Volvo Group Trucks Technology
Esteban R. Gelso
1 2017-02-24
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Outline

- Volvo Group Introduction
- Introduction to the engine control problem
- Diesel engine air path control problem
- MPC Design Process
- Application example
- Conclusions

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The Volvo Group is one of the world's leading manufacturers of trucks, buses, construction equipment and marine and industrial engines. The Volvo Group also provides complete solutions for financing and service.
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The Volvo Group, which employs about 100,000 people, has production facilities in 19 countries and sales of products in more than 190 markets.
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INTRODUCING GROUP TRUCKS TECHNOLOGY

Scope and responsibilities within Volvo Group

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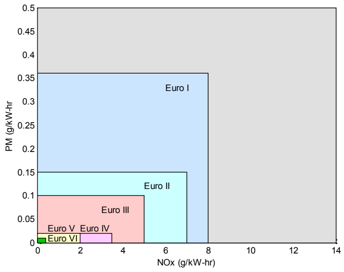
Sustainable transport solution technologies for society today and in the future

RENEWABLE FUELS | ALTERNATIVE DRIVELINES | FUEL ECONOMY | NOISE REDUCTION | SAFETY FOR DRIVERS AND SURROUNDINGS

Introduction

- Environmental requirements of Diesel engines have continuously increased over the last years.
  - *new emissions legislation limits*



For example, emissions of nitrogen oxides (NOx) and particulate matter (PM) have reduced approx. 97% since 1980 with help from the Euro VI* and US10 emissions standards.

*latest European Union directives concerning emission standards for vehicles sold in EU countries.

Introduction

- *Performance and fuel efficiency improvement*
- *Additional hardware*
  - multiple coupled actuators
  - increased complexity of the control strategies, more degrees of freedom available for control
  - systems with several input and output variables

multivariable control

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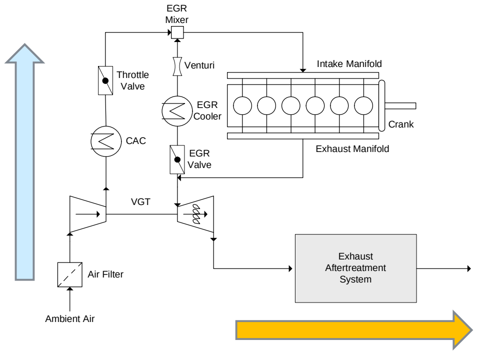
Diesel engine air path control problem

- For example, lets consider the air-path of an EGR-VGT engine



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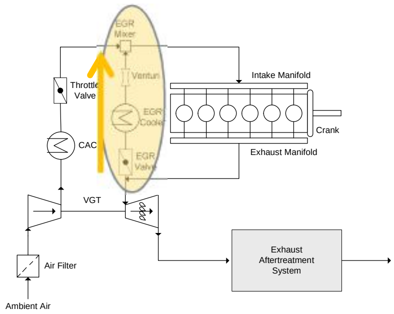
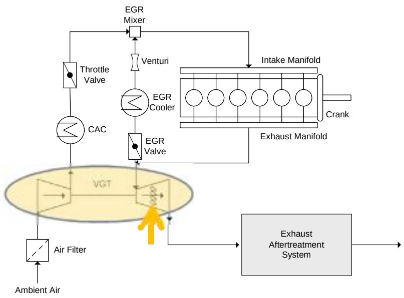
Diesel engine air path control problem



- Exhaust gas recirculation (EGR) has been introduced to reduce NOx emissions
  - *But fuel economy and performance are also affected*

Diesel engine air path control problem



- Variable Geometry Turbochargers (VGT) let control the turbine vanes position and then performance
  - *But fuel economy and NOx emissions are also affected*

Diesel engine air path control problem

- Exhaust gas recirculation (EGR) has been introduced to reduced NOx emissions
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- For example, Variable Geometry Turbochargers (VGT) let control the turbine vanes position and then performance
  - *But fuel economy and NOx emissions*

MIMO system - multivariable control

MPC is a very good alternative!

Diesel engine air path control problem

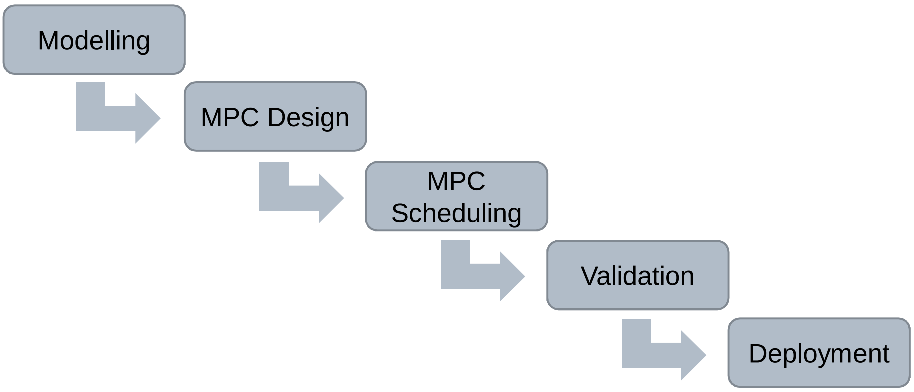
– Very challenging calibration of the traditional open-loop or SISO control loops approaches

+ Model Predictive Control handles constraints explicitly

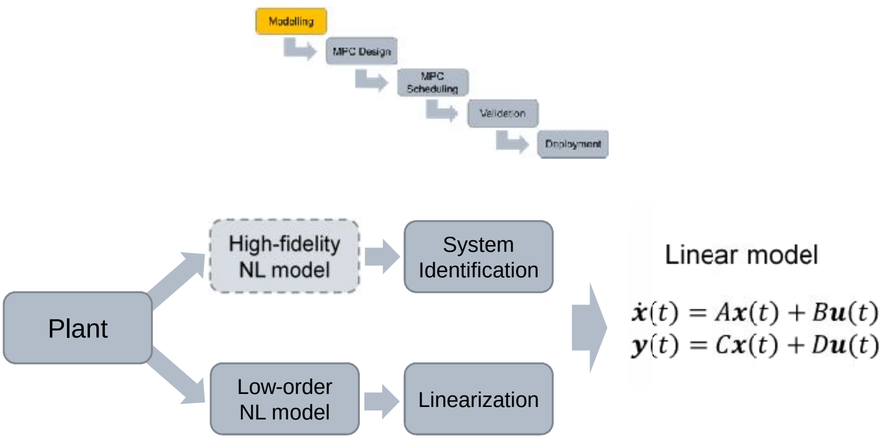
+ Plant behavior in the future predicted using the MPC internal models

– But in general with higher computational complexity and demanding more memory than traditional controllers based on feedforward maps and feedback controllers such as PID

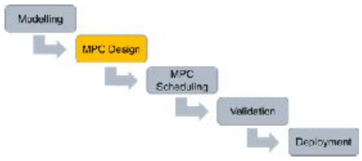
MPC Design Process
Example multilinear case



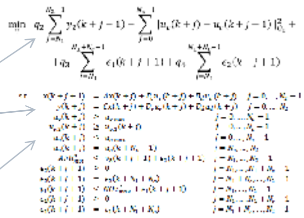
MPC Design Process
Example multilinear case



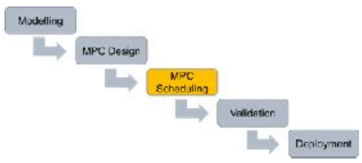
MPC Design Process
Example multilinear case



- The problem is formulated as an optimal control problem with constraints
  - *Cost function (e.g. to minimize fuel consumption)*
  - *Model*
  - *Inequality constraints (e.g. actuator limits)*



MPC Design Process
Example multilinear case



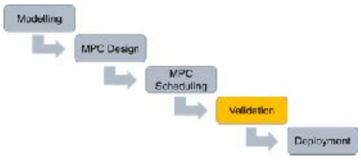
- Multiple linear models at different operating conditions.
- They are used for the design of a gain-scheduled model predictive controller.

Linear models

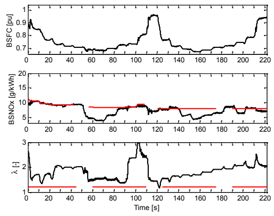
$$\dot{\boldsymbol{x}}(t) = A_i \boldsymbol{x}(t) + B_i \boldsymbol{u}(t)$$
$$\boldsymbol{y}(t) = C_i \boldsymbol{x}(t) + D_i \boldsymbol{u}(t)$$

$$i \in [1, n_{LM}]$$

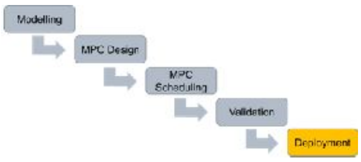
MPC Design Process
Example multilinear case



- Model-in-the-loop and SW-in-the-loop testing
  - *Calibration of the MPC controller*
  - *Validation of the MPC controller performance*

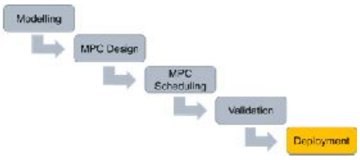


MPC Design Process
Example multilinear case

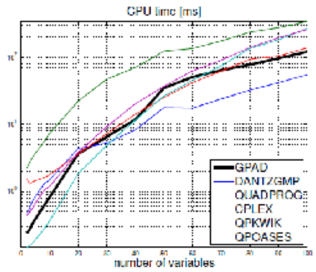


- Generation of code to be compiled to the Embedded System – EECU (engine electronic control unit)
- Implicit MPC → QP solver to be embedded must be fast enough to provide a solution within short sampling intervals (20-80 ms) and require little memory (order of kB)

MPC Design Process
Example multilinear case



- Extremely important to choose a suitable QP solver and keep the number of variables as low as possible.
- We have used among others
  - ➢ CVXGEN tool, Mattingley and Boyd (2012),
  - ➢ FORCES Pro tool, Domahidi and Jerez (2014)



*Bemporad & Patrinos (2012)

MPC Design Process
Example multilinear case

- We reformulate the MPC optimization problem in the form of a standard QP problem, so that it can be solved using an online standard QP solver.
- The MPC problem is stated as

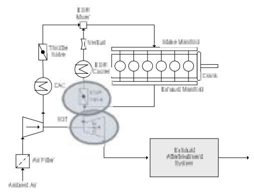
$$\min_U \frac{1}{2} U^T H U + U^T g(w)$$
$$\text{s.t. } GU \leq b(w)$$

with two matrices, the Hessian matrix H and the constraint matrix G; and two vectors depending affinely on a varying parameter w that includes e.g. set-points and input disturbances.

Application example
EGR-VGT engine

Main control objectives:

- *Minimize fuel consumption,*
- *Minimize tracking errors of the fraction of Burned Gases in the intake manifold*



Challenges:

- *Highly nonlinear MIMO system*
- *Fast sampling time (≈20 ms)*
- *Limited memory in ECU*
- *Hard constraints (limits on actuators)*
- *Soft constraints (safety limits, ...)*

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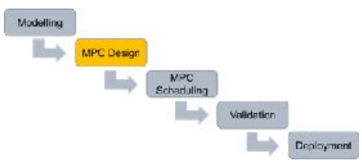
Application example
EGR-VGT engine



$$
\begin{aligned}
\min_{U}\; & q_1 \sum_{j=0}^{N-1} y_1(k+j+1) \\
& + q_2 \sum_{j=0}^{N-1} \left(y_2(k+j+1) - y_2^s(k)\right)^2 \\
& + \sum_{j=0}^{N} \|u_c(k+j) - u_c(k+j-1)\|_{Q_3}^2 \\
& + q_4 \sum_{j=1}^{N} \epsilon(k+j)
\end{aligned}
$$

$$
\begin{aligned}
\text{s.t. } & x(k+j+1) = A_i x(k+j) + B_{c,i} u_c(k+j) + B_{d,i} u_d(k+j) \\
& \qquad j = 0, \ldots, N-1 \\
& y(k+j) = C_i x(k+j) + D_{c,i} u_c(k+j) + D_{d,i} u_d(k+j) \\
& \qquad j = 1, \ldots, N \\
& u_c(k+j) \geq u_{cmin} \qquad j = 0, \ldots, N \\
& u_c(k+j) \leq u_{cmax} \qquad j = 0, \ldots, N \\
& y_{3min}^s(k) \leq y_3(k+j) + \epsilon(k+j) \\
& \qquad j = 1, \ldots, N \\
& \epsilon(k+j) \geq 0 \qquad j = 1, \ldots, N
\end{aligned}
$$

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Application example
EGR-VGT engine – Experimental results*

- 13 L heavy duty Volvo Diesel engine, certified for the Tier 4 final emission legislation
  - For heavy machines like articulated haulers, wheel loaders, and excavators.
- The number of stationary operating points used to obtain the local linear models and cover the entire engine operating region is 192.
- The sampling time is set to 20 ms.
- The prediction horizon is set to 1 s.

* *Gelso, Esteban R., and Johan Dahl. "Air-Path Control of a Heavy-Duty EGR-VGT Diesel Engine." IFAC-PapersOnLine 49.11 (2016): 589-595.*

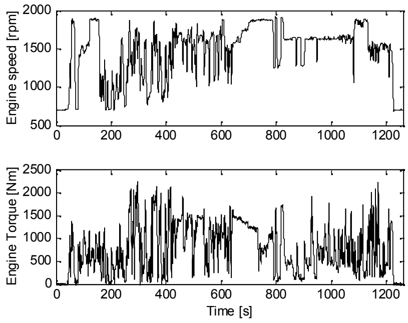
EGR-VGT engine – Experimental results

MPC controller results compared to the ones obtained with a baseline controller.

Baseline controller → standard control structure in industry: feedforward maps + feedback control.

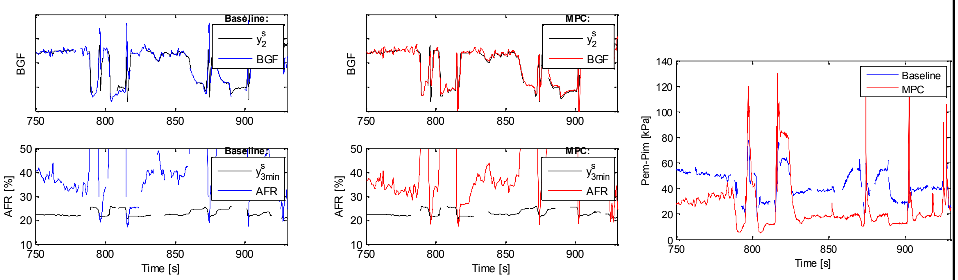
Experimental Results

- Experimentally validated on an engine test bench with the Non-Road Transient Cycle (NRTC), i.e. emission certification transient cycle for non-road Diesel engines.
- Cycle total duration approx. 20 min.



Experimental Results

- Comparison of the outputs during a 3 min transient portion of the NRTC.



	Baseline	MPC
BGF error	1.00	0.84
Pumping losses	1.00	0.65
AFR error	1.00	1.06
Cycle energy	1.000	1.004
BSFC	1.000	0.958
BSNOx	1.00	1.04
BSSoot	1.00	0.91
Mean exh.temp	1.00	1.08

Conclusions

- MPC successfully applied to the air-path control problem of Diesel engine
  - It can signicantly reduce the engine optimization time and at the same time improve e.g. transient response
- MPC controllers fitted in production ECUs and run in the order ms
  - Validated through real-world experiments in engine test bench and in vehicles
- Different engine concepts have been tested
  - Excellent performance