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Optimal Control of Electrified Powertrains

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The cover: Front: Formulation and solution of an optimal control problem, coincidentally the benchmark problem in Paper 6. Back: Positive and not so positive exit messages from the solvers used in the dissertation.

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Abstract

Vehicle powertrain electrification, i.e. combining the internal combustion engine (ICE) with an electric motor (EM), is a potential way of meeting the increased demands for efficient and low emission transportation, at a price of increased powertrain complexity since more degrees of freedom (DoF) have been introduced. Optimal control is used in a series of studies of how to best exploit the additional DoFs.

In a diesel-electric powertrain the absence of a secondary energy storage and mechanical connection between the ICE and the wheels means that all electricity used by the EMs needs to be produced simultaneously by the ICE, whose rotational speed is a DoF. This in combination with the relatively slow dynamics of the turbocharger in the ICE puts high requirements on good transient control. In optimal control studies, accurate models with good extrapolation properties are needed. For this aim two nonlinear physics based models are developed and made available that fulfill these requirements, these are also smooth in the region of interest, to enable gradient based optimization techniques. Using optimal control and one of the developed models, the turbocharger dynamics are shown to have a strong impact on how to control the powertrain and neglecting these can lead to erroneous estimates both in the response of the powertrain as well as how the powertrain should be controlled. Also the objective, whether time or fuel is to be minimized, influences the engine speed-torque path to be used, even though it is shown that the time optimal solution is almost fuel optimal. To increase the freedom of the powertrain control, a small energy storage can be added to assist in the transients. This is shown to be especially useful to decrease the response time of the powertrain, but the manner it is used, depends on the time horizon of the optimal control problem.

The resulting optimal control solutions are for certain cases oscillatory when stationary controls would have been expected. This is shown to be neither an artifact of the discretization used nor a result of the modeling assumptions used. Instead it is for the formulated problems actually optimal to use periodic control in certain stationary operating points. Measurements show that the pumping torque is different depending on whether the controls are periodic or constant despite the same average value. Whether this is beneficial or not depends on the operating point and control frequency, but can be predicted using optimal periodic control theory.

In hybrid electric vehicles (HEV) the size of the energy storage reduces the impact of poor transient control, since the battery can compensate for the slower dynamics of the ICE. For HEVs the problem instead is how and when to use the battery to ensure good fuel economy. An adaptive map-based equivalent consumption minimization strategy controller using battery state of charge for feedback control is designed and tested in a real vehicle with good results, even when the controller is started with poor initial values. In a plug-in HEV (PHEV) the battery is even larger, enabling all-electric drive, making it it desirable to use the energy in the battery during the driving mission. A controller is designed and implemented for a PHEV Benchmark and is shown to perform well even for unknown driving cycles, requiring a minimum of future knowledge.

Populärvetenskaplig sammanfattning

Elektrifiering av drivlinan i fordon är ett sätt att möta kraven på transporter med hög effektivitet och låga utsläpp. Att byta ut förbränningsmotorn mot en elmotor kan ge vinningar avseende effektivitet, prestanda och utsläpp, men till en kostnad av lägre mobilitet på grund av eletriska energilagers relativt låga energitäthet i jämförelse med fossila bränslen. Att istället komplettera förbränningsmotorn med en elmotor erbjuder möjligheten att kombinera de två systemens fördelar och samtidigt undvika nackdelarna.

Att använda mer än en motor i drivlinan ökar komplexiteten eftersom fler frihetsgrader har introducerats. Detta ställer ökade krav på utformningen av reglersystemet för att få ut det mesta av potentialen i drivlinan. I optimal styrning använder man matematiska modeller och optimeringsalgoritmer för att beräkna hur man bäst styr det modellerade systemet. Storleken på det elektriska energilagret påverkar dock valet av optimal styrnings-metod samt vilken detaljnivå på modellerna som behövs. I avhandlingen används optimal styrning i en serie studier av hur man bäst utnyttjar de extra frihetsgraderna som elektrifieringen har introducerat.

I en diesel-elektrisk drivlina finns det ingen mekanisk koppling mellan motorn och hjulen, likt en växellåda i ett vanligt fordon, vilket gör att dieselmotorns varvtal är en frihetsgrad som måste styras. Avsaknaden av elektriskt energilager leder också till att all elektrisk energi till elmotorn måste produceras av förbränningsmotorn exakt då den behövs. Dessa två egenskaper, i kombination med den långsamma dynamiken hos turboaggregatet, ställer höga krav på god transientreglering. För att studera optimal styrning krävs bra modeller med goda extrapoleringsegenskaper. Med avseende på detta utvecklas två fysik-baserade modeller som uppfyller dessa krav och dessutom är tillräckligt glatta i det relevanta arbetsområdet för att möjliggöra gradient-baserade optimeringstekniker. Med optimal styrning och en av de utvecklade modellerna visas turbons dynamik ha stor påverkan på hur drivlinan bör styras. Att försumma turbodynamiken kan leda till felaktiga uppskattningar, både av drivlinans responstid, men även hur den bör styras. Kriteriet, det vill säga om bränsle eller tidsåtgången minimeras, påverkar också vilken motorvarvtal-motormoment-väg som är optimal, även om det visas att den tidsoptimala lösningen är nästan bränsleoptimal. För att ytterligare öka frihetsgraden i drivlinan kan ett elektriskt energilager användas för att assistera i transienterna. Detta visar sig vara särskilt användbart för att minska responstiden hos drivlinan, men hur det ska använda beror på tidshorisonten på optimeringsproblemet

De resulterande optimala styrsignalerna är i vissa fall oscillerande där konstanta styrsignaler förväntas. Detta visas vara vare sig en effekt av den använda diskretiseringen eller modelleringsvalen som är gjorda. Istället är det för de lösta problemen faktiskt optimalt att använda periodiska styrsignaler för vissa stationära arbetspunkter. I experiment visas att pumparbetet skiljer sig beroende på om periodiska eller konstanta styrsignaler används, även om medelvärdet är detsamma. Huruvida detta ökar effektiviteten eller inte beror på arbetspunkt och periodtid.

För hybridelektriska fordon (HEV) så minskar batteriets storlek effekten

av dålig transientreglering då batteriet kan användas för att kompensera för den långsamma förbränningsmotordynamiken. Istället blir problemet i huvudsak hur mycket och när batteriet ska användas för att få god bränsleekonomi. En adaptiv mapp-baserad ekvivalentförbruknings-minimerande styrlag (ECMS) med återkopplad reglering baserad på batteriets laddningsnivå, utvecklas och testas i riktigt fordon med gott resultat, även vid dålig initialisering av regulatorn.

För plug-in hybrider (PHEV) är batteriet större och kan dessutom laddas från elnätet, vilket medför möjlighet till rent elektrisk drift och att det är önskvärt att använda energin i batteriet under köruppdraget. För att minska energiåtgången är det däremot ofta lönsamt att blanda energin från bränsle och batteriet kontinuerligt under köruppdraget och se till att batteriet töms lagom till slutet av köruppdraget. För att åstadkomma detta måste då även urladdningstakten bestämmas. En regulator utvecklas för att minimera energiåtgången för en PHEV, det vill säga som försöker använda lagom av batteriet så det ska räcka hela vägen, men inte längre. Denna regulator implementeras för ett referensproblem, med gott resultat även för okända körcykler, trots ett minimum av framtidskunskap.

Acknowledgment

What seemed like a daunting task almost five years ago, to produce a PhD dissertation, is now finished. It turns out that time really flies when you are solving NLPs, and all of a sudden it is time to concentrate the five years into one readable dissertation. Being a *more is more* type of person, the result is what you know hold in your hand. During these years several people have contributed in different ways making the journey more pleasant and the result possible.

First I would like to thank Lars Nielsen for giving me the chance to start my PhD at Vehicular Systems, but also for raising my awareness about the dangers of stretching, Lars Eriksson for supervising me through my PhD and being constantly interested in every little detail of optimal control of powertrains, pushing me to pursue every idea. I would also like to thank everyone at FS for never accepting *facts*, turning everything into discussions. Special thanks goes to Vaheed “it’s shameful” Nezhadali for showing me Iran, Kristoffer “gunz” Lundahl for being my constant traveling companion, Erik Frisk for all the discussions both concerning AIK and otherwise, and Tomas Nilsson and Christofer Sundström for proofreading parts of this manuscript.

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I would like to thank my family and friends for enriching the time between optimal control problems; my father for telling me to do something I was good at, my sister for leading the way and showing me it is possible to be this old and **not** have a *real* job, my mother for telling me I know it all (like I didn’t already know that), my brother for taking an opposing stance most of the time, and all of my friends, the ones starting with P and everyone else, you make me laugh!

Finally I want to thank Rebecca for pretending to be interested in all the fun stuff I did at work, even though material like periodic wastegate control sells itself, but mostly for just being there and making my life better.

Martin Sivertsson
Linköping, April 2015

Contents

Introduction

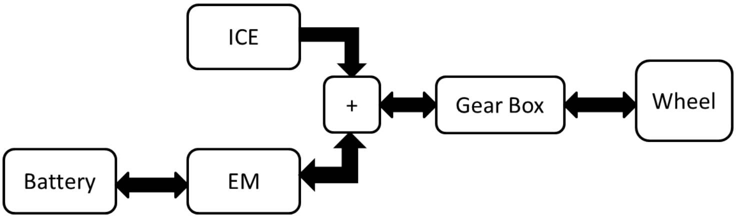
1

Introduction

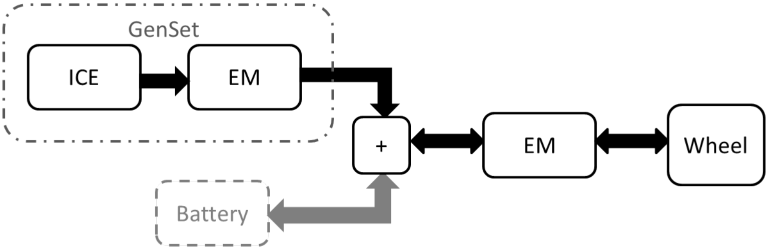
The most common source of power in vehicles is the internal combustion engine (ICE), converting chemical energy from fossil fuels to mechanical force. Since it's invention it has undergone continuous development, leading to a quadrupling of the power output without a significant increase in engine size in the last 70 years [69]. Key aspects of realizing the seen performance and efficiency increase are supercharging concepts and downsizing [24, 99]. Using turbochargers to supercharge the engine is a way of exploiting the energy in the exhaust to increase the amount of air flowing into the engine. This increases the power that can be produced by a certain engine displacement, but also introduces a difference between the power that can be produced in transients versus steady-state, since it takes time to spin up the turbocharger, a phenomenon normally called *turbocharger lag* [69]. Further, the mature nature of the ICE means that additional efficiency increases are getting harder to accomplish, while the efficiency of the combustion engine at part load is still relatively low [35, 36].

Electric motors (EM) on the other hand have significantly higher efficiency [28], and also the potential to recuperate kinetic energy when braking, making them a promising technology for efficient and low emission transportation. The energy density of the electric energy storages, e.g. batteries and supercapacitors, is however substantially lower than that of fossil fuels [36], decreasing the range of the vehicle.

Combining an ICE and an EM seems to be a good compromise both ensuring range and increasing efficiency at the price of increased cost of the vehicle. There are several ways, both with and without electrical energy storage, the two can be combined. If the vehicle has more than one source of energy, e.g. battery and fuel, it is denoted a hybrid. Several different hybrid architectures exist but the main delimitation is if the ICE is mechanically connected to the wheels, together with an EM this is called parallel hybrid, see Fig. 1.1-a, or if it is only used together with a generator to produce electrical power, i.e. series hybrid,



(a) Architecture of a parallel hybrid electric vehicle



(b) Architecture of a diesel-electric powertrain, or in the presence of battery, a series hybrid electric vehicle.

Figure 1.1: Main architectures of a electrified powertrain.

Fig. 1.1-b. There also exist combinations of the two denoted series-parallel or power split hybrids.

In a diesel-electric powertrain the architecture is that of a series hybrid, but without an energy storage, see Fig. 1.1-b. This means that a generator is mounted on the output shaft of the diesel engine and that the ICE-generator combination (GenSet) produces electrical power to the motors that propel the vehicle. These complex powertrains all have in common that they have at least one extra Degree of Freedom (DoF) compared to the conventional powertrain, EM torque in a parallel hybrid, generator power and engine speed for series hybrid and engine speed for the diesel-electric powertrain. In order to realize the full potential of the powertrain this DoF needs to be exploited, which requires a sophisticated control system optimizing the energy flow [70].

The size of the battery has a strong impact on the energy management of a vehicle. For a hybrid electric vehicle (HEV) a typical goal is to minimize the amount of fuel used while maintaining the battery state of charge (SOC), which is a measure on how much energy is left in the battery, around a prescribed level, see for instance [20, 50, 64, 71]. In a plug-in HEV (PHEV) the battery is larger and rechargeable from the power grid meaning that the vehicle can be driven as an electric vehicle for parts of, or entire, driving missions. Then, due to the higher efficiency and lower emissions of the EM, it is desirable to make use of the energy stored in the battery and deplete it during the driving mission, see for instance [45, 68, 93, 97]. In a diesel-electric powertrain the energy driving the vehicle needs to be produced simultaneously by the GenSet, any delay in power production, for instance due to turbocharger lag, will be a delay experienced by the operator. The difference in energy paths also impacts the complexity of the ICE. In an HEV the ICE can be made quite small since the EM and battery can assist when high power is demanded. In order to decrease cost, the ICE can also be of simpler type, and is therefore seldom turbocharged. In a diesel-electric powertrain on the other hand, the ICE has to be dimensioned for the maximum power of the powertrain.

The complexities of the discussed systems lead to that it is not obvious how they should be controlled in order to best exploit the benefits and avoid the drawbacks of the powertrains. Optimal control is an interesting tool that can be used to gain insights into how to best control the powertrain, and which effects are important, but also to implement in the powertrain controller. Even though the common goal for the control of all the discussed powertrains is to increase efficiency and/or decrease emissions, the difference in architectures and components lead to different types of models and optimal control techniques being suitable.

1.1 Outline

The first three introductory chapters aim at introducing the topics covered in the dissertation, relating the contributions to the research field and finally describing the experimental setups used.

In Chapter 2 the contributions in the dissertation are related to the research field. In Section 2.1 energy management of HEVs is discussed and related to what is done in Paper 9-11. Section 2.2 discusses modeling of diesel engines, the topic of Paper 5. Section 2.3 summarizes the related field of optimal control of diesel engines and relates it to Paper 1-4 and Paper 7-8. Section 2.4 discusses the different optimal control strategies and solvers used in the dissertation, which is the motivation for Paper 6. Chapter 3 discusses the experimental setups used in dissertation. The appended papers then cover the contributions in the dissertation regarding modeling and optimal control of electrified powertrains.

1.2 Summary and Main Contributions of the Papers Included in the Dissertation

This section summarizes the eleven papers included in the dissertation and highlights the main contributions. Unless specifically noted the author performed the study and wrote the majority of the paper.

In Paper 1 [89] optimal control of a diesel-electric powertrain in transient operation is studied. The main contributions are the presented model, how to formulate the optimal control problem to receive relevant solutions, and also the nature of the optimal control when only engine properties are considered. The paper demonstrates both the influence of the turbocharger dynamics as well as how the criteria and constraints affect the solution, both for simple steps in requested power, but also for a more complex sequence of steps.

Paper 2 [90] continues on Paper 1 and contributes with a study of how a non-ideal generator model as well as adding an energy storage to assist in the transients changes the results from Paper 1. Further contributions are a detailed study of how the energy storage efficiency influences the optimal solution and insights into optimal sizing of the energy storage, and also what the limiting factors are. Finally the trade-off between the minimum time and minimum fuel solutions, and how it changes with the presence of an energy storage, is studied.

The contribution in Paper 3 [52] is a quantitative and qualitative study of the impact of turbocharger dynamics on the optimal control of diesel powered powertrains. Two different applications, wheel loader and diesel-electric, are studied where the author contributed with the diesel-electric study. It is shown that the turbocharger impact is dependent on the architecture of the powertrain, but for a diesel-electric powertrain the optimal trajectories differ substantially, and that neglecting the turbocharger dynamics can underestimate the optimal transient duration and consumption.

In Paper 4 [83] the potential performance of different control strategies using the control principles used in industry is studied and evaluated, i.e. the SAE J1939-standard for engine control. Two main approaches are discussed and implemented with the control parameters tuned for minimum fuel or minimum time. This is then performed for several cases and the results are related to the previously presented optimal results, investigating the potential for optimal control. As a further contribution the controllers are extended and it is shown that it is possible to control the diesel-electric powertrain in an optimal manner using the SAE J1939-standard.

Paper 5 [85] contributes with a model of a diesel-electric powertrain. The developed model is a four state, three control physically based mean value engine model that is smooth in the region of interest and provided fully parametrized to the research community. This provides researchers without engine models or data with a relevant and validated open source model on which control design or optimization can be performed. A further contribution is the methodology how to model and parametrize a model of a diesel-electric powertrain, using measurements that are conducted without a dynamometer, the only requirements are a diesel-electric powertrain and sensors.

The contribution of Paper 6 [86] is the formulation and solution of an optimal control problem to serve as a benchmark on which to evaluate optimal control tools. The considered problem is the optimal control of the power response of a diesel-electric powertrain. The intent of the benchmark is to provide the research community with a relevant problem of reasonable complexity on which to benchmark optimal control tools. The benchmark is provided together with a simultaneously developed model, both available for download. To ensure that the benchmark is relevant for tools at different stages of development the problem is provided both with and without path constraints as well as with and without time as a parameter.

The resulting optimal control trajectories for diesel-electric powertrains are in certain operating conditions oscillatory, when stationary controls would have been expected. In Paper 7 [88] the model and discretization impact on the oscillating optimal control of a diesel-electric powertrains is presented. More specifically it studies whether the seen oscillations are an artifact of the discretization or if the oscillations can be explained by the models used and whether or not extending the model impacts the oscillating solutions. The paper also contributes with a computationally fast and accurate residual gas model suitable for use in an optimal control context.

Paper 8 [87] continues on Paper 7 and studies whether or not gains can be made by controlling the wastegate in a periodic manner in an otherwise stationary operation of a diesel engine. Experiments are conducted on an actual powertrain for several wastegate controls, both periodic and fixed, showing how the wastegate control strategy affects the efficiency and pumping torque of the engine. Further the model from Paper 5, built using measurements on the same powertrain, is used in an simulation and optimal control study, showing the operating point dependence of the seen phenomenon as well as that the oscillating controls under certain circumstances can be predicted by optimal periodic control theory. Further, the effect of the time constant of the wastegate actuator on the optimal controls is shown.

In Paper 9 [91] an adaptive Equivalent Consumption Minimization Strategy (ECMS) for the energy management problem of a HEV, is developed, implemented and experimentally tested in a real HEV. The optimal torque distribution is calculated offline and stored in tables and the effects of discretization on the fuel consumption is shown. Two ways of adapting the control to maintain the SOC within the desired limits are investigated and due to it's robustness to unknown driving missions one is suggested and implemented in a real vehicle.

Paper 10 [72] presents a benchmark PHEV energy management problem, on which to evaluate different control strategies, and analyzes a set of solutions. The benchmark was developed for a special session of the IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling (E-COSM '12), held in Rueil-Malmaison, France, in October 2012. The author participated in the writing of the paper and also designed and implemented the best performing controller for the benchmark, analyzed at length in the paper.

Paper 11 [84] presents the design, implementation, and analysis of the best performing controller for the benchmark in Paper 10. The contribution of the method proposed in the paper is an efficient way of solving and implementing the ECMS control strategy for a PHEV that is also self-contained, using driving distance and average speed to estimate the initial equivalence factor and then adapting it continuously throughout the driving mission to ensure that it is robust to unknown driving missions and that the desired discharge profile is followed. Further the performance in the benchmark is evaluated, the influence of some of the design choices is discussed, and finally, the controller is extended to incorporate topology information from GPS to improve the performance in the presence of altitude variations in the driving missions.

1.3 Other publications by the author

This section summarizes research publications that the author has been involved in, but that is not included in the dissertation.

A Lars Eriksson and Martin Sivertsson, *Computing optimal heat release rates in combustion engines*, 2015, SAE International Journal of Engines. [26]

B Lars Eriksson and Martin Sivertsson, *Computing optimal heat release rates in combustion engines*, Technical paper 2015-01-0882, 2015, SAE World Congress & Exhibition, Detroit, Michigan, United States [25]

C Vaheed Nezhadali, Martin Sivertsson and Lars Eriksson, *Turbocharger Dynamics Influence on Optimal Control of Diesel Engine Powered Systems*, Technical paper 2014-01-0290, 2014, SAE World Congress & Exhibition, Detroit, Michigan, United States [51]

D Martin Sivertsson and Lars Eriksson, *Generator Effects on the Optimal Control of a Power Assisted Diesel-Electric Powertrain*, 2013,IEEE Vehicle Power and Propulsion Conference, Beijing, China [82]

E Martin Sivertsson and Lars Eriksson, *Optimal Transient Control and Effects of a Small Energy Storage for a Diesel-Electric Powertrain*, 2013, Advances in Automotive Control, Tokyo, Japan [81]

F Bernhard Bachmann, Lennart Ochel, Vitalij Ruge, Mahder Gebremedhin, Peter Fritzson, Vaheed Nezhadali, Lars Eriksson, and Martin Sivertsson, *Parallel Multiple-Shooting and Collocation Optimization with OpenModelica*, 2012, International Modelica Conference, Munich, Germany [7]

G Martin Sivertsson and Lars Eriksson, *Optimal Short Driving Mission Control for a Diesel-Electric Powertrain*, 2012, IEEE Vehicle Power and Propulsion Conference, Seoul, Korea [80]

H Martin Sivertsson and Lars Eriksson, *Time and Fuel Optimal Power Response of a Diesel-Electric Powertrain*, 2012, IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling, Paris, France [78]

I Martin Sivertsson, *Adaptive Control Using Map-Based ECMS for a PHEV*, 2012, IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling, Paris, France [77]

J Martin Sivertsson and Lars Eriksson, *Optimal Step Responses in Diesel-Electric Systems*, 2012, The 13th Mechatronics Forum International Conference, Linz, Austria [79]

K Martin Sivertsson *Optimization of Fuel Consumption in a Hybrid Powertrain*, 2010, Masters Thesis, LiTH-ISY-EX-10/4376-SE, Linköping University [76]

The author's contributions to these publications are indicated by the author list, where the first author is the main contributor to a publication.

In the optimal heat release in combustion engines studies in **A** and **B**, the author contributed to the modeling and also performed the free combustion study and wrote that part of the paper. In **C** the author performed the diesel-electric study, a publication preliminary to Paper 3 in the dissertation [52]. Publications **D** and **E** are preliminary to Paper 2 in the dissertation [90]. In publication **F** the author contributed with the modeling and problem formulation and also assisted in the solution of the optimal control problems. Publications **G**, **H**, and **J** are preliminary to Paper 1 in the dissertation [89]. In publication **I**, describing the controller for the PHEV benchmark in Paper 10 [72], the author did all the work, a publication preliminary to Paper 11 in the dissertation [84]. Publication **K** is the author's masters thesis that contains work preliminary to Paper 9 in the dissertation [91].

2

Background

This chapter gives an introduction to modeling and optimal control of electrified vehicles. The aim is to give a short overview of the models and optimization methods commonly used and the previously published research and it's relation to the dissertation.

2.1 Modeling and Optimal Control of Hybrid Electric Vehicles

In HEVs and PHEVs the main energy management control problem is how and when to use the battery in order to minimize energy consumption and emissions. The models of the energy converters, ICE and EM, are normally simplified either to polynomials, [49, 59], or the efficiency/fuel consumption map [45, 71, 73]. Thus, only stationary operating points are assumed, leading to a quasistatic approach. The underlying assumption is that the dynamic effects of the components are faster than that of the energy flows to be optimized, [70]. Following this assumption, the state-space can be kept small and if the driving profile is known before-hand the optimal solution can be found using for instance Dynamic Programming (DP), [12], as in [1, 65, 66, 71], Pontryagin's Maximum Principle (PMP), [67], as in [19, 73], Convex Optimization, [14], as in [49], or a combination of dynamic programming and convex optimization as in [59].

For real-time energy management of hybrid powertrains there exist several solutions, for an overview see, [70] and [66]. A common choice for HEVs is the equivalent consumption minimization strategy (ECMS), going back to [63], used by for instance [20, 50]. ECMS is a convenient realization of PMP [73] and is normally expressed as that an equivalent consumption of both electrochemical power in the battery, P_{ech}, and fuel power, P_f, is minimized, and that the applied controls is the argument that minimizes this sum according to (2.1).

$$u^* = \arg\min \left(P_f + \lambda P_{ech}\right) \tag{2.1}$$

λ in (2.1) is called equivalence factor, or sometimes costate, relating the two costs. Other costs can also be included, like emissions and battery ageing, however each additional state introduced requires an additional equivalence factor [74]. If λ is known, the optimal controls can be found [19]. Thus, estimating λ is the key aspect of the controller [18, 20, 50], which is complicated by the driving mission dependency of the optimal λ. Paper 9-11 contribute to this field. Paper 9 and Paper 11 are focused on the efficient solution and implementation of the energy management problem for power split hybrids, using no, or a minimum of, information about the future driving conditions. Paper 10 instead presents a benchmark energy management problem for PHEVs on which to evaluate different control strategies, something also performed in the paper.

In the real-time control the motors are normally modeled using either simple polynomials or efficiency maps, as in the offline case. For parallel HEVs using naturally aspirated spark ignited ICEs, the engine speed is is a fixed function of the wheel speed, the torque response of the ICE is fast, and the emissions are handled by the three-way catalyst. For compression ignited ICE parallel hybrids, especially if turbocharged, both the emissions and response time of the engine needs to be considered and there are publications where effects of transient fuel consumption as well as emissions are included in the optimal control problem (OCP) [58, 98, 100].

For series hybrids the engine speed of the GenSet is a DoF that needs to be controlled. Normally the same approach is used, i.e. using the stationary efficiency maps when solving the OCP. This means that the stationary map is used to generate setpoints for the GenSet, see [8, 37, 75, 101]. This approach does not account for the transient cost of switching operating point and how to actually control the GenSet to the setpoints in an optimal manner is rarely studied. In [16, 101] the assumption is that the GenSet should not deviate too far from the optimal operating line, both stationary and during the transients. In [101] this is achieved by limiting the power after the setpoint generation, whereas in [16] the possible setpoint candidates are restricted, but both solutions mean that the battery is used to compensate for the GenSet dynamics. In [37], where a model for a turbocharged diesel GenSet is used, this leads to the engine not being able to produce the requested power, due to the time constant of the diesel engine. This power therefore has to be produced by the supercapacitor, an effect not accounted for in the optimization. The only paper known to the author studying optimal engine speed control for the GenSet of a series-hybrid is [56]. The considered problem is that a certain energy is required in a fixed amount of time. The engine of the GenSet is naturally aspirated and in the optimization the systems stationary efficiency maps are used. For a turbocharged diesel-electric powertrain, lacking energy storage to compensate for any power deficits, but incorporating turbolag, the question how to control the GenSet is highly relevant. Paper 1-4 contribute to this field by studying optimal transient control of turbocharged GenSets.

2.2 Modeling of Diesel-Electric Powertrains

To study optimal control of GenSets, control oriented models describing the dynamics are necessary. Since the model is evaluated a large number of times the model evalution needs to be fast, but still capture the qualitatitive phenomenons, be quantitatively accurate as well as have good extrapolation properties [3]. Further in order for gradient based optimization techniques to work well the model needs to be smooth in the region of interest. This leads to models of the Mean Value Engine Model (MVEM) type [38, 42]. MVEMs, 0-D, or *lumped* parameter models, ignore in-cycle events that occur on a crank angle basis, and instead average these effects over one or several cycles [24]. The MVEMs can be divided into two groups: data driven black-box models and physics based grey-box models [15, 33, 34]. For more information on modeling of combustion engines the reader is referred to [24, 35, 39].

Black-box models rely on auto-regression techniques to identify the model from data, [27, 62]. The advantages of this approach is it's relative simplicity, both in that no prior knowledge of the system is required and also that the resulting models are often very fast, [21, 33]. The resulting states often have no physical meaning, making analysis difficult [15, 62]. Further, the model is only valid around the operating conditions for which it was tuned, leading to questionable extrapolation properties and putting high requirements on training data [21].

Grey-box models are models based on physical properties, using tuning parameters to increase their fit to data. Due to the physical motivation the analysis and extrapolation properties are good, but the parametrization and derivation requires high effort and prior knowledge about the system [21, 62]. Further, the resulting model might be too complex for direct implementation in a control framework [15, 34, 62]. Discussions on grey-box MVEMs can be found in [23, 95]. Paper 1 and Paper 5 contribute with two grey-box MVEMs of two different engines that are smooth in the region of interest. Further, Paper 7 studies modeling extensions to the model presented in Paper 5, investigating whether the seen characteristics of the optimal control solutions depend on the modeling assumptions used.

2.3 Optimal Control of Diesel Engines

How to optimally control the GenSet in transients has received very little attention, especially for turbocharged GenSets. The related field of optimal control of diesel engines has gotten more attention, especially in diesel engines with variable geometry turbines (VGT) and exhaust gas recirculation (EGR). Unless specifically noted, a grey-box MVEM is used in the discussed study. In [6] optimal control of a VGT-EGR diesel is studied for fixed output power and engine speed. The fuel consumption is minimized subject to limits on emissions. A lot of attention is given to formulating and solving the problem, a topic also studied in [5], investigating effects of different discretization techniques as well as different nonlinear program (NLP) solvers. The optimal solutions are also validated on a real engine. In [10] sequential quadratic programming (SQP) together with single shooting is used to minimize pollutants during different load steps at constant speed. [60, 61] uses a quasi-Newton algorithm to minimize a trade-off between smoke and produced power for a VGT diesel engine over a specified torque and speed trajectory. In [44, 46] the torque and speed responses of VGT-EGR diesel engines are studied. In [46] fuel and time optimal trajectories from low to high output torque are studied and in [44] the final speed of vehicle is maximized.

None of the discussed studies above study optimal control, using the engine speed as a DoF. To the author, the only known publications where the freedom to select engine speed is considered, are [53, 54, 56] where very simplified models, one to two states, are used. Papers 1-7 contribute to this field, studying how to control the engine speed of a diesel powered powertrain in transients.

In [6] it is mentioned that the optimal results seen exhibit oscillations in the control signals. There exists some theory concerning optimal periodic control [11, 13, 17, 31] where it is actually better to oscillate the control than to use constant controls [30, 48]. Papers 7-8 contribute to this field by studying if it is optimal to use periodic control in an otherwise stationary operation of diesel engines.

For real-time implementation of optimal control a couple of different methods have been suggested. One method is implementing the optimal controls as transient compensation maps together with the normal stationary calibration. This approach is advocated in [4, 32, 47]. Another approach along the same lines, i.e. using a fixed mapping, is [61] where the optimal results are used to train an artificial neural network that is then used to control the engine. More flexible approaches are [27, 96], implementing model predictive control (MPC) where an optimization problem is solved online in real-time, or [55] where stochastic DP is used, and the optimal feedback laws are extracted and implemented in a real vehicle. Paper 4 studies how to use the framework common in industry to approximate the optimal trajectories extracted from the optimal control studies in Papers 1-2.

2.4 Selecting the Appropriate Solver

This section provides a short summary of the optimal control techniques used in in the dissertation and related research. For an overview on numerical optimal control and numerical optimization the reader is referred to [22, 57].

The model complexity is strongly related to which optimal control technique algorithm is most suitable. For instance in the HEV case a common choice for offline studies is DP, since the state-space is small and the curse of dimensionality [9] is not as severe. However even for PHEVs DP becomes impractical. This is since the battery is large to allow for all-electric drive and the SOC dynamics are slow, resulting in a very fine SOC grid and long computation times [65]. In Paper 9 only one state is used, making the offline problem very suitable for DP and the PMP related control strategy ECMS for the real-time control. This real-time control strategy is also used in Paper 11.

When studying optimal control of diesel engines and the number of states is larger, the common choice is instead to use a direct method. There exists several software packages implementing different direct methods. In this dissertation three of them are used. In Paper 1 and Paper 6 ACADO Toolkit [40] is used, which is an open source software implementing shooting algorithms and SQP. Papers 1-4 and Paper 6 uses PROPT [92] a commercial software implementing pseudospectral collocation and SQP. In Papers 7-8 CasADi [2] a symbolic framework for algorithmic differentiation is used together with direct collocation and IPOPT, a large-scale interior point algorithm for nonlinear optimization [94], with the MA57 linear solver from the HSL package, [41], for solving the resulting NLPs.

The evolution during the thesis is that larger OCPs with more complex constraints are solved, therefore the method and solver suitable has changed. Both ACADO and PROPT are packages that simplify defining the problem to be solved, however this also introduces a drawback, since the problem definition has to follow a certain format. With CasADi the user has to define the problem more on his own which is both a benefit and drawback. The coding requirements increase but it gives the user full control over defining the problem, which increases the complexity of problems that can be solved.

Evaluating the performance of the solver is not straight forward and often one has to rely on the provided solved examples to get an estimate on how good the solver is. These problems generally have in common that the solution is well known, typically meaning that they are simple and can be solved by most solvers, as for instance the Bryson-Denham problem, see [43]. However during the work on this thesis, problems have been encountered that were not indicated by looking at the solved example list of the used solver. Paper 6 contributes to this field, suggesting a benchmark problem on which to evaluate OCP solvers, as well as presenting the solutions using two different solvers. The intent of this benchmark is to provide developers of optimal control tools with a more challenging problem that can not be analytically solved, but where the solution is still available for comparison.

3

Experimental setups

This chapter describes the measurement setups used in Papers 1, 2, 5, 7, and 8 in the dissertation. In Paper 9 the vehicle speed, SOC and equivalence ratio, λ, are measured, however they are signals reported by the powertrain control system and not discussed further. For the diesel-electric studies measurements on two different powertrains are conducted. The first powertrain is the one modeled and used in Papers 1-2 where the measurements were conducted to validate the developed model. Measurements from a different powertrain is used in Papers 5, 7 and 8. In Papers 5 and 7 the measurements are used to build and validate a model over the powertrain. In Paper 8 the measurements are used to study optimal wastegate control. In this chapter the sensors used to measure the relevant quantities are briefly described, for a more thorough text on sensors and their characteristics the reader is referred to [29]. In Table 3.1 all signals measured in the different papers are shown. The quantities of interest in the measurements are:

- Engine Speed
- Pressures
- Turbocharger speed
- Generator power
- Wastegate position
- Massflow through compressor
- Fuel flow
- Temperatures
- Air/fuel equivalence ratio

The engine speed is measured with the internally mounted OEM sensor and accessed via the engina CAN bus and not discussed further. The signals measured with external sensors are discussed below.

3.1 Pressures

All pressures in Paper 1, 2, 5, 7 and 8 are measured using Dynisco PT130-50 Pressure Transducers. They have a range of 0-345 kPa and an accuracy of ±1.72 kPa including linearity, hysteresis and repeatability.

3.2 Turbocharger Speed

In Paper 1, 2, 5, 7 and 8 the turbocharger speed is measured with Acam PicoTurn PT2G Turbocharger Speed Sensor. The Digital-Out option is used, giving one pulse per revolution. The speed range is 390-400000 rpm and the precision is 390 rpm. The time constant is small, allowing for sampling rates in the range of 1-3 MHz.

3.3 Generator power

In Paper 1, 2, 5, 7 and 8 the generator and power electronics are lumped together so what is actually measured is the output voltage and current from the DC-converter and from these measurements the output power can be computed. The voltage is measured using a Tektronix P5200 High-voltage Differential Probe, having a bandwidth of up to 50 MHz and the current is measured using a LEM IT 1000-S High Performance Current Transducer with a linearity error less than 3ppm and a response time to 90% of full scale of less than 1 μs.

3.4 Wastegate Position

In Paper 1, 2, 5, 7 and 8 the wastegate position is measured with Firstmark Controls Series 170 Subminiature Position Transducer with a maximum independent linearity error ±0.5% per VRCI-P-100A, output smoothness 0.1% max, Resolution infinite signal, and an operating temperature of -65°C to +125°C.

3.5 Massflow

In Paper 5 and 7 the massflow through the compressor is measured with a ABB FMT500 Thermal Massflow Meter. The measuring error is less than $0.009 \cdot \dot{m}_{meas} + 2.78 \cdot 10^{-4}$ kg/s. Reproducibility error less than 0.2% and time constant 0.5 s. The time constant is relatively long therefore this measurement is only used for stationary operating points in the submodel tuning and validation.

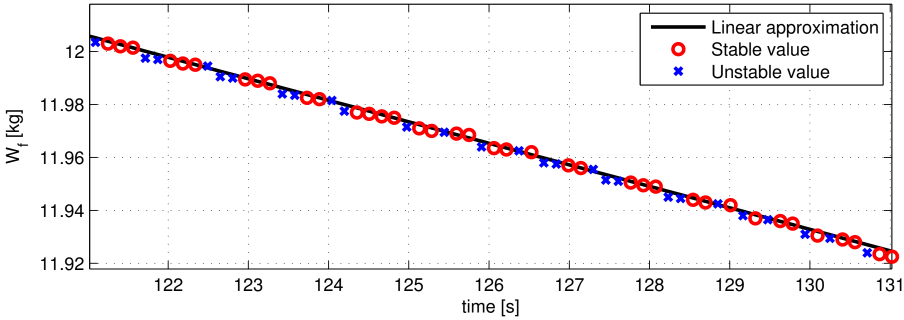


Figure 3.1: Measured fuel weight and the linear approximation.

3.6 Fuel Flow

In Paper 5 and Paper 8 the fuel weight is measured using a Kern IFS60K0,5DL Counting scale with a linearity of 2 g, reproducibility of 500 mg and a specified stabilisation time of 3 s. The stabilisation time in the specification is rather long, however the scale also reports when the measurement is stable which is a lot faster. To get an accurate approximation of the fuel flow a first order polynomial is fitted to the weight over time series, that minimizes the error in a least squares sense, using only the stable measurements, see Fig. 3.1. The slope of this polynomial is the fuel flow in kg/s. Due to the recirculating fuel flow of the diesel engine as well as response time of the scale and system itself, this technique only suitable for stationary points and therefore only used in stationary operating conditions.

3.7 Temperature

The temperatures in Paper 5, 7 and 8 are measured with TC 1.5mm mineral insulated type K thermocouples. The sensor has a measurement tolerance of $\pm 0.0075|T|$ and response time of 0.3 s when plunged into boiling water from air at $20°C$. The time constant in air or exhaust gas can be expected to be substantially longer and therefore the temperature measurements are only used in the tuning and validation of stationary models.

3.8 Air/fuel equivalence ratio

In Paper 8 the equivalence ratio, λ is measured with ETAS 636 Lambda module using Bosch LSU4.9 Wide Band Lambda Sensor mounted after the turbine. The measurement is only used as a reference since the instantaneous fuel flow into the cylinder is not measured.

Table 3.1: Quantities measured and used in Paper 1, 2, 5, 7 and 8

Name	Description
Measurements used in Paper 1, 2, 5, 7 and 8	
p_{amb}	Ambient pressure
p_{im}	Intake manifold pressure
$p_{em,f}$	Exhaust manifold pressure, front
$p_{em,r}$	Exhaust manifold pressure, rear
n_{tc}	Turbine rotational speed
u_{wg}	Wastegate position
I_{DC}	DC current
U_{DC}	DC voltage
n_e	Engine rotational speed
Extra measurements used in Paper 5 and 7	
p_{es}	Pressure after turbine
$p_{c,b}$	Pressure before compressor
$p_{c,a}$	Pressure after compressor
T_{amb}	Ambient temperature
T_{im}	Intake manifold temperature
$T_{em,f}$	Exhaust manifold temperature, front
$T_{em,r}$	Exhaust manifold temperature, rear
$T_{c,b}$	Temperature before compressor
$T_{c,a}$	Temperature after compressor
$\dot{m}_c$	Massflow through compressor
M_F	Fuel weight
Extra measurements used in Paper 8	
λ	Air-fuel equivalence ratio
M_F	Fuel weight

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