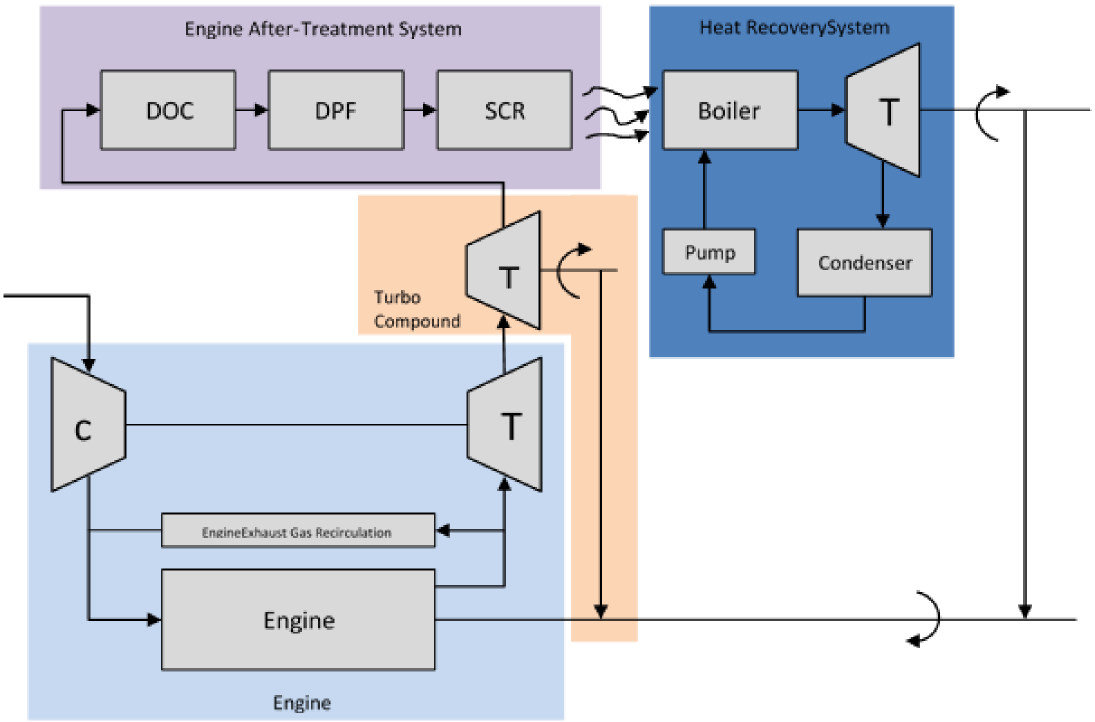
MultiMEC

Multivariabla metoder för energieffektiv motorstyrning

Publik rapport



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Projekt inom Komplex Reglering, Vinnova FFI

FFI Fordonsstrategisk Forskning och Innovation

Innehållsförteckning

För närvarande finns fem delprogram; Energi & Miljö, Trafiksäkerhet och automatiserade fordon, Elektronik, mjukvara och kommunikation, Hållbar produktion och Effektiva och uppkopplade transportsystem. Läs mer på www.vinnova.se/ffi.

Sammanfattning

Fordonsindustrin står idag inför en funktionstillväxt som kräver reglerstrategier som klarar av att hantera stora och komplexa system. Med en passande och modulär reglerdesign, så kan systemet växa, vilket möjliggör integration av ny teknologi. Det är också viktigt att hitta nya och tidseffektiva sätt att utveckla reglersystem, lämpliga för fordonsindustrin. Den bärande idén i detta projekt är att man framgångsrikt kan reglera komplexa system genom att använda sig av ett holistiskt synsätt i reglerdesignen, med användning av modellbaserade reglermetoder, som bygger på optimal styrning. Syftet med projektet är att realisera ett modulärt reglersystem för ett motorsystem som består av en motor, ett avgasefterbehandlingssystem och ett waste-heat-recovery system (enbart för tunga fordon), för att definiera en utvecklingsplattform för design av reglersystem som riktar sig mot komplexa system inom fordonsindustrin.

Executive summary in English

To cope with vehicle functionality grow a control strategy design methodology addressing large and complex control systems needs to be developed. With a proper and modularized control design the system has a possibility to grow, making new technologies possible to integrate during system evolution. It is also important to find efficient and time saving ways of developing control strategies suitable for the vehicle industry. The research hypothesis behind the proposal is that the control of a complex system may be successfully approached by adopting a holistic view in control system design and by using more powerful control strategies, which are model based and optimal control oriented. The aim with the project is to realize a modularized control system for an engine system, which includes an engine, an exhaust gas after-treatment system and, only for heavy duty vehicles, a waste heat recovery system, to define a control system design platform for complex systems within the vehicle industry.

Bakgrund

Due to higher demands on fuel economy and emissions, the engine related functionality in software is continuously growing. As a consequence, dependencies between functionality become hard to understand and the effort to further evolve the system becomes unmanageable. Most of the control functions today are typically developed heuristically with rule based solutions. Such an approach makes both the control functions development and the calibration time consuming since it is done mainly by physical testing. In addition, automotive control systems need to handle a large variety of vehicle and engine configurations in an efficient way.

To cope with the functionality growth a control strategy design methodology addressing large and complex control systems needs to be developed. With a properly modularized control design the system has a possibility to grow and new technologies and subsystems can be integrated in an efficient way to improve fuel economy.

This project will focus on a system consisting of the engine, exhaust gas after-treatment system (EATS) and, only for heavy duty applications, a waste heat recovery system (WHRS). In the future all vehicle will be connected to information systems and have navigation systems that can predict future power demand from engine. The controller will take the predicted power demand into account in order to improve fuel efficiency. Considering the complete engine system is from a control performance point of view a challenge since it has not been done before. The complexity of such a system is multifaceted. The time scales for important dynamic behavior ranges from milliseconds when considering emission formation to hours for long term look-ahead information. Most involved processes are highly non-linear and many control objectives are conflicting.

Also embedded system properties need to be taken into consideration, which e.g. include signal processing and execution loop time. Sensors that would improve control performance might be lacking due to product cost savings, which mean that states have to be estimated on-line. Also product variants and control system modularity need to be handled. The control system design aspects to deal with in the project are many and are the reason for the need of a complex control methodology.

Design of large-scale control systems has attracted attention by the control systems research community in the recent decade. The overarching objective is to provide systematic principles and tools that address the “curse of dimensionality” and provide reasonable guarantees of stability and performance. The research efforts are intense and deal with e.g. hierarchical, decentralized or distributed systems, coordination and autonomy, networked control systems, plug-and-play concepts etc. Each of these subfields is focused at special scientific events and in journal special issues, see e.g. (Antsaklis & Baillieul, 2004), (Johansson & al, 2014), (Hadjicostis & al, 2008), (Baheti & Gill, 2011), (INRIA, u.d.). One of the recurring themes of this current trend is that optimization often becomes a natural part of the design approach, and there are therefore strong ties with techniques for distributed optimization. One example of this is Model Predictive Control. It is believed that some of the research results in this area have relevance for the challenges underpinning this proposal, both in general and for the selected case study. One reason for this belief is that the challenges met in the automotive industry share some of the characteristics mentioned above; another reason is that the computational power available for on-board control functions is constantly growing, opening up for systematic approaches based on mathematical models and online optimization and adaptation.

The robustness issues for engine management systems have been dealt with in the FFI Project Robusta motorsystem (FFI-Project, 2011) as well as in the EU funded project CORE (EU-Project, 2012) addressing model based control of air-path system. However, these works have not considered the full integration with EATS and heat management systems, but only considered the constraints given by those.
In this project proposal the scope is expanded to comprise the engine and after-treatment systems as an integrated system and consequently to develop a supervisory control strategy to enable robustness to emission control and decrease fuel consumption. Control of such engine systems have been presented lately (Junqiang, Fiorentini, & Canova, 2014), (Murgovski & al, 2014), (Willems, 2012), (Tayamon, 2014), (Chen & Wang, 2013), (Zhao, o.a., 2014), (Huang, Nakada, Butts, & Kolmanovsky, 2014), which could be regarded as a state-of the art for the control of the technology system, however, several control solutions consent to monolithic control design structures which are less appropriate in industry systems, since they can be hard to implement and change during technology evolution. The scope for this project will therefore also include modularity of the control system. Additionally, the aim is to make use of look-ahead information of e.g. time left until next stop and the upcoming vehicle torque need, in order to improve the control of the system further, when possible.

Syfte, forskningsfrågor och metod

The research hypothesis behind this project is that the control of a large and complex system may be successfully approached by adopting a holistic view in control system design and by using more powerful control strategies, which are model based and optimal control oriented. To increase the control system efficiency over time the control system should also be able to utilize predictions, whenever possible. The idea is that a model based control design will also shorten development time, since parameterization and tuning of the system to a great extent is built-in in the control strategy by means of control models. The control system design needs to take many aspects into account, e.g. system dynamics, system constraints, choice of controllers and control models, variant handling, and continuously evolving technology. Hence, a generic control system design methodology is needed.
The purpose of this project is therefore to design a methodology to cope with the issues depicted so far. As we will discuss later on, the selected method is based on supervisory control techniques.

Mål

The main objectives of the project are:

- design a modularized control system for an application consisting of an engine system comprising engine with turbo compound and heat recovery systems (only for heavy duty applications) as well as after-treatment systems
- include the use of look-ahead information into the control design to improve the system performance of the engine in typical vehicle applications
- develop tools and guidelines for effective application of advanced control strategies in automotive systems
- enhance knowledge and experience of introducing advanced, multivariable, optimal, predictive and model based control methodology in an industrial context

The project proposes a joint venture where industry and university work together. By this, the research and innovation activities in the region will increase.

Meets general FFI objectives

Energy efficient combustion engine systems fulfilling emissions requirements is core for the Swedish automotive industry and a major objective within the FFI program. Furthermore, new methods that substantially reduce lead times is of great importance and relevance.

Meets specific objectives for FFI Complex Control

The project proposal is defined within the Program Complex Control and is aligned with the mission to develop a methodology for control engineering and control function integration, Figure 1. The most relevant research field for the project is to Combine Control Engineering and Systems Engineering Development to find a structured way to derive a modularized control system design for large systems with different applications. The project also covers the research areas Modular function architecture, and Environment for virtual development, simulation and verification, since the project scope also includes functional architecture as well as development of models suitable for control.

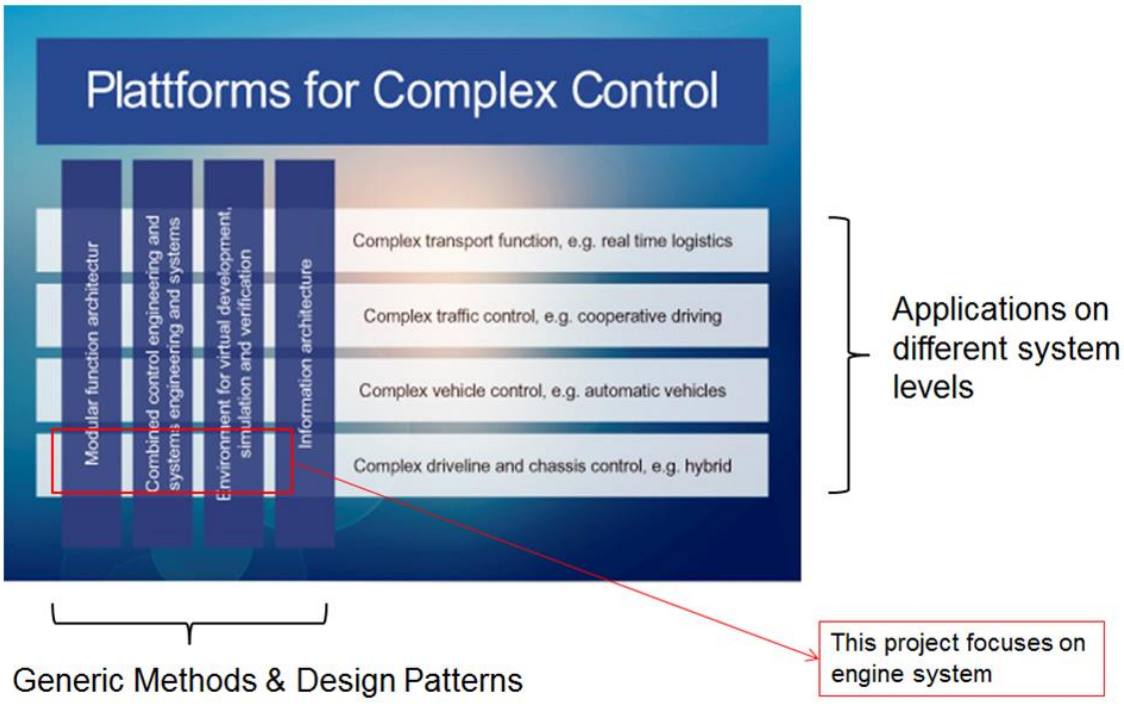


Figure 1: platform for complex control

Project contents
The project will consist of the following work packages:

WP1 System analysis and case study preparation

WP2 Control system structure and model abstractions

WP3 Control realization and calibration

WP4 Guiding principles for design of complex control systems

WP5 Assessment of control system design and guiding principles

WP6 Project coordination and dissemination

In WP1 a system analysis of the use case consisting of the engine system, engine after-treatment system and heat recovery system (only for heavy duty vehicles) will be made. WP1 also includes the setup of the simulation environments as well as the development of the prediction functionality based on the look-ahead information.
WP2 comprises the control system design synthesis.
WP3 will contribute with the realization of the proposed control system design and its calibration.
WP4 is aiming at formulating the control system design guidelines, whereas an assessment of both the guidelines as well as the proposed control strategy will be performed in WP5.
WP6 handles Project coordination and dissemination. WP1-WP5 are closely related and especially WP2-WP5 are large where the majority of the work will be performed. Most of the deliverables will not be ready until the end of the project. To assure project progress, milestones will be defined that will align the different work packages throughout the project.

Resultat och måluppfyllelse

WP1 System Analysis and case-study preparation

In this WP we perform a system analysis, we describe the addressed case studies and we formalize the problem of the common software platform development. Due to the different application requirements, we separate the cases of heavy duty powertrains (e.g. trucks, buses, etc.) and light duty powertrains (e.g. passenger cars).

Heavy duty powertrain

The powertrain considered for heavy duty application includes a Turbo-Compound (TC) engine, an after-treatment system (EATS) and a waste-heat recovery system (WHRS) as shown in the picture.

Engine

The engine concept that will be used in the project is a turbo compound (TC) engine showed in the following Figure.

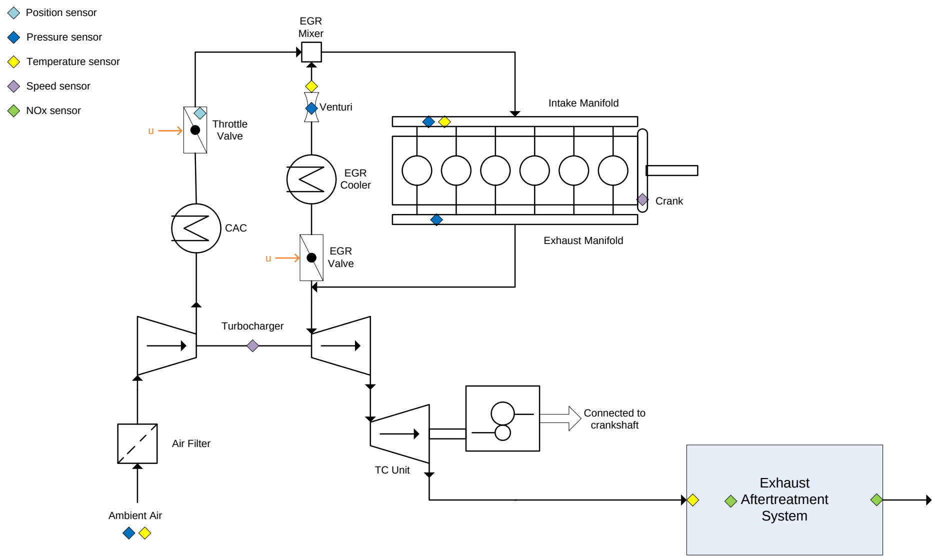


Figure 2 TC engine layout

Main components

- Air filter: it supplies filtered air to engine. This module also contains the ambient air temperature sensor.
- Turbocharger: a turbocharger is used to force extra air into the combustion chamber, and in this way, to increase the engine efficiency.
- Charge Air Cooler (CAC): heat exchanger to remove the heat of the compression and then, in this way, to increase the engine efficiency. It improves air temperature and its density.
- Intake Valve Throttle: it is mainly used for heat management. It could be used also for engine brake.
- Venturi: the Venturi is used for exhaust gas recirculation (EGR) rate calculation by using the delta pressure sensor over the Venturi and the EGR temperature.
- EGR cooler: the EGR cooler is used to increase the EGR rate efficiency.
- EGR valve: the EGR valve controls the EGR gas flow, and then, reduces nitrogen oxide (NOx) emissions by recirculating part of the exhaust gas back to the engine cylinders.

Sensors and actuators

Sensors	Estimated states	Actuators
• Ambient temperature. • Boost (intake manifold) temperature. • Coolant and oil temperatures. • EGR temperature. • Engine out temperature. • Ambient pressure. • Boost (intake manifold) pressure. • EGR delta pressure (Venturi). • Throttle valve position. • Engine speed. • Turbo speed. • Engine out NOx (in EATS). • Intake throttle position	• Air mass flow. • EGR mass flow. • Engine torque.	• EGR valve • Common rail injectors to combustion chamber

Table 1 Sensors and actuator layout for the TC engine

Limits of the system

- EGR valve position aperture between 0% and 100%.
- Inlet throttle valve position aperture between 0% and 100%.
- Minimum inlet throttle valve position limit of approx. 30%.
- Maximum torque as function of engine speed:

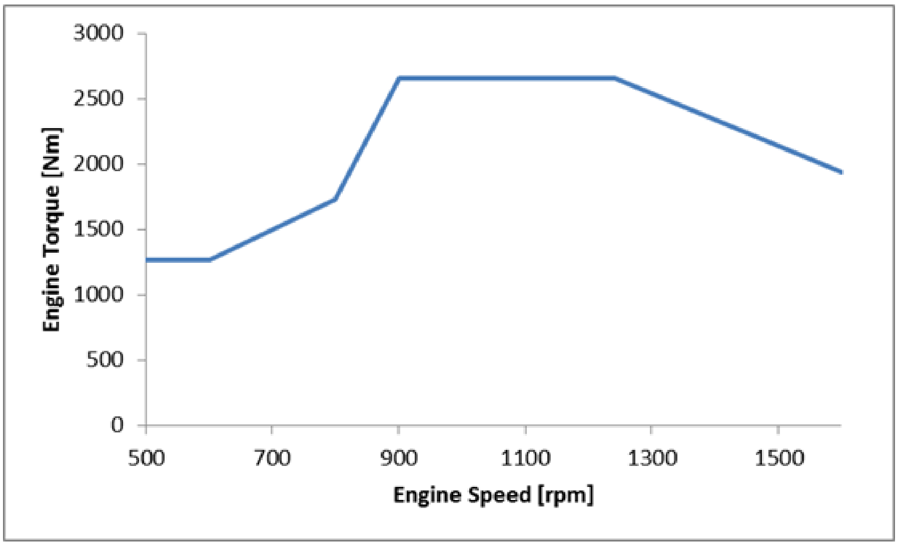


Figure 3 TC Engine speed-torque curve

EATS

The EATS system is depicted in the following Figure.

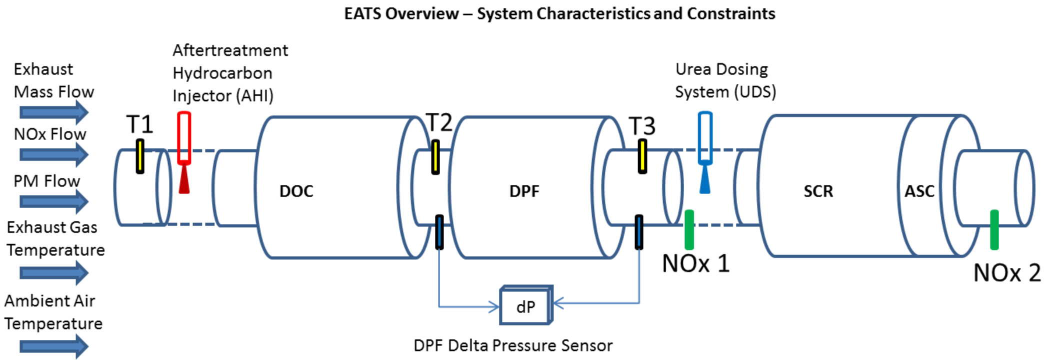


Figure 4 EATS system layout

Main Components

DOC – Diesel Oxidization Catalyst

- Conversion of NO to NO2.
- Conversion of CO.
- Conversion of HC from the engine exhaust.
- Conversion of HC injected from the AHI to produce heat.

DPF – Diesel Particulate Filter

- Collects soot and ash from the engine.
- Soot can be regenerated, passively using NO2 or actively using O2 and AHI injection.
- Ash consists of non-combustionable matter such as cheramics or metallic particles and therefore can only be removed in workshop or laboratory.

SCR – Selective Catalytic Reduction

- The type of SCR is CuZe (Copper-Zeolite)
- Converts NOx using NH3, formed from the injected urea.
- The CuZe SCR has a high NH3 buffer capacity
- The NH3 buffer characteristics of the CuZe SCR is highly non-linear
    - A powerful heat increase over the SCR will quickly releases the stored NH3, with the risk of emitting too high levels of NH3 or N2O from the system.
- NH3 slip from the SCR to the ASC should always be avoided, using suitable control strategies when possible.

ASC – Ammonia Slip Catalyst

- Efficiently converts excessive NH3 entering from the SCR into N2, H2O and to some degree N2O.

Sensors and actuators

Sensors	Estimated states	Actuators
• Exhaust Gas Temperature Sensor (T1) • DOC Out Temperature Sensor (T2) • DPF Out Temperature Sensor (T3) • DPF Differential Pressure (dP) sensor • SCR Inlet NOx Sensor (NOx 1) • SCR Outlet NOx Sensor (NOx 2)	• EATS temperature distribution including oxidization of injected AHI fuel • NH3 buffer distribution in SCR • The soot load within the DPF • Air mass flow. • EGR mass flow. • Engine torque. • NOx levels before and after the SCR. • NO/NO2 stoichiometric ratio.	• NOx levels before and after the SCR. • NO/NO2 stoichiometric ratio.

Table 2 Sensors and actuators layout for the EATS system

Limits of the system

General system constraints:

- 200 °C ≤ DOC Temp (T2) ≤ 700 °C (For best conversion efficiency)
- 200 °C ≤ DPF Out Temp (T3) ≤ 500 °C (For best conversion efficiency)
- DPF Out Temp (T3) ≤ 500 °C (Temp protection during normal operation)
- 200 °C ≤ SCR Temp ≤ 500 °C (For best conversion efficiency)
- SCR Temp < 500 °C (Temp protection during normal operation)
- 0 g/s ≤ Urea Flow ≤ 2 g/s (Based on max urea dosing flow limitation)
- DPF Regeneration Required Occasionally (Depending on drive cycle)

System constraints during regeneration:

- 230 °C ≤ Exhaust Gas Temp (T1) (Min allowed temp for AHI injection)
- 230 °C ≤ DOC Temp (T2) (Min allowed temp for AHI injection)
- 550 °C ≤ DPF Out Temp (T3) ≤ 600 °C (Target temp for DPF soot regeneration)
- 0 g/s ≤ AHI Flow ≤ 2 g/s (Based on AHI max flow limitation)
- Exhaust Mass Flow ≥ 0.1 kg/s (Needed for sufficient oxygen supply)

Base of technical solution and local control tasks

The TC produces torque that sum up to the torque generated by engine with the aim of reducing the fuel consumption while ensuring certain driveability constraints, while the EATS tries to reduce the emissions produced by the combustion process in the engine.

The Engine and the EATS are considered as components controlled by the same Electronic Control Unit (EECU). Therefore, the set Engine, EATS and EECU is viewed as a unique system.

WHRS

The considered WHRS is based on the Rankine cycle. The system layout is depicted in the following Figure.

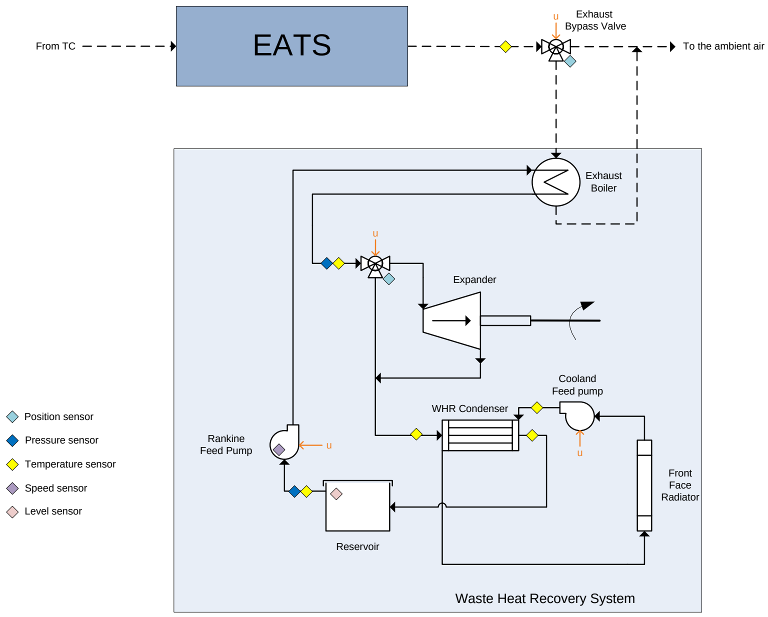


Figure 5 WHRS layout

Sensors and actuators

Sensors	Actuators
• Exhaust boiler IN gas temperature • Exhaust boiler OUT WF temperature • Condenser IN WF temperature • Condenser OUT WF temperature • Condenser coolant temperature • Pump IN WF temperature • Exhaust boiler OUT WF pressure • Pump IN WF pressure • Expander by-pass position • Exhaust by-pass position • WF pump speed • Condenser pump speed • Tank level sensor	• WF pump • Condenser pump • Exhaust boiler bypass valve • Expander bypass valve

Table 3 Sensors and actuators layout for the WHR system

Limits of the system

- Max working fluid pressure 30 bar
- Max working fluid temperature 230 °C
- Minimum working fluid pump speed 150 RPM
- Maximum working fluid pump speed 1400 RPM
- Cooling pump is ON/OFF type.
- Exhaust bypass valve aperture between 0% and 100%.
- Expander bypass valve ON/OFF aperture.

Base of technical solution and local control tasks

The WHRS considered in this project is based on the Rankine cycle. Such a thermodynamic cycle converts heat into mechanical work. The conversion is performed by exploiting the change of state of a working fluid (WF), which here is ethanol. A Rankine system includes a tank filled with a WF, a vaporizer, an expander and a condenser connected in a loop through pipes, and an external source of heat.

In the proposed implementation of the Rankine system the external source of heat is given by the exhaust gas flowing out from the EATS. Such a source of energy supplies an exhaust boiler that convert the WF into steam. The steam in the outlet of the exhaust boiler passes through a turbine that generates mechanical energy. The discharged steam at the outlet of the turbine is converted again into liquid through a condenser, and it flows back into the tank. The condenser is connected to the radiator in front of the vehicle. The tank is vented at atmosphere pressure to avoid possible leakages. The WF used in this implementation is ethanol. Although other WHRS architectures consider an additional boiler in the EGR channel, here we consider only a boiler located at the outlet of the EATS.

A major problem in Rankine cycles is that the expander may get some liquid into it, or that the pump may get vapor into it. Therefore, in the developed technical solution it is possible to regulate the exhausted gases mass flowing into the exhaust boiler through a proportional valve and the working fluid mass flow entering the turbine through on/off valves. To have a cheaper and easier solution, no proportional valve is used to control the mass flow through the turbine. Another problem is that the available heat power that can be harvested from the exhaust gas depend on the engine and EATS state. The control strategy shall take into account of these issues.

The local controller uses the working fluid pump and the exhaust bypass valve to track a constant super-heat set-point at the inlet of the expander. The expander bypass valve is not opened for all the time, but it is kept opened as long as the superheat is greater that a certain threshold for a sufficiently large time. Finally, if any of the system limit is violated (e.g. the working fluid temperature becomes more than 230 °C), then the controller will take a corrective action before coming back to its nominal mode. Therefore, the system operates in two modes: power generation or not.

Simulation platform for the heavy duty system

Within this WP, a high-fidelity simulation platform has been developed. Such a simulation platform is used as test-bench for evaluating in WP5 the developed software platform in WP2 and WP3.

The developed simulation platform includes a TC engine model connected with an EATS, a WHRS and a virtual ECU. The user can choose between a GT-Power and a Volvo proprietary format called ENE-dyn of the TC engine. The first is slower but more accurate whereas the latter allow fast simulation but it lose accuracy. Nevertheless, due to its speed, the ENE-dyn model is very appealing during the control design phase addressed in WP2.

The virtual ECU locally contains the production control software for the whole powertrain. This choice is dictated for placing the controller developed in WP2 and WP3 a higher TRL level.

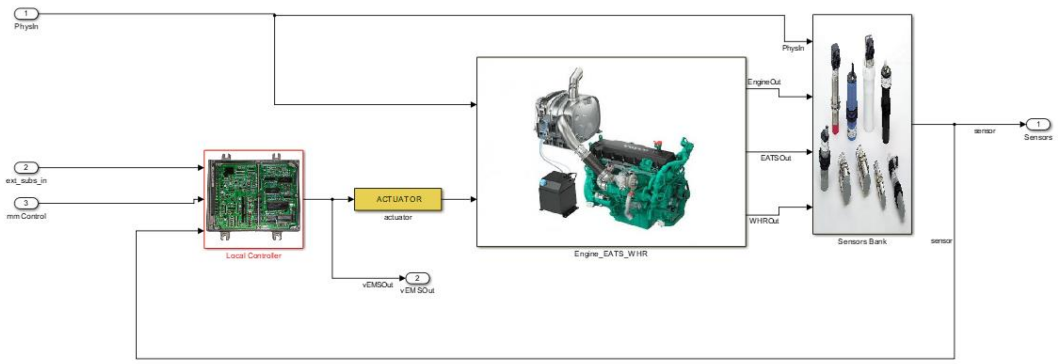


Figure 6 Heavy duty team simulation platform

Light duty powertrain

The analysis of the powertrain has been carried out in a manner such that the hardware is broken down into significant subsystems, as depicted in the following Figure.

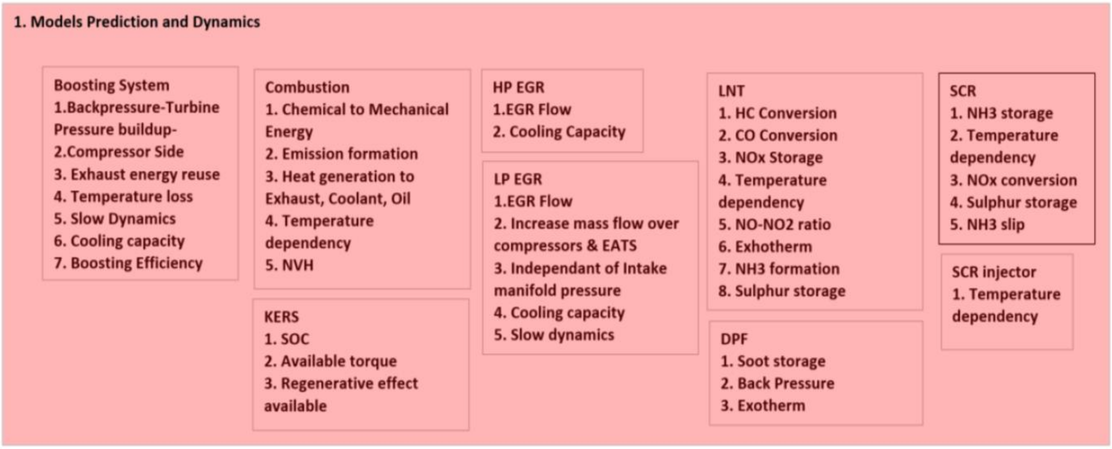


Figure 7 Light duty team system layout

Sensors	Actuators
• AMM - Air Mass Meter @ Intake Air Filter • AHS - Ambient Humidity Sensor? @ Intake Air Filter • IAT - Intake Air Temperature Sensor @ Intake Air Filter • EGR dp - Differential Pressure Sensor @ Across the LP EGR Cooler & Valve • TMAP - Manifold Air Pressure and Temperature @ U/s HP compressor • TMAP - Inlet Manifold • EMAP - Exhaust Manifold • Lambda 1 - D/s LP turbine • Lambda 2 - D/s LNT • NOx Sensor - D/s LNT • DPF dp - Across the SCRF • NOx sensor - D/s SCR • Soot sensor - D/s SCR	• LP-EGR throttle - Throttle Valve @ D/s Air Filter before LP EGR Valve • LP EGR Valve - D/s LP EGR Throttle • LPC bypass -Valve • LP VNT - M - Motor @ D/s LP EGR mixing • HPC bypass - Valve @ High Pressure compressor • HP VNT - M - Motor • Throttle A - U/s Charge Air Cooler • Swirl throttles - Cylinder head • EMAP - Exhaust Manifold • EGT - U/s SCRF • SCR injector - U/s SCRF

Table 4 Sensors and actuators for the light duty system under examination

The analysis of the powertrain has been carried out in a manner such that the hardware is broken down into significant subsystems, as depicted in Figure 7.

Boosting System

The boosting system of the engine is necessary to increase the fuel efficiency of down sized engines by recovering exhaust energy using a turbine to compress inlet air. At the same time it provides for an

increased power density by increasing air mass into the engine compared to naturally aspirate atmospheric air and hence more fuel can be injected to obtain higher power.
The chosen concept has a two stage Variable Nozzle Turbocharger (VNT) with the possibility to bypass the high pressure compressor.
A significant challenge in utilizing the exhaust energy is to maintain a relative high exhaust pressure compared to the inlet pressure. This is to enable the flow of the High pressure EGR in the intended direction to mix with the inlet fresh air.
The VNT allows for a much flexible variation of the air pressure (exhaust and inlet) by changing the nozzle geometry. The feedback from the system is by the Air Mass Meter (AMM) and the Manifold Air Pressure sensors (TMAP and EMAP).
The time taken to reach the set point targets for the VNT subsystem is slower in comparison to combustion due to the constraints listed above, thus having the slower dynamics.
Maintaining Backpressure on the turbine side is significant for operating the High pressure EGR. Effective EGR flow can only be obtained when the intake manifold pressure is lower than the Exhaust Manifold (HP EGR side). The exhaust flow through the High pressure and Low pressure turbine needs to be constrained limiting the amount of exhaust energy that can be recovered
To compress intake air increasing the fresh air mass so as to achieve the desired engine power with fast and smoother response. The by-pass valves are used to skip the high pressure compressor at low loads.
The exhaust energy is conserved by driving the exhaust turbine which is used to compress the intake air, reducing the pumping losses and increasing engine efficiency
Using the exhaust energy to drive the turbine by expansion cools down the exhaust gases which becomes a disadvantage for the after-treatment system
In comparison to combustion, the boosting system has slower dynamics in that it needs to accommodate the constraints listed above and is physically a slower process.
The intake air after being compressed needs to be cooled down to keep emissions and engine efficiency in check.

Combustion System
The fuel energy is converted to mechanical energy which is the prime objective of the diesel engine.
The undesired phenomenon of harmful exhaust resulting from combustion is dependent on in-cylinder combustion. Nearly a third of the fuel energy generated from combustion is lost to exhaust, coolant and oil.
Combustion process is heavily dependent on temperature (intake air, in-cylinder temperature).
Diesel engines are generally considered noisy and a significant efficiency loss is accepted to enhance the NVH performance of the diesel engine.

High Pressure EGR
The EGR flow determines the in cylinder NOx generation and the maximum possible flow is dependent on the differential pressure between the intake and exhaust manifold. Disadvantages include lowering the exhaust temperature for the EATS.
The Exhaust gas is cooled by the cylinder block so that the net effect of the mixed intake air temperature is controlled for better combustion efficiency. Also noteworthy is that soot accumulation is possible in this case due to sourcing the gases before the DPF.

Low Pressure EGR
The flow depends on the valve and the differential pressure although the exhaust is expected to almost always have a slightly higher pressure since the mixing occurs before the compressors and the intake air can be throttled.
Advantageous is that heat loss for EATS is lower compared to the HP EGR, although it might have an undesired ammonia in the recirculated gases.
The flow is independent of the intake manifold pressure and hence allows for better turbocharger operation due to reduced constraints compared to the HP EGR.

The EGR cooling necessary is lower compared to HP and is much cleaner in comparison. Risk for ammonia entering the cooling system needs to be considered.
The LP EGR is slower in response than the HP due to the longer path. Hence response time is significantly lower.

Kinetic Energy Recovery System (KERS)
The battery is efficient only at a certain range and has to be considered while regulating the SOC. Using the prediction horizon, a greater usage of the energy recovered can be optimized. SOC needs to be depleted in case prediction of probability for frequent charging is higher.
The available torque could be generated from either the engine or the KERS system. The maximum amount of regeneration is hardware limited.

Lean NOx Trap (LNT)
HC generated will fully with late post injection is used to react with the stored NOx for NOx conversion. The amount of fuel required depends on the NOx stored. Unintended HC emissions are oxidized with excess oxygen. CO is oxidized during the lean burn phase. NOx storage of the LNT is fixed and degrades over life time. Conversion efficiency depends on the temperature. An optimum NOx stored is desired considering the SCR downstream. NOx conversion efficiency is heavily temperature dependent. The prime design reasoning is to have an effective NOx reduction during the colder downstream SCR phases. Regeneration or NOx conversion occurs at the expense of fuel which increases the temperature to around 750-800°C. This needs consideration since this will cause the heat increase in the rest of the system which needs to be done in a more constructive manner. Ammonia formation during regeneration phase occurs which can have significant advantage if it can be passed on to the SCR for further NOx conversion or efficient NH3 storage.
Undesired sulfur poising reduces the NOx conversion efficiency of the system and also requires high temperature regenerations thereby costing additional fuel. Thermal ageing decreases LNT efficiency and reduces NOx storage also.

Diesel Particulate Filter (DPF)
Soot generated needs periodical thermal regeneration by spending more fuel. An optimum regeneration time and soot limit can be considered since the thermal events are occurring in other EATS as well as increased soot will cause increased back pressure. The catalyzed DPF increases overall exhaust temperature while undergoing thermal regeneration thereby increasing temperature downstream. The NH3 storage and soot storage time cycles need to be timed appropriately to have a low overall cost.

Selective Catalytic Reduction (SCR)
Ammonia storage is a function of SCR temperature. Conversion efficiency and storage are directly dependent on temperature and exhaust flow. NOx conversion is dependent on NH3 storage, flow and temperature. Oxides of sulfur accumulated in the SCR arising from the fuel decrease the SCR efficiency. An increase in temperature or urea injection after the maximum capacity will give rise to NH3 slip, thereby increasing running cost.

SCR injector
The AdBlue solution conversion to ammonia requires a threshold temperature around 180°C and the maximum quantity is limited to avoid deposit formation in the pipe or in the catalyst.

Simulation platform for the light duty system
A simulation based approach has been used for the development and evaluation of the software platform for complex control. To develop engine models, data from part-load mapping of the engines has been used. Exhaust pipe models from the thermal modeling of the exhaust system have been used. The SCR and LNT models could be used from both the in-house resource or from supplier developed models. Such

a simulation platform also enables software in loop simulations when engine software is available from the supplier. The schematic used for the controller development is shown in Figure 8.

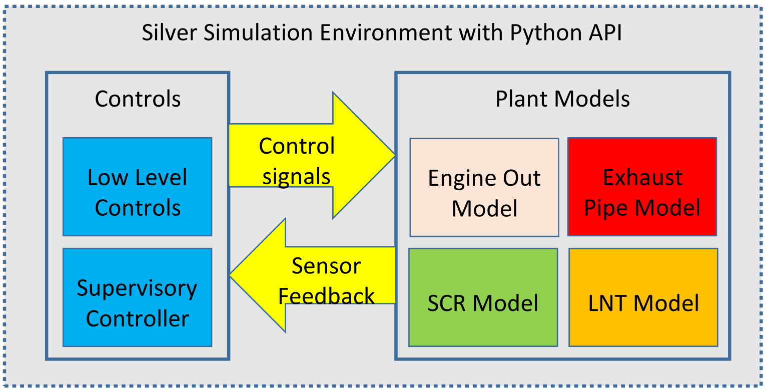


Figure 8 Light duty team simulation platform

Case studies

The assessment of control system design platform will consider the following aspects (see WP5 for a detail description of the assessment metrics)

- Control system performance, where engine system requirements must be fulfilled;
- Ability to handle product variants;
- Number of calibration parameters as well as the physical understanding of the same;
- Estimation of development and calibration time;

Such aspects are evaluated by comparison of the MultiMEC methodology VS a baseline technology within WP5, where an assessment matrix has been defined. We refer to baseline technology the current state-of-art in control system design and software development.

For both the heavy and the light duty applications the control performance embraces three competing constraints: emission level, fluid consumption (that is diesel plus AdBlue) and driveability. Such constraints are competing in the sense that the improvement of one penalizes the other two. For example, it is possible to reduce the emission by simply burning a higher quantity of fuel.

Nevertheless, although the competing constraints are the same for both the applications, they are evaluated by considering different case studies due to the different operation of heavy duty vehicles compared to light duty vehicles. For heavy duty vehicles we consider two powertrain configurations: one equipped with WHRS and one without it whereas for light duty we consider three different case studies as we discuss next.

The first case study for light duty applications is devoted to the control of the EATS. NOx emission management is considered in this part of the problem and Soot is excluded. The fuel and Adblue consumption balance for the effective operation of the EATS system is considered. The resultant formulation should result in an Equivalent Consumption Minimization Strategy (ECMS) of the EATS and include look ahead information incorporated in the control. Thus a single controller with and without the look ahead information is compared with the benchmark rule based control strategy against the Emission test Cycle matrix comprised of NEDC, WLTC, RDE-Aggressive and City Driving Cycle.

In the second case study the Engine is added to the chain and the DPF is added to the EATS system. Soot control is thus included here.

The third case study includes the KERS system. The addition is complex in that the addition of torque control is included and the maintenance of State of Charge is considered for optimal battery level.

WP2 System Analysis and case-study preparation

Heavy duty powertrain

Control-system structure

The main focus of the control design is to develop a supervisory control algorithm, which coordinates the operation of the engine and EATS subsystems. The proposed *modular control framework* is characterized by:

- *Modularity*: Powertrain components together with their local controllers are considered as *modules* (from software point of view), with a high degree of autonomy.
- *Supervisory control*: The supervisor generates reference trajectories for the lower level controllers, by solving an optimal control problem over a receding horizon. The reference trajectories will typically be set-points or states within the lower layer controllers, but they could also be co-states and control trajectories.
- *Local control:* The reference trajectories from the supervisor are tracked by the lower level controllers.
- *Hierarchy:* The supervisor gives the general trend for optimal control of the modules over a *long* receding horizon. Therefore, it can be considered on a higher hierarchical level than the modules. The supervisor itself may consist of several control layers.

These concepts are illustrated in the figure below.

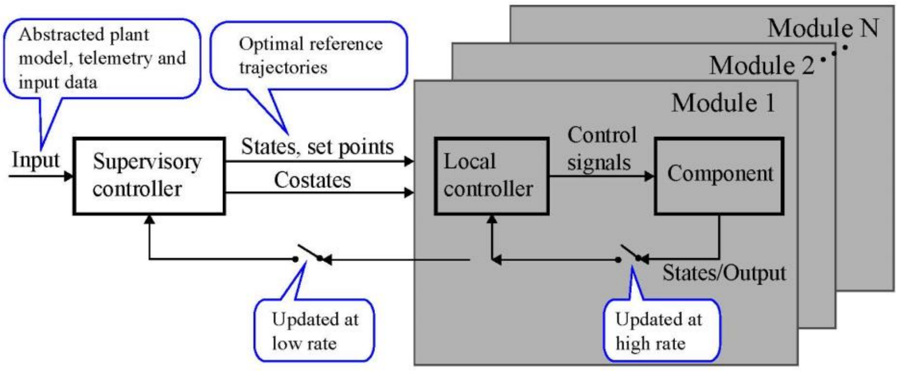


Figure 9 Modularized control system

To put the supervisor design in a broader context, the figure below shows how the supervisor, drawn in a white box, could be placed in a hierarchical control structure going all the way up to long-term, mission-oriented control layers.

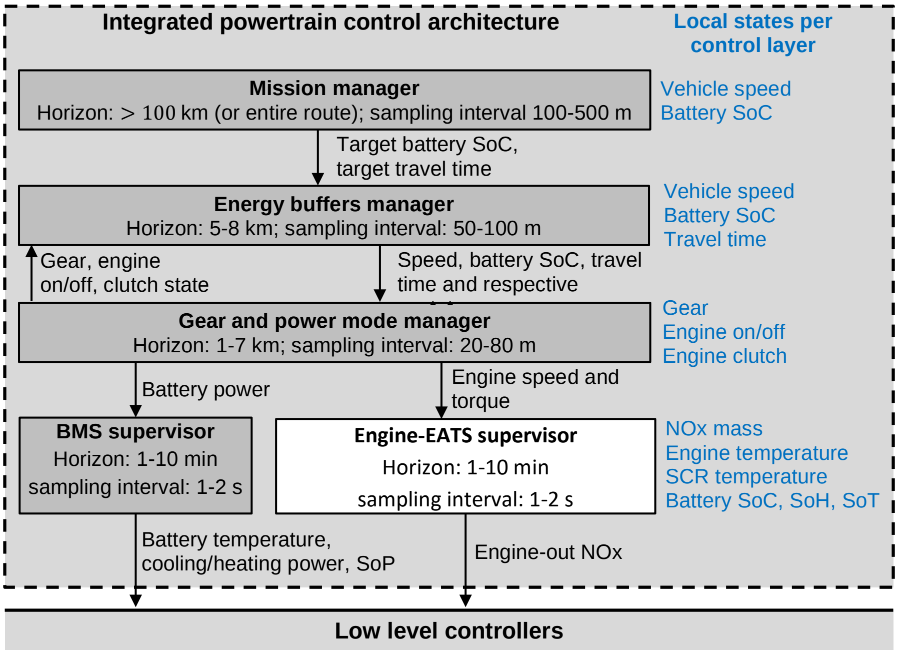


Figure 10 Layered control system architecture

Based on the systems analysis performed in WP1, the specific interface between the supervisor and the surrounding control layers was determined as depicted in the more detailed block diagram below.

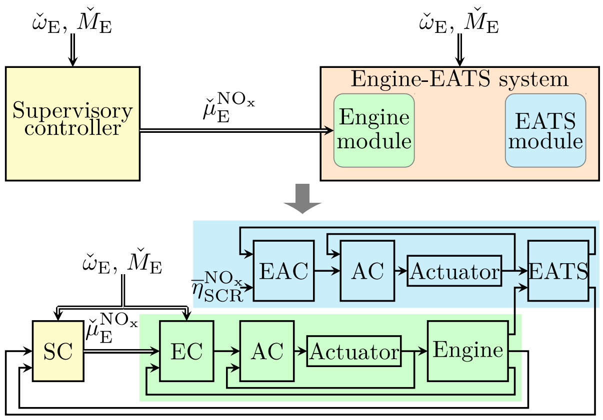


Figure 11 Detailed supervisory control scheme

The engine-EATS supervisor thus receives engine torque and speed set-point trajectories from higher-level controller along with current states of the engine-EATS system, e.g., engine-out temperature (T_E), SCR temperature (T_{SCR}), accumulated mass of tailpipe NOx (m_{tp}^{NOx}), and maximum achievable SCR NOx conversion efficiency ($\overline{\eta_{SCR}^{NOx}}$). The output of the engine-EATS supervisor is optimal set-point trajectories of engine-out NOx mass flow rate ($\breve{\mu}_E^{NOx}$).

Model abstractions – control models

Let us recall the *module* concept, introduced earlier: the engine and the EATS, *together with their respective control systems*, are considered to form a module, i.e. an engine module and an EATS module, respectively. As seen in the above figure, for both modules the controllers have two cascaded loops with inner loop having actuators controllers (AC). The outer loop has an engine controller (EC) and an EATS controller (EAC) for the engine module and the EATS module, respectively.

For a model-based supervisor design, we would need low-complexity, control oriented models for the sub-ordinate modules. The high complexity of available simulation models makes them less suitable for control design. However, they can favorably be used to generate simulation data, which describes the module behavior in an accurate way. Based on analysis of this simulation data, control oriented models have been derived. The resulting models are briefly described in the following.

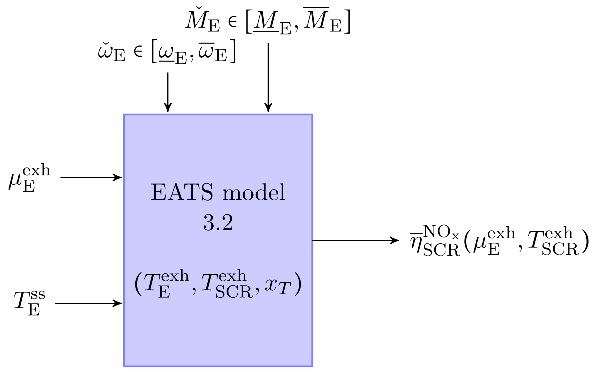


Figure 12 EATS model

- For the ***engine module***, several control models have been derived, and the one used for control design is depicted below. The model is quasi-static and has only one *input*, the set-point for engine out NOx flowrate, sent to the low-level control system. In addition, lower and upper bounds on this signal and on engine out exhaust temperature are given as maps with varying number of independent variables. The *outputs* from the control model are maps of inputs and disturbance signals, the latter being torque and speed signals. More specifically, the outputs are engine fuel flow, engine exhaust flowrate, and engine steady-state exhaust temperature.

- For the ***EATS module***, the control model consists of a combination of static maps and dynamic

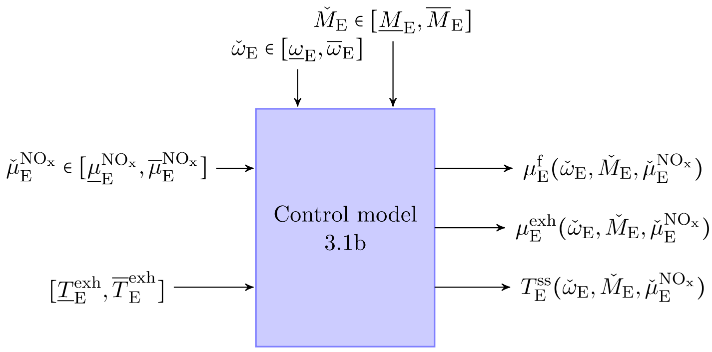


Figure 13 Control model

relations, the latter motivated by the slow temperature dynamics. The model, depicted below, has as *inputs* two of the outputs from the engine model, namely engine exhaust flowrate and engine out steady-state temperature. The temperature *dynamics* of first order describe the engine exhaust temperature and the SCR temperature, respectively – the latter has also a time delay, which necessitates a state vector x_T in the model. The only output of the EATS model is the maximum achievable NOx conversion efficiency, a function of engine exhaust flowrate and SCR temperature.

- ***The final control model*** developed describes the *NOx emissions* according to the so-called *work-based window* (WBW) mechanism. The latter is the basis for evaluating emissions during real-driving and is crucial for providing the constraints for the optimization to be carried out in the MPC-based supervisor. We will not go into the details here concerning the mathematical description of the WBW model; this is further described in the publications produced during the project. Let it suffice here to mention that the WBW control model has tailpipe NOx flowrate as input and as output the accumulated NOx emissions over the most recent work-based window. The model is dynamic and has a state vector holding a history of NOx flowrates over a window that is varying in range in terms of time, but is fixed in terms of power/energy. The model is depicted below.

Control design

Some of the underlying ideas behind the supervisor design has already been discussed, specifically the intent to adhere to a hierarchical structure, and to keep a limited interface between the different levels and modules. By combing the control models that were described above, the starting point for the control design is the complete control model depicted below. Notice that the AdBlue flow is estimated outside the control models, using the engine out NOx flowrate and the conversion efficiency.

The design of the supervisor follows the principles of model-predictive control, where some of the main ingredients can be summarized as follows:

- The basic control variable is the set-point for engine-out NOx mass flow rate ($\check{\mu}_E^{NOx}$).
- The other potential control variable for the engine, the exhaust temperature, is specified only in terms of upper and lower limits.
- The engine is modelled by three static maps, and maps for the bounds.
- It is assumed that the EATS is run at its maximum achievable conversion efficiency, and that the temperature dynamics is modelled by two first order models, plus a time delay.
- The assumption on maximum available conversion efficiency corresponds to using a set-point ($\check{\mu}_{tp}^{NOx}$) as shown in the figure below.
- The output of the WBW model represents the amount of tailpipe NOx within the windows, which are subject to constraints in the emission legislation. Note that computing emissions and constraints over a

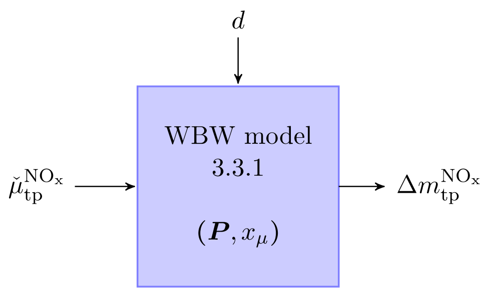


Figure 14 Work-based window model

  future horizon assumes that predictions of the engine speed and torque are available.
- The control objective to be minimized is the combined cost of diesel fuel and AdBlue, and the constraints to be respected are various lower and upper bounds, plus the essential legislative bound on tailpipe NOx emissions.

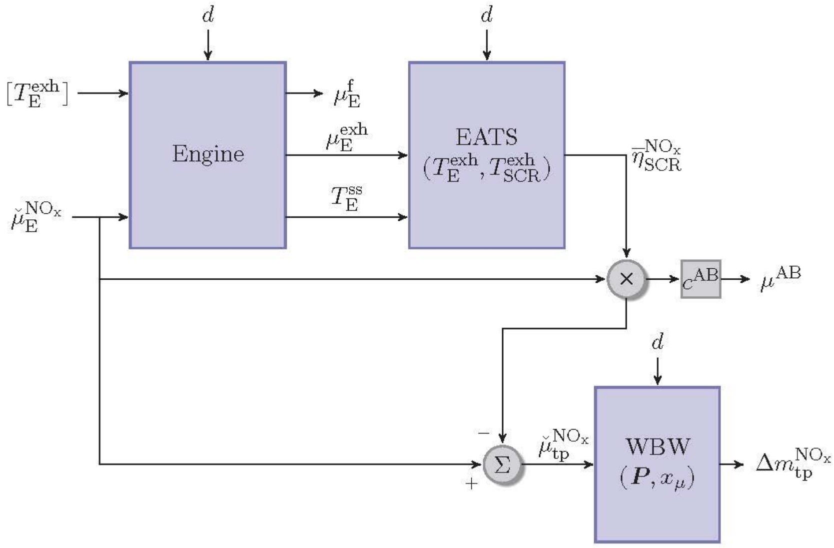


Figure 15 Complete supervisory control scheme

The solution to the formulated control problem is far from trivial. In the publications, it is demonstrated, however, how a distributed approach, dividing the optimization problem into two decoupled but communicating sub-problems, can indeed form the basis for a solution, viable for real-time implementation. The core of the solution is an application of Pontryagin's maximum principle. The algorithm has been implemented in the simulation environment, leading to promising results in terms of both fuel economy and compliance with NOx legislation.

Alternative controller

Another controller has been developed in parallel to the MPC-based controller. This to overcome the drawbacks induced by the MPC for what concerns the computational complexity. It is in-fact well-known that MPC schemes requires a large amount of processor load and memory footprint.

The alternative controller consists in decoupling the temperature and the emissions control loops and it is based on classic control theory. The emission control goal is to track a desired accumulated tailpipe NOx in the current work-based window m_{tp}^{*} whereas the temperature control goal attempts at tracking a desired SCR temperature T_{SCR}^{*}.

The emission loop includes an observer and a gain scheduling proportional controller plus a feedforward term. The observer is used to estimate the accumulated tailpipe NOx in the current work-based window m_{tp} and the proportional and feedforward terms attempt to reduce the difference $|m_{tp}^{*} - m_{tp}|$ as much as possible.

The temperature loop include a low-pass filter and a simple proportional controller. The low-pass filter compensates the transport time delay between the exhaust engine out temperature T and the SCR temperature TSCR whereas the proportional controller shall secure $|T_{SCR}^{*} - T_{SCR}|$ to be as small as possible.

The developed controllers have been implemented and calibrated as described in WP3 and compared as described in WP5.

Waste-heat recovery

After having performed several tests, we observed that there are no substantial changes in varying the requested super-heat in the waste-heat recovery system. That is, the generated power is more sensible to the heat contained in the exhaust gas coming from the EATS in terms of exhaust mass-flow and temperature rather that of a specific value of the super-heat. Hence, we kept the super-heat set-point fixed and we decoupled the waste-heat recovery system from the supervisory control scheme by considering it as a cascade sub-system to the combined engine-EATS system.

Light duty powertrain

Supervisory Controller

The control system concept is envisioned as in the following figure. The control models along with the prediction provide an input to the supervisory controller which decides the course of action considering the current state to satisfy the demands on the system for torque. Also, the system performance is monitored by the performance metrics calculator which provides a feedback for the supervisory control to necessitate immediate or future actions. The subsystem target set points are delivered by the supervisory control.

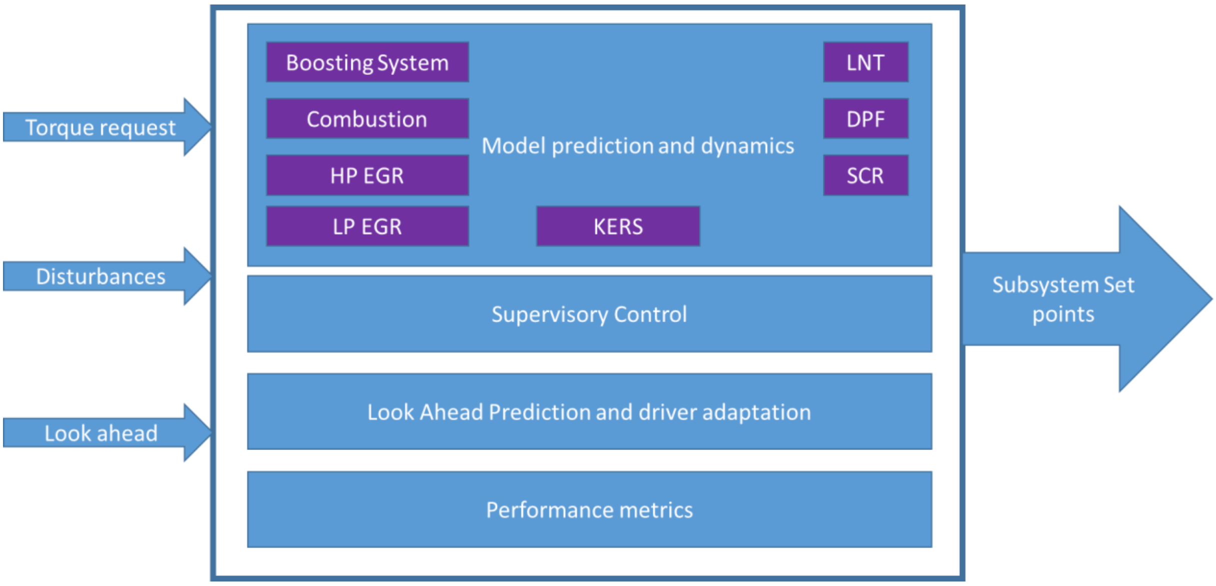


Figure 16 Supervisory control for light duty applications

Control Objective

The prime objective of the supervisory controller is to deliver the subsystem target set-points to attain the torque demand using information from the models and look ahead prediction while satisfying constraints on performance.

The control objective with the supervisory control is to minimize the total equivalent fuel consumption of the diesel powertrain using engine control, u_{Engine} and EATS control, u_{EATS} over the complete drive cycle beginning from time T_0 to T_f. This includes fuel consumption by the engine, C_{Engine} and the equivalent EATS cost, C_{EATS} comprised of fuel consumed by the LNT deNOx operation and urea consumed by the SCR system. Fuel equivalent factor for urea used is derived from the equivalent fuel consumed for the reduction of NOx by using fuel in the engine (using internal engine measures) and using urea in the SCR (at peak efficiency) for equivalent NOx reduction. The engineering constraints on the controller is set to meet engineering targets Cf_{eng} of tailpipe NOx emissions in all instances during the drive cycle denoted by time intervals t_0 to t_1. The control objective is expressed as

$$min_{u_{EATS},u_{Engine}} \qquad \int_{T_0}^{T_f} C_{Engine} + C_{EATS}\, dt$$

$$s.t. \qquad \frac{\int_{t_0}^{t_1} \dot{m}_{NOx}^{tp}\, dt}{\int_{t_0}^{t_1} V_{speed}\, dt} \leq Cf_{eng} \cdot 80 \left(\frac{mg}{km}\right)$$

Look-ahead information

Segmentation

The processed data that would be a time trajectory of the vehicle speed and road load is predicted using the user history or navigation system or a combination of both. It can be safely assumed here that the user interruption would impact the later sequence of the travel trajectory with a much higher probability than the short term horizon. The engine's response time is in the order of one second mainly due to the turbo charger rotational inertia. The LNT and SCR response time is dependent on
exhaust temperature and catalyst coverage fraction. A horizon of 60 seconds is chosen in consideration of the response time of the subsystems and distance that could be travelled

Segment characteristics

Given a certain destination, the supervisory controller takes into consideration the upcoming 60 seconds of the look ahead trajectory. Further dissection with patterns based on minimum and maximum vehicle speed and acceleration, smoothness of load and speed changes, traffic characteristic (such as stop and go) are possible. The objective is to have a segment where a certain engine-LNTSCR control might be optimal can be used within such a window and the homogeneous nature helps in segmenting such windows of look ahead operation. The segmentation idea is illustrated with the help of Figure 17.

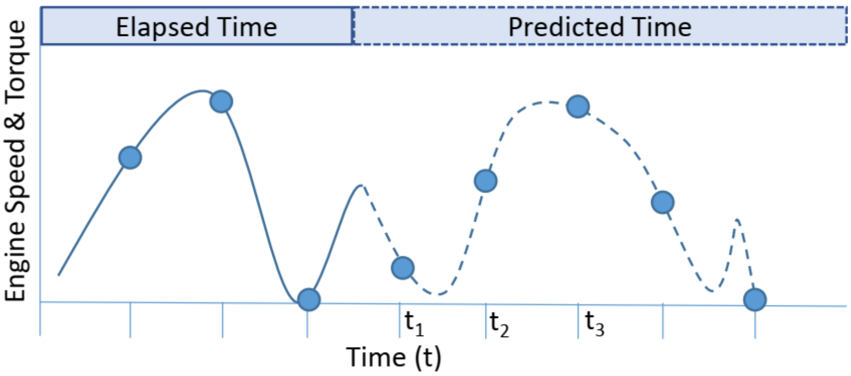


Figure 17 Segmentation idea

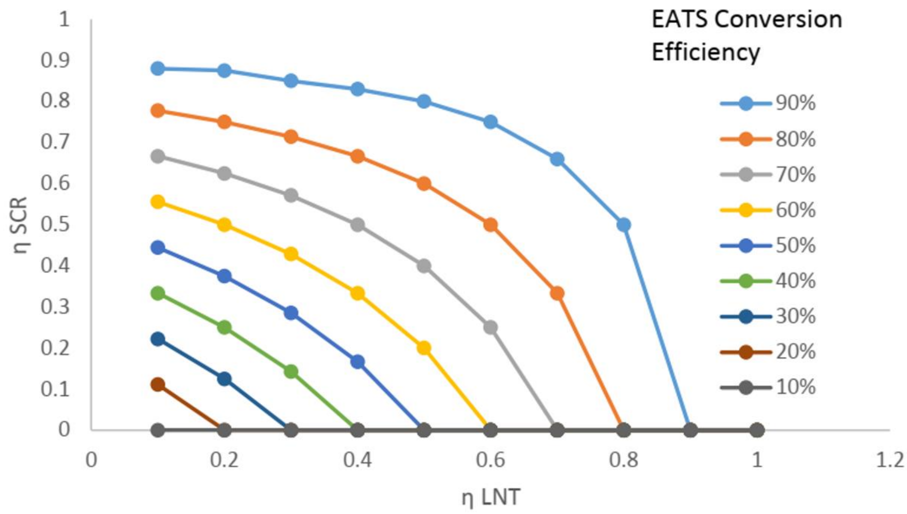


Figure 18 LNT-SCR NOx conversion efficiency for target EATS NOx conversion efficiency

Conversion Efficiency Distribution - Interface

The supervisory controller calculates and sets the conversion efficiency targets for the LNT and SCR local controllers. The control parameter for the LNT, u_{LNT} would track η_{LNT} and u_{SCR} would track η_{SCR}, subject to the physical limitations.

$$\eta_{EATS} = \eta_{LNT} + \eta_{SCR} - \eta_{LNT}\eta_{SCR}$$

In a predicted Load-Speed scenario, the complete drive cycle is broken down into segments that have a certain characteristic. For each identified segment (S), it is possible to estimate the Engine out NOx emissions (EONOx), Flow and Temperature with the help of an Engine model. This is then used to calculate the required $\eta_{EATS,trg}$ to ensure satisfaction of the tailpipe limit $TP_{lim,NOx}$

$$\eta_{EATS,trg} = f(EONOx, TP_{lim,NOx})$$

The challenge is then to optimally distribute η_{EATS} between the LNT and the SCR. The lowest cost combination of η_{LNT} and η_{SCR} for the necessary η_{EATS} is calculated using a cost function that is detailed later. The target η_{LNT} is tracked by altering the target NOx threshold curve for the LNT purge. This is shown in Figure 18. The greater the threshold, the lesser the LNT efficiency and lesser the fuel consumption. But the LNT becomes unavailable for NOx storage until purged. The decision on the SCR is imposed similarly by altering the NH3 buffer target as shown in Figure 18. However, targets greater than the NH3 slip risk are avoided to ensure that the low level controller is capable to eliminate such an instance. Thus the set points of LNT and SCR NOx conversion are suitably translated to the appropriate control actions for the subsystems. Degradation of SCR and LNT catalyst efficiencies due to ageing and temporary poisoning are overcome due to the compensation by the local controllers. The SCR local control usually has an additional compensation added to the urea dispenser. The LNT local control usually has a factor for modifying the LNT threshold.

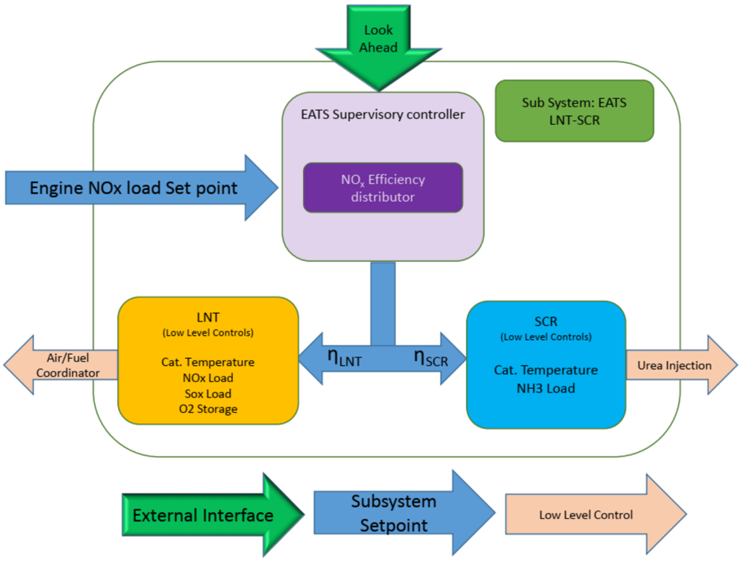


Figure 19 Supervisory control structure indicating signal flows and interface between the supervisory controller, the local controller and the actuators

Controller optimization

The cost incurred in the EATS system are from the joint usage of LNT and SCR. The EATS is to be optimized with the available controls of urea dosing (SCR) and the fuel rich purge (LNT). The combination of RDE legal demand and engineering target (C_f< 1.0) on the NOx tailpipe is set as a constraint along with a peak NH3 slip constraint. This leads to the setting of the cost function as:

$$min_{u_{EATS}} \qquad \int_{t_0}^{t_f} C_{EATS} dt$$

$$s.t. \qquad \frac{\int_{t_0}^{t_1} m_{NOx}}{\int_{t_0}^{t_1} V_{speed}} dt \leq C_f \cdot 80 \left(\frac{mg}{km}\right),$$

$$\max NH_3 \leq 10PPM$$

The controls available to the EATS are

$$u_{EATS} = [u_{LNT}, u_{SCR}]^T$$

$$u_{LNT} \in \{\eta_{LNT}^{Low}, \eta_{LNT}^{Medium}, \eta_{LNT}^{High}\}$$

$$u_{SCR} \in \{\eta_{LNT}^{Low}, \eta_{LNT}^{Medium}, \eta_{LNT}^{High}\}$$

Including the cost of Adblue (m_{adblue}) consumption, Fuel consumption during DeNox purges (m_f), difference between initial and final states of the catalyst (Ammonia coverage fraction ($\tilde{\theta}_{NH3}$)) for the SCR and NOx coverage fraction ($\tilde{\theta}_{NOx}$) for the LNT), the cost function is expressed as

$$C_{EATS} = C\theta_{EATS}^{T}$$
$$C = [C_1 \quad C_{11} \quad C_2 \quad C_{22}]$$
$$\theta_{EATS} = [m_{adblue} \quad \tilde{\theta}_{NH_3} \quad m_f \quad \tilde{\theta}_{NOx}]$$
$$\tilde{\theta}_{NOx} = \theta_{NOx}^{final} - \theta_{NOx}^{initial}$$
$$\tilde{\theta}_{NH_2} = \theta_{NH_3}^{final} - \theta_{NH_3}^{initial}$$

The target η_{EATS} must be attained using the u_{EATS} control. A full factor simulation with different initial conditions of the catalyst and u_{EATS} yields the associated cost that is stored as a function of the corresponding segment. The lowest cost pair u_{EATS} for the given segment S and initial condition $\theta_{EATS,init}$ defines the Supervisory control setpoint. The segment is defined by trace pairs of Vehicle Speed ($\tilde{V}_{spd}$) and Engine Load ($\tilde{T}_{Engine}$). The initial conditions considered are the coverage fraction of NOx stored in the LNT ($\theta_{NOx}^{initial}$) and the NH3 stored in the SCR ($\theta_{NH_3}^{initial}$). Alternately, an online model could also estimate the EATS cost for the provided look ahead horizon. This paper however focuses on an offline optimization that is used to obtain the optimal parameters for the supervisory controller. The optimization methodology is graphically summarized in Figure 20 and the following Equations.

$$C_{EATS} = g(u_{EATS}, S, \theta_{init})$$
$$\theta_{init} = [\theta_{NH_3}^{initial} \quad \theta_{NOx}^{initial}]$$
$$S = h(\tilde{V}_{Spd}, \tilde{T}_{Engine})$$

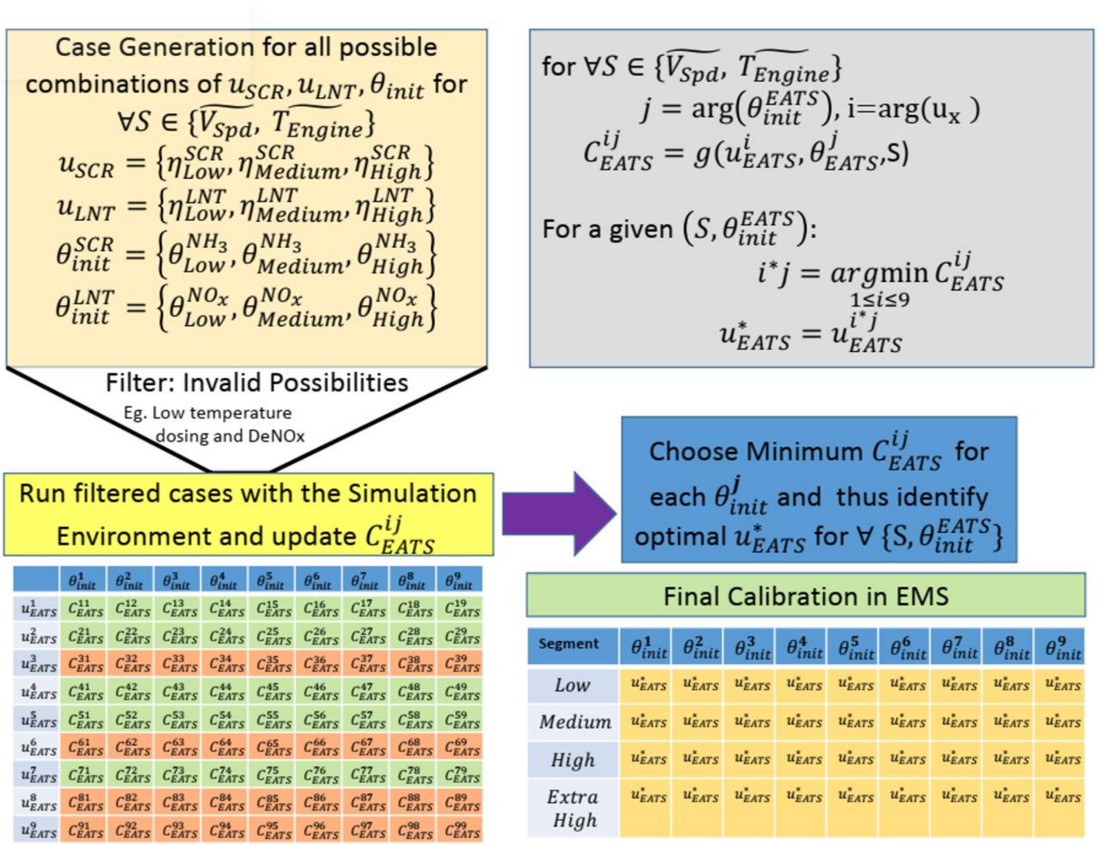


Figure 20 Visualization of the optimization methodology for light duty applications

WP3 Control realization and calibration

Heavy duty powertrain

Both the controllers developed in WP2 have been implemented in AB Volvo production ECUs. The choice of using a production ECU rather than a rapid prototyping unit as typically done in Research Projects increases the methodology TRL, thus favoring the technology transfer into real products.
Nevertheless, the utilization of a production ECU poses additional constraints. Firstly, the CPU and memory resources are limited; secondly, the software libraries used in embedded systems development environments offer only basic functions.
However, advanced control strategies requires the execution of advanced mathematics operations. For example, MPC methods often need the execution of a QP solver and classic control theory methods requires at least the execution of operations over matrices.
Therefore, a software platform capable to efficiently implement advanced control algorithms has been prepared and tested. For instance, the GNU Scientific Library (GSL) has been included in the production software platform to allow testing of advanced methods. Nevertheless, such GSL will not be used in product development but only for proof-of-concepts.

Light duty powertrain

A simulation platform to integrate the control software and the plant models was developed in WP1. The proposed controllers were tested in this environment for comparison with baseline controller.
The direct local controllers of the subsystem are left untouched. The set-points instead modify the target ammonia storage for the SCR as shown in Figure 21 and the frequency of denox events in the LNT modified as shown in Figure 21. This does not necessitate the calibration of the subsystems. Thus the modularity of subsystems can be maintained. Since the SCR and LNT models are calibrated for every physical change of such systems, there is no additional work load compared to the baseline system. The engine is also operated in a discrete fashion in that it switches between low fuel consumption and low engine exhaust emission. The developed methodology for light duty powertrain has not been implemented in actual software but it has been tested through models only.

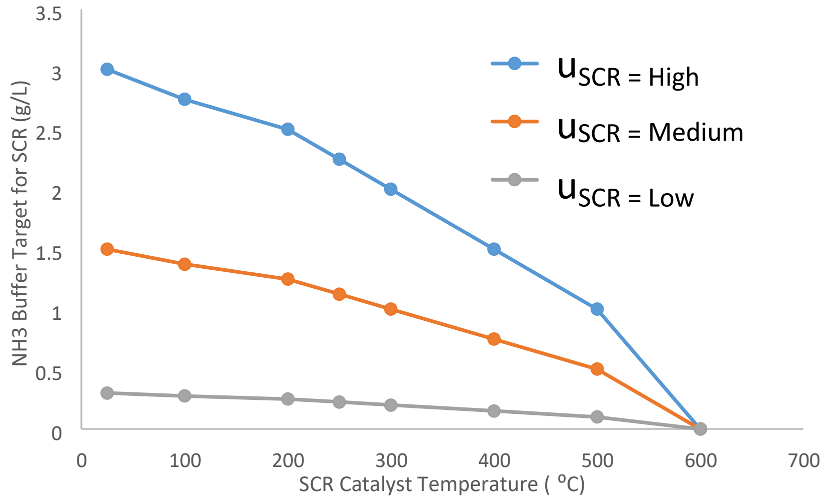


Figure 21 Target ammonia buffer in the SCR modified by introducing the SCR supervisory control parameter uSCR

WP4 Guiding principles for design of complex control systems

In this WP we provide guiding principles for a distributed controller for limiting vehicular NOx emissions, while minimizing fuel and AdBlue consumption. The design includes several steps that are explained via the development of a supervisory controller for an internal combustion engine (ICE) air-path and an exhaust-gas after-treatment system (EATS).

Heavy duty powertrain

Distributed control architecture

Control/optimization problems can be formulated in a centralized or distributed manner. Centralized formulation typically gives a better overview of the problem being studied, but solving the centralized problem is often computationally intractable. Therefore, a more common choice in control synthesis is dividing the global problem into sub-problems, which can then be solved with less computational effort, in a distributed manner.

Control/optimization problems can be distributed by using horizontal or vertical decomposition. In a horizontal decomposition, also known as multi-echelon decomposition, the plant is divided into multiple units and each unit is optimized separately. The units can be coordinated by a centralized coordinator, or a co-optimization procedure can be adopted where the units communicate their control decisions among themselves, until a compromise is reached and their independent solutions converge to a globally stable and optimal solution.

Compared to solving the global problem that suffers from computational complexity, solving the distributed problem may suffer from communication bottlenecks due to extensive coordination among the units. One way to reduce coordination can be achieved by adopting a vertical decomposition. In this architecture controllers are assigned different hierarchy depending on the desired level of control. Then, controllers in one level typically accept set-points (instructions) from higher levels and send correspondingly set-points to lower levels.

The selection of control levels is typically based on time-scale separation. It is generally assumed that the time constant gets shorter as we progress to lower levels. Moreover, the time constant of an immediate low level is assumed short enough that from the view of the higher (supervisory) level, the lower control level is assumed to have immediately set to a steady-state in effect to the set-point requested by the higher level. Notice that this type of hierarchical (vertical) decomposition offers only subordinations without enabling cooperation among the different control units, i.e. communication is generally limited or one-directional, from top to bottom.

Hierarchical architecture for NOx emission control

The studied NOx emission controller is decomposed into a vertical architecture, as illustrated below.

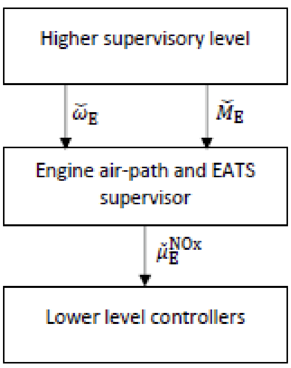


Figure 22 Hierarchical architecture for NOx emission control

High control levels generate set-points for engine speed $\breve{\omega}_{\mathrm{E}}$ and torque $\breve{M}_{\mathrm{E}}$ that are sent to the ICE air-path and EATS supervisor.

The ICE and EATS supervisor is a predictive controller that plans NOx emissions over a long look-ahead horizon, in the order of 30 min. Time-scale separation is used to separate the functionality of the supervisor from that of lower level controllers for engine and EATS. The lower level controllers are typically non-predictive or operate over a short look-ahead horizon, in the order of 10-100 ms.

The ICE and EATS supervisor sends a set-point for NOx flow $\breve{\mu}_{\mathrm{E}}^{\mathrm{NO_x}}$ to the lower levels. This interface is chosen to increase modularity and plug-and- play functionality. The signal $\breve{\mu}_{\mathrm{E}}^{\mathrm{NO_x}}$ is common in all engine configurations. The same interface can be kept even if a need arises for replacing the engine, although the supervisor may need to be updated with new parameters corresponding to the new engine.

The ICE and EATS supervisor can further be distributed into a horizontal distributed architecture with bidirectional communication.

Optimal control statement for the ICE and EATS supervisor
Modern model-based controllers incorporate predictive information and can plan optimal control inputs over a prediction horizon, subject to constraints. One of the most general problems encountered in vehicular control is where the control policy is the solution of a predictive, dynamic, mixed-integer, nonlinear and generally non-convex program. The ICE and EATS supervisor can be stated as such optimal control program (OCP), since the dynamics and the running cost are generally nonlinear and non-convex functions.

The main goal of the ICE and EATS supervisor is to keep NOx emissions under a certain limit, while minimizing fuel and AdBlue consumption. The OCP has only one control input, but this is sufficient to make the system operable. It is possible to increase the degree of freedom by also controlling EATS efficiency, which will require the introduction of at least one more control input and at least one state for ammonia coverage. In the rest of this report we focus on a simpler representation where the EATS is operated with the maximum achievable efficiency.

The ICE and EATS supervisor is operated in a closed loop, where a model predictive controller (MPC) is re-updated over a moving horizon. This enables the removal of tracking error due to uncertain disturbances, which may arise due to measurement error, uncertainty in predicted speed and torque, parameter changes during operation (e.g. switching ICE mode by states not considered in the control model), poor low-level control, etc.

Optimization methods
Various methods can be employed for solving the ICE and EATS supervisor OCP. In indirect optimal control, the OCP is not discretized, and an analytic solution is sought. However, deriving an analytical solution to mixed-integer OCP is still an open research question, although significant advances have been made in a slightly simplified setting, for problems with integer control inputs but continuous states. Yet, some techniques developed in indirect control reveal important problem properties that can be exploited for improving computational efficiency of the direct methods.

Optimal conditions of a plant or system have been derived and *summarized* by the Pontryagin Minimum Principle (PMP). The principles are derived by employing a dual representation of the OCP. A Hamiltonian is first formed, where system dynamics and constraints are adjoined to the objective function, with the help, of so called, Lagrange multipliers. For the studied OCP it has been observed that one of the Lagrange multipliers, $\lambda_{\mathrm{NO_x}}$, which interprets the associated cost to changing tailpipe NOx mass, $m_{\mathrm{tp}}^{\mathrm{NO_x}}$, is in fact a constant value, as long as $m_{\mathrm{tp}}^{\mathrm{NO_x}}$ does not activate intermediate constraints, except at the start and end of the prediction horizon. By assigning desired terminal state, it is possible to formulate a two-point boundary-value problem (2PBVP) with given initial and terminal points. The solution of a 2PBVP corresponds to solving a single shooting method that seeks the optimal initial values for $\lambda_{\mathrm{NO_x}}$ that steers the system to its target state.

A more common way of solving the OCP is by direct transcription to discrete time and then formulating the problem either as a smooth nonlinear program (NLP), or as a mixed-integer nonlinear program (MINLP). By using a combination of both indirect and direct optimal control, the studied OCP can be formulated as a bilevel NLP, such that the 2PBVP is shifted to the upper level, while the lower-level sub-problem is generating an optimal solution for the control input parameterised in $\lambda_{\mathrm{NO_x}}$. This sub-problem does not need to keep track of the state of tailpipe NOx, considering that a constant value for $\lambda_{\mathrm{NO_x}}$ exists that can satisfy all constraints related to $m_{\mathrm{tp}}^{\mathrm{NO_x}}$. The latter is exactly the objective of the upper level. Given an optimal control input as a function of $\lambda_{\mathrm{NO_x}}$, the upper-level problem finds the optimal costate that will steer the system from the initial to its target state.

The bilevel formulation may allow solving a simpler sub-problem in each level than the central formulation, although a real computational advantage may only be seen if these two levels are separated and solved independently. The bilevel problem can be solved separately, by iterating over various values for λ_{NO_x}. In each iteration, the problem is a smooth NLP that can directly be approached by sequential quadratic programming (SQP). Now, including the loop for MPC updates, the entire procedure can be described by three nested loops, as illustrated in sub-figure (a) below. Since the ICE and EATS supervisor considers a long prediction horizon, solving a quadratic program (QP) in three nested loops is not a viable solution for real-time applications. We propose using a real-time iteration procedure (RTI) by removing two of the loops, as shown in sub-figure (b), which can significantly improve computational performance, but may deliver suboptimal solutions, especially within the initial MPC updates.

Distributed ICE and EATS supervisor

The ICE and EATS supervisor can be further distributed in a horizontal architecture that enables bidirectional communication between the units. For the ICE and EATS supervisor we consider non-cooperative distributed control consisting of two units, where the single control input is assigned to unit 1

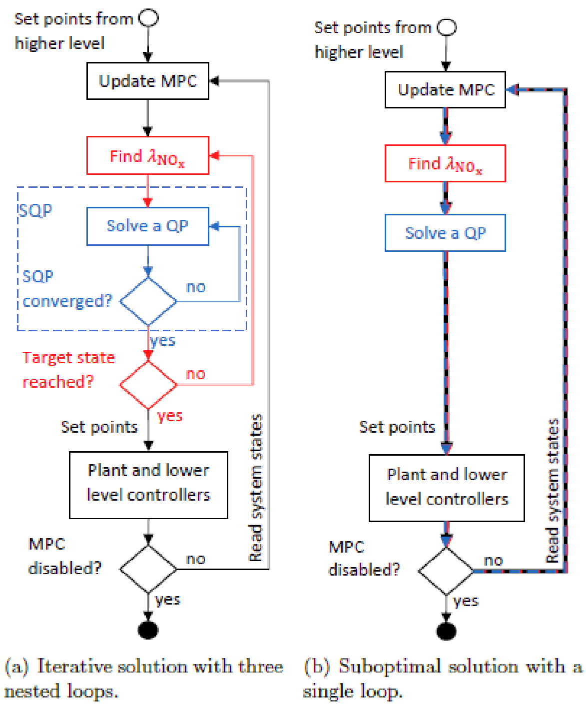
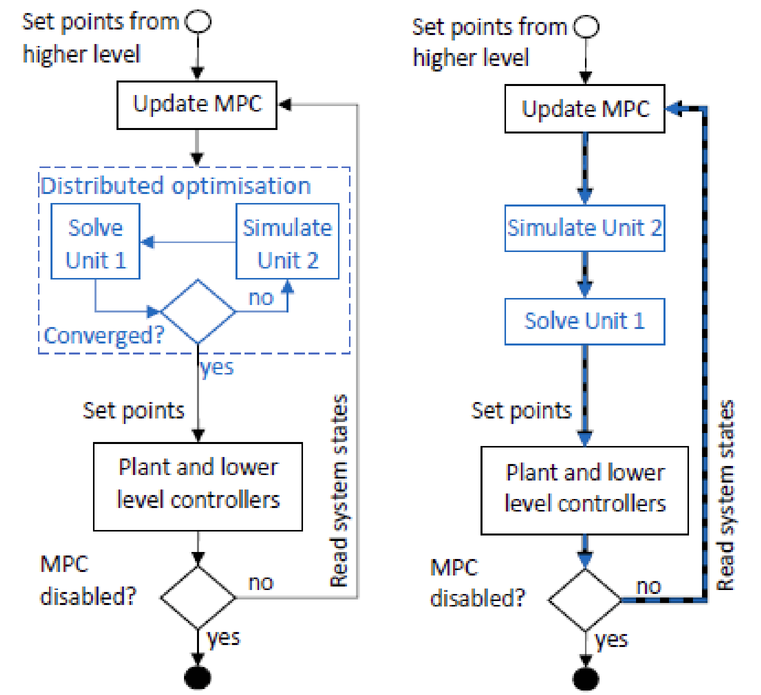


Figure 23 Centralized controller flow chart

and thermal states are moved to unit 2. A flow chart of the distributed solution is depicted in sub-figure (a) below. Notice that this solution requires two nested loops, one for the MPC updates and another for the distributed optimization. Similarly as with the RTI procedure taken above, it is possible to remove the inner loop, which will reduce computation time, but may provide suboptimal solutions. In that scenario, when simulating the second unit, the solution that was obtained during the previous MPC update of the first unit will be used. A flow chart of the solution with only a single loop is illustrated in sub-figure (b) below.



(a) Distributed solution with two nested loops.

(b) Suboptimal distributed solution with a single loop.

Figure 24 Decentralized control flow chart

Selection of variables

The benefit from properly selecting optimization variables (states, control inputs, and sometimes outputs) is being widely discussed, especially within the scope of supervisory control. Many guidelines, as proposed in previous studies, are quite general, e.g.:

- For cases with two or more controlled variables, the selected variables should not be closely correlated.
- State and control inputs should be chosen such that they are easy to measure so that implementation error is small.

Additional guidelines are proposed by investigating sensitivities:

- The state value should be sensitive to changes in the control input, i.e. the gain from u to x should be large.
- The optimal state values should be insensitive to disturbances (so that the setpoint error is small). However, any general (non-optimal value) of the states, could and should depend on disturbances since this will allow detecting the disturbances through the states.
- In connection to the previous item, it can generally be stated that it is desirable that the close neighborhood to the optimum is rather flat with respect to the states.

Another aspect that is becoming more relevant in recent studies is to investigate how the selection of variables and non-approximate relaxations affect the problem convexity (global or local). Such analysis is supported by the recent advent of faster processors and computationally efficient solvers that are being developed for various types of convex problems. These solvers are able, in real-time, to provide the optimum with a guarantee of global (or local) optimality. A burden in such analyses is that it is often difficult to generalize the approach across different control applications. Yet, few examples exist in literature, e.g. those applied in electromobility and autonomous driving.

Variable selection for the ICE and EATS supervisor

The main motivation for choosing the preliminary variables for the ICE and EATS supervisor is due to the interface with other control layers that, e.g., supports plug-and-play functionality. For example, the signal $\mu_{\mathrm{E}}^{\mathrm{NO_x}}$ is present in all engines, regardless of how they are constructed. Another choice of a signal that automatically linearizes system dynamics of the studied OCP is to use the tailpipe NOx flow, $\mu_{\mathrm{tp}}^{\mathrm{NO_x}}$, as a control input. One needs to be careful when performing such transformations, as nonlinearity or non-convexity may be shifted to other parts of the problem, which may not be particularly helpful. However, we can easily show that the domain of the OCP with the new control input, $\mu_{\mathrm{tp}}^{\mathrm{NO_x}}$ is identical to that with $\mu_{\mathrm{E}}^{\mathrm{NO_x}}$.

Another issue that is relevant for the ICE and EATS supervisor is that if the SCR efficiency is close to 1, then with the new control input, the OCP sensitivity to the optimal control input may be worsened. Sensitivity can then be improved by rescaling the optimization variables.

Scaling of variables for the ICE and EATS supervisor

Variable scaling is an important aspect for most optimization solvers. An attempt to generalize scaling of linear systems argues that the Hessian of the cost function should be close to unity. The concept of unity can be generalized to the condition number, which describes the ratio between the largest and smallest eigenvalue of the matrix. It has been shown that minimizing the condition number of a positive-definite matrix can be formulated as a convex semidefinite problem. Yet, the research performed does not consider nonlinear systems nor constraints in the problem. A straightforward generalization could be to investigate the Hessian of the Lagrangian, with respect to both primal and dual optimization variables.

In this project we investigate a simpler form of scaling, assuming that box constraints have been assigned to all variables and that the constraints are reasonably chosen to tightly cover the feasible range. The studied OCP has a single control input $\boldsymbol{\mu_E^{NO_x}}$ (or $\boldsymbol{\mu_{tp}^{NO_x}}$) with time varying box constraints. The problem has also a single state, $\boldsymbol{m_{tp}^{NO_x}}$, which is known to be a monotonically increasing function in time. If we assume that the objective of minimizing total fuel consumption will require the tailpipe NOx mass to reach its upper bound at the final instant, then a linear trend can be considered from the initial to final value of $\boldsymbol{m_{tp}^{NO_x}}$ and a change of state variable can be performed by removing the trend.

Light duty powertrain

The previous work packages go in to detail about the system analysis and the control design where an in depth coverage is provided. The learnings are summarized in this section. The guiding principles for the design of complex control systems involve learning from the following steps in the project:

1. System analysis that mapped the constraints and capabilities of the sub systems involved.
   1.1. All subsystems involved need to be analyzed for the degrees of freedom provided so that a suitable interface that could influence the overall objective of the system while not violating the constraints of the subsystem could be developed.
   1.2. The coordination on local and supervisory level mapping needs to be clearly understood so that there is no conflicting objective. The interaction among the subsystems need to be studied and modelled.

2. Framing the overall objective of the System and metric for performance evaluation.
   2.1. A system wide objective is to be framed considering the overall goal of the system. In this case, the equivalent fuel consumption minimization objective was chosen.
   2.2. The constraints imposed on the overall system need to be specified. In this case, the engineering targets for emission constraints were imposed.

3. Separation of local and supervisory control layer by an appropriately designed interface.
   3.1. The overall objective is met by coordinating the different subsystems by utilizing the synergy between them. A suitable interface that interacts with the supervisory control set point needs to be designed for the local controller. A suitable interface with such a characteristic is performed for the SCR subsystem.
   3.2. The interface design if carried out without interfering the local subsystem controller, recalibration work is avoided hence improving the development time. In the project, the SCR, LNT and the combustion engine are interfaced with the supervisory controller in a manner that doesn't require extensive recalibration.

WP5 Assessment of control system design and guiding principles

Heavy duty powertrain

The proposed control strategies are compared versus a baseline scenario where the set-points are kept constant. We consider two different baselines: one where the requested accumulated tailpipe NOx is set to a low value and one where it is set to a higher value. The comparison is done on the simulation platform developed in WP1. The evaluation has been done consider the Borås-Landvetter-Borås driving cycle. To have a quantitative measurement of the vehicle driveability we define the *driver-disappointment index* (DDI) as

$$DDI = \frac{1}{\tau}\int_{\tau} |M^*(s) - M(s)|ds,$$

Where

$$\tau \coloneqq \{t \geq t_0 : \frac{d}{dt}M^*(t) \geq 0\}$$

The DDI is essentially an Integral Absolute Error (IAE) measure between the requested torque M^* and the delivered torque M, but, differently than the classic notion of IAE, it only considers the vehicle acceleration phase.

The MPC version of the controller shows about 0.4% higher BSTC. Such difference may be further increased by using a longer prediction horizon at a cost of increasing the computational complexity. The Brake Specific Fuel Consumption (BSFC) is very similar. The legislation constraints are met in both the cases with a slightly larger margin for the MPC. Nevertheless, the DDI of the alternative controller is much lower, which also reflects in a higher delivered energy for this driving cycle. This traduces in a better vehicle driveability.
Regarding the computational complexity, the alternative controller is more efficient since it only requires the implementation of (10), (14) and (17) contrarily to the MPC that requires the execution of some online iterative method along with look-ahead information.

Feature	Baseline HI NOx	Supervisory LO NOx	MPC	Alternative Strategy
BSFC (%)	100.0	102.0	100.9	102.1
AdBlue (%)	100.0	58.4	69.1	49.0
BTSC (%)	100.0	100.7	100.0	100.4
Deliv. En. (%)	100.0	99.8	97.4	100.6
DDI (%)	100.0	118.2	215.0	92.7
90^{th} percentile tailpipe NOx [g]	74.9	13.9	8.7	11.6

Table 5 Results for the heavy-duty powertrain

Light duty powertrain

The structure of the baseline controller originates in a less complex engine architecture, to which additional subsystems have been added over the past fifteen years to improve the diesel engine properties and to reduce exhaust emissions. In the baseline the operation of the ICE is done by a group or set of settings for the actuators most likely by a collection of lookup tables. These tables can be viewed as a combination of an empirical reverse model of the respective response to each actuator bundled with an implementation of the requirements on each actuator.

Due to the narrow validity of the empirical models and the varying requirements on the actuators there is need for multiple sets of maps for operation of the ICE during e.g. warm up, fully warm and in extremely cold ambient weather conditions. The objectives of each set are different and could include lower fuel consumption, lower engine out exhaust emissions, quick light off of EATS, engine warm up, DPF regeneration etc. Each set is calibrated with a certain objective while compromising on other features under constraints set by legislation and technical limitations. A particular set is activated depending on engine, EATS, ambient and vehicle operating conditions. E. g., the engine may be operated less fuel efficient along the NO_x - Fuel trade-off to lower engine out emissions until EATS system light off has occurred, and then the engine is operated in a more fuel economical way once the EATS light off has occurred. Emission compliance can thus be guaranteed with fuel economical higher engine-out NO_x. A schematic is shown in the Fig. 1. Engine warm up, DPF regeneration and EATS heat up modes are not considered in this study.

The baseline engine controller operates the engine in either of the modes dependent on the light off of the SCR. SCR light off temperature used here is a slight abuse of terminology which refers to the catalyst bed temperature at which urea dosing is possible without any risk of urea deposits and more than 50% NO_x conversion is possible.

The EATS coordination is to large extent based on the SCR catalyst bed temperature. The LNT operates based on threshold levels set by the coordinator

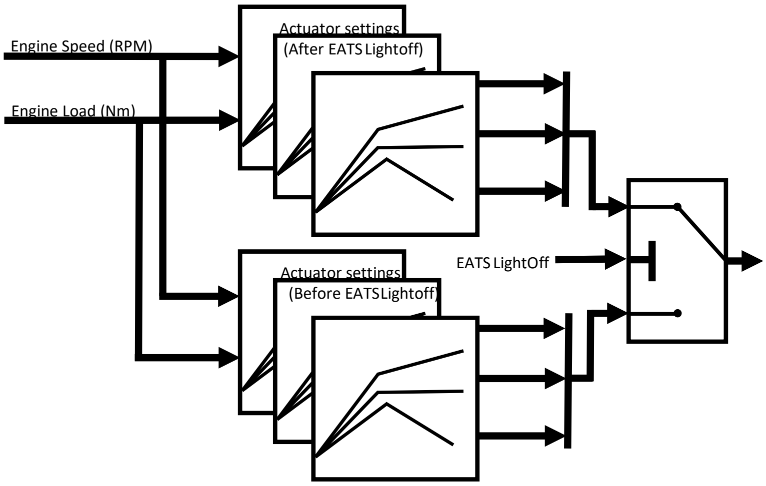


Figure 25 Baseline controller for light duty applications

which is based on the engine operating condition and the SCR temperature. The LNT is purged as soon as temperature allows for purge and the NOx threshold is reached. As the SCR becomes active, the LNT is used passively. The SCR prudently converts almost all the NOx upstream by maintaining the target ammonia buffer allowed without ammonia slip. A local ammonia slip control is used to limit ammonia slip.

Comparison presented in (Velmurugan, McKelvey, & Lundberg, Supervisory controller for a light duty diesel engine with an LNT-SCR after-treatment system, 2018)
The average tailpipe NO_x in the baseline case is lower compared to the average in the supervisory case. To see the effect on the tailpipe NO_x and the total cost, the optimization is done for 3 different engineering targets of tailpipe NO_x using the factor Cfeng. The optimization and experimental simulation was carried out for low, medium and high Cfeng values. A fuel equivalent penalty for the increased NO_x was also added to compare the controller's performance. Summary of the results is shown in Table 1. The average saving with all the sequences is calculated for the different features that the controllers have been evaluated for. Overall a fuel equivalent cost reduction around 0.6-1% has been possible with the supervisory controller. The average performance change (%) shown is calculated as the average of the cumulative difference between the two controllers for the evaluated features. While numerically fuel savings made might sound small, the potential demonstrated is significant given that these are fuel equivalent savings achieved by using a small set of discrete action variables and control horizon length of 60s (which is significantly longer than the engine response time).

Feature	Cfeng-High	Cfeng-Medium	Cfeng-Low
Total Cost (C)	-0.69	-0.98	-0.72
Fuel Engine m^{eng}_f	-0.25	-0.01	+0.0
LNT Fuel m^{lnt}_f	-53.3	-79.1	-67.9
Urea m_{urea}	-7.8	-5.4	-6.6
Tailpipe NO_x	+24.2	+18.7	+8.4

Table 6 Results for first controller proposal

Comparison presented in (Velmurugan, Lundberg, & McKelvey, Look ahead based supervisory control of a light duty diesel engine, 2018)
The 24 different cycles generated with placing the WLTC sequences in various order is simulated for the two controllers. Three different LNT NO_x coverage fractions and three different NH_3 coverage fractions in the SCR leading to 9 combinations of initial catalyst conditions are tested. On average about 0.6% total equivalent fuel consumption potential is realised with the supervisory controller compared to about the same in [2]. The shift observed between the urea and LNT usage in the single WLTC cycle is also observed on average for all the cycles. Marginal difference in tailpipe NO_x is observed. End state of LNT catalyst is observed to be nearly the same even as utilisation has been different. The final NH_3 coverage fraction however seems to differ even as the urea consumption is higher with the supervisory controller. This is owing to the redistribution of catalyst efficiencies by the supervisory controller. The results are summarised in Table 2.
Table 2: Performance comparison of the baseline controller and the supervisory controller. Performance indicated is averaged over the 24 cycles with 9 initial start conditions, normalised and shown as relative difference.

Feature	**Baseline**	**Supervisory**
Fuel (mass)	99.8	100.0
Urea (mass)	68.1	100.0
deNOx (fuel mass)	100.0	65.1
Cost (Eq. fuel)	100.0	99.4
Average final NO_x coverage fraction	97.1	100.0
Average final NH_3 coverage fraction	100.0	70.5

Table 7 Results for the light-duty powertrain

WP6 Project coordination and dissemination

The project has been led by following PMBOK principles (Project Management Institute, 2013) Nevertheless, given the different requirements and legislations for passenger cars and heavy duty vehicles, we split the activities in two parallel teams denoted as *heavy* and *light* duty teams. However, periodic so-called “Big project” meetings where all the project participants were invited were held periodically. During such meetings we performed status report for each WP and team and we discussed commonalities in our achieving in order to develop a common platform for complex control.
The project resulted in the following publications:

[1] D. Velmurugan, D. Lundberg, and T. McKelvey *Supervisory controller for a LNT-SCR Diesel Exhaust After-Treatment System*. European Control Conference, 2018.

[2] D. Velmurugan, D. Lundberg, and T. McKelvey *Supervisory controller for a Light Duty Diesel Engine with an LNT-SCR After-Treatment System* International Powertrain, Fuels and Lubricants Meeting, SAE International 2018.

[3] D. Velmurugan, D. Lundberg, and T. McKelvey *Look Ahead based Supervisory Control of a Light Duty Diesel Engine* IFAC Conference on Engine and Powertrain Control, Simulation and Modeling, 2018

[4] Velmurugan, D., McKelvey, T., & Grahn, M. *Diesel Engine Emission Model Transient Cycle Validation*. IFAC Symposium on Advances in Automotive Control, Kolmården, Sweden, 2018

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[6] M. R. Karim, B. Egardt, N. Murgovski, and E. Gelso, *Supervisory Control for Real-Driving Emission Compliance of Heavy-Duty Vehicles*, IFAC-PapersOnLine, vol. 51, no. 31, pp. 460–466, 2018, doi: 10.1016/j.ifacol.2018.10.103.

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[9] M. R. Karim, B. Egardt, E. R. Gelso, N. Murgovski. *Supervisory Control for Emission Compliance of Heavy-Duty Vehicles*. To be submitted to IEEE Transactions on Vehicular Technology.

[10] U. Tiberi, E.R. Gelso, *A Heuristic Engine and EATS Supervisory Control Scheme for Heavy Duty Vehicles*, IFAC 1st Virtual World Congress, 2020.

[11] U. Tiberi, *Introducing Control Theory in Industry: The Case of V-Model Embedded Software Developers*, IFAC 1st Virtual World Congress, 2020.

Conclusions

In this project a software platform for complex control has been developed and evaluated. Such software platform is based on a supervisory control scheme and it applies for both heavy duty vehicles, such as trucks, and light duty vehicles, such as passenger cars. With such a control scheme it is possible to tackle competing constraints such as fuel consumption, emissions and driveability in an efficient way. The modularity offered by the proposed supervisory control scheme allows for a better product variants and shortened development time since software dependencies becomes clearer compared to the traditional rule-based approach. In practice this means that possible changes in a sub-component, like for example the engine or the EATS or even some local controllers, will most likely require the sole adaptation of the supervisory control layer and not larger part of the software. The exploitation of look-ahead information has been actively used in the MPC formulation.

In the case of heavy duty vehicles, the proposed scheme has not been evaluated solely on a simulation model, but it has been taken a step forward by implementing it into a software-in-the-loop production environment and a production ECU, thus placing the proposed methodology at a higher TRL.

Guidelines for the design of complex control according to the supervisory control methodology adopted in this project have been issued.

Finally, knowledge and experience of introducing advanced, multivariable, optimal, predictive and model based control methodology in an industrial context have been enhanced.

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