 \text{ s}$$

EKF:

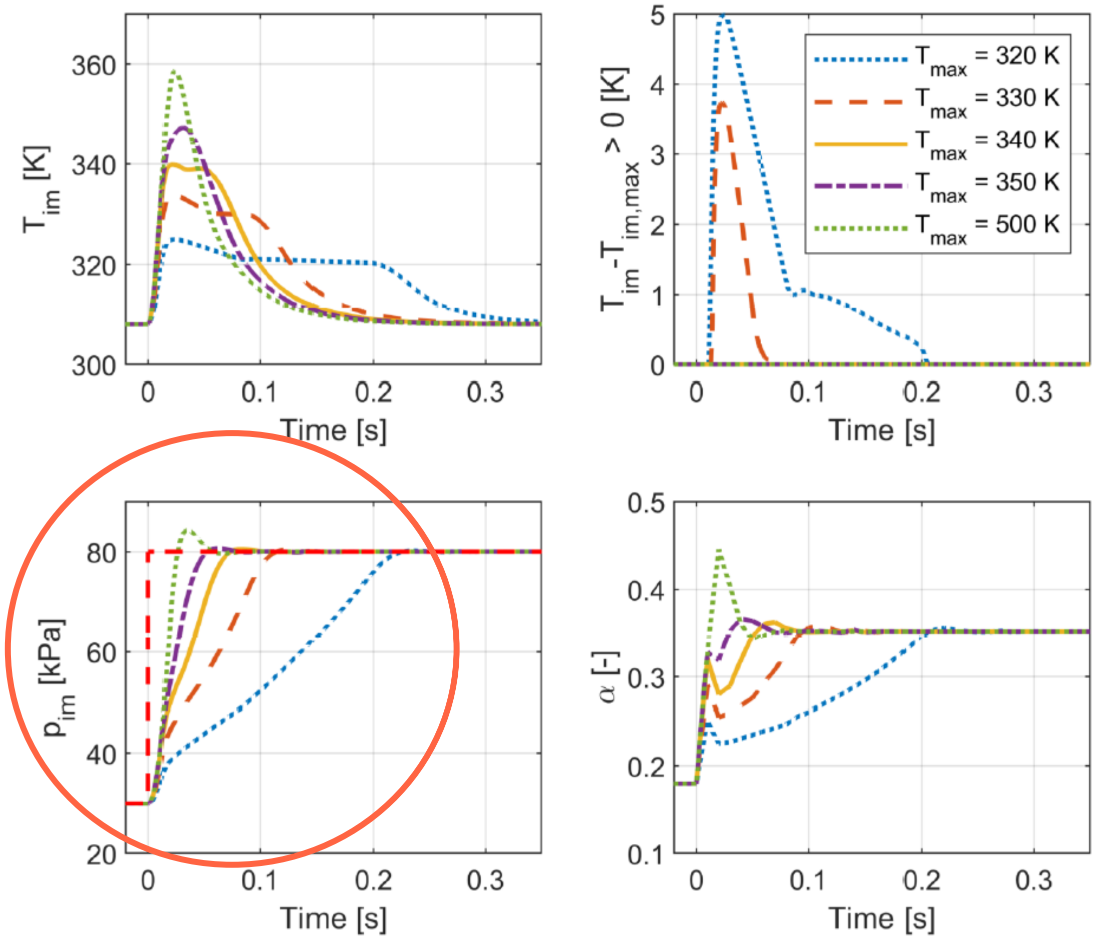
- Transient Switching, trust model during transients and measurement during stationary operation.

$$Q_{EKF} = diag([25 \cdot 10^8, 100, 0.01])$$

$$R_{EKF} = diag([25 \cdot 10^8, \boxed{R_T}, 0.01])$$



T_im [K]
340
330
320
310
300
0
0.05
0.1
0.15
0.2
0.25
Time [s]
Final Path
Pred.@t=0
Pred.@t=0.01
Pred.@t=0.02
Pred.@t=0.03
T_im,max
p_im [kPa]
90
80
70
60
50
40
30
20
α [-]
0.5
0.4
0.3
0.2
0.1



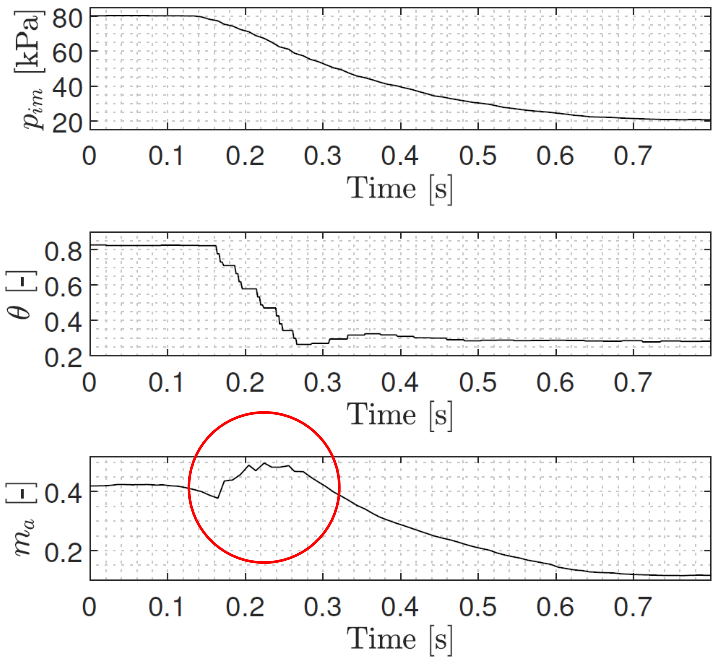
T_im [K]
360
340
320
300
0
0.1
0.2
0.3
Time [s]
T_im-T_im,max > 0 [K]
5
4
3
2
1
T_max = 320 K
T_max = 330 K
T_max = 340 K
T_max = 350 K
T_max = 500 K
p_im [kPa]
80
60
40
20
α [-]
0.5
0.4
0.3
0.2
0.1

Paper V - Real-Time Implementation of an Intake Manifold Pressure Controller with Dependence on Intake Cam Phaser using Nonlinear Model Predictive Control

Robin Holmbom, Lars Eriksson

"Since the dynamic behavior of the inlet pressure control and the cam phasing control are not the same, a mismatch between actual inlet pressure and cam phasing can occur, leading to unwanted effects in air fill and in extreme cases misfire."
Source: The New Volvo Mild Hybrid Miller Engine, MTZ 2021

$$\theta = h(p_{im})$$

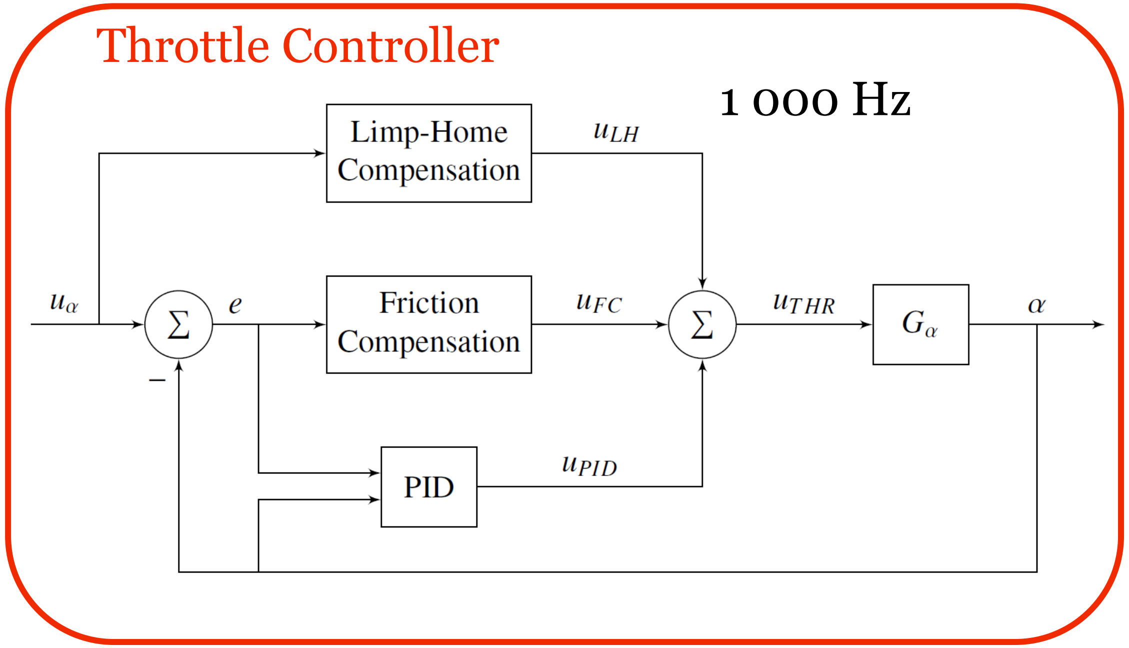


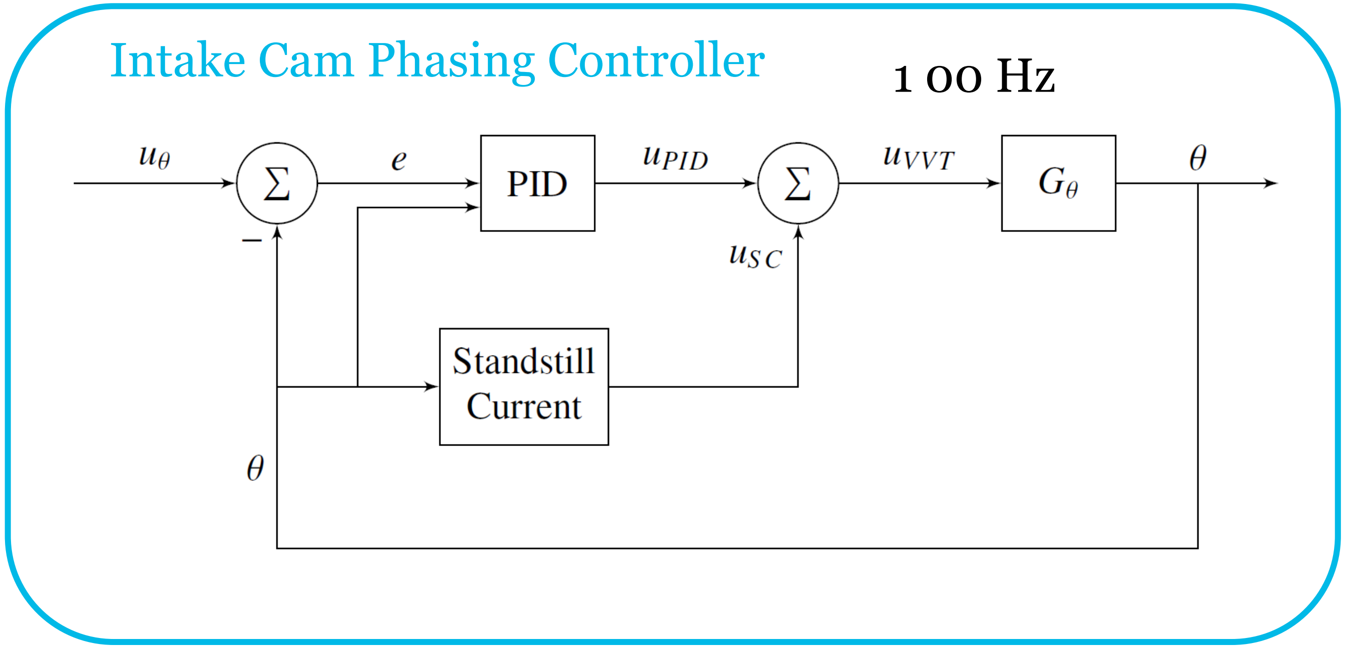
- Coordination using MPC as reference governor.

$$\theta_{ref} = h(p_{im}) = \begin{cases} c_1\sqrt{p_{im}} + c_0, p_{im} > 20\ kPa \\ 0, otherwise \end{cases}$$

$h(105\ kPa) = 50$

MPC as Reference Generator





- Let the control of the actuators be developed separately.

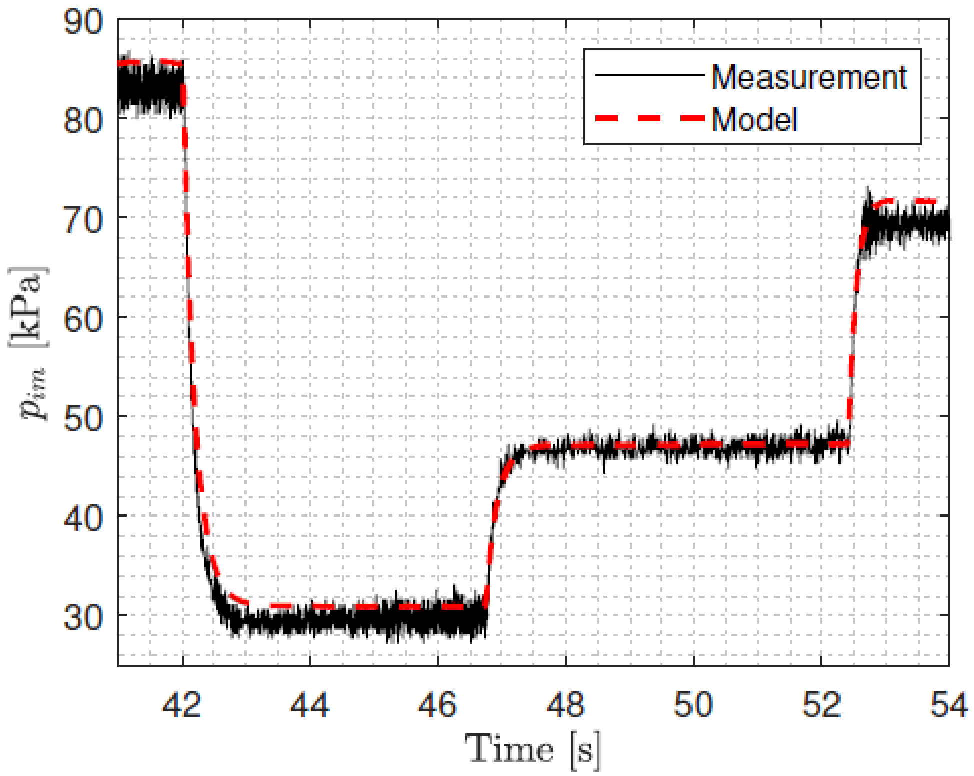
System Model

$$\dot{x}_1 = \dot{p}_{im} = \frac{RT_{im}}{V_{im}} \left(\boxed{\dot{m}_{thr}} - \boxed{\dot{m}_{cyl}} \right)$$

$$\dot{x}_2 = \dot{A}_{eff} = \frac{1}{\tau_A} \left(u_A - A_{eff} \right)$$

$$\dot{x}_3 = \dot{\theta} = \frac{1}{\tau_\theta} \left(u_\theta - \theta \right)$$

$$\begin{aligned}
\dot{m}_{thr} &= \frac{p_{bef,thr}}{\sqrt{RT_{im}}} A_{eff}(\alpha)\, \Psi_{cv}(\Pi)\,, \\
A_{eff} &= a_0 + a_1\alpha + a_2\alpha^2 \\
\Psi_{cv}(\Pi) &= \sqrt{\frac{\gamma+1}{2\gamma}(1-\Pi)\left(\Pi + \frac{\gamma-1}{\gamma+1}\right)} \\
\Pi &= \begin{cases} \frac{p_{bef,thr}}{p_{im}}, & \text{if } \frac{p_{bef,thr}}{p_{im}} \geq \frac{1}{\gamma+1} \\ \frac{1}{\gamma+1}, & \text{otherwise} \end{cases}
\end{aligned}$$



$$\begin{aligned}
\dot{m}_{cyl} &= n_{cyl} V_{IVC}(\theta) \left(k_{cyl} \frac{p_{im}}{p_{em}} + m_c(\theta) \right) \\
m_c(\theta) &= m_0 + m_1\theta + m_2\theta^2
\end{aligned}$$

MPC Formulation

$$\arg\min_{u} \sum_{k=1}^{N_p} \left(Z^T[k] Q_1 Z[k] + \Delta U^T[k] Q_2 \Delta U[k] \right)$$

$$z_1 = p_{im,ref} - p_{im}$$
$$z_2 = \theta - h(p_{im})$$

$$h(p_{im}) = \begin{cases} c_1\sqrt{p_{im}} + c_0, p_{im} > 20\ kPa \\ 0, otherwise \end{cases}$$

$h(105\ kPa) = 50$

$$\Delta U = \begin{bmatrix} u_1 - u_{0|k-1} \\ u_2 - u_1 \\ u_3 - u_2 \\ \vdots \\ u_N - u_{N-1} \end{bmatrix}$$

- Euler Forward
- 100 Hz
- Linearized around nominal trajectory*
- Prediction horizon, N = 15 (150 ms)

*Nominal trajectory is given by having last control signal solution as input.

Integral Action:

$$z_3[k] = I_0 + T_s \sum_{k=0}^{k-1} z_1[k]$$

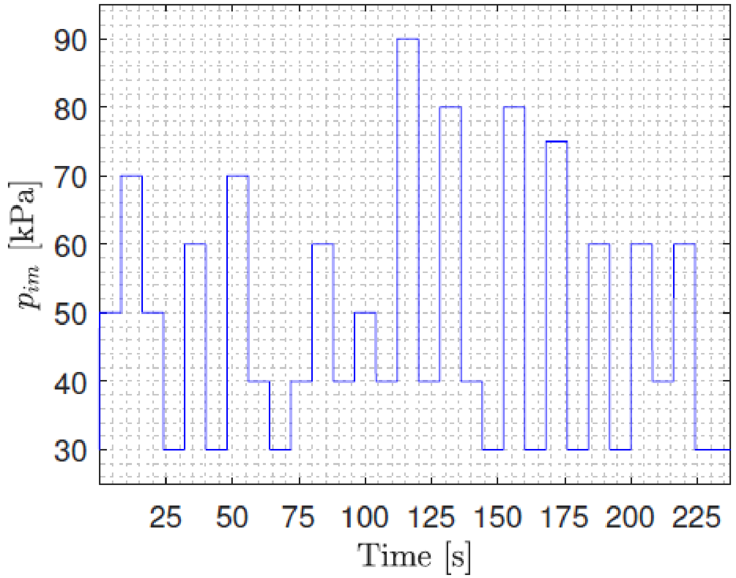
I_0 *is the integral of the error of* z_1*, and an input*

qpOASES

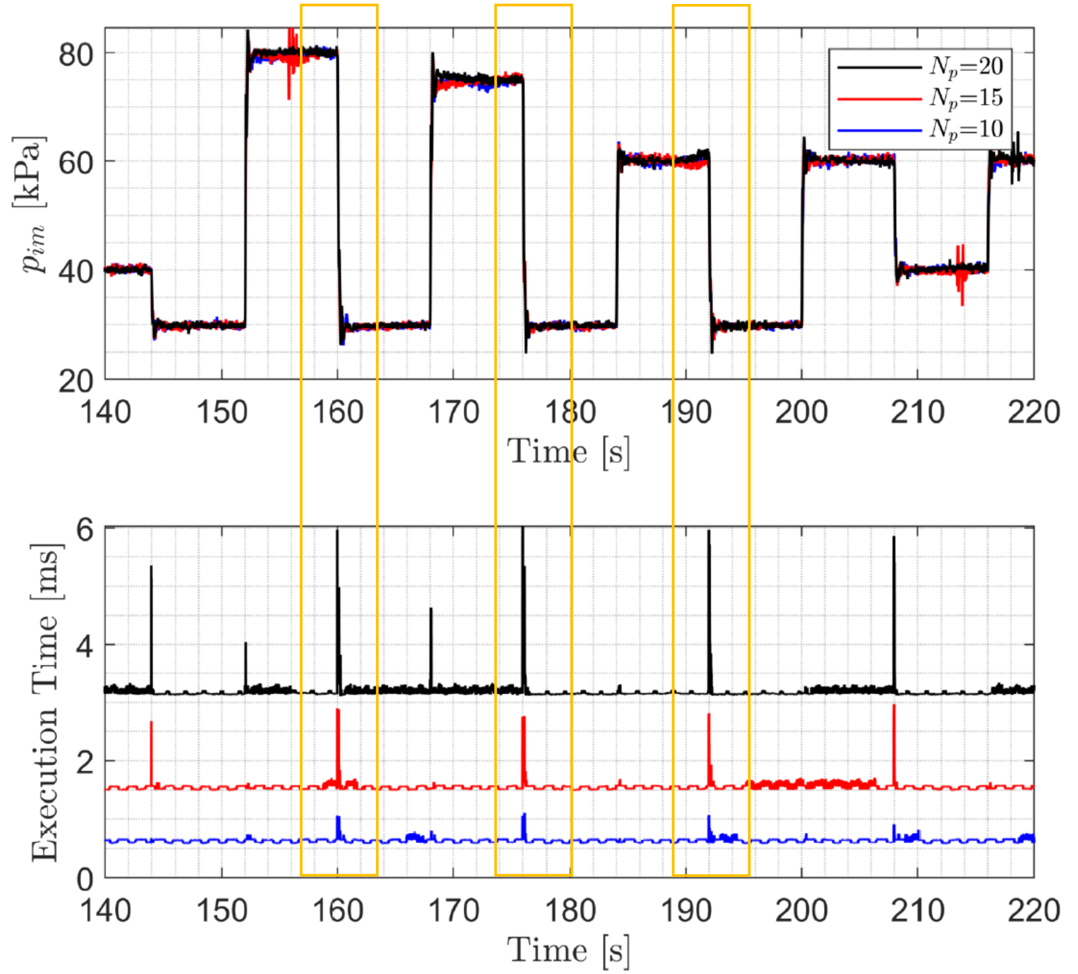
Hardware

- Inline 4 Cylinder 2 Liter SI-Engine
- dSpace MicroAutoBox II (DS1401)
    - PowerPC 750 GL (released: 2004)
    - 900 MHz, 1 MB (L2-cache)

Automated sequence:



Execution Time



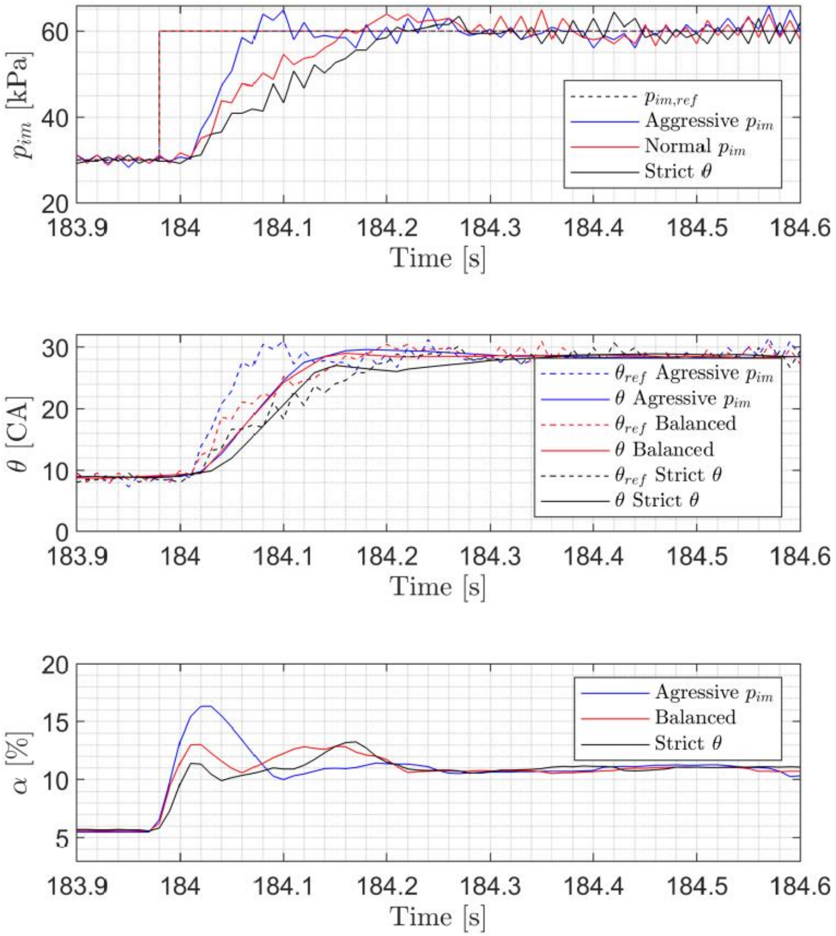
- Longest computation times for negative pressure transients
  - Same preparations -> More QP iterations

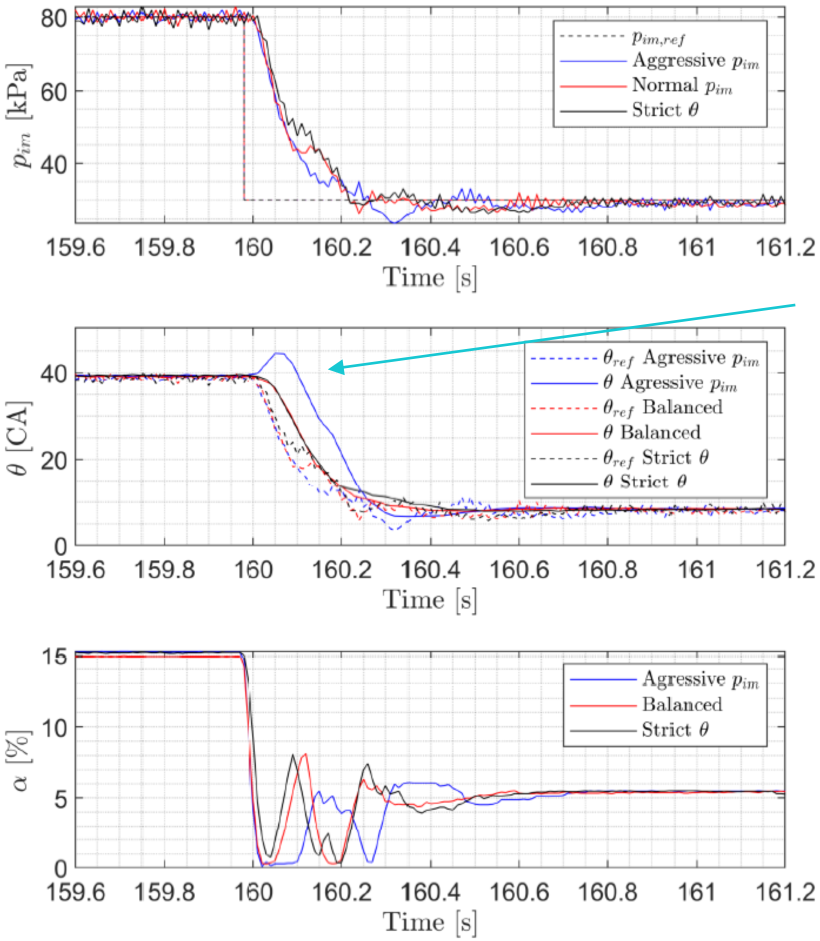
$$\dot{p}_{im} = \frac{RT_{im}}{V_{im}} \left(\overset{\alpha}{\dot{m}_{thr}} - \overset{\theta}{\dot{m}_{cyl}} \right)$$

- Negative transient, close throttle and wait for outflow.
- $\theta = h(p_{im}) \Rightarrow not\ able\ to\ freely\ control\ the\ outflow\ term.$

$$z_1 = p_{im,ref} - p_{im}$$
$$z_2 = \theta - h(p_{im})$$

Different strategies through changing weights





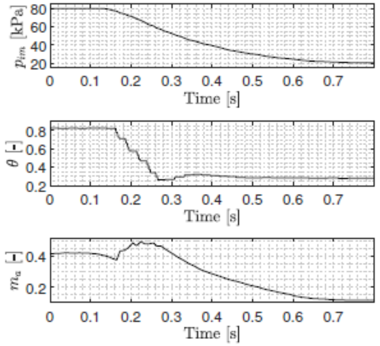
Tries to speed up outflow

Poster

Modeling and Model-based Control of Automotive Air Paths

Robin Holmbom

The strive towards cleaner and more efficient combustion engines, driven by legislation and cost, introduces new configurations, as exhaust gas recirculation, turbocharging, and variable valve timing, to name a few. Beside all the positive effects on the emissions and fuel consumption. They all affect the air-charge system, which increases the cross-couplings within the air-path control, making it an even more complex system to control. As the SI engine uses a three-way catalytic converter, which enforces a condition of stoichiometric combustion, the amount of air flow and fuel flow are connected. This means that the air flow has a direct impact on the driveability of the engine, through the torque.



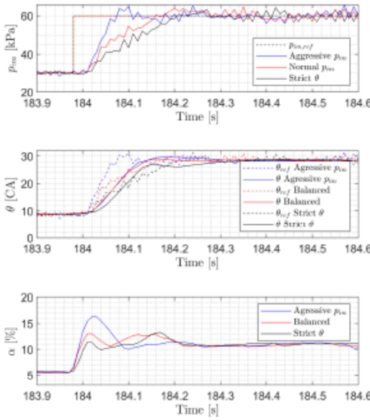
The previous figure is from Paper V[5] and displays the effects on the air mass flow, from the intake manifold pressure and intake cam phasing. The increase in air mass flow corresponds to an unwanted torque increase during the negative transient.

A component and model-based methodology were chosen in the thesis, as it would bring flexibility and the possibility to reuse previous development.

To be precise in the control of the air mass flow, the actuators are also constantly developed and becoming both faster and more precise. One example of this is the wastegate investigation in Paper I[1].

The air-charge system's task is to supply the combustion chamber with the correct air mass flow, in the most energy efficient way. Air mass flow models are investigated in Paper II[2] and III[3], where Paper II focuses on compact compressible flow models, used to model throttles, EGR valves, wastegates, poppet valves, etc.

Paper III focuses on modeling the volumetric efficiency with a dependency on actuation of the cam phasing. In the last part of the thesis, Paper IV[4] and V[5], model predictive controllers (MPC) are used as reference governors to control the system with different constraints active. In Paper IV the throttle is controlled to fulfill an intake manifold pressure demand while keeping down the intake manifold peak temperature.



Paper V demonstrates a real-time implementation of MPC, that controls both the intake cam phasing (θ) and the throttle (α), to fulfill an intake manifold pressure (p_{im}) demand, while having a constraint for the intake cam phasing that depends on the intake manifold pressure. Above figure demonstrates different weights on error in p_{im}, in the MPC formulation, resulting in different behaviors.

Included Papers

- *[1] Investigation of Performance Differences and Control Synthesis for Servo Controlled and Vacuum Actuated Wastegates.* Robin Holmbom, Bohan Liang, Lars Eriksson. SAE 2017 WCX Technical Paper 2017-01-0592.
- *[2] Analysis and Development of Compact Models for Mass Flows through Butterfly Throttle Valves.* Robin Holmbom, Lars Eriksson. SAE 2018 WCX Technical Paper 2018-01-0876.
- *[3] Development of a Control-Oriented Cylinder Air-Charge Model for Gasoline Engines with Dual Independent Cam Phasing.* Robin Holmbom, Lars Eriksson. Submitted to SAE WCX 2022.
- *[4] Throttle Control using NMPC with Soft Intake Temperature Constraint for Knock Mitigation.* Robin Holmbom, Lars Eriksson. E-COSM 2021.
- *[5] Real-Time Implementation of a Intake Manifold Pressure Controller with Dependence on Intake Cam Phaser using Nonlinear Model Predictive Control.* Robin Holmbom, Lars Eriksson. To be submitted.

LINKÖPING UNIVERSITY