THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Supervisory control of complex propulsion subsystems

with look ahead information

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To my family.

Supervisory control of complex propulsion subsystems
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Abstract

Modern gasoline and diesel combustion engines are equipped with several subsystems with the goal to reduce fuel consumption and pollutant exhaust emissions. Subsystem synergies could be harnessed using the supervisory control approach. Look-ahead information can be used to potentially optimise power-train control for real time implementation. This thesis delves upon modelling the exhaust emissions from a combustion engine and developing a combined equivalent objective metric to propose a supervisory controller that uses look-ahead information with the objective to reduce fuel consumed and exhaust emissions.

In the first part of the thesis, the focus is on diesel engine application control for emissions and fuel consumption reduction. Model of exhaust emissions in a diesel engine obtained from a combination of nominal engine operation and deviations are evaluated for transient drive cycles. The look ahead information as a trajectory of vehicle speed and load over time is considered. The supervisory controller considers a discrete control action set over the first segment of the trip ahead. The cost to optimise is defined and pre-computed off-line for a discrete set of operating conditions. A full factorial optimisation carried out off-line is stored on board the vehicle and applied in real-time. In a first proposal, the subsystem control of the after-treatment system comprising the lean NO_x trap and the selective reduction catalyst is considered. As a next iteration, the combustion engine is added to the control problem. Simulation comparison of the controllers with the baseline controller offers a 1 % total fuel equivalent cost improvement while offering the flexibility to tailor the controller for different cost objective.

In the second part of the thesis, the focus is on cold-start emissions control for modern gasoline engines. Emissions occurring when the engine is started until the catalyst is sufficiently warm, contribute to a significant proportion of tailpipe pollutant emissions. Electrically heated catalyst (EHC) in the three way catalyst (TWC) is a promising technology to reduce cold-start emissions where the catalyst can be warmed up prior to engine start and continued after start. A simulation framework for the engine, TWC with EHC with focus on modeling the thermal and chemical interactions during cold-start was developed. An evaluation framework with a proposed equivalent emissions approach was developed considering the challenges associated with cold-start emission control. An equivalent emission optimal post-heating time for the EHC is proposed that adapts to information which is available in a real-time on-line implementation. The proposed controller falls short of just 1 % equivalent emissions compared to the optimal case.

Keywords: Look-ahead control, supervisory control, engine control, exhaust after-treatment.

List of Publications

This thesis is based on the following publications:

[A] **Dhinesh Velmurugan**, Markus Grahn, Tomas McKelvey, "Diesel engine emission model transient cycle validation". Presented at the *IFAC Symposium on Advances in Automotive Control*, June 2016, Kolmården, Sweden.

[B] **Dhinesh Velmurugan**, Daniel Lundberg, Tomas McKelvey, "Supervisory controller for a LNT-SCR diesel exhaust after-treatment system". Presented at the *European Control Conference*, June 2018, Limassol, Cyprus.

[C] **Dhinesh Velmurugan**, Tomas McKelvey, Daniel Lundberg, "Supervisory controller for a light duty diesel engine with an LNT-SCR after-treatment system". Presented at the *SAE International Powertrains, Fuels & Lubricants Meeting*, September 2018, Heidelberg, Germany.

[D] **Dhinesh Velmurugan**, Tomas McKelvey, Jan-Ola Olsson, "A simulation framework for cold-start evaluation of a gasoline engine equipped with an electrically heated three-way catalyst". Presented at the *IFAC Conference on Engine and Powertrain Control, Simulation and Modeling*, August 2021, Tokyo, Japan.

[E] **Dhinesh Velmurugan**, Tomas McKelvey, Jan-Ola Olsson, "Evaluation of electrically heated catalyst control strategies against a variation of cold engine start driver behaviour". Accepted for presentation at the SAE WCX, April 2022, Detroit, USA.

[F] **Dhinesh Velmurugan**, Tomas McKelvey, Jan-Ola Olsson, "Data-driven near-optimal on-line control for an electrically heated catalyst equipped gasoline engine". Submitted, January 2022.

Other publications by the author, not included in this thesis, are:

[G] **Dhinesh Velmurugan**, Daniel Lundberg, Tomas McKelvey, "Look ahead based supervisory control of a light duty diesel engine". Presented at the *IFAC Conference on Engine and Powertrain Control, Simulation and Modeling*, September 2018, Changchun, China.

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Dhinesh Velmurugan
Göteborg, March 2022

Acronyms

ICE:	Internal combustion engine
LNT:	Lean NO_x trap
SCR:	Selective reduction catalyst
TWC:	Three-way catalyst
EHC:	Electrically heated catalyst
CO:	Carbon monoxide
HC:	Hydrocarbons
NO_x:	Oxides of nitrogen (NO and NO_2)

Contents

Part I

Overview

CHAPTER 1

Introduction

1.1 Motivation and research question

Current generation internal combustion engines (ICE) in passenger cars incorporate a range of subsystems to comply with exhaust emission legislation and consumer demand. These subsystems include but are not limited to fuel injection systems, air-charge systems, valve-train systems, electrical motor-generator systems and a variety of exhaust after-treatment systems. They vary widely in their characteristics such as response times, performance constraints and energy demands. A holistic supervisory controller that unifies the coordination of the subsystems towards a multi-objective goal of minimal fuel consumption and lower exhaust emissions could potentially outperform widely employed rule based controllers. With the advancements in connectivity and cloud based services, look-ahead information could be made available for optimisation of power-train control. Exploration of the research questions in this thesis that arise from the above discussion are summarised below:

Question1: Can a supervisory control strategy perform better than the baseline rule based controller with respect to fuel consumption minimisation and exhaust emission control?

Question2: How can additional look-ahead information be used in implementing real-time control strategies?

In the first part of the research period, a diesel ICE supervisory controller that uses look-ahead information was developed. In the second part of the research period, an on-line controller for the electrically heated catalyst (EHC) in a gasoline ICE was developed.

1.2 Thesis outline

The thesis consists of two parts. Part I consists of background and basics of the combustion engine system hardware and control followed by a summary of contributions and future work. This part serves as an introduction and motivation for the included papers in Part II. In Chapter 2, an introduction to the societal impact of ICE in passenger cars and legislation development ensuring technology adoption to reduce harmful exhaust gas emissions is described. The associated hardware, optimisation challenge and control techniques in diesel and gasoline ICE systems are introduced that lay the basis for the appended papers. Within the individual applications, discussion on control problem complexity and potential of additional look-ahead information is included. Chapter 3 serves to summarise the papers included in the thesis. Chapter 4 details the contribution and future outlook for the research area.

Part II consists of six scientific papers with the first three papers focusing on the diesel application while the last three focus on the gasoline application.

In paper A, the performance of a model for exhaust emissions prediction of a diesel engine is evaluated. Comparison of prediction of soot particulates and NO_x from on-board engine control signals in transient cycles is carried out. In paper B, a smaller subset of the diesel supervisory control problem is considered that includes only the NO_x after-treatment control. A control interface and a scheme is proposed which is evaluated. In paper C, the complexity is increased by the additional consideration of the combustion engine. The modifications associated with the additional subsystem for the supervisory control is discussed, implemented and evaluated.

In paper D, a simulation framework with focus on modeling the ICE components for cold-start of a gasoline ICE equipped with an EHC is described. The simulation of ICE, three-way catalyst (TWC) with non-uniform discretised axial sections and inclusion of EHC is detailed. In paper E, an evaluation methodology and a precursor to the EHC control development is examined. An equivalent emission cost is defined and performance of the EHC under expected challenges in cold-start is analysed. In paper F, an on-line control for the EHC is developed that is based on pre-computed optimal solutions for known drive cycles. This model free data-driven control approach is compared to other possible control candidates.

CHAPTER 2

Background

2.1 Transport and society

Transport has greatly influenced civilisation and its development. Today, transport is regarded as a basic necessity and the sector is an integral part of the global economy. Irrespective of the disruptions in economy and society, passenger car usage has been growing over the past decades and is estimated to have reached a billion cars (0.450 billion cars in EU and USA 2020) with projections from [1]–[3], illustrated with the help of Fig. 2.1.

2.1.1 Energy efficiency and CO_2 legislation

Global observations in [4] attributed 21.8 % of the world green house gas (GHG) generated in 2018 to the transport sector as illustrated in Fig. 2.2. In EU from data reported in [5], road transport contributed to 31.1 % of the total CO_2 emissions and passenger cars contributed to 17.5 % (2119 MMT) of the total CO_2 emissions (12097 MMT) in 2019. The unit of measurement is million metric tonnes or 1000 Giga grams (1 MMT = 10^9 kg = 1000 Gg). The equivalent CO_2 emissions are obtained from the product of the respective gas global warming potential and the respective mass although CO_2 is still the predominant GHG including this factor. According to [6] in the USA, transport accounted for 28 % (1820 MMT CO_2 eq) of the total GHG CO_2 eq emissions (6676 MMT CO_2 eq) in 2018 with passenger cars contributing to 11.6 % (777 MMT CO_2 eq) of the total GHG emissions. United nations framework convention on climate change (UNFCCC) dealing with greenhouse gas emissions mitigation, adaptation, and finance brought 196 nations come to an agreement (the Paris

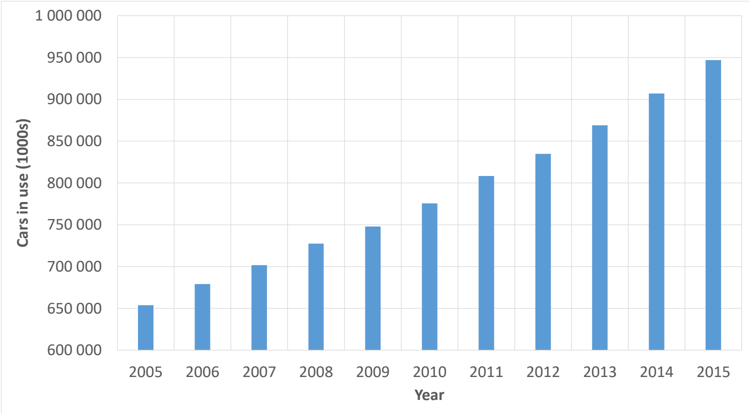

Figure 2.1: Global in use cars. Data from [1]

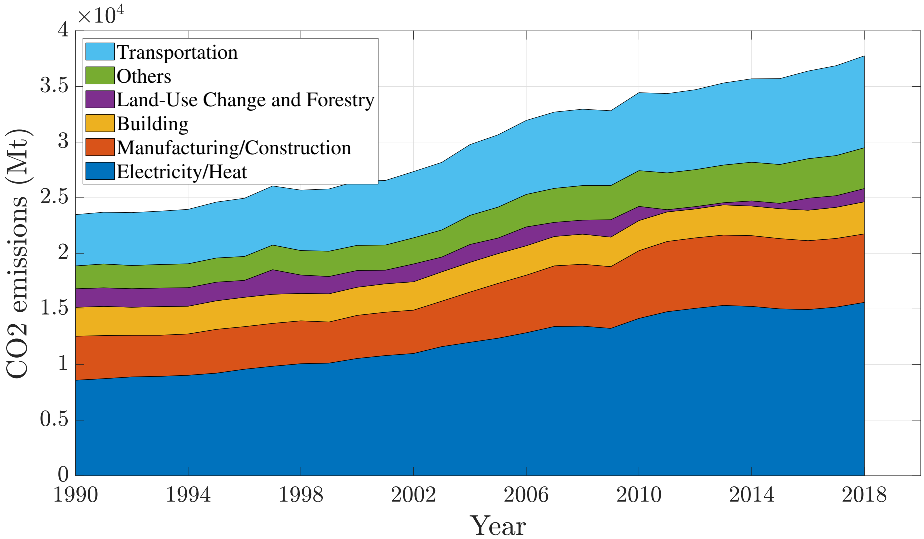

Figure 2.2: Global CO_2 emissions by sector. Data from [4]

agreement) to govern emission reductions from 2020. Energy effectiveness is crucial to limit global warming to 1.5°C relative to pre-industrial levels by fulfilling the UNFCCC commitment and COP26 pact [7]. To meet the UNFCCC commitment, EU GHG reductions in transport sector will have to amount to at least 30 % by 2030 compared to 2005. In 2018 in the EU, 365 million cars emitted an estimated 2107 MT of CO_2 compared to 2072 MT of CO_2 estimated to be emitted by 329 million cars in 2010 [5], [8]. The EU legislation is moving in this direction with 95 g/km being enforced for new registrations in 2021 based on the NEDC. A further 15 % and 30 % reduction for 2025 and 2030 is based on the equivalent WLTC target set in 2021. [9]–[11]

2.1.2 Environmental impact and pollutant emissions legislation

Apart from CO_2, exhaust emissions of concern from combustion engine propelled automobiles include carbon monoxide (CO), unburned hydrocarbon (HC), oxides of nitrogen (NO and NO_2) and particulate matter. The environmental impact of exhaust emissions with effects such as smog, acid rain, ozone reaction has been widely accepted across the world [12]. The impact of poor air quality (caused by exhaust emissions) on human health leading to respiratory problems, shortening of life expectancy and degradation of life quality is also recognised by national authorities and health practitioners [13].

In the EU, road transport exhaust emissions contributed to 28 % of the total NO_x generated, 18 % of the total CO generated, and 6 % of the non-methane organic compounds (NMVOC that includes HC) as is shown in Fig. 2.3 [14], [15]. The level of NO_x emissions have been on a downward trend in the EU (-42 % NO_x and -29 % NMVOC since 2005) and US, and have been on the rise in growing economies especially in China and India.

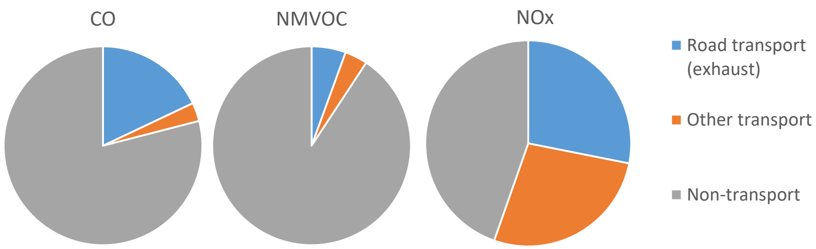

Figure 2.3: CO, Non-methane volatile organic compounds (NMVOC), NO_x generated by road transport, non-road transport and other sectors in the EU. Data from [15]

Regulatory bodies for monitoring, control and certification of vehicles have designed increasingly stringent test procedures since 1980. Effective reduction in pollutant emissions is expected to align with real driving conditions with stringent emission norms and use of real driving emissions (RDE) test procedure [16], [17].

2.2 Diesel power-train application

Modern day passenger cars are propelled by combustion engines, electric machines or a combination. Development of diesel engine technology for energy efficiency has been driven by legislation and customer demands. The diesel cycle description is followed by an introduction to subsystems in the engine and the after-treatment system in this section.

2.2.1 Diesel engine

The Diesel cycle comprises of 4 strokes as shown in Fig. 2.4. Fresh air is drawn in to the engine cylinder during the intake stroke when the intake valve is open. The fresh air is compressed which increases the temperature in the engine cylinder during the compression stroke. Diesel is injected into the cylinder which causes combustion by self ignition and delivers work at the piston in the power stroke. The burned gases are removed by opening the exhaust valve. Modern diesel engines are direct injected, usually turbocharged and with advanced catalysts for exhaust after-treatment [18].

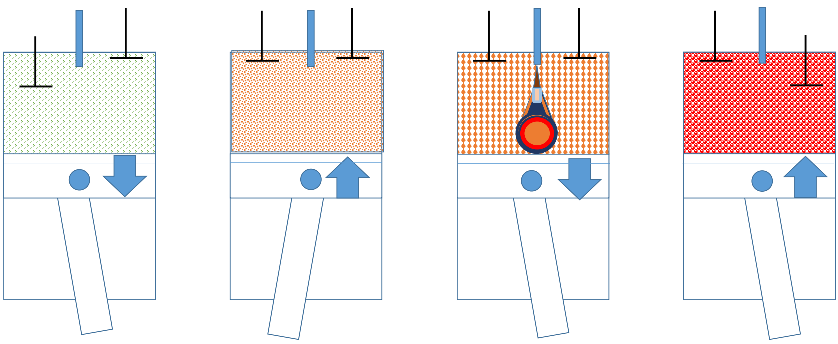

Figure 2.4: The Diesel cycle shown with the four strokes from left to right: Intake, Compression, Combustion and Exhaust stroke

Common rail direct injection

Diesel engine noise primarily due to diesel combustion has been a long impediment in their adaptation to passenger car applications. The introduction of common rail direct injection systems with split injection strategies significantly improved the noise generated by diesel engines. The system comprises of a high pressure pump that accumulates pressurised fuel in a fuel rail. The high accuracy electrically actuated fuel injectors used in conjunction with the common rail offer greater degree of freedom to inject a wide range of fuel quantity accurately at precise timing. These systems provide for better NO_x and soot trade-off in comparison to legacy mechanical systems due to accurate fuel control and very high pressure. It also provides for increasing the exhaust temperatures to quicken the light-off of the catalysts downstream the diesel engine in a fuel efficient manner [19].

Turbocharged diesel engines

The diesel engine is lean burn since diesel fuel is burnt with air in a ratio that exceeds the stoichiometric air-diesel fuel mass ratio (14.5 : 1) usually by factors in the range of 2-5. The amount of fuel that can be injected is limited by the amount of fresh air in the cylinder. It is natural here to consider that more fuel injected leads to more power produced. In order to increase the power of the engine and improve energy efficiency, modern diesel engines are equipped with turbochargers. A turbine placed in the exhaust is rotated by the exhaust energy which drives the compressor that is mechanically linked to the turbine. The compressor placed in the intake air system increases the pressure of air which is drawn into the cylinder thereby increasing the engine power. The increased efficiency is a result of using the exhaust energy to increase the volumetric efficiency of the engine. While it increases efficiency and power, the response time of the engine is lowered due to the air charge dynamics, inertia of the turbine and the associated mechanical systems [18].

Exhaust gas recirculation

In order to reduce the NO_x generated by diesel engines, exhaust gas recirculation (EGR) technology is widely adapted by diesel engine manufacturers as an in-cylinder measure [20]. A fraction of the exhaust gases is diverted back to the cylinder. The exhaust gas acts as an inert species in the combustion chamber to reduce the combustion temperature thereby reducing the generation of NO_x. It increases the soot due to lower combustion temperature. Modern day diesel engines could employ low pressure (derived after turbine expansion), high pressure (derived before the turbine expansion), cooled (passing the exhaust air through a cooler) or warm (without any cooler) EGR systems or a combination.

Hybridisation

Hybridisation of vehicles with addition of one or more electrical motor-generators and battery acting in cohort with the ICE is a surging trend. The degree of hybridisation, source of energy and sizing of the components offer a wide variation in the potential energy efficiency increases and emission control. Mild hybrids could be utilised to reduce the effect of transient power demands on the combustion engine thus reducing exhaust emissions and fuel consumption. They could be used to alter engine loads so as to operate the combustion engine more fuel efficiently even as driver demand is different. Plug-in hybrids offer the potential to tap into energy produced from the power grid as opposed to generating it on-board the vehicle. Hybrid vehicles could also offer the possibility to be run in pure electric mode which could be used effectively for ICE and EATS optimisation.

2.2.2 Diesel exhaust after treatment system

Car manufacturers have equipped diesel engines with exhaust after-treatment systems (EATS) to meet stringent emission legislation which has been tightened continuously over the last decade. Specially developed systems are used for reduction of NO_x, capture, oxidation of soot and oxidation of HC and CO [21]. The EATS system of a Euro 6 diesel engine used in our work is shown in Fig. 2.5.

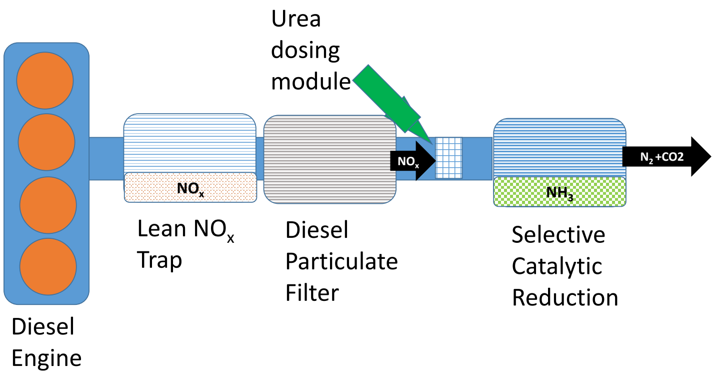

Figure 2.5: Exhaust after-treatment system for a Euro 6 diesel engine

Diesel oxidation catalyst

The Diesel oxidation catalyst (DOC) contains precious metals and the objective with the catalyst is to oxidise the HC and CO species in the diesel exhaust. Upon light-off which is usually around 100°C, the catalyst is almost 90% efficient. The catalyst along with the diesel particulate filter (DPF) oxidises nitrogen monoxide to nitrogen dioxide. This is useful for the selective catalytic reduction (SCR) catalyst to attain increased NO_x conversion efficiency [22]. The functionality of the DOC is summarised in Fig. 2.6.

Diesel particulate filter

The DPF captures and traps the soot particulates in the diesel exhaust. A simple visualisation of the mechanism is shown in Fig. 2.7. The trapped particles are burnt with the help of passive regeneration by oxidising soot using nitrogen dioxide or by active regeneration. Active regeneration is achieved by increasing the exhaust temperature by using split post injections in the combustion engine or by using a fuel injector in the exhaust pipe. The DPF

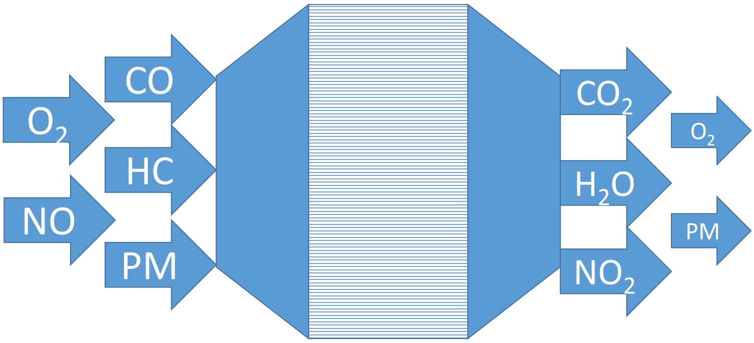

Figure 2.6: Schematic summarising the functionality of the diesel oxidation catalyst

is usually catalysed to increase the nitrogen dioxide that enables burning soot economically, treating unburnt HC and also for improving SCR efficiency by having a higher $NO_2 : NO_x$ ratio in the treated gases. [23]

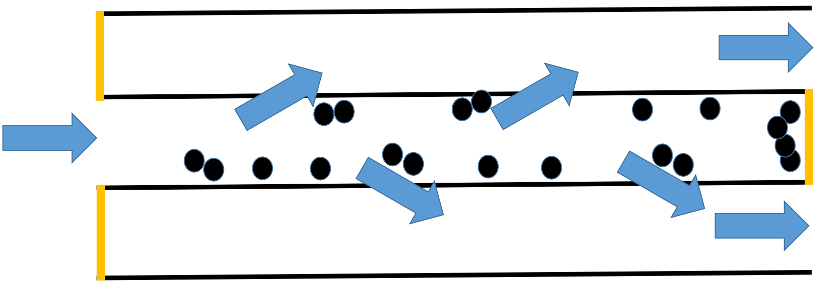

Figure 2.7: Illustration of simplified mechanism of soot accumulation in a diesel particulate filter

Lean NO_x trap

A Lean NO_x Trap (LNT) operates by adsorbing the NO_x species as nitrates in the catalyst. The amount of adsorption is limited by the catalyst volume and the catalyst temperature. The adsorbed nitrates are reduced in a fuel rich environment by operating the diesel engine fuel rich for short time instances. An illustration of the main mechanism is shown in Fig. 2.8. The LNT is not efficient at high loads and high exhaust temperatures. But the LNT systems are capable of treating NO_x at a lower light-off temperature compared to SCR catalyst. The LNT system imposes a higher fuel consumption due to the regeneration events when the catalyst reaches a certain NO_x threshold. Also, operating the diesel engine in fuel rich conditions poses drivability issues and hence need to be limited to certain driving conditions. [24]

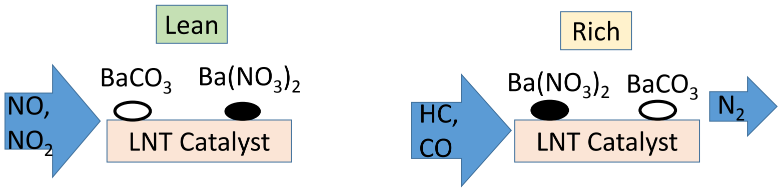

Figure 2.8: Simplified mechanism of lean NO_x trap shown during NO_x adsorption under fuel lean conditions (left) and NO_x reduction under fuel rich conditions (right).

Selective catalytic reduction

Most on-road Euro 6d and later emission standard compliant diesel engines use SCR technology to treat NO_x. This is highly suitable for applications where the exhaust temperatures are higher due to their relative higher load in their applications. Ammonia is used as the NO_x reducing agent which is generated by injecting aqueous urea solution in the exhaust pipe before the SCR. The temperature and flow need to be sufficient enough for urea decomposition to ammonia. The injection could be limited to avoid wastage, crystallisation and deposit formation. The ammonia generated reduces NO_x in the exhaust in the SCR. Excess ammonia is stored on the SCR, the capacity of which is dictated mainly by the catalyst temperature. The SCR catalyst functioning along with the associated dosing system is shown in Fig. 2.9. The SCR NO_x conversion is almost negligible until the SCR light-off has been reached, which is higher than the LNT catalyst light-off temperature. The poor performance in low temperature conditions sets the requirement for heating up the catalyst using the engine exhaust thereby increasing fuel consumption. [25]

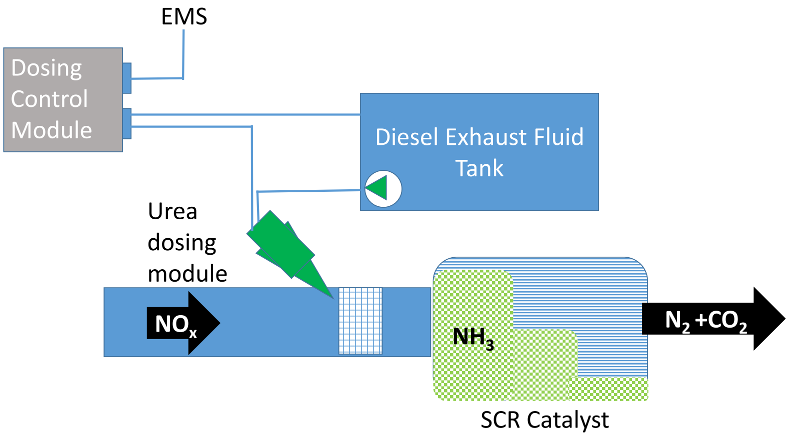

Figure 2.9: Selective catalytic reduction with associated diesel exhaust fluid dosing system

2.2.3 Subsystem complexity in diesel engines

There has been an incremental change in emission control legislation over the years. Manufacturers have adapted combustion engines by adding subsystems to stay in line with the requirements. Fig. 2.10 is an brief of technology adaptation by manufacturers to meet legal demands.

Presence of varied actuator mechanisms in the subsystems impacts their response time. Combustion systems controlled by fuel injection systems are electrically actuated (piezo-electric or solenoid). Fuel injection systems are able to respond cycle to cycle [26]. Air path related systems such as exhaust gas re-circulation and turbocharger systems depend on turbine mass inertia, limited by compressor speeds, the actuator valves, engine speed-load, the volumes and associated air dynamics. The complex air path circuit that includes cooling circuits and compression or expansion paths make the response time slower in comparison to the combustion systems. The response time of such systems are thus slower and in the range of 1 to 3 seconds [27].

In case of Lean NO_x trap, the adsorption of NO_x on the catalyst is complex and dependant on the NO_x coverage fraction and catalyst temperature. The regeneration of LNT catalyst is controlled both by fuel injection as well as air path actuators. The additional impact of LNT regeneration on torque delivery makes the LNT system regeneration response slower than the air path system to around 5 to 15 seconds. The SCR system depends on NH_3 storage on the catalyst and the NO_x conversion efficiency depends on the exhaust flow, temperature and the NH_3 coverage fraction. The response time of SCR systems depend on urea delivery and sufficient conditions for dosing thus having a response time in the order

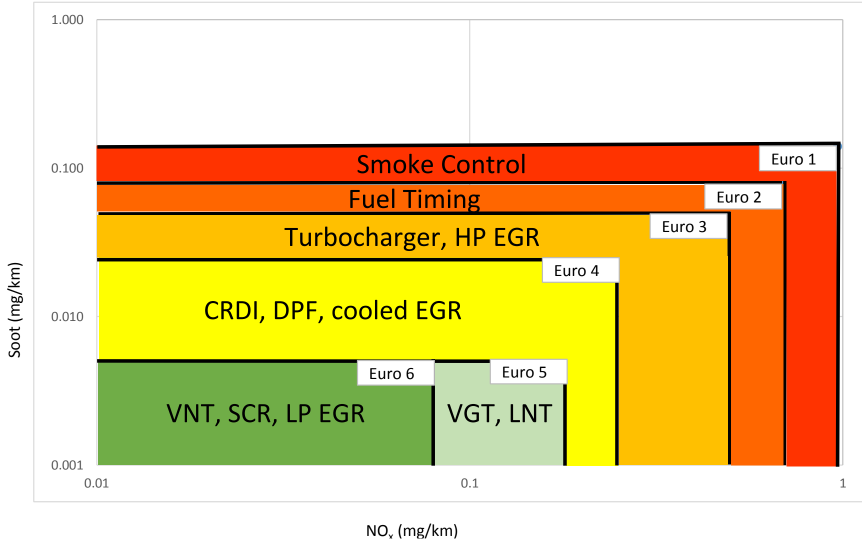

Figure 2.10: Incremental emission standards with corresponding diesel technology adopted popularly to fulfil

of 30 seconds.

These subsystems vary in their implementation due to their response times, dependency on driving cycle, EATS catalyst and engine states. With incremental addition of subsystems constrained by low computational powered control systems, rule based coordination has been the main stream control implementation due to experience and rich experimental data with these systems. Coordination of subsystems were not extremely difficult when the number of subsystems were low and they were relatively simple. Mechanical control systems and later PID controls were sufficient for earlier propulsion systems. But current generation systems use a variety of subsystems that have a common goal and are dependent on one another. The use of slave-master type of systems loose the potential synergy offered by the subsystem interactions. With the introduction of Euro 6d temp, several subsystems need a tighter coordination to fulfil legislation effectively while being fuel efficient.

2.3 Diesel power-train control

The driver in a passenger car sets a reference speed request that is processed by the vehicle control unit. The engine control unit (ECU) delivers the demanded power by the vehicle control by coordinating subsystem controllers to fulfil legal requirements. The coordination could use a holistic objective to take advantage of the subsystem synergies.

Baseline subsystem control

The engine subsystems are usually operated with settings that have been calibrated on the ECU based on the current engine speed and torque required. The ECU utilises the sensors and models of the systems developed to generate these actuator settings. In early generation engines, fewer and simpler subsystems meant that they could be calibrated with experience from expected behaviour and testing. The complexity started to mount with the use of turbochargers which improved efficiency and power but at the cost of response time. Since then there has been a substantial focus on improving the performance with advanced control techniques. The addition of more subsystems that are complex such as the after-treatment system pose new challenges. The degrees of freedom offered with the array of systems on the modern diesel engine provide for operating the engine in diverse manners depending on the objective. Conventional subsystem coordination has primarily been rule based since the complexity growth has been incremental. Thus experience in these systems has been used to coordinate the subsystems so far.

2.3.1 State of the art control techniques

With increased subsystems and the interdependence of subsystems with the same and conflicting objectives, the need for more integral subsystem coordination has become necessary. Turbocharged diesel engine control using mean value models has been a popular approach [28]. Feed-forward controls based on mean value models is a widely applied industry approach. Feedback based control approaches using mean value models has also been used for turbocharged diesel engines with EGR [29]–[31] and layered or cascaded control approaches.

Studies with EGR-SCR balancing along with fuel consumption minimisation have been carried out that have shown potential fuel savings [32]. A control oriented model for integrated engine control has been studied in [33]. An equivalent cost based integrated diesel engine control approach is studied in [34], [35] where equivalent costs have been proposed for total fuel consumption minimisation under emission constraints. Hybrid electric vehicle control where optimal power split of propulsion power source is the main objective has shown similar control techniques. A variety of available control techniques for hybrid vehicle control has been presented in [36]–[42].

Model predictive control (MPC) has been an active technique in research propositions for integrated engine control. Model predictive controllers have also been proposed in studies [43] with inherent limitations of computational capacity limiting their implementation. An MPC implementation is mainly hindered by the absence of algorithms that are capable of execution in the limited memory framework in the ECU or increased accuracy requirements on the underlying control model. The use of data based methods have prevailed in engine control strategies that minimise the computational requirements.

Optimal control techniques have been mainly studied and suggest that heuristic based systems for online implementation could be derived from a mix of targeted drive cycles. A summary of control techniques in propulsion control as discussed above is summarised in Fig 2.11.

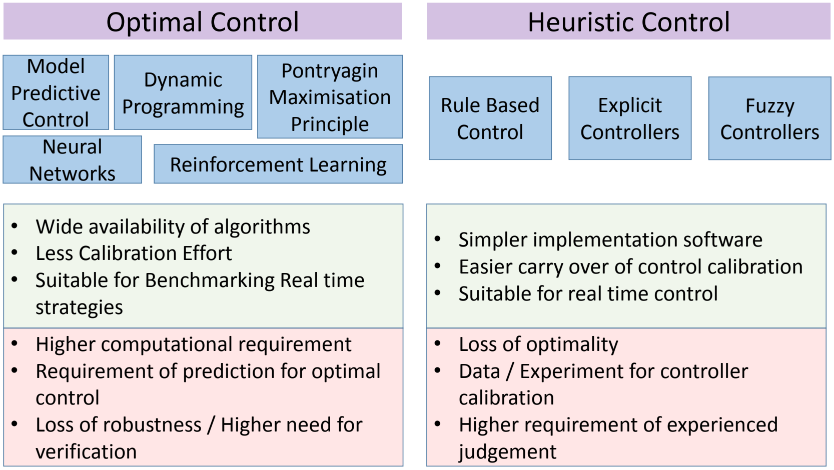

Figure 2.11: Comparison of optimal and heuristic control techniques for supervisory control of powertrain systems

2.3.2 Supervisory control

In our research, a supervisory controller that takes a holistic perspective of the engine and its subsystems is developed which is not computationally demanding and can be implemented in a production engine controller. An equivalent consumption management strategy (ECMS) is proposed with quantification of cost of control actions in fuel equivalent terms.

To propose a suitable framework for the coordination of subsystems, a system analysis of the subsystems was carried out on the Volvo Euro 6d diesel engine. The division into subsystems is done such that the power-train is broken down into significant functional blocks. Each subsystem has a prime objective and can affect other subsystems. For example: EGR, SCR and LNT systems have the main objective to reduce NO_x emissions. Fuel injection timing can be used to control NO_x emissions too. But this would also increase fuel consumption. A look-ahead knowledge based controller that has information of how much NO_x can be treated by the EGR, LNT and the SCR could be used such that fuel consumption can be minimised while also controlling NO_x emissions. We have developed a supervisory control approach for such complex subsystems which is robust and achieve better fuel consumption and controlled exhaust emissions compared to a master-slave interaction between the subsystems described in Section 2.3.

2.3.3 Look-ahead prediction

With the growth of navigation systems and general acceptance of mobile devices, route prediction where the destination can be predicted along with the expected driver characteristics and vehicle acceleration demand is a certainty in wait. Advances in autonomous vehicles have made significant contributions in development of hardware and infrastructure for route prediction. Optimal route or trajectory prediction based on real time traffic and statistical analysis is already available as a service. In a study with 252 drivers in Washington and Seattle to predict route from trip observations, it was noticed that on average 40% of trips taken were repeat trips [44]. This opens up the possibility to predict a vehicle trajectory given a history of routes. With information on the existing position and historic logs of the user travel, the destination and the entire route can be predicted to an accuracy of about 90 % within 2-3 minutes or kilometres driving from the initial position. Route characteristics such as traffic flow, road grade, wind speed also affect fuel consumption and emissions. [45], [46]. The potential benefits of using knowledge of driving route ahead has been demonstrated in publications such as [47], [48].

Driving profile including characteristics of acceleration, braking, distance travelled play an important role in the behaviour of power-train systems. These characteristics have been acknowledged to impact energy efficiency and emission control also by legislation in using relative positive acceleration (RPA) for representative real drive cycles [49]. In a study on driving style, fuel consumption increased by 20-40 % while NO_x was increased by 50-255 % with higher RPA [50]. Regional and cultural influence on driving behaviour has indicated variations and similarities as identified in a survey [51]. Knowledge of driver behaviour offers a potential to increase energy efficiency and control exhaust emissions.

2.4 Gasoline power-train application

There has been a drastic drop in demand for conventional diesel engine powered passenger cars since 2017 in Europe. Share of conventional pure ICE powered passenger cars are continuing to drop. Sales of hybrid vehicles (including plug-in) have seen a significant increase almost equalling the drop in demand for conventional powered cars. See [2], [52], [53]. A majority of hybrid vehicles are powered or assisted by a gasoline ICE on-board. Most EU cars sold are powered by gasoline ICE (new car registrations) and are thus a dominant power-train choice. The gasoline power-train system studied in this thesis comprises of a gasoline ICE, with an electrically heated catalyst (EHC) sandwiched between a two-brick three-way catalyst (TWC) as shown in Fig. 2.12. This section introduces the gasoline combustion engine system hardware and the associated control challenges within the scope of this thesis.

2.4.1 Gasoline combustion engines

The Otto cycle comprises of 4 strokes. Fresh air is drawn in to the engine cylinder during the intake stroke when the intake valve is open. Fuel is injected by an electronically controlled injector, the timing and quantity of which are degrees of freedom that offer optimisation potential. The homogeneous charge is compressed by the piston motion and closure of the intake valve. An electronically controlled spark plug is employed in close proximity to the end of the compression stroke. Combustion of the mixture initiated by the spark delivers mechanical power through the piston. The exhaust valves are opened near the completion of the power stroke and the burnt gas is flushed out by the piston motion coordinated by the control of intake and exhaust valve timings.

The legislated exhaust pollutants included in the scope of this thesis are CO, HC and

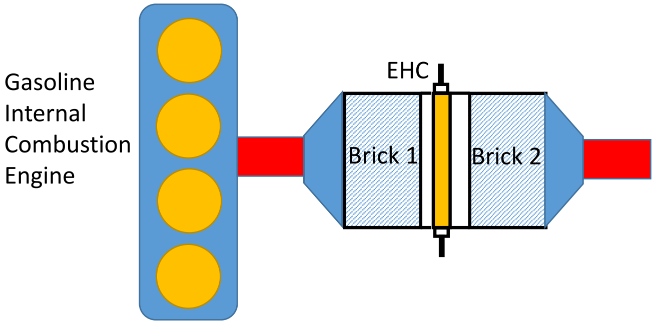

Figure 2.12: The Gasoline power-train system and the associated after-treatment system layout comprising the TWC and EHC used in this thesis.

NO_x. With increasing requirement of low CO_2 and exhaust pollutant emissions, significant technology updates have been incorporated in production engine series. Current generation gasoline engines are to a large extent down-sized ranging from sub 1-L to 2-L, 3-cylinder to 4-cylinder and equipped with a range of fuel consumption reduction technology. These include but are not limited to electronically controlled direct fuel injection, air-charge (turbo-charged, super-charged), cylinder deactivation, variable valve timing (Miller / Atkinson cycle), alternate non-stoichiometric gasoline combustion (lean combustion, compression ignition) and electrification (mild hybrids to plug-in electric hybrids) [54].

Production gasoline ICE are operated predominantly in stoichiometric air-fuel ratio as an optimal compromise between fuel consumption, engine peak power and exhaust emissions (including TWC). The variation of these significant properties with air-fuel ratio is shown in a representative plot in Fig. 2.13. Fuel enrichment which is common for engine warm-up leads to higher CO and HC emissions. Apart from the air-fuel ratio, the ignition timing influences the formation of NO_x emissions significantly. Higher NO formation occurs with advanced spark timing and vice-versa due to high burned gas temperature [18].

2.4.2 Three-way catalyst

In-order to fulfil today's emission standards, most production gasoline engines in passenger cars are equipped with a TWC as the default after-treatment system. The TWC treats engine-out emissions of CO, HC and NO_x over a series of simultaneous reduction-oxidation chemical reactions converting them to H_2O, CO_2 and N_2. The TWC consists of active catalyst material consisting usually of platinum group metals (PGM) such as platinum,

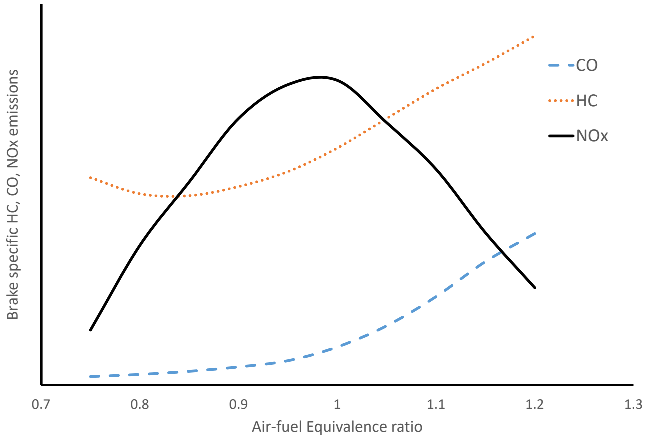

Figure 2.13: Exhaust gas concentration of CO, HC and NO_x variation as a function of fuel-air equivalence ratio in a gasoline engine.

palladium and rhodium. Impregnating the active elements in porous wash-coat (alumina, ceria, zirconia based) on a ceramic or metallic substrate with a cell or honeycomb pattern to distribute the active catalyst components over a large surface area is common practice. The wash-coat is chosen considering the oxygen storage and thermal stability properties apart from the increased surface area characteristics. PGM loading choice is based on light-off temperature properties, pollutant conversion efficiency and thermal stability. Substrate choice is governed by expected exhaust temperature regimes. See [55], [56] for a review of advancements in TWC.

TWC pollutant conversion efficiency depends on a number of factors including the oxygen concentration in the exhaust, oxygen storage in the TWC and the temperature of the TWC. Other factors such as poisoning (oil, sulphur and other impurities in fuel), ageing (thermal, calendar) are not included in the scope of this thesis. Due to stoichiometric air-fuel ratio engine operation, the exhaust contains modest amount of oxygen (during slightly lean operation) or slightly more CO (during slightly rich operation). The exhaust gas temperature is usually in the range of 400 to 600°C. The ICE is operated in stoichiometric air-fuel conditions since the TWC is extremely efficient and functional in reducing CO, HC and NO_x emissions under this condition.

2.4.3 Cold-start emissions

During the start (cold engine-start) of the combustion engine, the engine and after-treatment components are at ambient temperatures and thus tailpipe exhaust pollutant emissions are relatively higher due to the TWC dependency on temperature. Production engine systems emit a large amount of pollutants from the tail-pipe during the cold-start of the gasoline ICE. Tailpipe hydrocarbon emission during the engine cold-start phase make up 60 - 80 % of the total hydrocarbon emission emitted in a standard drive cycle. The tailpipe cold start NO_x emissions make up more than 50 % of the total NO_x emissions similarly. Catalyst light-off, the temperature at which 50 % of pollutant conversion efficiency is attained is usually in the range of 250 to 350°C. The conversion efficiency dependency on catalyst temperature discussed is illustrated with the help of Fig. 2.14. See [18], [56], [57] for details.

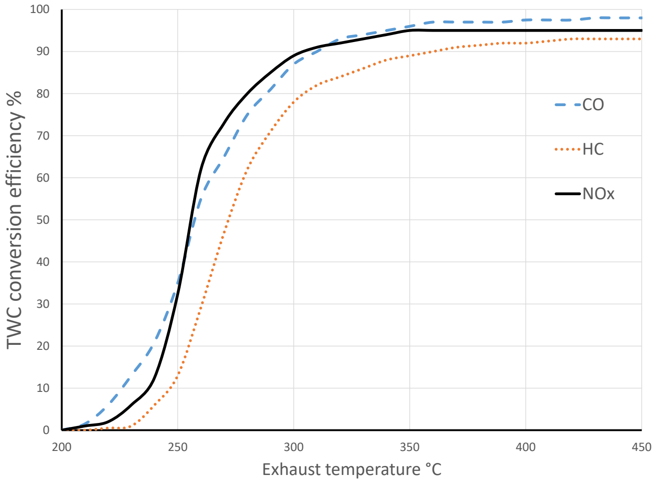

Figure 2.14: TWC conversion efficiency of CO, HC and NO_x as function of catalyst temperature.

The time to reach catalyst light-off depend on several factors and is in the range of 10-200 s for production cars depending on the drive cycle. The volume of the catalytic converter that reaches light-off temperature constrains the maximum engine power that can be generated without emitting significant quantity of untreated pollutants in the beginning of the drive cycle. System design measures to achieve quicker catalyst light-off include positioning of the TWC closer to the engine exhaust, increased insulation of the TWC and exhaust line. Choice of catalyst PGM, wash-coat and substrate formulation for lower catalyst light-off temperature is done depending on the ICE configuration and expected operation.

2.4.4 Electrically heated catalyst

A system design measure to achieve further reduction of cold-start emissions include using an EHC that could be air-assisted or not. Several variants have been investigated with some in limited production stages. The EHC could be used to preheat the TWC before engine-start. This would enable pollutant conversion rapidly as the EHC is heated and a certain volume of the TWC (depending on the power and the EHC design) can reach catalyst light-off temperature before engine start or during high power engine starts in hybrids. See [58]–[60] for more details. The EHC considered in this thesis comprises a honeycomb disc made from a metal foil package that has an active TWC wash-coat. The heating disc is mechanically supported by means of support pins plugged into the normal three-way catalyst. Heat is generated by the resistance of the metal foil package when electrical power is supplied at one end. An illustration of the EHC hardware composed of the foil package is shown in Fig. 2.15.

Figure 2.15: EHC hardware with supporting pins.

2.5 Gasoline engine cold-start emissions control

2.5.1 Engine cold start control strategies

The engine control strategies to reduce cold-start emissions include a combination of increasing heat to the TWC and reducing engine-out emissions. Achieving quick catalyst light-off is essential to reduce and treat cold-engine start emissions. Engine control measures broadly used in production include strategic air-fuel ratio operation, high engine start idle speed, retarded ignition timing and split injection. The engine control measures are calibrated to act in coherence to attain high engine exhaust temperatures and enhance catalyst heating. All these actions lead to increased fuel consumption and affect driveability due to underlying constraints on pollutant limited engine power before catalyst light-off. See [56], [61],

[62] for more details. The engine control software gradually reduces the catalyst heating actions with progress of catalyst heating to achieve a balance between the fuel consumption penalty and pollutant emissions reduction.

Engine idle speed

Higher engine idle speed increases the exhaust air flow and provides additional heat to the TWC. Increased engine speeds ranging from 300 up to 500 rpm over the default engine idle speed is set as target for the initial start idle to support catalyst heating [63]. Fuel consumption increase is a natural consequence with increasing the engine idle speed, where calibration effort is to deliver additionally generated heat to the TWC. The turbocharger is operated such that all exhaust energy flows to the TWC. This is carried out for the initial idle period time ranging from 5 to 20 s. During initial idle, when the vehicle wheel torque demand is zero, ignition retard is used in conjunction with high engine idle speed to provide faster catalyst heating.

Ignition retard

Achieving late burn of the cylinder charge leads to increased heat energy transfer to the TWC. The late burn of the cylinder naturally increases fuel consumption compared to operating the engine at maximum brake torque (MBT) timing. With ignition before the top dead center (TDC) referred to as spark advance, NO_x and HC engine-out emissions tend to increase. Brake specific fuel consumption however decreases with spark advance and also increases brake torque (eventually reaching maximum brake torque). Retarding the ignition timing with spark after TDC lowers NO_x and HC engine-out emissions. The effect of ignition timing on the fuel consumption and engine exhaust emissions summarised is illustrated in Fig. 2.16. See [63], [64] for details.

After engine start, spark timing is usually retarded by 10 to 30 crank angle degree (CAD) after the top dead center. Significantly retarded timing than MBT timing is chosen until catalyst light-off. The adaptation is active for the initial start to about 20 to 30 seconds. The ignition retard is ramped-off as the catalyst warming progresses. Combined with split injections, this is an actively used strategy widely adapted in engines equipped with such a possibility. Split injection with a pilot injection followed by a main injection in conjunction with retarded ignition is calibrated to maximise heat flow to the after-treatment system.

Air-fuel ratio

With increasing air-fuel ratio (fuel lean operation), CO and HC engine-out emissions decrease while NO_x emissions increase. With lower air-fuel ratio (fuel rich operation), CO and HC engine-out emissions increase while NO_x emissions decrease. The engine is usually operated at the stoichiometric air-fuel ratio to balance the emissions load and the TWC treats the emissions with almost 99 % efficiency upon catalyst light-off. When operating the engine rich, oxygen insufficiency in the exhaust leads to less efficiency in oxidising CO and HC. When operating the engine lean, high oxygen content in the exhaust hinders the NO_x reduction reaction and hence the NO_x conversion efficiency. With the usage of oxygen storage materials in the TWC and operating the engine in a tight stoichiometric window,

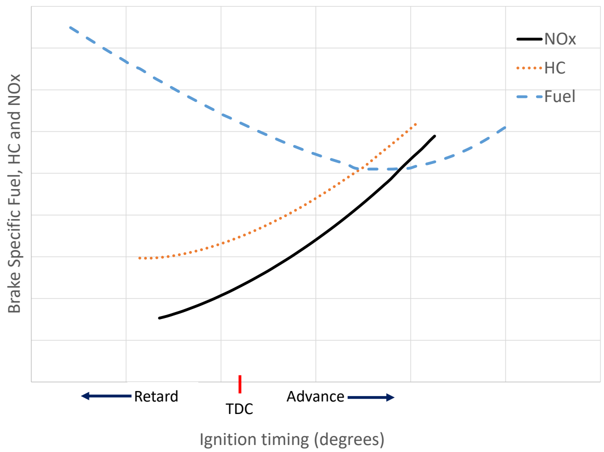

Figure 2.16: Effect of ignition timing on fuel consumption and engine emissions of HC and NOx.

the TWC emission conversion efficiency can reach as high as 99 % which is necessary to fulfill exhaust emission regulations. The dependency of the TWC conversion efficiency on the air-fuel ratio for a typical TWC summarised above is shown in Fig. 2.17. See [18], [63] for details.

A unique combination between operating the engine significantly rich and significantly lean is usually chosen in gasoline ICE powered cars when the catalyst light-off temperature has been reached. To reduce cold-start emissions and increase catalyst heating, some manufacturers choose to have initial rich operation followed by a lean operation to increase the catalyst light-off by promoting the exothermic reactions in the catalyst. Beginning with a higher lean operation to reduce HC and CO is also an alternate strategy adapted by some manufacturers. A choice is made between using air-fuel ratio to increase the catalyst heating or to bring down the HC-CO cold-start raw engine-out emissions. After a short time in conjunction with the wake-up of the lambda sensors and sensor feed-back loop activation, the air-fuel ratio hovers near stoichiometric operation.

2.5.2 EHC control for cold start emissions

The EHC offers the potential to pre-heat the catalyst before engine start. This could enable the engine to be operated in a fuel-efficient manner reducing the need for catalyst heating engine control measures. Due to non-interference with engine control and operation, the EHC provides a cold-start emission control technology with no compromise in driveability. Without a secondary air-system, the EHC has inherent limitations such as

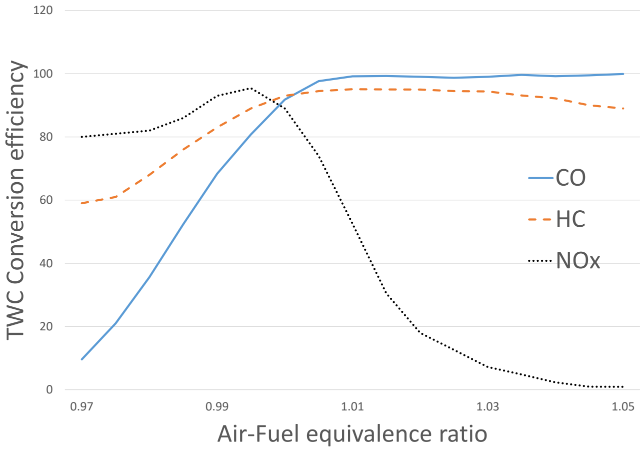

Figure 2.17: Air-fuel ratio dependency of the TWC conversion efficiency.

maximum temperature of the EHC and thereby the possibility to heat the complete TWC is not possible. When the engine is started, engine exhaust flow promotes convection heat transfer from the EHC to down-stream TWC bricks. The EHC heating post engine-start would help in faster catalyst heating. Post-heating the catalyst after engine start can thus be advantageous when expected pollutant load on the TWC is high due to high exhaust flow (from high power demand). The EHC has potential to reduce cold-start emissions in pure ICE powered vehicles and in hybrid electric vehicles to also reduce high-power cold-starts emissions. However the focus of the work carried out in this thesis is limited to the (initial) engine cold-start control in a drive cycle when initial state of engine and exhaust system are at ambient temperature (23-25°C).

2.5.3 Control development approach

To propose a control for the EHC, a simulation framework capturing the phenomenon significant in a cold-start event was developed. The engine control software for cold start control was mimicked to produce the production like control actions for cold-start. This approach provides for a standalone EHC control. A supervisory control approach or integrated engine-EHC control would require a coordinated subsystem effort and engine-out exhaust emission composition could thus be variable. The complexity would increase due to the number of subsystems (air-charge, fuel, engine idle speed, ignition retard) needed to consider. Further, including prediction information is considered for developing the control. The focus is balanced between modelling the systems, developing an evaluation framework, exhaust emissions reduction control by the EHC and usage of look-ahead information. The scope of this thesis is limited to development of a standalone EHC control that could use additional prediction information.

To simulate the different EHC pre-heating conditions it is essential to segment or discretise the TWC axially. For increasing accuracy of cold-start emissions, simulating the catalyst light-off for all of the axial segments is significant. The initial state of the TWC axial segments at the point of engine start is variable due to the use of the EHC in between the TWC bricks. Upon simulation, the first part of the TWC was concluded to play a significant role in achieving greater accuracy in emissions and thermal prediction.

2.5.4 EHC prediction based control

The engine software control actions for reducing cold-start emissions last in the range of 10-200 s. Pre-heating the EHC by switching on the EHC can be done when the engine-start is known with a high certainty using signals such as cabin pre-heating (remote and pre-set timing), door unlocking state, state of charge & power demand (hybrid vehicles) etc. Pre-heating the catalyst would be ideal to reduce exhaust emissions right from the engine-start. However, the duration of pre-heating would be variable depending on the user, environmental conditions and drive cycle power requirement. A post-heating time target for the EHC is thus necessary.

User acceleration demand following engine-start varies widely both with respect to vehicle start idle duration and acceleration demand characteristics. Cold-start emissions are sensitive to these variations. Predicted information after engine-start such as idle duration and user acceleration demand for initial 100-200 seconds would thus be useful in reducing cold-start emissions using adequate EHC post-heating. The main impact that is essential to be predicted would be the catalyst heating variation with varying user demand and adapt the EHC post-heating accordingly. For a real-time on-line control of EHC, the prediction information needs to be utilised that is prone to changes significantly while the control action needs to be implemented in the limited time frame where the EHC is effective in reducing cold-start emissions. A set of possible fuel consumption trajectories with pre-computed optimal EHC post-heating time has been used in our work which is used to adapt the target EHC post-heating time by tracking fuel consumption on-line.

CHAPTER 3

Summary of included papers

This chapter provides a summary of the included papers.

3.1 Paper A

Dhinesh Velmurugan, Markus Grahn, Tomas McKelvey
Diesel engine emission model transient cycle validation
Published in proceedings of the
IFAC Symposium on Advances in Automotive Control,
Kolmården, Sweden,
Vol 49, Issue 11, pp. 1–7, June 2016.
DOI: 10.1016/j.ifacol.2016.08.001

A data driven B-spline based model for NO_x and soot for a 2-Liter passenger car diesel engine was evaluated for its performance. The model was developed using steady state engine measurements under nominal engine operating conditions and extended deviant operating conditions. The deviant operating conditions included fuel injection timing, intake oxygen fraction, global equivalence ratio and fuel-rail pressure. It is hypothesised that such a modelling technique would capture the transient dynamics and effects of engine operation. The transient performance of the model is validated by comparing against engine test cell measurements of NO_x and soot in a NEDC cycle and a normal road drive cycle.

3.2 Paper B

Dhinesh Velmurugan, Daniel Lundberg, Tomas McKelvey
Supervisory controller for a LNT-SCR diesel exhaust after-treatment system
Published in proceedings of the
European Control Conference,
Limassol, Cyprus,
pp. 1900–1907, June 2018.
DOI: 10.23919/ECC.2018.8550256

In this paper, as the first sub-problem, the LNT-SCR coordination is explored in the context of developing a supervisory controller for the diesel powertrain while using look ahead information. An interface that indirectly controls the NO_x conversion efficiency of the LNT and the SCR is developed. A controller that minimises emission equivalent fuel consumption (EEFC) is proposed. Using the engine speed and torque trajectory from a WLTC cycle segmented in parts, controller setpoints for the defined objective is calculated using simulation of the subsystem models. The result is compared to a conventional rule based controller used for the LNT-SCR coordination under different initial catalyst conditions and differently arranged sequenced WLTC parts.

3.3 Paper C

Dhinesh Velmurugan, Tomas McKelvey, Daniel Lundberg
Supervisory controller for a light duty diesel engine with an LNT-SCR after-treatment system
Published in proceedings of the
SAE International Powertrains, Fuels & Lubricants Meeting
September 2018, Heidelberg, Germany.
DOI: 10.4271/2018-01-1767

In this paper, the complexity of the developed LNT-SCR controller is extended by the addition of the combustion engine as a third subsystem. The same interface is carried over. For the combustion engine, two discrete modes are chosen with two distinct objectives. The first mode has the objective of least engine exhaust NO_x while compromising on fuel consumption. The second mode has the objective of least fuel consumption while compromising on engine exhaust NO_x emissions when the EATS is warmed. In this approach, the drive cycle is broken into 60 s segments. The LNT-SCR NO_x conversion efficiency interface is made discrete with three levels that reduces the computational effort for the controller. A full factorial simulation of the combination of engine-LNT-SCR actions is done to determine the least equivalent fuel consumption combination that satisfies the emission constraints. The result is compared to the rule based controller used for the engine-LNT-SCR coordination under different catalyst conditions and sequenced WLTC.

3.4 Paper D

Dhinesh Velmurugan, Tomas McKelvey, Jan-Ola Olsson
A simulation framework for cold-start evaluation of a gasoline engine equipped with an electrically heated three-way catalyst
Published in proceedings of the
IFAC Conference on Engine and Powertrain Control, Simulation and Modeling,
August 2021, Tokyo, Japan,
Volume 54, Issue 10, pp. 526-533, 2021.
DOI: 10.1016/j.ifacol.2021.10.216

In this paper, a control-oriented simulation model of a gasoline ICE with a two-brick three-way catalyst (TWC) equipped with an EHC between the bricks is described and analysed for use in cold start evaluation of the complete system. The ICE is modelled using a mix of static lookup tables optimized using part load engine test bench measurements, to provide the exhaust emission species flow and gas temperature to the downstream TWC. An axial and radially resolved TWC model, including non-uniform axial lengths of the TWC slices that are relevant for cold start emission control is used. The EHC is modelled as a TWC component with the possibility to generate heat from electrical energy. A set of proposed heating profiles of the EHC is simulated and available measurements are used for comparison. The resultant framework is 100 times faster than real-time and can simulate the use of engine control measures and the EHC impacts with desired accuracy for carrying out the development and analysis of cold start controller strategies

3.5 Paper E

Dhinesh Velmurugan, Tomas McKelvey, Jan-Ola Olsson
Evaluation of electrically heated catalyst control strategies against a variation of cold engine start driver behaviour
Accepted for presentation at the
SAE WCX, Detroit, USA,
April 2022.

The EHC can be started before switching on the ICE, thereby offering the possibility to pre-heat (PRH) the TWC, in the absence of exhaust flow. The EHC can also provide post engine start heat (PSH) when the heat is accompanied by exhaust mass flow over the TWC. A mixed heating strategy (MXH) comprises both PRH and PSH. All the three strategies are evaluated under a range of engine start variations using an ICE-exhaust aftertreatment (EATS) simulation framework. The basis for comparison of the EHC cold-start control strategies with the equivalent emission metric and evaluation frame consisting of engine start idle duration and drive cycle immediately following engine start are laid out.

3.6 Paper F

Dhinesh Velmurugan, Tomas McKelvey, Jan-Ola Olsson
Data-driven near-optimal on-line control for an electrically heated catalyst equipped gasoline engine
Submitted, January 2022.

EHC pre-heating can be started when the engine start is known with greater confidence and post-heating the catalyst could be followed. It would then be natural to turn off the EHC when the pay-off for the electrical energy spent no longer is effective in cold engine start emission reduction. A model-free on-line adaptive controller aimed at minimising the total equivalent emissions is proposed, that is based on a set of pre-computed look-up optimum EHC stop times for the various possible fuel consumption trajectories. The simulation framework for cold start control and the equivalent emissions metric developed earlier are used in conjunction with a validation proposal to compare the performance of the candidate controllers.

CHAPTER 4

Contributions and future outlook

4.1 Contributions - Diesel application

With the background described in 2.3, an objective function with equivalent fuel consumption of the diesel engine was framed. LNT-SCR coordination for NO_x after-treatment complying with exhaust emission constraints while also minimising equivalent fuel consumption was taken up as the first problem to solve. An interface with NO_x conversion efficiency was used considering the holistic perspective of the system as motivated in 2.3. Segmentation of look ahead information was used while considering discrete action sets of controls. After the control structure was designed, discrete engine control modes were introduced to add the engine as a subsystem. The optimisation procedure is to run discrete action cases of the subsystems with the introduced interface on the simulation models of the subsystems. In order to carry out the work on-line the ECU, lumped parameter models were used to evaluate the discrete action sequences. The controllers are evaluated on the simulation platform using variations of the worldwide harmonised light vehicle test cycle (WLTC). The individual contributions are elaborated in the following paragraphs.

4.1.1 Equivalent fuel consumption

The objective of the control problem is to minimise fuel and urea consumption using engine and EATS controls over a drive cycle while fulfilling NO_x legislated tailpipe requirements. A formulation for the cost function in fuel equivalent terms was derived for usage in control optimisation. The cost of engine fuel usage is direct and straight-forward. The EATS cost was derived by the combination of equivalent fuel components of urea used by the SCR and fuel used by the LNT. Apart from them costs for difference between initial and final catalyst states of LNT and SCR were used. The methodology behind the costs are detailed in papers B and C.

4.1.2 Sub-system control interface

A control architecture was proposed for coordinating subsystems that differ in their nature of response time and complexity in system objective. A discrete control action set enables the applicability of such a control architecture in conjunction with the subsystem interface. The discrete control action sets for the engine, LNT and the SCR subsystem were derived. The idea to use discrete control action sets is to minimise the computational requirement to optimise the control problem. While this may come at a cost of loosing optimum, the decision for this approach is motivated by its usability in a standard EMS on board the vehicle.

The engine action set is a choice between two sets of actuator maps with objective of (1) attaining low engine out NO_x when the EATS has a lower NO_x conversion efficiency Low_{NO_x} and (2) achieving best fuel consumption when the EATS is capable of higher NO_x conversion Low_{CO_2}. The choice of two engine modes provides for simplicity in the interface and computation while it does come at an unknown cost from the optimal control.

The control interface for the LNT is the choice of a factor that modifies the target threshold for LNT regeneration. A low factor (<1) would result in a lower threshold than default leading to more frequent regeneration thereby higher NO_x conversion efficiency through the LNT. The fuel consumption would thus be higher. The vice-versa would be applicable for a higher factor. Similar to the LNT, the control interface for the SCR was obtained by modifying target buffer for ammonia in the SCR using a multiplication factor. A higher factor (=1) would lead to maximum NH_3 target buffer thus resulting in higher NO_x conversion from the SCR at the cost of higher urea consumption. The reverse is true for a lower factor. A choice of three factors was used so as to obtain a reasonable spread between the conversion efficiencies.

4.1.3 Look ahead information based control

The supervisory control interface was defined considering look ahead segmentation. The optimisation algorithm considered here was to use the look ahead trajectory and calculate the lowest cost control action combination set for each segment of the trajectory. This was applied as the supervisory control set point.

In a first approach, the trajectory was broken into small segments. The idea was to use characterisation classified segments. Each classified segment was optimised off-line by considering the discrete control action set and parametrised by the engine, catalyst states and the segment type. This would be stored on-board the ECU and applied for each segment. This approach is detailed in paper C. In [65], an alternative approach with a lumped model for the subsystems was used. This was driven by the complete segment and the cumulative effect was modelled. The discrete set of control actions was simulated and optimal control action was derived. The lumped models are a combination of lookup tables and simple parameters. Being computationally non-intensive, these models are intended to be fast and hence possible to implement in the EMS.

In both approaches described above, a full factorial simulation of all the discrete actions from the subsystems is computed. The action set combination that guarantees the emission constraints while having the lowest equivalent fuel consumption was chosen and applied as the supervisory control set point for the upcoming segment in the drive cycle.

4.2 Contributions - Gasoline application

In order to optimally use information and control the gasoline ICE with EHC equipped TWC, a simulation framework with focus on cold-start control was developed where the TWC model was extended from [66]. An evaluation methodology that served as the basis for comparison was developed that combines the emissions and the fuel consumption impact of the competing control strategies. A controller that uses information on-board and off-line precomputed optimisation results is proposed and evaluated in the developed simulation framework using the evaluation mechanism outlined. The individual contributions are elaborated in the following paragraphs.

4.2.1 Modelling the gasoline engine system and TWC with EHC

The simulation framework aiming at capturing the key phenomenon occurring during cold-start is developed. The simulation of the ICE exhaust temperature and emissions species is based on steady state engine-out measurements from part load engine tests. Effect of the warming up phase of the engine with approximate coolant and oil temperature is also incorporated. Production engine control measures for catalyst heating using high engine start idle speed, ignition retard and strategic air-fuel ratio are emulated. In-order to capture the catalyst light-off and replicate cold-start sensitive emission conversion, the TWC was divided into non-uniform axial discretised segments. The non-uniform segmented slices were key to obtain representative emission conversion and temperature profile in the simulation. Each of the main TWC bricks were divided into two non-uniform volumes to enable faster and representative exhaust simulation. The EHC was modelled as a TWC slice with the capability to generate heat from the electrical power supplied. The combined TWC model including the EHC could simulate the cold-start behaviour deemed sufficient for control development.

4.2.2 Equivalent emissions comparison for cold start control

To evaluate a cold start control strategy, the effect of exhaust emission reduction, the fuel penalty and the electrical energy spent need to be sufficiently accounted for. With the EHC the focus is more on emissions reduction. Hence a combined emission equivalent for the total effort was a logical comparison mechanism that has been developed. Fuel equivalence for electrical energy would vary depending upon the energy source for the on-board energy storage. In case of a plug-in hybrid vehicle, this could be from the power grid and the fuel equivalence would depend on the power mix. For a hybrid vehicle where the energy source is the engine fuel converted electrical energy, a few considerations need to made. The energy in surplus is usually stored on-board in the battery. The surplus could be generated by pushing additional torque (load) on the engine when operating in a high brake specific fuel consumption (bsfc) operating point or from energy recuperated from braking. Recuperated energy could be considered free of fuel cost. The surplus generated could be considered to be generated at the best or nearly best bsfc operating point of the engine. The reason is that the additional load in most engine operating points pushes the engine to operate in a more fuel optimal operating point. There are also losses associated with mechanical power transferred from the engine to the generator, the loss in the battery and the inverter. Combining the losses, the associated equivalent fuel for the electrical energy was approximately the average of the best and worst bsfc of the gasoline ICE which is an extension of the approach in [67]. Comparison of fuel equivalence to estimations presented in [67], [68] indicates that this is a reasonable approach. Now, the equivalent fuel and absolute emissions need to be weighed together. Since the fuel equivalent considered here is for generating the electrical energy by the gasoline ICE, equivalent emissions for the fuel have been calculated. The fuel mass consumed in a regulatory test procedure could be considered to yield the net tailpipe exhaust emissions mass reported. This would thus comprise one cold-start effect and the net effect of the warm catalyst during which the electrical energy was generated. Equivalent emission mass of species emitted for each gram of fuel consumed is thus calculated. To analyse the effect of the EHC, a sum of the obtained equivalent emission species mass for the electrical energy consumed by the EHC and tailpipe emissions mass of the respective emission species is divided by the tailpipe emissions when no EHC is used. Since the normalised values are comparable, they can be summed together and divided by 3 (the number of pollutant emission species: CO, HC and NO_x). This score would indicate directly the improvement in total emissions reduction capability of the EHC cold start control strategy.

4.2.3 Evaluation framework for engine cold start control

A metric for the comparison of the cold-start control strategy was concluded with the equivalent emissions. To utilise the metric over the expected cold-start control challenges, an evaluation framework was developed. The primary cold start control challenges arise from the disturbances to the expected usage of the system. The user power request is the main disturbance, the expected characteristics of which need to be included in the evaluation framework. Most important of the main disturbances from the user is the initial start vehicle idle duration. The next disturbance is the driver acceleration demand following the engine start up to catalyst light-off. Since catalyst light-off is in the range of 10-100 s after engine start, varying the initial drive demand would be important to capture varying expected user behaviour. Various vehicle idle periods were pre-fixed to the generated drive cycles to represent both the disturbances. The vehicle idle period distribution from the literature survey was used to weigh the net results from the total normalised equivalent emission simulation results.

4.2.4 Usage of look-ahead information

For cold start EHC control development, the controller sensitive information needed would be the engine start time, engine start idle duration and the immediate driver demand up to the catalyst light-off period. The net useful information that is essential from these disturbances is the net heating effect from the engine. The fuel consumed by the engine was used as the information summarising signal. In the scope of the thesis, the control choice to be made are the EHC heater start time and the heater stop time. A full factorial simulation of EHC pre-heating time and the post-heating time was done for the drive cycle under evaluation. The resulting equivalent emissions metric provided the optimal pre-heating and respective post-heating time pair. On-line available information when the engine is started includes the EHC pre-heating time and the fuel consumed up to the current engine run time. At each time instance, a comparison of the current engine fuel consumption trajectory is compared to a set of on-board stored template cycles for which pre-computed optimal EHC time pairs are also stored. The pre-computed EHC post heating time of closest matching cycles are averaged if multiple template cycles are matched and are set as the target EHC post-heating time. The EHC is turned off when the target time exceeds the current engine run time. In comparison to the equivalent emissions from the optimal time pair, the on-line controller demonstrated close performance in the recommended evaluation framework.

4.3 Future outlook

The control application in this thesis was changed from a diesel power-train to a gasoline power-train in response to the business direction with the motivation to produce research results that are relevant to the changing power-train development scenario. In doing so, some of the wish list tasks that could be performed as an extension of the results from this thesis are presented in this section.

4.3.1 Verification of controller proposals

The simulation models can be tuned as in paper D to enable controller calibration for verification on physical test objects such as a vehicle. The evaluation methodology proposed in paper E can be used to setup a target method to evaluate performance of the calibrated controller. The on-line adaptive controller presented in paper F can be applied and evaluated to validate the proof of concept and propose any modifications. Focus on real world performance and adaptation to driver disturbance can be compared to the performance from a fixed controller.

4.3.2 Integrated gasoline engine and EHC control

In paper F, a standalone EHC control was developed to optimise cold-start emissions and equivalent fuel consumption. The approach in paper E could be extended to quantify engine cold-start control measures such as idle speed, ignition retard and air-fuel ratio control. A suitable control interface to coordinate and jointly optimise these engine control measures and the EHC control actions in a supervisory control fashion similar to the diesel application results in papers B and C could be developed.

4.3.3 Extended engine-starts

The scope of this thesis could be extended to cover a range of other possible engine-starts. This could include accounting for ambient temperature differences. High power cold-starts events in hybrid vehicles where look-ahead information and predictive TWC pre-heating could be used to mitigate the high exhaust emission impacts could be investigated. Different vehicle soak times in different ambient temperatures could also be an interesting direction to carry out further research work.

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