THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Model-Based Diesel Engine Management System Optimization

A STRATEGY FOR TRANSIENT ENGINE OPERATION

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To Anna

Abstract

To meet increasingly strict emission legislation and stronger demands on fuel consumption, typical passenger car diesel engines become increasingly complex with more and more controllable systems added. These added systems open up for the possibility to operate the engine at more efficient conditions, but it also becomes more challenging to optimize the settings in the engine management system. Methods to optimize settings in an engine management system based on steady-state engine operation are well developed and described in the literature, and also used in practice. Methods to handle transient engine operation are not as well developed, and typically various compensations are added in an engine management system to account for effects during transient engine operation. Calibration of these compensations is currently a manual process and is largely performed to meet regulations rather than to optimize the system.

This thesis consists of papers that describe the introduction of a novel method to optimize settings in a diesel engine management system with an aim to minimize fuel consumption for a given dynamic vehicle driving cycle while keeping accumulated engine-out emissions below given limits. The strategy is based on existing methods for steady-state engine operation, but extended to account for transient effects in the engine caused by dynamics in the gas exchange system in a systematic manner. The strategy has been evaluated using a simulation model of a complete diesel engine vehicle system. The optimization strategy has been shown to decrease fuel consumption for a diesel engine vehicle compared to existing methods based only on steady-state engine operation. Using the simulation model, the strategy has been shown to decrease fuel consumption for a vehicle driving according to the New European Driving Cycle with 0.56%, compared to a strategy based only on steady-state engine operation.

This thesis also consists of papers that describe the complete diesel engine vehicle system simulation model. The model can perform a simulation of a vehicle driving according to a predefined dynamic driving cycle, and it estimates fuel consumption together with NO_X and soot emissions throughout the simulation depending on settings in the engine management system.

Abstract

The model accounts for transient effects on fuel consumption and emissions caused by dynamics in the engine gas exchange system. The simulation model is implemented in the Matlab Simulink environment, and the simulation time is in the range of 10 to 20 times faster than real-time.

Keywords: Diesel engine, Engine control, Engine management system, Fuel Consumption, Emissions, Optimization, Modeling, Simulation, Calibration

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Göteborg, September 2013

List of publications

This thesis is based on the following six appended papers:

Paper 1

Markus Grahn, Krister Johansson, Christian Vartia, and Tomas McKelvey, “A Structure and Calibration Method for Data-driven Modeling of NO_X and Soot Emissions from a Diesel Engine”, *SAE 2012 World Congress*, April 2012, Detroit, MI, USA.

Paper 2

Markus Grahn, Krister Johansson, and Tomas McKelvey, “B-splines for Diesel Engine Emission Modeling”, *2012 IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling (E-COSM’12)*, October 2012, Paris, France.

Paper 3

Markus Grahn, Krister Johansson, and Tomas McKelvey, “Data-driven Emission Model Structures for Diesel Engine Management System Development”, *Accepted for publication in International Journal of Engine Research.*

Paper 4

Markus Grahn, Krister Johansson, and Tomas McKelvey, “A Complete Vehicle System Model for Diesel EMS Development”, *Technical report.*

Paper 5

Markus Grahn, Krister Johansson, and Tomas McKelvey, “A Diesel Engine Management System Strategy for Transient Engine Operation", *7th IFAC Symposium on Advances in Automotive Control*, September 2013, Tokyo, Japan.

Paper 6

Markus Grahn, Krister Johansson, and Tomas McKelvey, "Model-Based Diesel Engine Management System Optimization for Transient Engine Operation", *Manuscript submitted for publication.*

Other relevant publications

In addition to the six appended papers, the following two papers, authored and co-authored by the thesis author, are relevant to the topic of this thesis:

Markus Grahn, Jan-Ola Olsson, and Tomas McKelvey, "A Diesel Engine Model for Dynamic Drive Cycle Simulations", *2011 IFAC World Congress*, August 2011, Milano, Italy.

Nikolce Murgovski, Markus Grahn, Lars Johannesson, and Tomas McKelvey, "Optimal Engine Calibration and Energy Management of Hybrid Electric Vehicles", *Manuscript submitted for publication.*

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Part I

Introductory chapters

Chapter 1

Introduction

This thesis is written within the scope of a project entitled *Diesel Engine Optimization*. The project is initiated by Volvo Car Corporation and is carried out within the Combustion Engine Research Center (CERC) at Chalmers University of Technology, financed by Volvo Car Corporation and the Swedish Energy Agency. The aim of the project is to develop methods and strategies for diesel engine management system (EMS) optimization. The method to do this within the project is to use a model-based approach, i.e. to utilize simulation models in the EMS optimization process.

This thesis consists of papers that describe a novel diesel EMS optimization strategy. The strategy calculates set points for controllable engine quantities with an aim to minimize fuel consumption for a dynamic driving cycle while fulfilling constraints on accumulated engine-out emissions. The strategy is designed to handle transient effects in an engine caused by dynamic effects in the gas exchange system, and has been evaluated using a complete diesel engine vehicle system simulation model. The thesis also contains papers that describe the development and implementation of this simulation model.

1.1 Outline

The thesis consists of two parts. Part I contains background information which explain challenges within the field of diesel engine management system optimization. A description of current state of the art within industry and within the research field is presented, followed by a description of the scope of the thesis. The contributions to the field provided by the papers included in this thesis are provided, followed by a summary of the included papers. Part I is ended with some concluding remarks and an outlook.

Part II contains the six scientific papers that constitute the base for the thesis.

Chapter 2

Background

2.1 Diesel engine fundamentals

The diesel engine was developed in 1893 by Rudolf Diesel. Detailed description of the fundamentals for a diesel engine can be found in for example [1, 2], but a brief introduction is presented here.

Most passenger car diesel engines operate as four-stroke engines, i.e. the pistons in the engine complete four separate strokes during two revolutions of the engine's crankshaft. A schematic illustration of the four strokes during a diesel cycle is shown in Figure 2.1. The four different strokes are:

1. **Intake stroke**
   The piston moves from the top of the cylinder to the bottom of the cylinder, while the intake port is open. As the piston moves, air enters the combustion chamber from the intake manifold via the intake port.

2. **Compression stroke**
   The intake valve closes, and the piston returns to the top of the cylinder. The trapped air within the cylinder is compressed, and pressure and temperature increase. At the end of the compression stroke, fuel is injected into the cylinder, where it self-ignites due to the high temperature and pressure.

3. **Power stroke**
   The combustion of the fuel increases the pressure in the combustion chamber, which produces mechanical work on the piston as it moves towards the bottom of the cylinder.

4. **Exhaust stroke**
   The exhaust valve opens, and the piston moves from the bottom of the cylinder to the top of the cylinder again. The products from the combustion exit the combustion chamber via the exhaust valve.

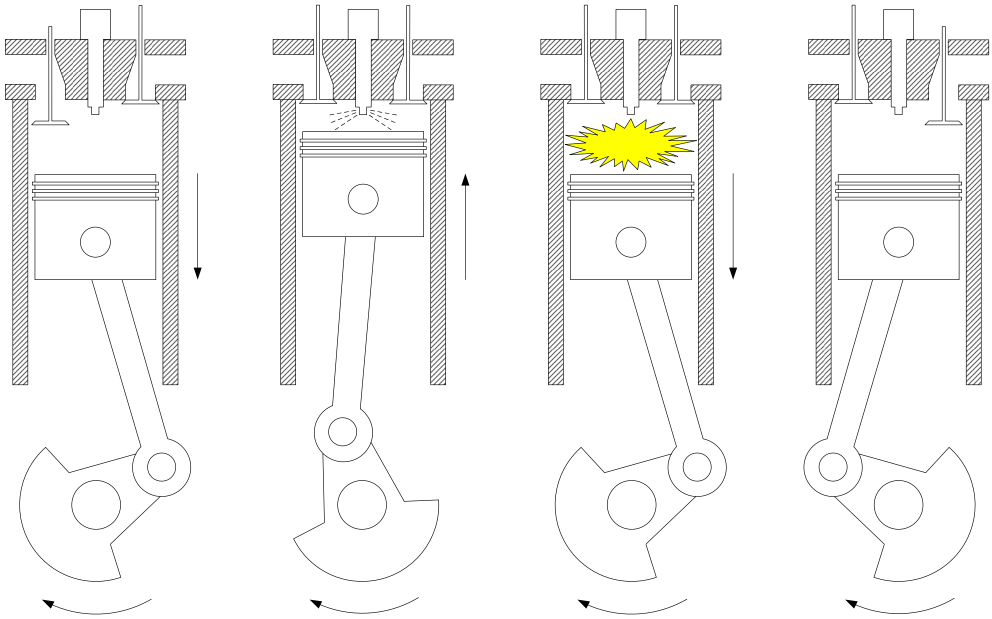

Figure 2.1: Illustration of the four strokes during a diesel cycle. From left to right the figure shows the intake stroke, the compression stroke, the power stroke, and the exhaust stoke. (Image courtesy of Mikael Thor.)

A standard diesel engine is typically direct-injected and compression-ignited, i.e. fuel is injected directly into the compressed air in the cylinders where it self-ignites due to the high temperature and pressure. This can be compared with port-injected and spark-ignited engines. In a port-injected engine, fuel is injected outside the cylinders, close to the intake ports, and enters the combustion chamber together with the air. In a spark-ignited engine a spark plug is used to ignite the fuel-air mixture after compression. A standard gasoline engine is typically port-injected and spark-ignited, although direct-injected gasoline engines are becoming increasingly common.

A diesel engine is normally operated with a global excess of air in the cylinders. After ignition in a diesel engine, fuel is combusted at a rate which is mainly determined by the rate of with which the fuel is mixed with the air. The combustion in a diesel engine is therefore said to be mixing-controlled.

The combustion results in that chemical energy in the fuel is converted to mechanical work on the piston. The efficiency of this energy conversion is dependent on the details of the combustion process. In broad terms, a fast combustion that occurs close to piston top dead center (TDC) results in high fuel conversion efficiency, and slow combustion located further away from TDC results in low fuel conversion efficiency. The conversion efficiency is directly linked to the fuel consumption of the engine.

Diesel fuel mainly consists of hydrogen (H) and carbon (C), and ideally the combustion of fuel and oxygen (O_2) would only result in carbon dioxide (CO_2) and water (H_2O) according to the reaction

$$H_xC_y + \left(\frac{x}{4} + y\right) O_2 \rightarrow yCO_2 + \frac{x}{2}H_2O \tag{2.1}$$

where x is the number of hydrogen atoms and y is the number of carbon atoms in a fuel molecule. It can be noted that the excess air within the cylinders is not included in this description of the reaction.

Unfortunately, this ideal reaction is not a full description of the combustion process in a diesel engine. Unwanted products are also formed during the combustion. The main issue for a diesel engine is the formation of the harmful emissions nitrogen oxides (NO_X) and soot. NO_X is formed during the combustion in regions with high temperature and an excess of oxygen available, and soot is mainly formed during the combustion in regions with lower temperature and little oxygen available. Most of the formed soot is oxidized later during the combustion at high temperatures when there is oxygen available.

Because soot and NO_X are formed by very different and sometimes competing processes; combustion control to decrease one of them typically generates an increase in the other. This is commonly known as the diesel dilemma, and is a well-known issue with diesel engines. Furthermore, as the fuel consumption is also directly linked to the combustion process, there is often a trade-off between fuel consumption, NO_X emissions and soot emissions in a diesel engine.

Besides the emissions of NO_X and soot, issues for a diesel engine are also unwanted emissions of carbon monoxide (CO), which are formed during the combustion, and unburned hydrocarbons (HC), which is a result of incomplete combustion of the fuel.

2.2 Driving forces for diesel engine development

Although diesel engines have been around since 1893, there is an ongoing development on diesel engines for passenger cars. The main driving force for this development during the last years has been the increasingly stricter legislation on emissions.

In Europe, the emission regulations are set by the European Union. The regulations were once specified in Directive 70/220/EEC, but in 2007 this Directive was replaced by Regulation 715/2007. An illustration of the progress of the emission regulations in Europe for NO_X and soot emissions is shown in Figure 2.2. The emission levels for a vehicle are measured by driving the vehicle in a chassis dynamometer. A standardized test cycle defined in Directive 98/69/EC, called the New European Drive Cycle (NEDC) is used. The NEDC cycle is a dynamic driving cycle, and is designed to represent both city driving and highway driving. The duration of the cycle is 1180 seconds, and during the cycle, emissions are sampled and analyzed. The emission limits are expressed in grams per kilometer driving.

Another strong driving force for the development of diesel engines is fuel consumption, or equivalently emissions of CO_2. Low fuel consumption is a strong selling argument for passenger cars, but there is also upcoming legislation regarding CO_2 emissions. In 2007, the European Commission proposed legislation for new passenger cars regarding CO_2 emissions. This legislation, adopted in 2009 by the European Parliament and the Council ensures that fleet average emissions from new passenger cars in EU do not exceed 120 grams per kilometer [3]. The legislation is valid from 2015 with a phase in period that started in 2012. A target of 95 grams per kilometer is also specified for the year 2020.

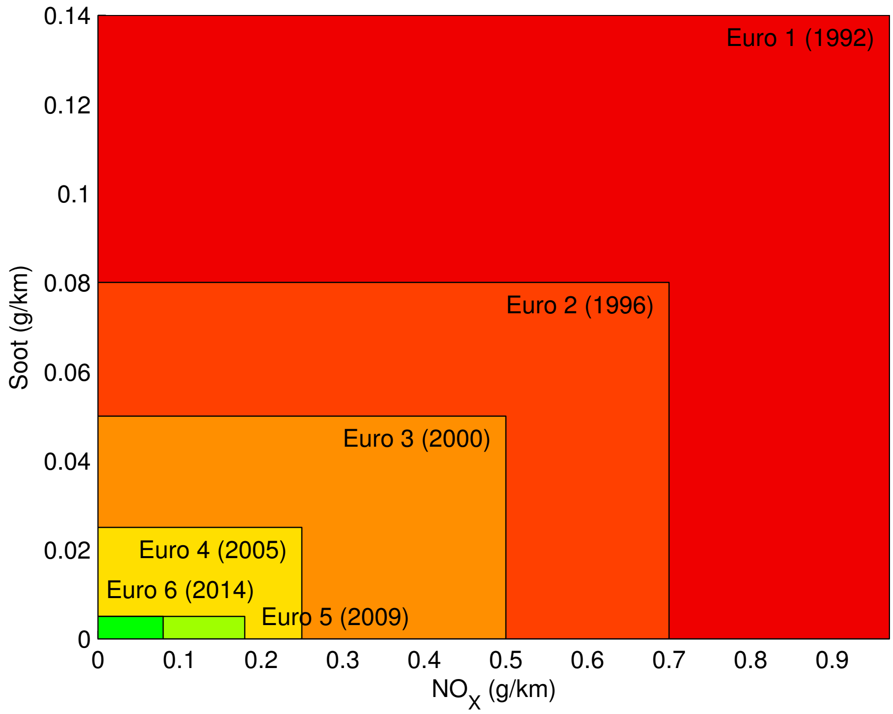

Figure 2.2: The progress of NO_X and soot emission standards in Europe for diesel engine passenger cars.

2.3 Diesel engine controllable systems

To be able to handle the increasingly strict emission legislation and stronger demands on fuel consumption, there is an ongoing rapid development of diesel engines. A major part of this development is that different systems within the engine are enhanced or added. These systems can be divided into two main categories; the first one is that systems are used such that the operation of the diesel engine itself can be better controlled, and the second one is after-treatment systems that remove harmful emissions from the combustion process after the emissions leave the cylinders. The operation of the engine itself can be influenced either by designing the hardware of the combustion system, by controlling the air that enters the combustion chamber via the gas exchange system, or by controlling how fuel is injected into the air. This section describes common controllable systems in a typical passenger car diesel engine today.

2.3.1 Gas exchange system

The air that is compressed in the cylinders enters the combustion chamber via the gas exchange system. There are several controllable system within the gas exchange system.

To be able to increase the amount of air that enters the combustion chamber, a diesel engine is usually equipped with a turbocharger system. The hot exhaust gases produced by the engine are driving a turbine, which in turn drives a compressor on the intake side of the gas exchange system. The compressor increases the pressure in the intake manifold which in turn increases the amount of air that enters the combustion chamber. By increasing the amount of air in the combustion chamber, the possible amount of fuel that can be injected before too much soot is formed is increased (as described in Section 2.1, soot is formed when there is little oxygen available). Therefore, the turbocharger system is used to increase the upper load limit of a diesel engine. The pressure in the intake manifold is controlled by adjusting the amount of exhaust gases that is fed through the turbine. A turbocharger system is more or less standard on a passenger car diesel engine today. To be able to increase turbocharger efficiency, one possibility is to use a two-stage turbocharger system. This is becoming more and more common for passenger car diesel engines.

Furthermore, it is possible to feed some of the exhaust gases out from the engine back into the intake side of the engine, where it is mixed with fresh air. This is called exhaust gas recirculation (EGR). EGR leads to dilution of fresh intake air with combustion products, which in turn results in a decrease in combustion temperature. Use of EGR is a tool to decrease

NO_X emissions, but it typically leads to an increase in soot emissions and fuel consumption. The amount of EGR is controlled via a valve between the exhaust and intake manifolds.

Also, the intake system in a diesel engine is normally designed such that air enters the combustion chamber with a rotating motion. The rotating motion is called swirl, and it is used to increase the mixing speed between the fuel and the air during combustion. Some engines are equipped with a variable flap such that the swirl rate can be controlled.

An important property of the gas exchange system is that it has dynamic behavior. The turbocharger is a rotating system with a moment of inertia, which causes the main dynamics of the turbocharger system. The EGR system transports exhaust product from the exhaust manifold to the intake manifold, but since the manifolds have certain volumes, there are also dynamics for this system. Typically, the turbocharger dynamics are the slowest dynamics in the gas exchange system, while the manifold dynamics are faster. The dynamic behavior limits the control of pressures and flows in the gas exchange system. Pressures and flows cannot be changed arbitrarily from combustion event to combustion event by the control system actuators.

2.3.2 Fuel injection system

The fuel injection system in a typical passenger car diesel engine has several parameters that can be controlled. First, the fuel injection pressure, i.e. the pressure at with which fuel is injected into the combustion chamber, can be controlled. The fuel injection pressure directly affects the fuel injection rate, which in turn influences the injection duration for a given fuel amount. This influences the combustion process. Furthermore, the fuel injection introduces turbulence in the combustion chamber, which in turn influences the mixing rate between the fuel and the air. Therefore, the mixing rate is also affected by the fuel injection pressure.

The timing of the fuel injection, and therefore the timing of the combustion, can be controlled. Early injection typically leads to increased pressure and temperature within the cylinders, and higher efficiency, but it also leads to increased NO_X emissions due to the higher temperature. Later injection timing can typically cause incomplete combustion, reduced efficiency and an increase in soot emissions.

Furthermore, it is possible to split the fuel injection during one combustion event into several individual injection pulses. Each injection pulse can be controlled individually regarding timing and duration. The injection is typically divided into one main injection, where most of the fuel is injected, one or several pilot injections which appear before the main injection, and one or several post injections. Pilot injections are mainly used to decrease the combustion rate to limit combustion noise from the engine, and post injections are mainly used to enhance soot oxidation during the late stage of the combustion.

2.3.3 After-treatment systems

Unwanted engine-out emissions that are formed during the combustion can be reduced in a diesel engine by using after-treatment systems. A diesel engine is usually operated with a global excess of air, which means that the very effective three-way-catalyst (TWC) used in gasoline engines cannot be used in a diesel engine. A diesel engine is usually equipped with an oxidation catalyst to convert carbon monoxide (CO) and hydrocarbons (HC) to carbon dioxide (CO_2) and water (H_2O).

Furthermore, a typical passenger car diesel engine today is also equipped with a Diesel Particulate Filter (DPF). A DPF captures most of the engine out soot, but it needs to be regenerated regularly. Regeneration is performed by operating the engine inefficiently such that the exhaust gases become hot enough to burn the accumulated soot in the DPF. The process of operating the engine inefficiently leads to an increase in fuel consumption during DPF regeneration.

NO_X emissions cannot be reduced using the oxidation catalyst, and usually this is handled by operating the engine such that NO_X emissions are low enough already out from the engine. However, due to the increasingly stricter legislation on emissions, special after-treatment systems for NO_X emissions have started to be introduced for passenger car diesel engines. Examples of after-treatment systems for NO_X emissions are Selective Catalytic Reduction (SCR) systems and Lean NO_X Traps (LNT). SCR is a means of converting NO_X into diatomic nitrogen (N_2) and water (H_2O). To do this, a reactant, usually ammonia or urea, is added to the stream of exhaust gases. LNT is a system that absorbs NO_X molecules, similar to a DPF system for soot emissions. The LNT system needs to be regenerated regularly, since only a limited amount of NO_X molecules can be trapped.

2.4 Engine management system challenges

The operation of an engine is controlled by the engine management system (EMS). In the EMS, control strategies and set points for the controllable systems should be defined such that optimal engine operation is achieved. The complexity of a typical passenger car diesel engine today, with the many different controllable systems presented in Section 2.3 makes it possible to operate a diesel engine at efficient conditions, but finding optimal control strategies and set points in the EMS is a difficult challenge.

First of all, due to the different properties of NO_X formation, soot formation, and fuel efficiency described in Section 2.1, it is a challenge to control the various system in an engine such that the optimal trade-off between fuel consumption and emissions is always achieved. Since the performance of an engine regarding emissions and fuel consumption is evaluated for a complete vehicle driving cycle, it is even a challenge to *define* the optimal operation of one single combustion event during the cycle. For example, it is beneficial to allow an increase of emissions in favor for lower fuel consumption in one combustion event during the cycle, if emissions can be decreased in *any* another combustion event during the cycle with less penalty on fuel consumption. The optimal trade-off for one single combustion event cannot be determined unless all combustion events throughout the driving cycle are considered simultaneously.

Furthermore, due to the dynamics in the gas exchange system described in Section 2.3.1, the different combustion events throughout a driving cycle cannot be controlled individually, but is dependent on previous control actions.

The many degrees of freedoms for the engine control systems together with the dynamic behavior of the engine make the task of optimizing the EMS very challenging.

It can also be noted that since emissions and fuel consumption are evaluated using a complete vehicle, the engine operation during a given driving cycle is not only dependent on the engine itself, but also on the vehicle in which it is used. For example, a heavier vehicle result in that the engine typically operates at higher engine loads during a cycle, and vice versa. This implies that optimal EMS settings for an engine in one vehicle are most likely not the optimal settings for the same engine used in a different vehicle.

Chapter 3

Engine management system calibration procedure

As described in Section 2.4, it is a challenging task to find optimal control strategies and set points in an EMS for the controllable engine systems. The following chapter describes the author's view of the typical procedure to perform EMS calibration today within industry. The target with the procedure is to define set points in the EMS for all controllable engine systems such that fuel consumption is minimized for a dynamic vehicle driving cycle while constraints on accumulated engine-out emissions are fulfilled.

3.1 Initial calibration

Due to the very many degrees of freedom in an engine system, it is not (yet) possible in practice to account for all systems in a sophisticated global optimization procedure. Therefore, the operation of a number of the controllable systems is calibrated separately at an early stage in the EMS calibration process. These systems are calibrated based on the engine speed and load operating range of the engine. Examples of systems that are typically calibrated at this stage are number of injection pulses for each combustion event, individual dwell times between the different injection pulses, relative injection amounts in the different injection pulses, and the fuel rail pressure. Settings for these quantities are calibrated manually using an engine in an engine test cell, with an aim to find a reasonable balance between fuel consumption and emissions throughout the complete working range of the engine. This calibration is possibly also performed in conjunction with tuning of the engine hardware design, i.e. for example design of the pistons, design of the cylinder head, and physical location of the injectors can be tuned at this stage together with the manual EMS calibration.

3.2 Drive cycle optimization based on steady-state engine operation

The next step is to calibrate settings in the EMS for the remaining systems, but now account for the complete driving cycle instead of calibrating settings in various engine operating points individually. Typically, the calibratable parameters accounted for at this stage are set points for boost pressure, oxygen fraction in the intake manifold (closely coupled to the amount of EGR), and the injection timing, i.e. the timing of the complete injection package. There are several reasons for choosing these three. First, they have a large impact on fuel consumption and emissions. Second, as described in Section 2.3.1, boost pressure and oxygen fraction in the intake manifold are associated with dynamic behavior in the gas exchange system, and therefore they should be accounted for when the complete vehicle system is considered.

3.2.1 Drive cycle approximation

First, a vehicle is driven according to the specified driving cycle, while the speed and load of the engine throughout the cycle is registered. Alternatively, a simulation model for a complete vehicle can be used. From the resulting speed and load profiles throughout the driving cycle, a limited number of steady-state engine operating points are chosen such that the complete vehicle driving cycle can be reasonably well approximated as a weighted sum of engine operation in these engine operating points.

3.2.2 Engine mapping

Measurements are performed in an engine test cell, where the engine is operated at steady-state conditions in the complete speed and load operating range. In the various speed and load operating points, considered set points, i.e. typically set points for boost pressure, oxygen fraction in the intake manifold, and injection timing, are varied according to a suitable design of experiments methodology.

3.2.3 Drive cycle optimization

Using the measured data from the engine test cell together with the chosen representative engine operating points that approximate the vehicle driving cycle, off-line calculations are performed to minimize fuel consumption for the approximated driving cycle, while fulfilling constraints on accumulated emissions. These optimization calculations typically account for the trade-off challenge described in Section 2.4, i.e. they account for all engine operating points simultaneously as it calculates optimal set points for the individual engine operation points. Methods for this are well developed and described in the open literature. The approach is that a trade-off between fuel consumption and emissions is selected, and that all individual operating points are optimized based on this selected trade-off. The process is iterated with different trade-offs until the performance of the approximated driving cycle is satisfactory. Simulation models for emissions and fuel consumption are typically used in this stage to speed up the process. This steady-state based optimization procedure is discussed in detail in Chapter 4.

Finally, by using information from the optimal solution together with the engine measurements that cover the complete working range of the engine, optimal set points are calculated not only for the selected representative engine operating points, but for the complete operating range of the engine with respect to engine speed and load. These set points are stored in the EMS. The structure in an EMS is mostly based on two-dimensional grid maps [4], and the calculated set points can be implemented directly into this structure. Doing this, set points are defined in the EMS for the complete working range of the engine, not only the working range covered by the approximated driving cycle.

The reason for that not all systems are considered in this optimization stage is that it would be too time consuming to perform measurements in an engine test cell to completely cover all degrees of freedom for all controllable systems. Therefore, some of the systems are calibrated manually before this procedure, as described in Section 3.1.

3.3 Transient compensations

Until now, the drive cycle optimization has only been performed based on steady-state engine operation. For the set points associated with systems with dynamics, feedback controllers are used to obtain the predefined set points. Even though feedback controllers are used, the set points cannot be directly reached during transient engine operation due to the dynamics in the gas exchange system described in Section 2.3.1. This leads to different emissions and fuel consumption figures during transient engine operation compared to steady-state engine operation. As an example, during a positive load transient the boost pressure does not directly reach its higher set point within the new engine operation point owing to dynamics in the turbocharger system. This in turn leads to reduced availability of oxygen for combustion, and that in turn most likely leads to an increase in soot emissions during the transient (as described in Section 2.1, soot is formed when there is little oxygen available during combustion).

To handle this transient behavior, additional compensations are used to keep emissions within a reasonable range during the transients. Typically compensations to adjust the set point for the oxygen fraction in the intake manifold and the injection timing based on the magnitude of the engine load change are used. The calibration of these compensations is a manual process and is largely performed to reduce emissions spikes rather than to optimize the overall system.

3.4 Final calibration

After the EMS calibration has been performed by first optimizing the driving cycle approximated as a number of steady-state engine operating points, and then manually calibrating compensations for transient operation, the performance of a real vehicle, driving according to the specified cycle, is evaluated. Doing this, the defined limits on accumulated amount of emissions are most likely not reached. The reason for this is that even though compensations for transient engine operation are used, emissions during transients are most likely higher than corresponding emissions during steady-state engine operation used in the steady-state based drive cycle optimization.

The approach to solve this problem is typically to perform the drive cycle optimization procedure based on steady-state engine operation again, but this time with lower limits on accumulated emissions for the approximated driving cycle. The whole process of steady-state drive cycle optimization and transient compensation calibration is iterated several times with different limits on accumulated emissions in the steady-state optimization procedure, until resulting vehicle performance is satisfactory. This is a time consuming process associated with a large amount of manual calibration work, both in a complete vehicle and in an engine test cell. It also results in an EMS calibration that is not aimed at optimizing the system, but instead is focused on meeting emission regulations.

A schematic illustration of the complete EMS calibration procedure described in this Chapter is shown in Figure 3.1.

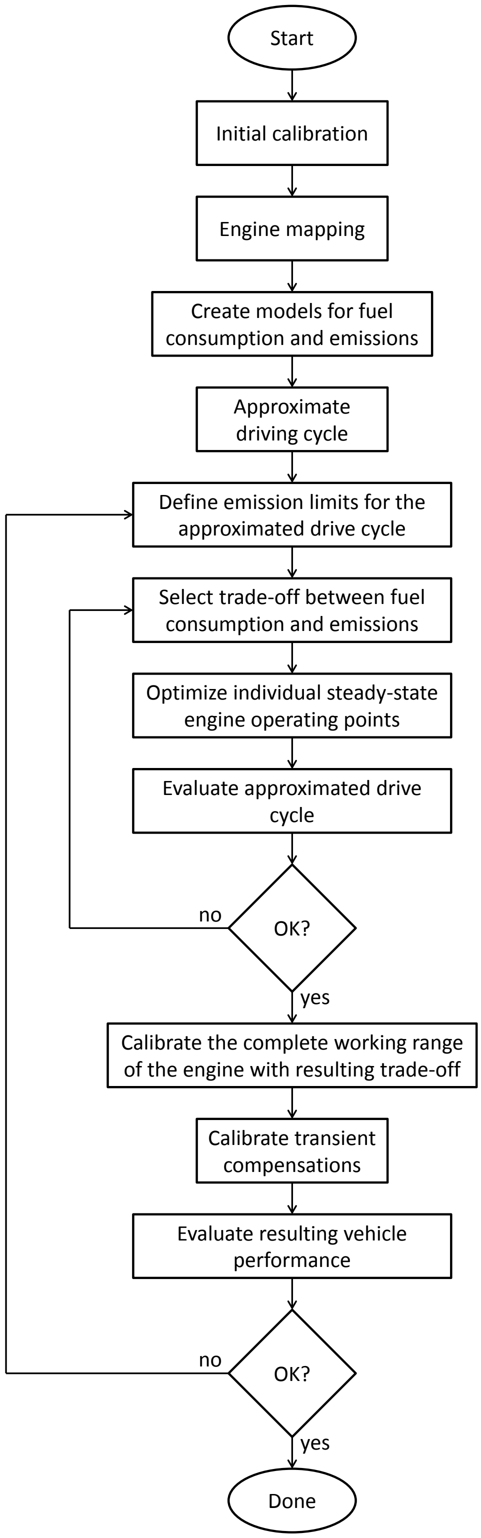

Figure 3.1: Schematic illustration of a typical EMS calibration procedure.

Chapter 4

State of the art

This chapter describes current status within the research field of EMS optimization. A common approach within the field is to use a model-based strategy for EMS optimization, and this is also the approach applied in the *Diesel Engine Optimization* project. Therefore, a section describing related work within the field of diesel engine modeling is also included.

4.1 Engine management system optimization

This section attempts to describe the research status within the field of engine management system optimization. As described in Chapter 3, the procedure to perform EMS calibration is typically separated into optimization of steady-state engine operation and transient engine operation. Research within the area of EMS optimization is to a large extent also divided into research for drive cycle optimization based on steady-state engine operation, and research within optimization of transient engine operation.

4.1.1 Optimization based on steady-state engine operation

EMS optimization methods based on steady-state engine operation are well developed and described in the open literature. These methods are developed to handle the trade-off challenge described in Section 2.4, i.e. to find set points for the EMS such that the full vehicle system meets the legislative limits of soot and NO_X emissions. The optimization problem for the approximated driving cycle can be formulated mathematically as:

$$\begin{aligned} &\min_{\mathbf{z}} \sum_{i=1}^{n} f\left(n_{\mathrm{e}i}, T_{\mathrm{e}i}, \mathbf{z}_i\right) t_i \\ &\text{s.t.} \\ &\sum_{i=1}^{n} g_j\left(n_{\mathrm{e}i}, T_{\mathrm{e}i}, \mathbf{z}_i\right) t_i \leq G_j, j = 1 \ldots m \end{aligned} \tag{4.1}$$

where $f\left(n_{\mathrm{e}i}, T_{\mathrm{e}i}, \mathbf{z}_i\right)$ if the fuel mass flow (g/s) at engine speed $n_{\mathrm{e}i}$, engine torque $T_{\mathrm{e}i}$, and set points $\mathbf{z}_i$ corresponding to engine operating point i. The number of engine operating points is denoted n. The time spent in engine operating point i in the approximated driving cycle is denoted t_i. The number of emission constraints is denoted m, and the mass flow (g/s) of emission j in engine operating point i is denoted $g_j\left(n_{\mathrm{e}i}, T_{\mathrm{e}i}, \mathbf{z}_i\right)$. The constraint on maximum accumulated mass of emission j for the approximated driving cycle is denoted G_j.

A common approach to solve the optimization problem (4.1) is to use a Lagrangian relaxation approach [5]. The Lagrangian function to the optimization problem is

$$L\left(\mathbf{z}, \boldsymbol{\lambda}\right) = \sum_{i=1}^{n} f\left(n_{\mathrm{e}i}, T_{\mathrm{e}i}, \mathbf{z}_i\right) t_i + \sum_{j=1}^{m} \lambda_m \left(\sum_{i=1}^{n} g_j\left(n_{\mathrm{e}i}, T_{\mathrm{e}i}, \mathbf{z}_i\right) t_i - G_j\right) \tag{4.2}$$

where $\lambda_j \geq 0, j = 1 \ldots m$ are Lagrangian multiplicators (or dual variables) corresponding to each emission constraint. Since the n engine operating points are completely independent from each other in the approximated driving cycle, the Lagrangian function can be reformulated as

$$L\left(\mathbf{z}, \boldsymbol{\lambda}\right) = \sum_{i=1}^{n} \left(f\left(n_{\mathrm{e}i}, T_{\mathrm{e}i}, \mathbf{z}_i\right) + \sum_{j=1}^{m} \lambda_m g_j\left(n_{\mathrm{e}i}, T_{\mathrm{e}i}, \mathbf{z}_i\right)\right) t_i - \sum_{j=1}^{m} \lambda_m G_j \tag{4.3}$$

The dual function to the optimization problem (4.1) is defined as

$$h\left(\boldsymbol{\lambda}\right) = \min_{\mathbf{z}} L\left(\mathbf{z}, \boldsymbol{\lambda}\right) \tag{4.4}$$

The function $h\left(\boldsymbol{\lambda}\right)$ is concave [5], and for given values of $\lambda_j \geq 0, j = 1 \ldots m$, the function value can be calculated by solving n optimization problems. For each engine operating point in the approximated driving cycle, the following optimization problem is solved

$$\min_{\mathbf{z}} \left(f\left(n_{\mathrm{e}}, T_{\mathrm{e}}, \mathbf{z}\right) + \sum_{j=1}^{m} \lambda_m g_j\left(n_{\mathrm{e}}, T_{\mathrm{e}}, \mathbf{z}\right)\right) \tag{4.5}$$

where $\mathbf{z}$ are set points for the considered controllable systems in the engine operating point, n_e is the engine speed, and T_e is the requested engine torque.

According to the theory of weak duality [5] it follows that for all $\boldsymbol{z}_i, i = 1 \dots n$ that are feasible in (4.1), the following relation holds

$$h(\boldsymbol{\lambda}) \leq \sum_{i=1}^{n} f(n_{\text{e}i}, T_{\text{e}i}, \boldsymbol{z}_i)\, t_i \tag{4.6}$$

This means that if it is possible to find values $\lambda_j^\star \geq 0, j = 1 \dots m$ and $\boldsymbol{z}_i^\star, i = 1 \dots n$ such that

$$h(\boldsymbol{\lambda}^\star) = \sum_{i=1}^{n} f(n_{\text{e}i}, T_{\text{e}i}, \boldsymbol{z}_i^\star)\, t_i \tag{4.7}$$

and $\boldsymbol{z}_i^\star, i = 1 \dots n$ yields a feasible solution to (4.1), then $\boldsymbol{z}_i^\star, i = 1 \dots n$ is the optimal solution to (4.1). If it is possible to meet the emission requirements this solution exists and can be found by using a gradient search algorithm acting on the concave dual function $h(\boldsymbol{\lambda})$. Early work based on this approach for gasoline engine applications can be found in [6, 7] and early work for diesel engine applications in [8].

It can be noted that the optimal solution to (4.1) is given by minimizing a weighted sum of fuel consumption and emissions in each individual engine operating point in the approximated driving cycle, where the same weights are used for all points (in each engine operating point (4.5) is solved). This can also be motivated from a non-mathematical perspective. As described in Section 2.4, it is beneficial to allow an increase of emissions in favor for lower fuel consumption in one operating point in the cycle, if emissions can be decreased in *any* another operating point during the cycle with less penalty on fuel consumption. This implies that for the optimal solution it is *not* possible to allow an increase of emissions in favor for lower fuel consumption in one operating point, and decrease emissions in another operating point with less penalty on fuel consumption. This means that for the optimal solution, there should be exactly the same trade-off between fuel consumption and emissions at all operating points. This is achieved by minimizing a weighted sum of fuel consumption and emissions in all engine operating points in the cycle, using the same weights for all points, i.e by solving (4.5) in each operating point.

The typical procedure to perform EMS calibration using this approach is to first select values for the weights (Lagrangian multipliers) between fuel consumption and emissions. When all engine operating points are optimized with the selected weights, the performance of the approximated driving cycle is evaluated (the approximated driving cycle consists of a weighted sum of the optimized engine operating points). Depending on the resulting performance, different weights between fuel consumption and emissions are selected, and the process is repeated. The process is repeated until resulting performance of the approximated driving cycle is satisfactory.

At the stage where an individual engine operating point is optimized with given weights between fuel consumption and emissions, it is common to utilize a simulation model to find optimal set points. Using measured engine data from an engine mapping as described in Section 3.2.2, models for emissions and fuel consumption that account for changes in the set points are created. Instead of optimizing set points manually in an engine test cell, the optimization is performed using the simulation models. Using this approach, the complete steady-state optimization procedure can be performed off-line. There are several examples of model-based methods described in the literature [9, 10, 11, 12, 13, 14, 15, 16, 17]. There are also commercial software developed for this. Examples are AVL CAMEO™, Ricardo μCal, ETAS ASCMO, FEV TOPexpert, IAV EasyDoE, and D2T IC^2.

4.1.2 Optimization of transient engine operation

Research within the field of transient engine operation is not as well developed, and the research work has mainly been focused on finding optimal actuator trajectories for specified single engine transients. Examples of methods for this are presented in [18, 19, 20]. Optimal actuator trajectories for single transients cannot be directly transferred to a general EMS strategy that can handle any transient engine scenario, and much research has been focused on developing transient control strategies based on the identified optimal actuator trajectories. Based on this, there are several examples of control strategies for transient engine operation based on the oxygen fraction in the intake manifold [21, 22, 23, 24]. The research based on optimal actuator trajectories for single transients has mostly been focused on reducing emission spikes during transient engine operation, not to find the optimal trade-off between emissions and fuel consumption with respect to a complete driving cycle. This means that the approach is similar to the work procedure when transient compensations are calibrated as described in Section 3.3.

Some work has been performed to optimize the EMS in a diesel engine for a complete driving cycle, taking both steady-state and transient engine operation into consideration. Atkinson et. al. has used a model-based approach based on neural networks to achieve a proof-of-concept of the benefit of a model-based transient calibration process [25, 26]. Brahma et. al. has developed a model-based transient calibration process to optimize settings in a standard EMS, taking both steady-state and transient engine operation into consideration [27, 28]. The approach in their work is to complement the manual work process of performing EMS calibration, rather than to replace it. Based on an existing EMS calibration, simulation models and search algorithms are used to adjust the calibration such that emissions for a driving cycle are decreased without increasing the fuel consumption.

It can be noted that the possibility to account for transient engine and vehicle behavior during EMS optimization becomes more important as a new global harmonized test cycle, the World-Harmonize Light-Duty Test Cycle (WLTC), is being developed. The development of this new test cycle is ongoing, but the test cycle will most likely include a larger portion of transient driving compared to the currently used test cycle in Europe, the New European Driving Cycle (NEDC) [29].

4.2 Diesel engine modeling

The approach taken in the *Diesel Engine Optimization* project is to use a model-based strategy for EMS optimization, i.e. to utilize a simulation model as a tool in the EMS optimization process, and also to use a simulation model to evaluate the resulting vehicle performance. This implies that a complete diesel engine vehicle system simulation model is needed, including sub-models for the engine, the vehicle, and the driver. The main focus within the complete simulation model is the model of the diesel engine itself, including the gas exchange system and the combustion within the cylinders. For the other systems, simple models that capture the main dynamic effects are used.

This section attempts to describe current state of the art within the field of diesel engine modeling. Engine modeling is usually separated into modeling of the gas exchange system and modeling of the combustions. This is the approach taken also within the *Diesel Engine Optimization* project.

4.2.1 Gas exchange system modeling

For the gas exchange system, there are different simulation models available in the open literature, and there are also commercial software specialized for this. Examples of commercial software for gas exchange modeling are Gamma Technologies GT-POWER, AVL BOOST, and Ricardo WAVE. These software are advanced, and have the capability to model a gas exchange system in detail, including estimation of crank-angle resolved pressures, flows, and temperatures in the system. In this project, the model of the gas exchange system only needs to capture the main dynamic effects in the engine. Therefore, a more suitable approach is to use a mean value model for the gas exchange system. Mean value models for diesel engines are well developed and described in the literature [30, 31, 32], and there are also simulation toolboxes available for this, e.g. the Engine Dynamics Library for Modelica® [33].

4.2.2 Combustion modeling

Much research has been performed within the field of diesel engine combustion modeling, although most of the the research has not been focused on the application of using the simulation models for EMS optimization.

In general, models can be derived from two opposite directions. The classical approach is to use first principles modeling, leading to multi-dimensional computational fluid dynamic (CFD) models combined with detailed models for the combustion chemistry. Such models give insight into fundamental properties of the combustion but are less adequate to predict absolute levels of emissions and are also computationally demanding. Models of this type are described in detail in [34] and [35].

Less demanding is to use zero-dimensional or low-dimensional combustion models, which are based on first principle models, but that are substantially reduced in model complexity. Examples of this are models for NO_X emissions based on the extended Zeldovich mechanism [36, 37, 38]. Another example of reduced models is a mean value model for soot emissions described in [39]. Although less computational demanding, these models are too simple to give accurate predictive information.

On the other side of the scale is to use models that are based purely on measured data from a real engine, where a smooth function is typically used to interpolate between measured data points. Such models are known as data-driven, or black-box since the predicted outputs are based on simple functions of the measured data. Data-driven models can perform accurate predictions within the measured operating range of the engine, but have very limited prediction performance outside the range. Several different types of data-driven combustion models are described in the literature. Examples of this are models based on neural networks [25, 40], models based on Gaussian processes [41], global regression models [42], and global-local model approaches where a global model is constructed by switching or weighing between different local models depending on the engine speed and injected fuel operating point of the engine [43, 44, 45]. The data-driven models described above are all designed for specified limited applications, different from the application in this project, and general information regarding calibration procedure and prediction performance of the models is typically not available. Therefore, none of the described models have been able to be identified as suitable for this project.

Chapter 5

Scope and Limitations

This chapter describes the overall goal for the *Diesel Engine Optimization* project. Based on this goal, the scope and limitations applied to the work presented in this thesis is presented.

5.1 Main goal and approach

The overall goal within the *Diesel Engine Optimization* project is to develop a method such that the work load and cost to perform EMS calibration in an engine development project can be decreased.

The approach within the project to be able to decrease the work load is to develop methods such that less parts of the EMS calibration process have to be performed manually in a complete vehicle or in an engine test cell, and to instead be able to perform larger parts of the work using automated measurements in an engine test cell and off-line calculations based on these measurements. To be able to do this it is suitable to utilize simulation models, and a model-based approach has been adopted within the project.

Furthermore, since a large part of the manual work load within the EMS calibration process consists of calibration of compensations for transient engine operation, a focus within the project is to develop a method to handle transient engine operation in a structured way.

5.2 Engine modeling

The model-based approach implies that a simulation model for a diesel engine vehicle system is needed. The model should describe how fuel consumption and emissions for a complete vehicle, driving according to a dynamic driving cycle, depend on settings in the EMS. Furthermore, the focus on transient engine operation implies that the simulation model needs to account for the main effects on fuel consumption and emissions also during transient engine operation. The simulation model also needs to be as fast as possible to execute, since its intended usage is to develop EMS optimization strategies. It is advantageous if various EMS strategies can be compared within a reasonable amount of time during the development. The main intended usage for the model is to use it as a tool in the EMS optimization procedure. In this project, the simulation model will also be used to evaluate resulting performance of the developed EMS strategy, since a real vehicle is not available for this.

The main focus within the complete simulation model is the model of the diesel engine itself, including the gas exchange system and the combustion within the cylinders. For the other systems, simple models that capture the main dynamic effects are used. For the gas exchange system, a mean value modeling approach is applied according to descriptions in [30, 31, 32]. For the combustion, as described in Section 4.2, a wide range of models are available in the open literature. However, a model suitable for this project has not been found, and included in the scope of the thesis is to develop and implement a combustion model for this application.

5.3 Engine management system optimization

The scope of the work regarding EMS optimization is to develop a method that fulfills the goals of the project, i.e. a method such that the work load to perform EMS calibration can be decreased, and also that a larger part of the work can be performed off-line by using engine measurements from an engine test cell, instead of performed manually in an engine test cell or in a complete vehicle. An important aspect is that the developed method should be able to be implemented in practice. As described in Section 4.1, much research has been performed with respect to transient engine operation, although few results have been adopted by industry as methods that are used in practice [4].

5.4 Limitations

To be able to approach the complex task of developing an EMS optimization strategy within the frame of this thesis, a number of limitations have been introduced.

First, after-treatment systems are not considered, i.e. the optimization problem in this project is defined as minimizing fuel consumption for a dynamic driving cycle while fulfilling constraints on *engine-out* emissions. Furthermore, the considered constraints are only limitations on accumulated NO_X and soot emissions. The reason for choosing these constraints is that, as described in Section 2.1, NO_X and soot emissions are the main issues for a diesel engine.

Second, engine warm-up is not considered, i.e. the simulation model and the EMS optimization strategy only need to account for a fully warmed up engine.

Finally, as described in Section 2.3, there are several degrees of freedom in a typical passenger car diesel engine, but in this project, these are limited to only three. The considered degrees of freedom are the boost pressure, the oxygen fraction in the intake manifold, and the timing of the complete injection package. The reason for choosing these three is that the boost pressure and oxygen fraction in the intake manifold are related to the gas exchange system, and are associated with the main dynamic effects in an engine during transients. The injection timing is the most significant calibration parameter for the fuel injection with respect to the late stages in a typical EMS calibration process, where complete vehicle performance is considered. As described in Chapter 3, other fuel injection related degrees of freedom, such as number of injections, and fuel amounts and individual timings for the different injection pulses, are typically calibrated in an earlier stage in the calibration process.

An important aspect is that the EMS strategy should be developed with the defined limitations taken into consideration. The strategy should be developed such that it is possible to extend it to account also for the effects that are neglected due to the introduced limitations.

It can be noted that the defined limitations are very similar to the limitations applied also in the drive cycle optimization procedure as described in Chapter 3.

Chapter 6

Contributions

The aim of the research presented in this thesis is to develop methods and strategies for diesel engine management system optimization. The method for doing this is to use a model-based approach, i.e. to use a simulation model of a diesel engine vehicle system as a tool in the EMS optimization procedure. The research has resulted in scientific contributions both within the field of engine management system optimization, and also within the field of diesel engine modeling.

6.1 Diesel Engine Modeling

This thesis includes papers that describe the development and implementation of a complete vehicle system simulation model intended to be used for development of engine management system strategies. The simulation model consists of four main sub-models; a model for the engine, a model for the vehicle, a model for the driver, and a model for the engine management system. A schematic illustration of the complete diesel engine vehicle system simulation model is shown in Figure 6.1. The main focus in the complete simulation model is modeling of the engine with its gas exchange system, combustion and emission formation. The other sub-systems are modeled using simple, physical based models, which capture the main interaction effects with the engine.

The model can perform a simulation of a vehicle driving according to a predefined vehicle driving cycle and it estimates fuel consumption together with emissions of NO_X and soot during the complete cycle depending on settings in the EMS. The model reacts on calibration changes in the engine management system with respect to set points for boost pressure, set points for oxygen fraction in the intake manifold, and injection timing. It also accounts for transient effects in the engine caused by dynamics in the

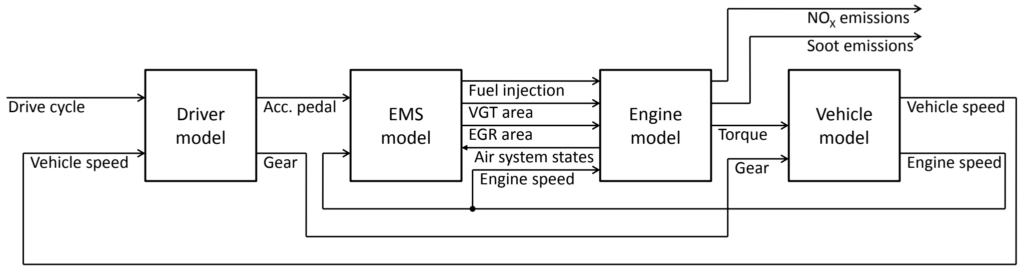

Figure 6.1: Schematic illustration of the implemented complete diesel engine vehicle system simulation model with its four sub-models and the main interfaces between them.

gas exchange system. The simulation model has been implemented in the Matlab Simulink environment, and the simulation time is in the range of 10 to 20 times faster than real-time on a standard computer. These properties make the model a useful tool for development of EMS optimization strategies.

A detailed description of the combustion models within the complete simulation model can be found in Paper 1, Paper 2, and Paper 3. The complete vehicle system simulation model is described in detail in Paper 4.

6.2 Diesel Engine Management System Optimization

This thesis also includes papers that describe the development and evaluation of a novel method to calculate set points in an EMS for controllable engine quantities. The set points are calculated with an aim to minimize fuel consumption for a given vehicle driving cycle, while fulfilling requirements on accumulated engine-out emissions. The method to do this is based on existing methodologies developed for steady-state engine operation, described in Section 4.1.1, but extended to handle transient effects caused by dynamic effects in the gas exchange system.

As described in Section 4.1.1, optimal set points for a driving cycle, if all engine operating points in the cycle can be controlled arbitrarily, are set points such that all engine operating points are operated with the same trade-off between fuel consumption and emissions. Methods are developed to account for this during steady-state engine operation. However, using the calibration method described in Chapter 3, this optimization criterion is violated during transient engine operation due to the dynamic behavior of the gas exchange system. In transient engine operation, compensations are used, but these compensations are only focused on reducing emissions spikes.

The main idea with the EMS optimization method introduced in this thesis is to try to fulfill the optimization criterion also during transient engine operation. The method to do this is to separate the various engine systems with respect to their different corresponding dynamic time scales. The idea is to adapt faster systems to fulfill the optimization criterion when slower systems do not reach their optimal steady-state values. In this thesis, the considered set points are the set point for boost pressure, the set point for oxygen fraction in the intake manifold, and the injection timing. It is assumed that the dynamics associated with the boost pressure set point is slowest, the dynamics associated with the set point for the oxygen fraction in the intake manifold is a little bit faster, while, for obvious reasons, there are no dynamics associated with the injection timing.

To be able to fulfill the optimization criterion also in transient engine operation, the vehicle driving cycle can not be approximated as a limited number of steady-state engine operating points, instead it is represented by all combustion events during the cycle, and the aim is that all combustion events during the cycle should be operated with the same trade-off between fuel consumption and emissions.

In the calibration procedure described in Chapter 4, all set points are calibrated based on the engine speed and load with an aim to fulfill the optimization criterion in the complete working range of the engine. The idea with the introduced method is to first perform the optimization in a similar way. The boost pressure set points is then assumed to be associated with slow dynamics, and during transient operating the dynamics of the boost pressure will violate the optimality. Therefore, a second optimization stage is performed, where the set points for faster systems (i.e. the set point for the oxygen fraction in the intake manifold and the injection timing) are optimized in the complete working range of the engine with respect to engine speed, load and actual boost pressure in the system. This way, the set point for the oxygen fraction in the intake manifold and the injection timing are adjusted to fulfill the optimization criterion even when the actual boost pressure in the system has not reached its set point. Finally, a similar step is performed again where only the injection timing is considered. The injection timing is optimized in the complete working range of the engine with respect to engine speed, load, actual boost pressure in the system, and actual oxygen fraction in the intake manifold. This leads to an adjustment of the injection timing such that the optimization criterion is fulfilled also when the oxygen fraction in the intake manifold has not reached its set point.

Using this method, transient compensations are automatically introduced in the drive cycle optimization stage of the EMS calibration process, and there is thus no need to add extra functionality for this purpose. The compensations are calculated similarly to the settings for steady-state engine operation, with the same system optimization approach. This means that the compensations during transient engine operation are calculated with the aim to optimize the complete system, with respect to a complete driving cycle, instead of calibrated with the aim to reduce emission spikes

Furthermore, optimal set points for the complete working range of the engine can be calculated off-line and stored in an EMS using for example grid maps, similar as for the steady-state approach described in Section 3.2. This leads to optimization results that can be implemented as a general EMS strategy that calculates set points for *any* (transient or steady-state) driving scenario.

The intended work flow to implement the EMS strategy in a EMS calibration procedure is to first perform initial calibration as described in Section 3.1. Then, an engine is mounted in an engine test cell, where automated measurements are performed such that models for emissions, generated engine torque, and the gas exchange system can be created. The described EMS optimization strategy is then performed such that the performance of a simulated driving cycle is satisfactory. Finally, using the resulting EMS settings, the performance of a real vehicle is evaluated. If the result is not satisfactory, the EMS optimization strategy is performed again but with updated limits on accumulated emissions for the simulated driving cycle. This process is iterated until resulting vehicle performance is satisfactory. Ultimately, if it is possible to produce models that are accurate enough, the complete calibration process can be performed off-line using only measurements from an engine test cell, and then just validated in a real vehicle.

A schematic illustration of the suggested EMS calibration procedure when using the introduced strategy is shown in Figure 6.2. The main difference compared to the EMS calibration procedure described in Chapter 3 is that there is no separate calibration of transient compensations in this proposed procedure. Therefore, the complete process within the outer loop of the calibration procedure can be performed off-line when using the EMS optimization strategy just introduced. The amount of iterations that are needed in the outer loop illustrated in Figure 6.2 is dependent on the prediction performance of the simulation models. If the simulation models are perfect, the outer loop can be removed and replaced with just a validation of the EMS calibration in a real vehicle.

An alternative option to use the described EMS optimization strategy

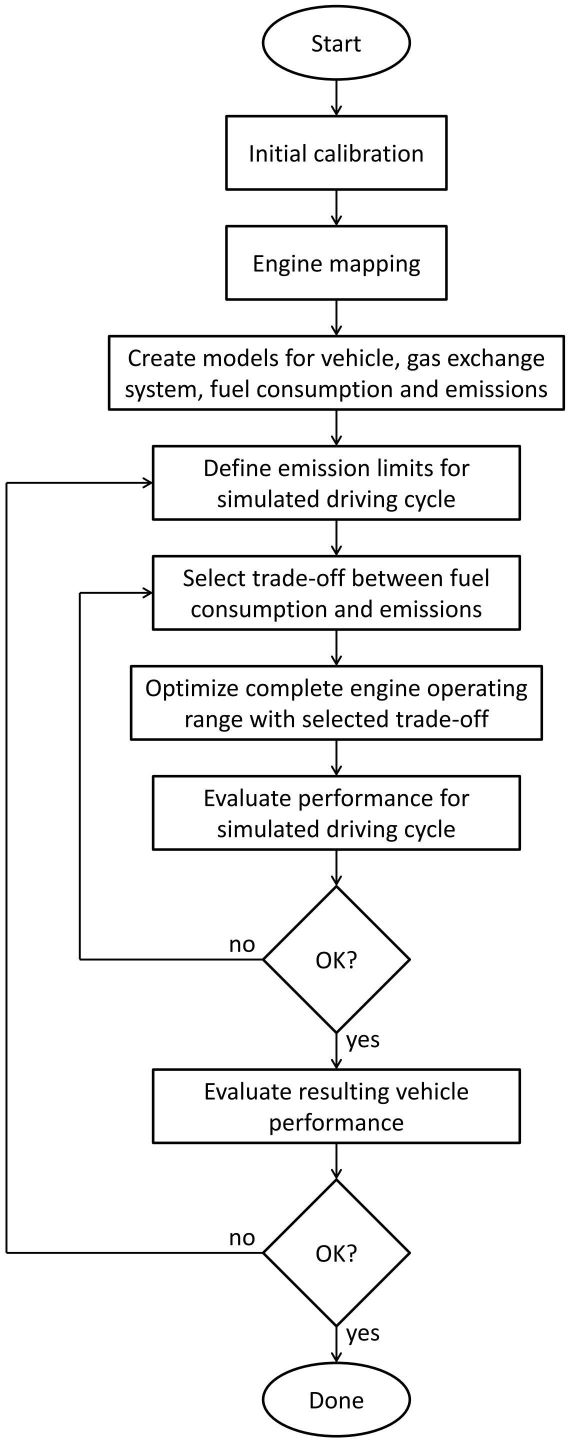

Figure 6.2: Schematic illustration of the suggested complete EMS calibration procedure using the introduced optimization strategy described in this thesis.

in an EMS calibration procedure is to directly evaluate the resulting performance for a selected trade-off between fuel consumption and emissions using a real vehicle instead of using a simulation model. This alternative procedure removes the need for simulation models of the vehicle or for the gas exchange system. However, when using this alternative calibration procedure, most likely more iterations with a real vehicle in the loop are needed to achieve satisfactory performance. This alternative procedure might be a good option if the EMS has already been optimized, but a small hardware change is introduced somewhere in the system. In that case, small adjustments in the optimal trade-off between fuel consumption and emissions can be expected, and few iterations are needed. A schematic illustration of this alternative procedure is illustrated in Figure 6.3.

The optimization strategy has been shown to decrease fuel consumption for a diesel engine vehicle compared to existing methods based only on steady-state engine operation. Using the simulation model described in this thesis, the strategy has been shown to decrease fuel consumption for a vehicle driving according to the New European Driving Cycle with 0.56%, compared to a strategy based only on steady-state engine operation.

A more detailed description of the EMS optimization strategy can be found in Paper 5 and Paper 6.

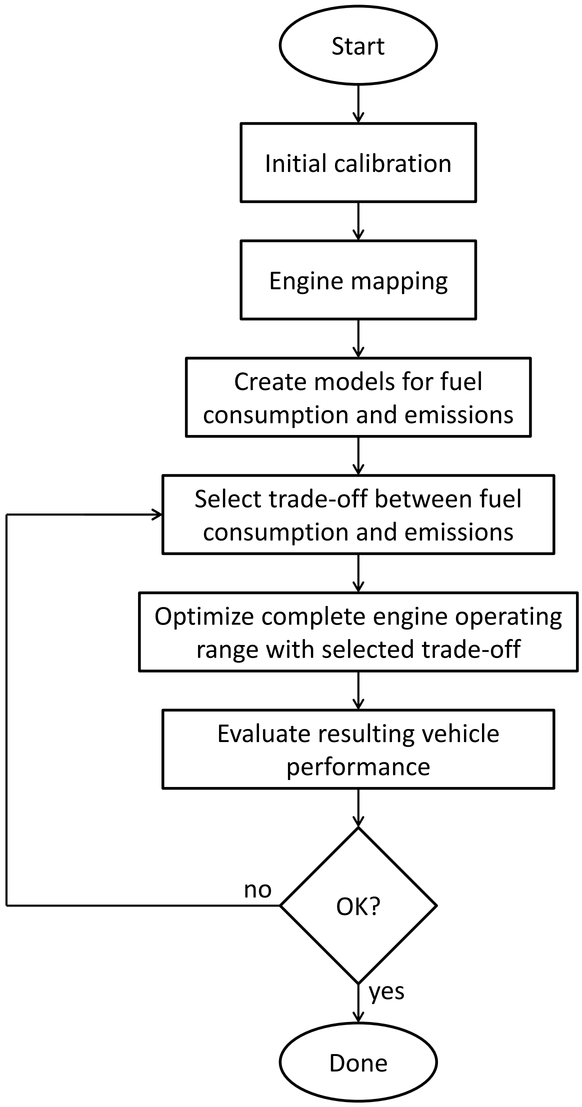

Figure 6.3: Schematic illustration of an alternative complete EMS calibration procedure using the introduced EMS optimization strategy.

Chapter 7

Summary of included papers

This chapter provides a brief summary of the papers that constitute the base for the thesis. Full versions of the papers are included in Part II.

Paper 1

> Markus Grahn, Krister Johansson, Christian Vartia, and Tomas McKelvey, "A Structure and Calibration Method for Data-driven Modeling of NO_X and Soot Emissions from a Diesel Engine", *SAE World Congress*, Detroit, MI, USA, April 2012.

This paper describes the development and implementation of a new structure for data-driven models for NO_X and soot emissions. The model structure is a linear regression model, where physically relevant input signals are used as regressors, and all the regression parameters are defined as grid-maps in the engine speed/injected fuel domain. The method of using grid-maps in the engine speed/injected fuel domain for all the regression parameters enables the models to be valid for changes in physical parameters that affect the emissions that are dependent only on the engine speed and the amount of injected fuel, without having to include these parameters as input signals to the models. This means that models can handle changes for different parameters in the complete working range of the engine, without having to include all signals that actually effect the emissions into the models. The approach possibly also enables for the model to handle the main differences between steady-state engine operation and transient engine operation, thus possibly being able to use steady-state engine measurement data to calibrate the model, but still achieve acceptable performance for transient engine operation. This, however, is not evaluated in this study. The model structure has been used to create models for NO_X and soot emissions. These models have been calibrated using measured steady-data from a 5 cylinder Volvo passenger car diesel engine with a displacement volume of 2.4 liters, equipped with a turbocharger, an exhaust gas recirculation system, and a common rail injection system. The models estimate NO_X mass flow with a root mean square error of 0.0021 g/s and soot mass flow with a root mean square error of 0.59 mg/s for the steady-state engine data used in this study. The models are capable of reacting to different calibratable engine parameters, and they are also fast to execute. This makes them suitable for development of engine management system optimization. The models could also be implemented directly into an engine management system. For comparison, three other fast models of different types for NO_X and soot emissions have been implemented and evaluated.

The author of the thesis is responsible for implementing and evaluating the models. The author has written the main parts of the paper.

Paper 2

> Markus Grahn, Krister Johansson, and Tomas McKelvey, "B-splines for Diesel Engine Emission Modeling", *2012 IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling (E-COSM'12)*, Paris, France, October 2012.

This paper describes the equivalence between linear interpolation and B-spline functions of degree 1. The equivalence is used to express interpolation based diesel engine NO_X and soot emission models as B-spline functions, and to apply data fitting methods for B-spline functions to perform calibration of the models. Using this strategy, the globally optimal model calibration can be calculated directly by analytically solving a minimization problem. The B-spline representation also makes it possible to control the smoothness and extrapolation behavior of the interpolation maps in the models in a controlled manner. The models have been calibrated using measured steady-state data from a 5-cylinder Volvo passenger car diesel engine with a displacement volume of 2.4 liters, equipped with a turbocharger, an exhaust gas recirculation system, and a common rail injection system. The calibrated model for NO_X emissions estimates the NO_X mass flow with a root mean square error of 0.0013 g/s, and the calibrated model for soot emissions estimates the soot mass flow with a root mean square error of 0.56 mg/s. The established equivalence between linear interpolation and B-spline functions of degree 1 could also be used for calibration of other models of similar structure.

The thesis author is responsible for the calculations performed in this paper. The author has written the main parts of the paper.

Paper 3

Markus Grahn, Krister Johansson, and Tomas McKelvey, "Data-driven Emission Model Structures for Diesel Engine Management System Development", *Accepted for publication in International Journal of Engine Research.*

This paper discusses some specific data-driven model structures suitable for prediction of NO_X and soot emissions from a diesel engine. The model structures can be described as local linear regression models where the regression parameters are defined by two-dimensional look-up tables. It is highlighted that this structure can be interpreted as a B-spline function. Using the model structure, models are derived from measured engine data. The smoothness of the derived models is controlled by using an additional regularization term and the globally optimal model parameters can be found by solving a linear least-squares problem. Experimental data from a 5-cylinder Volvo passenger car diesel engine is used to derive NO_X and soot models, using a leave-one-out cross validation strategy to determine the optimal degree of regularization. The model for NO_X emissions predicts the NO_X mass flow with an average relative error of 5.1% and the model for soot emissions predicts the soot mass flow with an average relative error of 29% for the measurement data used in this study. The behavior of the models for different engine management system settings regarding boost pressure, amount of exhaust gas recirculation, and injection timing has been studied. The models react to the different engine management system settings in an expected way, making them suitable for optimization of engine management system settings. Finally, the model performance dependence on the selected model complexity, and on the number of measurement data points used to derive the models has been studied.

The thesis author is responsible for the calculations performed in this paper. The author has written the main parts of the paper together with Tomas McKelvey.

Paper 4

Markus Grahn, Krister Johansson, and Tomas McKelvey, "A Complete Vehicle System Model for Diesel EMS Development", *Technical report.*

The development and implementation of a complete vehicle system simulation model for diesel engine management system development is described. A complete system model is needed to fully evaluate how changes in the engine management system affect the total fuel consumption and emissions for a vehicle during a transient cycle. The complete system model consists of four sub-models with well-defined interface between them. The different sub-models are a model for the vehicle, a model for the driver, a model for the engine, and a model for the engine management system. The model reacts to engine management system calibration perturbations with respect to boost pressure settings, EGR ratio settings, and injection timing settings.

The detail level of the different sub-models are chosen such that the models catch the main fuel consumption and emission affecting phenomena, but still are reasonably fast to simulate. The model is implemented in the Matlab Simulink environment, and the simulation time of the complete system model is in the range of 10 to 20 times faster than real-time.

The thesis author is responsible for implementing the complete simulation model, and for performing the simulations. The author has written the main parts of the paper.

Paper 5

> Markus Grahn, Krister Johansson, and Tomas McKelvey, "A Diesel Engine Management System Strategy for Transient Engine Operation", *7th IFAC Symposium on Advances in Automotive Control*, Tokyo, Japan, September 2013.

A strategy for diesel engine management systems has been introduced and evaluated. The strategy calculates set points for engine management system controllable quantities with an aim to minimize fuel consumption for a given engine speed and requested torque profile, while keeping accumulated emissions below given limits. The strategy is based on existing methodology for steady-state engine operation, but extended to handle transient effects in the engine caused by dynamics in the air system. The strategy has been evaluated using a simulation model of a diesel engine system. The model estimates fuel consumption together with NO_X and soot emissions for a transient simulation cycle depending on set points in the engine management system for boost pressure, oxygen fraction in the intake manifold, and injection timing. For the transient simulation scenario used in this paper and with given limits on accumulated emissions, the strategy has been shown to decrease fuel consumption with up to 0.7% compared to a strategy that is based only on steady-state engine operation.

The thesis author is responsible for developing and implementing the EMS optimization strategy, and for performing the simulations. The author has written the main parts of the paper.

Paper 6

> Markus Grahn, Krister Johansson, and Tomas McKelvey, "Model-Based Diesel Engine Management System Optimization for Transient Engine Operation", *Manuscript submitted for publication.*

A strategy to calculate set points for controllable diesel engine systems is described and evaluated. The strategy calculates set points with an aim to minimize fuel consumption for a given dynamic vehicle driving cycle, while keeping accumulated emissions below given limits. The strategy is based on existing methodology for steady-state engine operation, but extended to handle transient effects in the engine caused by dynamics in the engine air system. Using the strategy, set points for the complete operating range of the engine can be calculated off-line and stored in an engine management system, hence set points can be derived for any (steady-state or transient) driving scenario. The strategy has been evaluated using a simulation model of a complete diesel engine vehicle system. The model estimates fuel consumption, NO_X, and soot emissions for a dynamic vehicle driving cycle depending on set points for boost pressure, oxygen fraction in the intake manifold, and injection timing, throughout the simulation. Using this simulation model, the strategy has been shown to decrease fuel consumption for the New European Driving Cycle with 0.56%, compared to a strategy based only on steady-state engine operation.

The thesis author is responsible for developing and implementing the EMS optimization strategy, and for performing the simulations. The author has written the main parts of the paper.

Chapter 8

Concluding remarks and outlook

A novel strategy to calculate set points for controllable engine systems has been developed. The introduced strategy has been evaluated using a simulation model of a complete diesel engine vehicle system model, also developed within this project. The strategy has been shown to be able to decrease fuel consumption for a given dynamic vehicle driving cycle with given limits on accumulated emissions, compared to a strategy that is based only on steady-state engine operation.

By using this strategy, set points are calculated in the EMS for any (steady-state or transient) engine operation scenario, and no other tuning or calibration for this is needed. Compared to how EMS optimization is normally performed, where set points are first optimized for steady-state engine operation, and then compensations for transient engine operation are added manually [4], this method is expected to both enhance the resulting fuel efficiency of the vehicle, and also to decrease the work load to perform EMS calibration.

To implement the developed EMS optimization approach, the structure in a standard EMS needs to be modified. The control structure in an EMS today is typically based on two-dimensional grid maps [4], but for the developed EMS optimization strategy, a three-dimensional grid map for the oxygen fraction set point is needed, and a four-dimensional grid-map for the injection timing is needed. It is possible to modify the structure in an EMS according to this, but three- and four-dimensional grid maps require a large amount of storage space in the EMS, and should therefore be avoided if possible. It might be possible to modify or simplify the EMS optimization strategy described in this thesis such that it can be implemented using only two-dimensional grid maps. Possibly, one option is to keep a similar structure as in an existing EMS, but to use the EMS optimization approach described in this thesis to calibrate the functionality for transient compensations in a more structured way. This however has not been studied within the scope of this thesis.

The strategy has not been evaluated using a real vehicle. But since the comparison between the introduced strategy and a strategy based only on steady-state engine operation has been performed using the same simulation model, improvement in fuel efficiency is expected also when implementing the strategy in a real vehicle. The resulting performance of the EMS strategy in a real vehicle compared to the performance of the strategy using a simulation model is dependent on the prediction performance of the simulation model. The prediction performance of the different sub-models influence different part of the optimization. The performance of the final application is only influenced by the accuracy of the combustion models, i.e. the models for generated engine torque, NO_X, and soot emissions. All other sub-models, i.e. the engine gas exchange system, the driver, the EMS, and the vehicle are only used to find the optimal values of the Lagrangian multipliers. Therefore, the prediction performance of these systems will only influence the number of iterations that has to be performed using a real vehicle. In this thesis, data-driven models based only on steady-state engine measurement data have been used to model the combustion. The models are designed to account for transient effects in the engine, but the resulting prediction performance of the models during transient engine operation has not been experimentally evaluated.

To reach the point where no iterations with a real vehicle is needed, there are still some unresolved issues. One major challenge is to create models that can predict emissions and generated torque from an engine mounted in a real vehicle, using only measurements from an engine in a test cell. There are several challenges associated to this. First, it is a challenge to use an engine in an engine test cell to fully replicate the operation of an engine mounted in a propulsing vehicle. For example, the temperature distribution in the engine compartment and the influence from the air flow around the engine caused by the motion of the vehicle is difficult to replicate in an engine test cell, and the influence on emissions due to this is most likely not negligible. This is discussed in e.g. [27, 28]. Furthermore, there are typically different emissions measurement techniques used when measuring emissions from a real vehicle compared to when measuring emissions in an engine test cell. For certification purposes, emissions are collected in a bag during a complete driving cycle, and the total amount of emissions during the cycle are measured by weighing the collected emissions [29]. This is a time consuming process, and it does not give any information regarding instantaneous emissions throughout the cycle. In an engine test cell, there are several different other techniques used to measure emissions. Different measurement techniques have been shown to result in different measured results. Especially for soot measurements, there are large discrepancies involved in using different measurement techniques [46, 47]. Also, emission measurements are always associated with dynamics and time delays, and typically faster emission measurement systems are less accurate. Therefore, it is a challenge even to evaluate the performance of emission models on a real vehicle during transient engine operation. These issues need to be resolved until an engine can be fully optimized using engine test cell experiments only.

In this thesis, the optimization problem has been limited to calculate EMS settings in order to minimize fuel consumption for a vehicle driving cycle while fulfilling constraints on accumulated engine-out emissions. However, to fully optimize the complete vehicle system is a more complex task. First, as described in Section 2.3.3, modern passenger car diesel engines are equipped with after-treatment systems with a possibility to remove emissions after they leave the cylinders. There are several trade-off associated to this. For example, the particulate filter can trap soot emissions to a certain extent, but when the filter is full it has to be regenerated. Regeneration is performed by operating the engine with poor efficiency, generating an engine-out gas temperature that is high enough to burn the accumulated soot in the filter. There is a trade-off associated with this. It might be beneficial to allow more engine-out soot in favor for lower fuel consumption, but doing so will require more frequent filter regeneration, which in turn leads to an increase in fuel consumption. Furthermore, the size of the particulate filter is important. A larger particulate filter can trap more soot emissions, but is also more expensive. This is also a challenging trade-off to account for. Similar trade-offs exist if the engine is equipped with a NO_X trap. A model-based approach is suitable to find a good balance for these various trade-offs, and the simulation model and EMS optimization strategy described in this thesis could be included as useful tools for this. After-treatment systems are not included in the simulation model, but due to the well-defined interfaces in the model, this can be added if the model should be used for a applications where this is needed.

The optimization strategy described in this thesis has been limited to only consider three degrees of freedom for the engine control, i.e. the set point for boost pressure, the set point for oxygen fraction in the intake manifold, and the injection timing. Regarding the optimization method, it is straightforward to add more degrees of freedom. The main issue associated to this is the amount of engine measurements that are needed in the engine mapping stage of the optimization procedure to cover more degrees of freedom, as described in Section 3.2.3.

Furthermore, the optimization problem in this thesis has been limited to account only for constraints on accumulated NO_X and soot emissions. Regarding the optimization strategy it is straightforward to add more constraints, although additional models are needed if this is to be implemented. For example, it is straightforward to add a constraint for accumulated CO emissions in the optimization procedure, but to do this, a model for CO emissions is needed.

The optimization problem has also been limited to a fixed vehicle with fixed engine hardware. To fully optimize the system, also the design of the vehicle and the engine hardware should be considered. Except the models for combustion, all sub-models in the complete simulation model described in this thesis are physical based. Therefore, the model and the EMS optimization strategy could be used to predict how changes in any of those systems would affect the fuel consumption of a vehicle. For example, it can be used to investigate how a different turbocharger or how a lighter vehicle would affect the fuel efficiency of a vehicle. First, the simulation model can be used to evaluate the performance of the new vehicle if no changes are introduced in the EMS, but together with the optimization strategy it can also be used to evaluate the resulting performance of the new vehicle if the EMS is re-optimized for the new hardware. The same approach can be used if an engine is to be used in several different vehicle applications. The EMS optimization strategy could be used to produce individual EMS calibrations for each application, without performing separate engine measurements for each application. The optimization strategy can also be used to adapt EMS calibration for hybrid vehicle applications. An initial study of the benefit to re-optimize EMS calibration for an engine used in a hybrid application, where the EMS is originally calibrated for a non-hybrid application, has been performed in [48].

For the combustion system, data-driven models are used, and therefore the model cannot be used to predict how hardware changes in the combustion system would affect the resulting vehicle performance, without performing new engine measurements. To overcome this, also the combustion models need to be replaced with physical based models with accurate prediction performance. At this stage, such models do not yet exist in the open literature [34, 35].

To summarize, the optimization of a complete vehicle system is very complex, and there are many unresolved challenges to develop a fully optimized system, and to develop methods to optimize a system with a minimum amount of work load. Huge improvements in fuel efficiency can be expected for a fully optimized system, but large improvements can still be expected if some of the unresolved issues are addressed. The research presented in this thesis is one step in the direction of a fully optimized system.

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