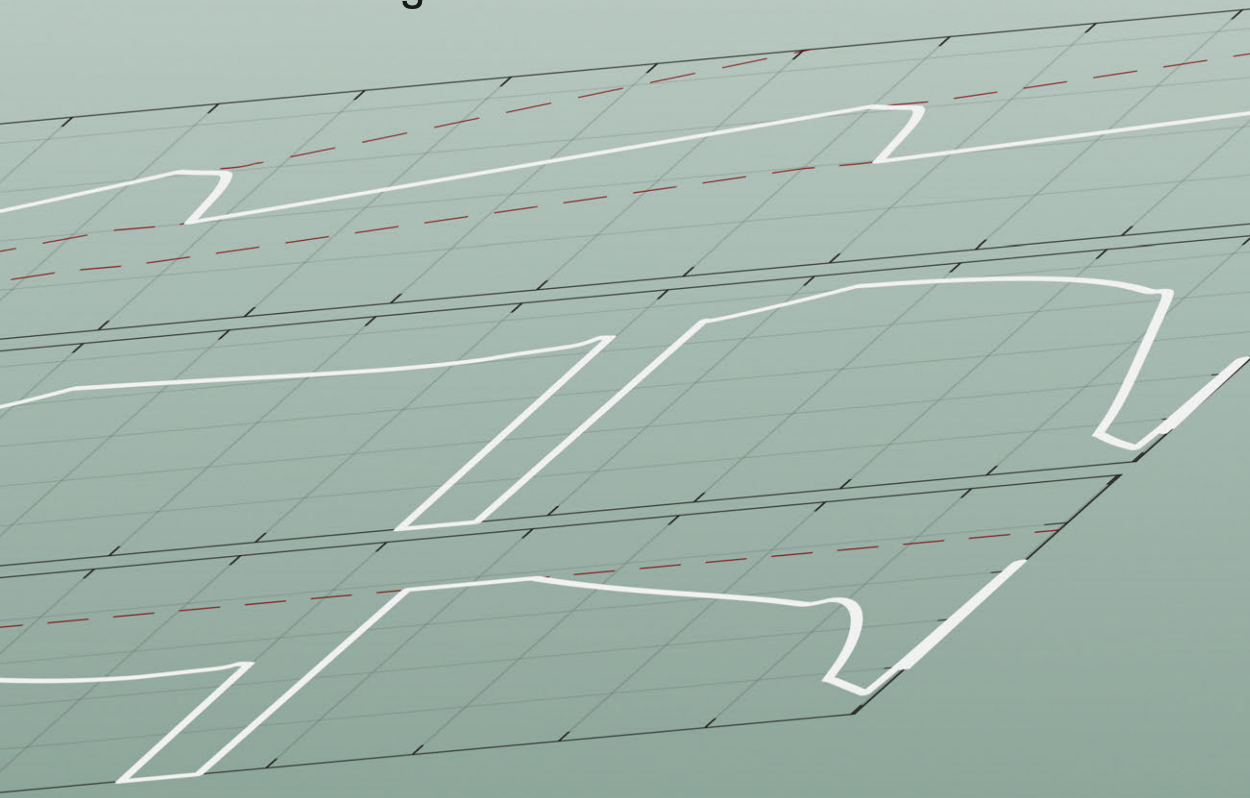
Linköping Studies in Science and Technology
Dissertations No. 2145

Modeling and Optimal Control for Dynamic Driving of Hybridized Vehicles with Turbocharged Diesel Engines

Kristoffer Ekberg



LINKÖPING
UNIVERSITY

Linköping Studies in Science and Technology
Dissertations, No. 2145

Modeling and Optimal Control for Dynamic Driving of Hybridized Vehicles with Turbocharged Diesel Engines

Kristoffer Ekberg

Linköping University
Department of Electrical Engineering
Division of Vehicular Systems
581 83 Linköping, Sweden

Linköping 2021

Edition 1:1

ISBN 978-91-7929-644-5
ISSN 0345-7524
URL `http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-175469`

Typeset using XƎLATEX

Printed by LiU-Tryck, Linköping 2021

Book cover: The cover shows the results from performing a fuel optimal acceleration, showing engine speed with corresponding projected speed for a set of gears, fuel injection control and fuel-air ratio including the limit.

POPULÄRVETENSKAPLIG SAMMANFATTNING

Dagens fordon drivs till stor del på fossila bränslen, som vid förbränning bland annat avger utsläpp som är skadliga för både hälsa och miljön. Den mängd utsläpp som tillåts från fordon regleras av utsläppskrav, som också är en teknikdrivare som tvingar fordonsindustrin att utveckla mer miljövänliga fordon. Idag ligger en stor del av industrins fokus på att utveckla fordon som klarar de utsläppskrav på exempelvis kolväten och kväveoxider som ställs, samt minska fordonens bränsleförbrukningen. Nya koncept där fordon drivs av andra energislag än fossila bränslen blir idag mer vanliga, och dessa koncept bidrar till minskad användning av fossila bränslen om de används på rätt sätt. En vanlig variant idag är plugin-hybrider, som drivs av både en elmaskin och en förbränningsmotor. Fördelen med dessa fordon är att de två energikällorna kan användas för att optimera fordonets framdrift, genom att välja om de ska användas tillsammans, eller var för sig. När de används tillsammans så kan elmaskinen bland annat användas för att hjälpa förbränningsmotorn i driftsfall där den är sämre på att omsätta bränsle till nyttigt arbete för att driva fordonet framåt. Ett exempel på ett sådant driftsfall är en acceleration. Hur snabbt eller långsamt fordonets hastighet ökas, samt vilka växlar som används påverkar bränsleåtgången. För att undersöka hur ett fordon kan accelereras så bränsle- eller energisnålt som möjligt så kan optimal styrning användas. Optimal styrning kallas en familj av metoder som använder en matematisk modell av systemet, för att beräkna hur systemet skall styras för att minimera en förutbestämd kostnad, t.ex. bränsle. För att använda optimal styrning så behövs en modell som beskriver det verkliga systemet som man är intresserad av att undersöka. Modellen skall också inneha vissa matematiska egenskaper för att vara lämplig att använda i ett optimalstyrningsramverk. För att få en beräkningseffektiv modell så vill man ofta hålla modellen så enkel som möjligt, men fortfarande tillräckligt komplicerad för att beskriva de viktigaste egenskaperna hos det system man är intresserad av. I arbete undersöks hur en bränsleoptimal acceleration för en lastbil skall utföras, samt vilken inverkan två olika hybridiseringsteknologier har på dess prestanda och energiförbrukning. En teknologi benämns som elektrisk turbo, den ger en möjlighet att förse motorn med extra luft i arbetspunkter där den inte klarar det i vanliga fall, samt att lagra elektrisk energi då det finns mer avgasenergi vid turbinen än vad kompressorn kräver. Den andra teknologin kan beskrivas som en parallellhybrid, där en elmaskin placeras på samma axel som förbränningsmotorn. I ett första tillämpningsexempel utvecklas en styrstrategi för en elturbo i en lastbil som kör ett längre köruppdrag. Resultaten visar att bränsleförbrukningen kan minskas, samt att motorn kan leverera högre moment vid lägre varvtal med elturbon. Därefter utvecklas en dieselmotormodell som är lämplig för optimal styrning av dynamiska förlopp, där hänsyn tas till turbons inverkan på systemet. Med modellen som bas utvecklas en metod för att undersöka bränsleoptimala accelerationer, där modellstrukturen anpassas för att inkludera motorns dynamik när växelbyten sker. Med modellen och metoderna på plats utvärderas likheter och skillnader mellan en stel och flexibel drivlina när en bränsleoptimal acceleration utförs. Slutligen implementeras och utvärderas både en elturbo och en parallellhybridlösning. De två koncepten utvärderas både var för sig, och i samverkan med varandra, under en kort acceleration, samt en längre acceleration med flertalet växelbyten. Resultaten visar när, och hur, de två elmotorerna och dieselmotorn skall användas på bästa sätt, för olika kostnadsrelationer mellan diesel och el.

ABSTRACT

Reducing the fuel consumption of today's vehicle fleet is of great importance due to the environmental impact of using fossil-based fuels. The turbocharged compression ignition (CI) engine is widely used for trucks. The CI engine efficiency is dependent on the operating point, in terms of rotational speed and load. The selection of load point can be controlled by selecting suitable gears, but remains a challenging task during dynamic driving, due to the turbocharger dynamics which introduces a lag in the system. Electric turbocharger technologies can improve the engine response time, but developing efficient control strategies can be challenging. Due to turbocharger lag, all conditions that are reachable in stationary operation for the turbocharged CI engine are not always reachable during dynamic events, for example after an up-shift where the engine speed and torque demand changes rapidly.

In this work the fuel saving potential of electric turbocharging for a heavy-duty truck performing a long-haulage driving mission is investigated. An electric turbocharger control strategy is proposed and evaluated. The results show that the fuel consumption can be reduced using the electric turbocharger, when comparing to a conventional turbocharged CI truck performing a long-haulage driving mission.

A turbocharged CI engine model suitable for optimal control of transient behavior is developed. Sub-models are validated using data describing the components, and the model suitability for optimal control is shown with a tip-in example. To increase the model accuracy, the torque model is extended with a further dependence on the air-fuel ratio and operating point dependent losses. The complete engine model is parameterized for a set of stationary load points. The model is validated using data from a dynamic engine test, where it is shown that both the stationary and dynamic features in the data is represented well by the model. The developed engine model is used as a foundation in an optimal control problem setup to solve fuel optimal accelerations including gear changes. The setup is used to investigate the impact of driveshaft flexibility on the optimal control results, when compared to a stiff driveshaft model. Apart from a slight increase in fuel consumption, the driveshaft flexibility is shown to have minor effects on the fuel optimal control signals, in terms of general torque output and gear shift characteristics.

The hybrid electric vehicle (HEV) technology can potentially reduce the consumption of diesel fuel, but how to design and control the system, consisting of several degrees of freedom remains a challenging task. Energy optimal accelerations of a CI parallel HEV with electric turbocharger is investigated using the optimal control problem setup. The results show that the electric turbocharger is used when the electrical energy cost is high, and the usage of the crank shaft motor is increasing with decreasing electrical energy cost.

To summarize, the developed models and problem setups enable investigations of different powertrain configurations and optimal control of these. One conclusion is that the energy savings using an electric turbocharger and crank shaft motor during accelerations are significant.

Acknowledgments

I would like to express my gratitude to Lars Eriksson for presenting the opportunity of pursuing a PhD degree at Vehicular Systems, and for supervising me along the way. Thanks to Lars Nielsen for giving me the opportunity to join the group at Vehicular Systems, first as a research assistant, then as a PhD student. Thanks to Viktor Leek for providing support and tailoring of the YOP toolbox. I am grateful for my colleges at Vehicular Systems who contributes to a fantastic working environment, as well as great discussions in the fika-room. Thanks to Christofer Sundström for proofreading the thesis and providing feedback. Thanks to Erik Frisk for helping me out with the LaTeX configurations of the thesis. Thanks to Daniel Jung for developing discussions about my work. I would also like to thank Robin Holmbom, Olov Holmer and Viktor Leek for a number of fantastic evenings with beer and great food.

A special thanks to my wife Anna, for showing great interest in my work, reading most of the papers and listening to my never ending talks about turbocharged combustion engines.

Funding

Linköping Center of Informatics and Control LINK-SIC is acknowledged for funding the research.

Contents

1 Introduction

Long haulage trucks transport the main of our goods. 71.3% of land transports in Europe 2017 where performed by trucks, and 98% of the heavy duty trucks where powered by diesel (*Trucks What are Trucks Fact Sheet* Accessed: 2021-04-12). Renewable fuels such as biodiesel (Heywood, 2018), can be blended into, or completely replace the fossil based diesel, but only if the production rate is able to supply the demand. The consumption of diesel fuel in a vehicle depends on the usage, both how it is driven, as well as for example the mass of the vehicle. Some drawbacks with diesel fuel are the emissions released from the vehicle, as well as the diesel fuel being a fossil fuel which is a limited resource. The compression ignited (CI) engines ability to transform the diesel fuel to mechanical work depend on the engine operating point, which can be expressed in terms of torque and rotational speed of the engine. The selection of operating points can be made by selecting suitable gears, as well as deciding the torque output. A heavy-duty long haulage truck faces different types of driving, such as accelerations, cruising at constant speed, decelerations, uphills and downhills. Accelerating a truck requires a lot of energy, in comparison to driving at constant speed.

During an acceleration the engine speed can be influenced by the selected gear. The CI engine is operated fuel lean, and the engine output torque is controlled mainly with the fuel injection (Heywood, 2018). Turbocharging a CI engine can improve fuel economy, but the turbocharger introduces a delay in the system (Rakopoulos and Giakoumis, 2009). The rate of change of the turbocharger rotational speed depends on the power balance between the compressor and turbine, as well as the combined inertia of the compressor and turbine wheels. If the fuel injection is rapidly increased, in for example the beginning of an acceleration, the amount of injected fuel can be increased faster than the rotational speed of the turbocharger. The absence of air results in a rich combustion, with the risk of emitting black smoke from the exhaust (Rakopoulos and Giakoumis, 2009). Due to regulations on heavy-duty diesel engines release of visible smoke at high load (Heywood, 2018)(p.661), this event has to be avoided. During a dynamic event such as an acceleration, the turbocharger dynamics plays an important role due to its impact on the intake manifold pressure, which affects the air mass flow into the cylinders. Experimental investigations on a turbocharged CI engine has been performed in (Rakopoulos, Dimaratos, et al., 2011) where the turbocharger lag was concluded to be a major cause for high smoke and nitric oxide (NO) values.

One way to speed up the turbocharger dynamics is to use an electric motor that supports the turbocharger (Tavčar et al., 2011), having an electric machine on the turbocharger shaft could also enable generation of electric energy when there is a surplus in exhaust gas energy. Another way is to use an electrically driven compressor to increase the boost pressure, without the direct need of exhaust gas energy, as in (Xiao et al., 2018).

To evaluate and analyze the best possible solution to the problem of accelerating a truck, while taking both the turbocharger dynamics and gear shifts into account, optimal control can be used. The power with optimal control is to find, in some cases unintuitive, results to how a system should be controlled in for example a fuel optimal way. The scenario of accelerating a truck has many free variables to consider, for example, when should the gear change take place, which gears should be used, for how long should each gear be used, when and how much fuel should be injected, how should the wastegate be actuated, how long should the total acceleration time be, etc. By using a suitable system model and problem setup, these questions can be investigated. Studies have investigated optimal control strategies for gear shifts, how a gear shift should be performed (Haj-Fraj and Pfeiffer, 2001), as well as finding fuel saving gear shift strategies during longer driving missions (Ngo, Navarrete, et al., 2013), but these studies does not include the turbocharger characteristics.

If introducing electric motors in the vehicle driveline architecture, the control problem becomes even more challenging due to increased number of control signals. Deciding the power output from the electric motor as well as the turbocharged CI engine during an acceleration, where the CI efficiency depend on the turbocharger rotational speed, load, and gear selection, is a highly non-linear problem.

1.1 Motivation & Aim

Accelerating a vehicle is a dynamic and energy consuming event. To investigate how the least fuel consuming acceleration should be performed while taking the turbocharger dynamics into account, there is a need for a optimal control framework to handle the multiple inputs and outputs in the system, as well as the mixed-integer problem of selecting suitable gears. The engine dynamics, time spent in each gear, engine inputs and clutch control results in several degrees of freedom. The amount of turbocharger boosting, as well as the air-fuel ratio, are both variables which have effect on the compression ignited engines ability to convert energy from the diesel fuel to useful work on the engine output shaft. The combination of a hybrid electric vehicle, equipped with a CI engine with electric turbocharger poses a complicated control problem, especially during accelerations.

The thesis aim is to investigate how to solve the problem of accelerating a truck using the least amount of energy, as well as investigating the impact of electric turbocharging and hybrid propulsion technologies on the system performance.

2 Background

2.1 Electric Turbocharger

The concept of electric turbocharging enables the possibility to add, or subtract, power from the turbocharger shaft. One possibility with the electric turbocharger is the ability to change the turbocharger operating point without the extra need of exhaust gas energy. Applying extra power with the use of the electric turbocharger results in for example improved response time (Winward et al., 2016). The electric machine can also be used to generate electrical energy (Hopmann and Algrain, 2003). Controlling a complete powertrain with an electric turbocharger might be a challenging task since it introduces an extra degree of freedom. Control of the electric turbocharger can be achieved by using model predictive control (MPC) (Zhao, Stobart, and Mason, 2019a,b), or using the equivalent consumption minimization strategy (Zhao, Stobart, Dong, et al., 2015). The use of such control strategies often require simplifications of the system models in order to run optimization algorithms online, for example developing linearized models describing the system in specific operation points, as in (Zhao, Stobart, and Mason, 2019a). Acceleration performance with electric turbocharger is also investigated in (Jain et al., 2016), where a method to include the turbocharger lag in a dynamic programming framework is used to find the optimal control.

2.2 Diesel Engine Modeling

The diesel engine is a compression ignition engine, and its torque output is mainly controlled with the injected amount of fuel (Heywood, 2018). Diesel engines need to be operated fuel lean, which means that they run with excess air. Today's diesel engines are often turbocharged (Rakopoulos and Giakoumis, 2009). The turbocharger technology use otherwise wasted exhaust gas energy to increase the intake manifold pressure, but one drawback is that the turbocharger introduces turbo-lag into the system due to the turbocharger flow and shaft inertia (Rakopoulos and Giakoumis, 2009)(p.24). A diesel engine model can be developed for different purposes, where the intended use of the model influences the model complexity. A 0D model (mean value model) can be used for describing pressure, temperature or rotational speed for different components in the engine, see for example (Jensen et al., 1991; Payri et al., 2011; Wahlström and Eriksson, 2011), while a 1D model has the capability of investigating wave propagation (Li et al., 2020), or can be used for emission formation studies by gas kinetics modeling as in (Fröjd et al., 2011). The complexity of a 0D-model is suitable for developing control strategies for the diesel engine operation, since a model can be developed with the inputs and outputs expected for a real engine, for example fuel injection, throttle position, wastegate positing etc., while it at the same time uses few states which is beneficial for calculation time. Using a 1D model would most likely increase the calculation time due to increased number of states, as well as requiring a finer discretization in time depending on the system, which also increase the computational time of the optimal control software.

2.3 Optimal Control of Accelerations

An acceleration is a highly dynamic event where the goal is to increase the vehicle speed. The turbocharger dynamics results in a constrained utilization space of the diesel engine, compared to stationary performance (Rakopoulos and Giakoumis, 2009). During congested traffic conditions, vehicle speed planning might be troublesome, due to the high divergence of velocity compared to non-congested situations. Development of gear shift maps to specify when the vehicle should change gear can be developed using dynamic programming, se for example (Ngo, Hofman, et al., 2014; Škugor et al., 2016), but these investigations seldom include the turbocharger dynamics. The optimal control for vehicle acceleration can be performed with for example model predictive control (Kamal et al., 2013), but when using such methods, simplifications are often made about how the gear change is supposed to happen as well as often neglecting the turbocharger dynamics. In for example (Kamal et al., 2011) the fuel consumption of the engine is described by a function including a term for the vehicle acceleration and the gearbox ratio is assumed to be a linear function.

2.4 Hybrid Electric Vehicles

The hybrid electric vehicles (HEV) usually has two sources of energy onboard the vehicle. The extra energy source, often electrical energy stored in a battery, can be used to support the combustion engine, or as stand-alone to propel the vehicle. To decide when to use electric energy, or diesel fuel, studies have investigated the use of MPC (He et al., 2016), dynamic programming (Pérez et al., 2006; O. Sundström et al., 2008), dynamic particle swarm (Chen et al., 2018) and as a mix of dynamic programming and convex optimization (Duhr et al., 2021; Nüesch et al., 2014). An extensive review of different approaches for calculating the optimal controls for hybrid vehicles is performed in (Salmasi, 2007). Simplifications about the diesel engine air path dynamics are often made when developing models for optimal control of HEV's, which might be fair for longer driving missions, but the dynamics should be considered during shorter dynamic events such as an acceleration. The impact of the turbocharger dynamics on optimal control results for two different diesel engine applications is examined in (Nezhadali, Sivertsson, et al., 2014), were it is concluded that the turbocharger dynamics are important, since excluding the dynamics might lead to overestimating the diesel engine performance.

2.5 Publications

A short summary of the papers included in the thesis will follow. Paper I investigates the concept of electric turbocharging using a diesel engine model. Paper II and III develops a compression ignited engine model suitable for optimal control. Paper IV develops a method for solving fuel optimal accelerations of a truck, while taking gear changes into account. Paper V investigates the difference in characteristics of a fuel optimal acceleration, when comparing a flexible and stiff driveshaft model representation. Paper VI investigates the power split between, and the impact of, using an electric turbocharger and crank shaft motor during accelerations.

Paper I - Improving Fuel Economy and Acceleration by Electric Turbocharger Control for Heavy Duty Long Haulage

The paper develops and implements a control strategy to evaluate the system benefits of using an electric turbocharger in a long haulage driving scenario. A fuel injection controller is tuned to fulfill a specified engine air-fuel ratio. Boundary controllers are implemented to keep the turbocharger rotational speed within the specified limits. An addition of power to the turbocharger is applied during gear changes, to reduce the risk of limiting the output torque due to smoke limitations at the beginning of the upcoming gears. The control strategy is capable of supporting the diesel engine during transients, while also recuperating energy in for example downhills. The results in simulation show that it is possible to achieve a 0.9 % fuel saving, while keeping the solution charge sustainable for the selected driving scenario.

Paper II - Optimal Control of Wastegate Throttle and Fuel Injection for a Heavy-Duty Turbocharged Diesel Engine During Tip-In

The development of a diesel engine model suitable for optimal control is presented. Data from components in a heavy-duty truck engine is used, and models are fitted to the data in order to describe the engine in a mean value engine model perspective. The model inherits the property of being twice differentiable, which makes the model suitable for optimal control investigations. To ensure this property, for example if-else statements are replaced by mathematical functions, with the ability to describe the transition from one function description to another. An existing turbine model is extended to take the rotational speed characteristics of the turbine into account. The resulting engine model is used in a test case to evaluate the model response, where a time optimal tip-in is performed at constant engine rotational speed.

Paper III - Modeling and Validation of an Open-Source Mean Value Heavy-Duty Diesel Engine Model

The paper describes the modeling process and validation of a mean value engine model, describing a 13 liter compression ignited inline 6 cylinder heavy-duty engine, and releases it as open-source. This work is an extension of Paper II, the torque model is extended with a further dependence on the air-fuel ratio and operating point dependent losses. The resulting model is developed using different sources of data sets, and the complete system model is validated using a dynamic data set. The model is able to capture both the stationary and dynamic behavior of the reference engine.

Paper IV - Development and Analysis of Optimal Control Strategy for Gear Changing Patterns During Accelerations

A method to enable analysis of fuel optimal accelerations while taking gear changes into account is developed. The engine model in Paper III is connected to a truck chassis and driveline model to investigate optimal gear shift patterns during accelerations. To enable the change of gear, a clutch model is implemented where the clutch control signal regulates the amount of transferred torque over the clutch. The paper presents a method for how to formulate and solve a fuel optimal non-linear control problem of accelerating a vehicle, with the possibility of performing gear shifts. The method indicates which gears that should be used during the acceleration, due to the utilization time of each gear being a free variable. The problem formulation is presented for both up and down shifts. The optimal controls of the diesel engine, gear shift pattern, clutch control, and gear utilization time are found for an acceleration to a predefined target speed.

Paper V - A Comparison of Optimal Gear Shifts for Stiff and Flexible Driveshafts During Accelerations

The model in Paper IV is extended with a driveshaft flexibility to investigate the impact of flexible driveshafts on the fuel optimal gear shift strategy. A comparison of a fuel optimal acceleration using a stiff or a flexible driveshaft model is performed. Data from a truck performing on-road tip-ins using a low gear is used to parameterize a lumped model of the driveline flexibilities existing in the truck. Restrictions on the clutch control are imposed to fulfill constraints on maximum closing speed and actuation direction of the clutch. In comparison to Paper IV, the clutch characteristics are updated to better represent the non-linear behavior of the component. The results show that there are similarities in the fuel optimal control in terms of torque output and engine speed range utilization when comparing the two model representations, but the finer details differ due to the driveshaft flexibility. Both driveline representations are limited by the CI engine fuel-air ratio at the beginning of each up-shift, revealing that the engine output torque is restricted by the turbocharger dynamics. The results also show that the fuel consumption is slightly increased when using the flexible driveshaft model, which is expected due to the dampening element in the driveshaft model which has an additional dissipation. Both model representations are robust to changes in number of control intervals used in the optimal control problem.

Paper VI - Electrification of a Heavy-Duty CI Truck—Comparison of Electric Turbocharger and Crank Shaft Motor

The goal with the study is to find out how the energy optimal power split between the two electric motors and combustion engine is performed, for a parallel hybrid CI truck with electric turbocharger. One single gear acceleration and one full acceleration to 80 km/h is considered to analyze the energy optimal control signals. A model of an electric motor is developed with the current and rotational speed as inputs. The electric motor model is parameterized to describe the efficiency of the crank shaft electric motor and the turbocharger electric motor. The cost function in the optimal control formulation summarize the consumed diesel energy and consumed electrical energy. A weight term is multiplied with the electrical energy to investigate different optimal control actions depending on the relations in cost of the two energy sources. The results show that the main difference in control action when comparing a single gear acceleration and full acceleration to 80 km/h, is the utilization of the electric crank shaft motor. Analyzing different weight terms results in the conclusion that the electric turbocharger is preferably used if the electrical energy is expensive, while the usage of the crank shaft motor increase with decreasing cost of electrical energy.

3 Applied Optimal Control

Optimal control methods will shamelessly exploit every opportunity to minimize the objective function value. To get reliable results the objective functions, the implemented system models and constraints are important to ensure that the problem formulation restricts the model to the bounds of the real system. Defining the problem of performing an acceleration is a challenging task, especially if gear shifts are taken into account due to the mixed integer and non-linearity of the problem. There are many different methods for solving optimal control problems, some examples are dynamic programming, convex optimization methods, Pontryagin's maximum or minimum principle, multiple shooting and direct collocation. Dynamic programming has the benefit of converging to the global optimum of the problem, but due to the method structure, the complexity increase exponentially with the number of states (Machlev et al., 2020). Dynamic programming can be used to find optimal velocity profiles, as well as controlling the power split in hybrid electric vehicles (Lin et al., 2003; Uebel et al., 2018). Convex optimal control strategies can be used to find fuel optimal speed profiles for vehicle platoons (Hoef et al., 2015), speed profiles to preserve kinetic energy of a truck (Johannesson et al., 2015), and energy management control in serial hybrid electric vehicles (Elbert et al., 2014). Pontryagin's minimum principle can be used to calculate the optimal power split in hybrid electric vehicles (Kim et al., 2011; Serrao and Rizzoni, 2008). If the system models are non-linear, non-linear model predictive control can be implemented to handle the vehicle speed planning over a limited horizon as in (Kirches et al., 2013). Solving a optimal control problem of a dynamic non-linear system such as a diesel engine model can be performed using direct collocation, as in for example (Asprion et al., 2014), or multiple shooting as in (Nezhadali and Eriksson, 2016). Direct collocation and multiple shooting are two of several numerical optimal control methods, an overview of numerical optimal control methods is performed in (Asprion, 2013). Solving the optimal control problem of accelerating a turbocharged CI truck while taking gear changes and into consideration is a non-linear mixed integer problem, such a problem can be studied using the method described in Paper IV.

This chapter describes briefly how an optimal control problem is constructed, how the gear shift modeling is performed and how to construct the initial guess when solving the problem of accelerating a truck. The tools used to solve the optimal control problem are briefly discussed. The impact of the clutch model introduced in Paper V is discussed more in depth to highlight the comparison to the clutch representation in Paper IV.

3.1 Optimal Control Problem

A general optimal control problem can be summarized as:

$$\min_{x(t),u(t)} \quad J(x(t),u(t)) \tag{3.1}$$

$$s.t. \quad \dot{x}(t) = f(x(t),u(t)) \tag{3.2}$$

$$x_{\min} \leq x(t) \leq x_{\max} \tag{3.3}$$

$$u_{\min} \leq u(t) \leq u_{\max} \tag{3.4}$$

$$t_{\text{end}}^{\min} \leq t_{\text{end}} \leq t_{\text{end}}^{\max} \tag{3.5}$$

$$h(x(t),u(t)) \leq 0 \tag{3.6}$$

$$g(x(t),u(t)) = 0 \tag{3.7}$$

where (3.1) is the objective function which the optimal control procedure should minimize the value of, with respect to the states $x(t)$, controls $u(t)$, while fulfilling the state dynamics (3.2). In real world systems, the controls and states are often limited due to the physical nature of the systems, or by design. The limitations has to be included in the description of the problem, to ensure that the solution is valid on the real system. The state and control limits can be clarified as in (3.3) and (3.4). The end time of the phase can also be upper and lower bounded (3.5). Inequality (3.6) and equality constraints (3.7) can also be implemented in the optimal control problem to limit for example internal variables in the system model. If multiple phases of the problem are required, when for example the description of the state dynamics (3.2) are changing, multiple of these problem formulations can be connected in series, which is described in Paper IV.

3.2 Methodology

The development methodology used in the thesis is depicted in Figure 3.1. A model of the real system is needed to enable calculations of the optimal control. To develop models, data from the real system is often needed to parameterize and validate the model fit, see for example Paper II and Paper III where a CI engine model is developed. The optimal control problem can be formulated when the objective function and constraints of the model are defined. To initiate the optimal control solver, an initial guess is formulated, using an initial set of control signals. The optimal control problem is solved using a suitable solver. The solution to the problem can be used to, for example, develop closed loop control strategies to mimic the behavior of the optimal control. The goal with the optimal control problem can be savings in some form depending on the selected objective function.

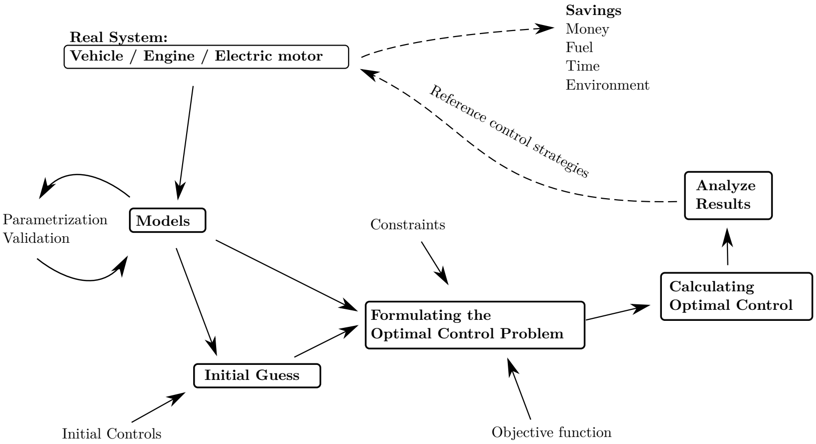


Figure 3.1: Methodology used for defining and solving optimal control problems. Solid lines represents the work flow in the thesis, dashed lines represents possible future use of the methods and results.

Defining the Scenario

The scenario of accelerating a truck from slow rolling speed to a predefined target speed on flat road is selected as the case of investigation. Performing an acceleration is a dynamic event where the load points of the CI engine, or electric motors if considering an HEV, are changing as vehicle speed increase. Finding the control strategies to perform the most fuel, or energy efficient accelerations, is a challenging task, especially when investigating complicated systems with several control signals, such as the hybrid electric vehicle in Paper VI.

Modeling a Gear Shift

A gear shift can be modeled with the four phases:

- **In-gear phase** - Main phase for vehicle propulsion using a fixed selected gear.
- **Clutch opening phase** - Decoupling of the engine and gearbox by using the clutch is assumed to happen instantly, this phase is therefore omitted from the problem setup. The instant clutch opening is performed when entering the Synchronization phase.
- **Synchronization phase** - The synchronization phase has a restricted minimum time, which simulates the time it takes for an automated manual transmission to apply the new gear. The engine and gearbox side of the clutch are allowed to rotate freely during this phase.
- **Clutch closing phase** - When the new gear is engaged mechanically (which is simulated with the restricted minimum time in the synchronization phase), the clutch is closed to synchronize the engine and gearbox rotational speeds.

The number of phases needed to describe a gear shift depends on the model purpose, for example (Glielmo et al., 2006) use five phases to describe a gear shift for an automated manual transmission. The chosen strategy of how to model a gear shift in Paper IV is to divide each gear in the three phases, in-gear phase, synchronization phase and clutch closing phase. The clutch opening phase in the list above is omitted and included in the synchronization phase. At the end of the in-gear phase the clutch is assumed to instantly disengage, the change of gear is mathematically performed by introducing the new gear ratio when the problem enters the synchronization phase. The three different phases are described by different system dynamics. The activation of the clutch results in different rotational speed of the engine and gearbox, which require an extra state to be described properly. The benefit of the proposed method in Paper IV is the loss of propulsion torque when the engine and gearbox are disconnected, as well as the energy transfer between the engine and driveline when closing the clutch.

Engine Model

The CI engine model used in this work is developed in Paper II and Paper III. The model is a mean value engine model which captures the dynamics of the turbocharger rotational speed and the pressure in the intake and exhaust manifolds. The model control signals are fuel injection, wastegate position, and throttle position. The throttle is used for emission abatement, it is excluded in the analysis of fuel optimal accelerations since energy savings is the scope of the research. The exclusion of the throttle reduces the model with one state as well as one control signal. The engine model restrictions are implemented as inequality constraints (3.6) in the problem formulation to ensure valid engine operation, these constraints include for example the air-fuel ratio limit as well as compressor surge limit.

Clutch Model

When a gear shift is performed, the engine and driveline are separated by the clutch to enable the change of gear. When the clutch is active the rotational speed of the engine and gearbox are independent of each other. When an upshift is made, the rotational speed of the engine has to be decreased to meet the rotational speed of the next gear. The decrease of engine speed can be achieved by for example reducing the fuel injection to reduce the engine torque, or by closing the clutch to lower the engine speed with mechanical friction. When the clutch closes, the friction between the clutch discs results in a torque transfer between the engine and gearbox. When the clutch slips, the energy which is not transferred between the engine and the driveline is heating the clutch components as well as being dissipated (Sun et al., 2013). The amount of thermal energy dissipation, as well as the clutch temperature and change of characteristics due to the temperature change is a research area of its own, see for example (Myklebust and Eriksson, 2012). The transferred torque in the clutch is assumed to be controlled in Paper IV and V. The reason for controlling the clutch torque directly is the complexity of the clutch models, as well as the increased number of states which would then be needed to describe such system, see for example (Dolcini et al., 2005) where a non-linear model is used to validate the results from a developed optimal control strategy for clutch engagement. By controlling the clutch torque, the synchronization of the engine and gearbox rotational speeds can be achieved. The transferred clutch torque model differs between Paper IV and V. In Paper IV the clutch torque is considered to be linear in relation to the control signal output. In Paper V the addition is made where the clutch is restricted to move only in the closing direction, the clutch maximum closing speed is restricted, and the clutch torque characteristics has a non-linear behavior in relation to the control signal (the characteristics are displayed in Figure 8.2 in Paper V). The updated clutch model results in a smoother increase of the clutch torque when applying the control signal, but the closing time is longer. An example clutch maneuver during a gear shift is shown in Figure 3.2, where the two torque characteristics are shown in relation to time.

Initial Guess

By simulating the system model with a made-up control strategy, an initial guess for the optimal control problem solver can be constructed. The ini-

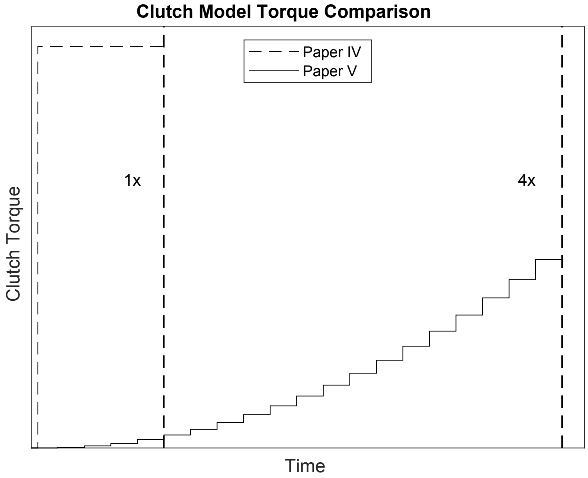


Figure 3.2: The clutch slip time is 4x longer for the example case with restricted clutch closing speed.

tial guess is developed by deciding the gear shift sequence which should be investigated, dividing each gear into three phases. The initial guess control strategy is decided by the user, the controls as well as the duration of each phase has to be defined. The complete series of gears is simulated to construct the acceleration mission. The gear shift is assumed to happen instantly when the synchronization phase is started. Complete synchronization after each gear shift is necessarily not achieved when simulating the initial guess. The incomplete synchronization is handled by the optimal control procedure due to terminal constraints in the clutch slip phase which requires complete synchronization. The state dynamics used when simulating the initial guess are the same models as used in the problem setup for the optimal control. To reduce the risk of violating any model constraints in the simulated initial guess, controls to perform a very slow acceleration are simulated. Knowledge of the system boundaries and expected control signals comes in handy when developing the initial guess, since a better model knowledge might results in a quicker initial guess setup. The results from the simulation is used as the initial guess to the optimal control solver.

Constraints on Trip Time

When solving the fuel optimal accelerations in Paper IV-VI, a large number is selected as the upper bound on time for each in-gear phase to ensure that the utilization of each gear is left free for the solver to decide. The benefit with having a non-restricted upper bound on time of each phase, is the freedom for the solver of the optimal control problem to select the least (for example) fuel consuming gear shift strategy without being limited by time. A very slow acceleration is not necessarily the most fuel optimal one due to the friction in the engine as well as the aerodynamic drag and road resistances acting on the vehicle.

Software Tools

Three main software tools has been used when solving the optimal control problems in the thesis, these are briefly described here.

YOP

An important enabler for formulating and solving the optimal control problems presented in this thesis has been the use of software tools for optimal control. YOP (Leek, 2016), is used to construct the optimal control problem setup in Matlab. The benefit with YOP is the ease of constructing the problem formulation. By defining the system dynamics in continuous time, defining state and control bounds, and implementing the constraints, the optimal control problem can be formulated. The methods direct collocation and multiple shooting are implemented in YOP. Direct collocation is used to discretize and integrate the system dynamics and controls when solving the optimal control problems in Paper IV-VI

CasADi

CasADi (Andersson et al., 2019) is used by YOP to assemble the non-linear program (NLP). CasADi is a symbolic framework, which is very useful for setting up the NLP and performing efficient algebraic operations. The assembled NLP is solved using IPOPT.

IPOPT

The NLP is solved using IPOPT (Wächter and Biegler, 2006), which is an interior-point optimizer developed to solve large scale non-linear optimal control problems.

Example: Objective Function Formulations

The selection of objective function will influence the result from the optimal control solver. The objective function is the main measure which the optimal control method use to decide the optimal controls. As an example, the following objective function can be implemented in each phase in an optimal control problem of accelerating a truck:

$$\min_{x(t),u(t)} J = \min_{x(t),u(t)} \int_{t_{\text{initial}}}^{t_{\text{final}}} \beta + (1 - \beta)\, \dot{m}_{\text{fuel}}\, dt \tag{3.8}$$

where $0 \leq \beta \leq 1$. By tuning β, the goal for the optimization will be to either minimize time if $\beta = 1$, consumed fuel mass during the mission if $\beta = 0$, or a trade-off between time and consumed fuel mass if $0 < \beta < 1$. As an example, solutions to the optimal control problem for three different values of β, using the methodology in Paper IV and the clutch model described in Paper V, are displayed in Figure 3.3, where a single up-shift is performed. The time of the gear change (which is seen as the rapid change of engine speed), engine speed utilization range, and fuel-air ratio (depicted as $1/\lambda$ in the figure) are all different depending on the selected β value. The example show the relation between acceleration time and consumed fuel mass, as well as the change of the gear utilization strategy. The high β-value solution utilize the first gear for a longer time than the other two solutions, which results in a faster acceleration due to the higher power output. The mid-β solution is a ”in-between” option of saving fuel or time. The utilized engine speed range is lower for the solution which consumes the least amount of fuel, a lower engine speed results in lower engine friction losses, and consequently lower power output. All three solutions are smoke-limited at the beginning of each gear, this is due to the rotational speed of the turbocharger not being high enough to fulfill the needed intake manifold pressure for a ”non-restricted” injection of fuel.

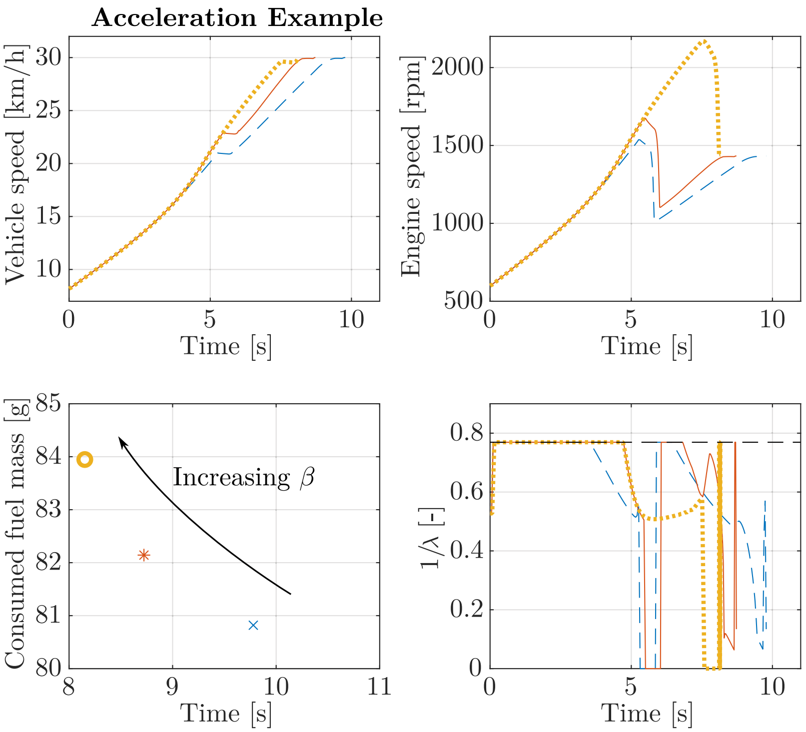


Figure 3.3: The effect of β on acceleration time, fuel consumption, engine rotational speed, vehicle speed and the fuel-air ratio as well as its upper restriction to reduce the risk of emitting black smoke. The optimal accelerations are obtained by using the problem setup developed in Paper IV and the clutch model described in Paper V.

Bibliography

Andersson, Joel A E, Joris Gillis, Greg Horn, James B Rawlings, and Moritz Diehl (2019). "CasADi – A software framework for nonlinear optimization and optimal control." In: *Mathematical Programming Computation* 11.1, pp. 1–36. DOI: `10.1007/s12532-018-0139-4`.

Asprion, Jonas (2013). "Optimal control of diesel engines: modelling, numerical methods, and applications." PhD thesis. ETH Zurich. DOI: `https://doi.org/10.3929/ethz-a-010050065`.

Asprion, Jonas, Oscar Chinellato, and Lino Guzzella (2014). "Optimal control of diesel engines: Numerical methods, applications, and experimental validation." In: *Mathematical Problems in Engineering* 2014.

Chen, Syuan-Yi, Chien-Hsun Wu, Yi-Hsuan Hung, and Cheng-Ta Chung (2018). "Optimal strategies of energy management integrated with transmission control for a hybrid electric vehicle using dynamic particle swarm optimization." In: *Energy* 160, pp. 154–170. ISSN: 0360-5442. DOI: `https://doi.org/10.1016/j.energy.2018.06.023`.

Dolcini, Pietro, Carlos Canudas de Wit, and Hubert Béchart (2005). "IMPROVED OPTIMAL CONTROL OF DRY CLUTCH ENGAGEMENT." In: *IFAC Proceedings Volumes* 38.1. 16th IFAC World Congress, pp. 25–30. ISSN: 1474-6670. DOI: `https://doi.org/10.3182/20050703-6-CZ-1902.01892`.

Duhr, Pol, Grigorios Christodoulou, Camillo Balerna, Mauro Salazar, Alberto Cerofolini, and Christopher H. Onder (2021). "Time-optimal gearshift and energy management strategies for a hybrid electric race car." In: *Applied*

Energy 282, p. 115980. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2020.115980`.

Ekberg, Kristoffer and Lars Eriksson (2017). "Improving Fuel Economy and Acceleration by Electric Turbocharger Control for Heavy Duty Long Haulage." In: *IFAC-PapersOnLine* 50.1. 20th IFAC World Congress, pp. 11052–11057. ISSN: 2405-8963. DOI: `https://doi.org/10.1016/j.ifacol.2017.08.2486`.

— (2019). "Development and Analysis of Optimal Control Strategy for Gear Changing Patterns During Acceleration." In: *IFAC-PapersOnLine* 52.5. 9th IFAC Symposium on Advances in Automotive Control AAC 2019, pp. 316–321. ISSN: 2405-8963. DOI: `https://doi.org/10.1016/j.ifacol.2019.09.051`.

— (2020). "A Comparison of Optimal Gear Shifts for Stiff and Flexible Driveshafts During Accelerations." In: *IFAC-PapersOnLine* 53.2. 21th IFAC World Congress, pp. 14413–14419. ISSN: 2405-8963. DOI: `https://doi.org/10.1016/j.ifacol.2020.12.1410`.

Ekberg, Kristoffer, Lars Eriksson, and Christofer Sundström (2021). "Electrification of a Heavy-Duty CI Truck—Comparison of Electric Turbocharger and Crank Shaft Motor." In: *Energies* 14.5. Licenced under CC-BY. ISSN: 1996-1073. DOI: `10.3390/en14051402`.

Ekberg, Kristoffer, Viktor Leek, and Lars Eriksson (Dec. 2018). "Modeling and Validation of an Open-Source Mean Value Heavy-Duty Diesel Engine Model." In: *Simulation Notes Europe* 28(4), pp. 197–204. ISSN: 2306-0271. DOI: `https://doi.org/10.11128/sne.28.tn.10451`.

— (2019). "Optimal Control of Wastegate Throttle and Fuel Injection for a Heavy-Duty Turbocharged Diesel Engine During Tip-In." In: *SIMS 2017, Reykjavik, Island*. DOI: `http://dx.doi.org/10.3384/ecp17138317`.

Elbert, Philipp, Tobias Nüesch, Andreas Ritter, Nikolce Murgovski, and Lino Guzzella (2014). "Engine On/Off Control for the Energy Management of a Serial Hybrid Electric Bus via Convex Optimization." In: *IEEE Transactions on Vehicular Technology* 63.8, pp. 3549–3559. DOI: `10.1109/TVT.2014.2304137`.

Fröjd, Karin, Cathleen Perlman, Adina Tunér, and Fabian Mauss (2011). "1D engine modeling with detailed reaction kinetics." In: *Swedish-Finnish Flames Days*, pp. 26–27.

Glielmo, L., L. Iannelli, V. Vacca, and F. Vasca (2006). "Gearshift control for automated manual transmissions." In: *IEEE/ASME Transactions on Mechatronics* 11.1, pp. 17–26. DOI: `10.1109/TMECH.2005.863369`.

Haj-Fraj, A. and F. Pfeiffer (2001). "Optimal control of gear shift operations in automatic transmissions." In: *Journal of the Franklin Institute* 338.2. Dynamics and Control of Structural and Mechanical Systems, pp. 371–390. ISSN: 0016-0032. DOI: `https://doi.org/10.1016/S0016-0032(00)00091-0`.

He, Hongwen, Jieli Zhang, and Gaopeng Li (2016). "Model Predictive Control for Energy Management of a Plug-in Hybrid Electric Bus." In: *Energy Procedia* 88. CUE 2015 - Applied Energy Symposium and Summit 2015: Low carbon cities and urban energy systems, pp. 901–907. ISSN: 1876-6102. DOI: `https://doi.org/10.1016/j.egypro.2016.06.109`.

Heywood, John B. (2018). *Internal Combustion Engine Fundamentals, second edition.* United States: McGraw-Hill Education.

Hoef, Sebastian van de, Karl H. Johansson, and Dimos V. Dimarogonas (2015). "Fuel-optimal centralized coordination of truck platooning based on shortest paths." In: *2015 American Control Conference (ACC)*, pp. 3740–3745. DOI: `10.1109/ACC.2015.7171911`.

Hopmann, Ulrich and Marcelo C. Algrain (June 2003). "Diesel Engine Electric Turbo Compound Technology." In: *SAE Technical Paper*. SAE International. DOI: `10.4271/2003-01-2294`. URL: `http://dx.doi.org/10.4271/2003-01-2294`.

Jain, A., T. Nueesch, C. Naegele, P. M. Lassus, and C. H. Onder (2016). "Modeling and Control of a Hybrid Electric Vehicle With an Electrically Assisted Turbocharger." In: *IEEE Transactions on Vehicular Technology* 65.6, pp. 4344–4358. DOI: `10.1109/TVT.2016.2533585`.

Jensen, J-P, AF Kristensen, Spencer C Sorenson, N Houbak, and E Hendricks (1991). *Mean value modeling of a small turbocharged diesel engine.* Tech. rep. SAE Technical Paper.

Johannesson, Lars, Nikolce Murgovski, Erik Jonasson, Jonas Hellgren, and Bo Egardt (2015). "Predictive energy management of hybrid long-haul trucks." In: *Control Engineering Practice* 41, pp. 83–97. ISSN: 0967-0661. DOI: `https://doi.org/10.1016/j.conengprac.2015.04.014`.

Kamal, M. A. S., M. Mukai, J. Murata, and T. Kawabe (2011). "Ecological Vehicle Control on Roads With Up-Down Slopes." In: *IEEE Transactions on Intelligent Transportation Systems* 12.3, pp. 783–794. DOI: `10.1109/TITS.2011.2112648`.

— (2013). "Model Predictive Control of Vehicles on Urban Roads for Improved Fuel Economy." In: *IEEE Transactions on Control Systems Technology* 21.3, pp. 831–841. DOI: `10.1109/TCST.2012.2198478`.

Kim, Namwook, Sukwon Cha, and Huei Peng (2011). "Optimal Control of Hybrid Electric Vehicles Based on Pontryagin's Minimum Principle." In: *IEEE Transactions on Control Systems Technology* 19.5, pp. 1279–1287. DOI: `10.1109/TCST.2010.2061232`.

Kirches, Christian, Hans Georg Bock, Johannes P. Schlöder, and Sebastian Sager (2013). "Mixed-integer NMPC for predictive cruise control of heavy-duty trucks." In: *2013 European Control Conference (ECC)*, pp. 4118–4123. DOI: `10.23919/ECC.2013.6669210`.

Leek, Viktor (2016). "An Optimal Control Toolbox for MATLAB Based on CasADi." MA thesis. Linköping University, Vehicular Systems, p. 56.

Li, Guoxiu, Wanlin Zhao, Lili Tian, Chunlong Xu, and Min Wang (2020). *Simulation Study on the Process of Pressure Wave Propagation for High-Pressure Common Rail Diesel Engine.* Tech. rep. SAE Technical Paper.

Lin, Chan-Chiao, Huei Peng, J.W. Grizzle, and Jun-Mo Kang (2003). "Power management strategy for a parallel hybrid electric truck." In: *IEEE Transactions on Control Systems Technology* 11.6, pp. 839–849. DOI: `10.1109/TCST.2003.815606`.

Machlev, R., N. Zargari, N.R. Chowdhury, J. Belikov, and Y. Levron (2020). "A review of optimal control methods for energy storage systems - energy trading, energy balancing and electric vehicles." In: *Journal of Energy Storage* 32, p. 101787. ISSN: 2352-152X. DOI: `https://doi.org/10.1016/j.est.2020.101787`.

Myklebust, Andreas and Lars Eriksson (2012). "Torque model with fast and slow temperature dynamics of a slipping dry clutch." In: *2012 IEEE Vehicle Power and Propulsion Conference*, pp. 851–856. DOI: `10.1109/VPPC.2012.6422728`.

Nezhadali, Vaheed and Lars Eriksson (2016). "Optimal control of engine controlled gearshift for a diesel-electric powertrain with backlash." In: *IFAC PAPERSONLINE :* vol. 49. IFAC PAPERSONLINE. IFAC, pp. 762–768. DOI: `10.1016/j.ifacol.2016.08.111`.

Nezhadali, Vaheed, Martin Sivertsson, and Lars Eriksson (2014). "Turbocharger Dynamics Influence on Optimal Control of Diesel Engine Powered Systems." In: *SAE International Journal of Engines* 7.1, pp. 6–13. DOI: `10.4271/2014-01-0290`.

Ngo, Viet Dac, Theo Hofman, Maarten Steinbuch, and Alex Serrarens (2014). "Gear shift map design methodology for automotive transmissions." In: *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 228.1, pp. 50–72. DOI: `10.1177/0954407013506698`.

Ngo, Viet Dac, Jose A. Colin Navarrete, Theo Hofman, Maarten Steinbuch, and Alex Serrarens (2013). "Optimal gear shift strategies for fuel economy and driveability." In: *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 227.10, pp. 1398–1413. DOI: `10.1177/0954407013491240`.

Nüesch, Tobias, Philipp Elbert, Michael Flankl, Christopher Onder, and Lino Guzzella (2014). "Convex Optimization for the Energy Management of Hybrid Electric Vehicles Considering Engine Start and Gearshift Costs." In: *Energies* 7.2, pp. 834–856. ISSN: 1996-1073. DOI: `10.3390/en7020834`.

Payri, F., P. Olmeda, J. Martín, and A. García (2011). "A complete 0D thermodynamic predictive model for direct injection diesel engines." In: *Applied Energy* 88.12, pp. 4632–4641. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2011.06.005`.

Pérez, Laura V., Guillermo R. Bossio, Diego Moitre, and Guillermo O. García (2006). "Optimization of power management in an hybrid electric vehicle using dynamic programming.” In: *Mathematics and Computers in Simulation* 73.1. Applied and Computational Mathematics - Selected Papers of the Fifth PanAmerican Workshop - June 21-25, 2004, Tegucigalpa, Honduras, pp. 244–254. ISSN: 0378-4754. DOI: `https://doi.org/10.1016/j.matcom.2006.06.016`.

Rakopoulos, C.D., A.M. Dimaratos, and E.G.´ Giakoumis (2011). “Experimental Study of Transient Nitric Oxide, Smoke, and Combustion Noise Emissions during Acceleration of an Automotive Turbocharged Diesel Engine.” In: *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 225.2, pp. 260–279. DOI: `10.1243/09544070JAUTO1493`.

Rakopoulos, C.D. and E.G. Giakoumis (2009). *Diesel engine transient operation: principles of operation and simulation analysis.* Springer Science & Business Media.

Salmasi, Farzad Rajaei (2007). “Control Strategies for Hybrid Electric Vehicles: Evolution, Classification, Comparison, and Future Trends.” In: *IEEE Transactions on Vehicular Technology* 56.5, pp. 2393–2404. DOI: `10.1109/TVT.2007.899933`.

Serrao, Lorenzo and Giorgio Rizzoni (July 2008). “Optimal control of power split for a hybrid electric refuse vehicle.” In: pp. 4498–4503. DOI: `10.1109/ACC.2008.4587204`.

Škugor, Branimir, Joško Deur, and Vladimir Ivanović (Apr. 2016). “Dynamic Programming-Based Design of Shift Scheduling Map Taking into Account Clutch Energy Losses During Shift Transients.” In: *SAE 2016 World Congress and Exhibition.* SAE International. DOI: `https://doi.org/10.4271/2016-01-1116`.

Sun, Shaohua, Yulong Lei, Yao Fu, Cheng Yang, and ShunBo Li (Apr. 2013). “Analysis of Thermal Load for Dry Clutch under the Frequent Launching Condition.” In: *SAE 2013 World Congress & Exhibition.* SAE International. DOI: `https://doi.org/10.4271/2013-01-0814`.

Sundström, Olle, Lino Guzzella, and Patrik Soltic (2008). “Optimal Hybridization in Two Parallel Hybrid Electric Vehicles using Dynamic Programming.” In: *IFAC Proceedings Volumes* 41.2. 17th IFAC World Congress, pp. 4642–4647. ISSN: 1474-6670. DOI: `https://doi.org/10.3182/20080706-5-KR-1001.00781`.

Tavčar, G, F Bizjan, and T Katrašnik (2011). “Methods for improving transient response of diesel engines – influences of different electrically assisted turbocharging topologies.” In: *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 225.9, pp. 1167–1185. DOI: `10.1177/0954407011414461`.

Trucks What are Trucks Fact Sheet (Accessed: 2021-04-12). `https://www.acea.be/publications/article/factsheet-trucks`.

Uebel, Stephan, Nikolce Murgovski, Conny Tempelhahn, and Bernard Bäker (2018). “Optimal Energy Management and Velocity Control of Hybrid

Electric Vehicles." In: *IEEE Transactions on Vehicular Technology* 67.1, pp. 327–337. DOI: `10.1109/TVT.2017.2727680`.

Wächter, A. and L.T. Biegler (2006). "On the implementation of a primal-dual interior point filter line search algorithm for large-scale nonlinear programming." In: *Mathematical Programming, 106(1):25–57.* preprint at `http://www.optimization-online.org/DB_HTML/2004/03/836.html`.

Wahlström, Johan and Lars Eriksson (2011). "Modelling diesel engines with a variable-geometry turbocharger and exhaust gas recirculation by optimization of model parameters for capturing non-linear system dynamics." In: *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 225.7, pp. 960–986.

Winward, E, J Rutledge, J Carter, A Costall, R Stobart, D Zhao, and Z Yang (2016). "Performance testing of an electrically assisted turbocharger on a heavy duty diesel engine." In: *Proceedings of the 12th international conference on turbochargers and turbocharging.*

Xiao, B., Erik Hellström, T. Kelly, Timothy Stolzenfeld, D. Bell, M. Jankovic, Julia H. Buckland, and John Rollinger (2018). "Dynamic Pressure Ratio Allocation for Electric Supercharger and Turbocharger Coordination." In: *2018 Annual American Control Conference (ACC)*, pp. 2455–2460.

Zhao, Dezong, Richard Stobart, Guangyu Dong, and Edward Winward (2015). "Real-Time Energy Management for Diesel Heavy Duty Hybrid Electric Vehicles." In: *IEEE Transactions on Control Systems Technology* 23.3, pp. 829–841. DOI: `10.1109/TCST.2014.2343939`.

Zhao, Dezong, Richard Stobart, and Byron Mason (2019a). "Optimising the energy efficiency and transient response of diesel engines through an electric turbocharger." In: *2019 American Control Conference (ACC).* IEEE, pp. 298–303.

— (2019b). "Real-time energy management of the electric turbocharger based on explicit model predictive control." In: *IEEE Transactions on Industrial Electronics* 67.4, pp. 3126–3137.

Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-175469

Dissertations
Division of Vehicular Systems
Department of Electrical Engineering
Linköping University

No. 1 Magnus Pettersson, *Driveline Modeling and Control*, 1997.

No. 2 Lars Eriksson, *Spark Advance Modeling and Control*, 1999.

No. 3 Mattias Nyberg, *Model Based Fault Diagnosis: Methods, Theory, and Automotive Engine Applications*, 1999.

No. 4 Erik Frisk, *Residual Generation for Fault Diagnosis*, 2001.

No. 5 Per Andersson, *Air Charge Estimation in Turbocharged Spark Ignition Engines*, 2005.

No. 6 Mattias Krysander, *Design and Analysis of Diagnosis Systems Using Structural Methods*, 2006.

No. 7 Jonas Biteus, *Fault Isolation in Distributed Embedded Systems*, 2007.

No. 8 Ylva Nilsson, *Modelling for Fuel Optimal Control of a Variable Compression Engine*, 2007.

No. 9 Markus Klein, *Single-Zone Cylinder Pressure Modeling and Estimation for Heat Release Analysis of SI Engines*, 2007.

No. 10 Anders Fröberg, *Efficient Simulation and Optimal Control for Vehicle Propulsion*, 2008.

No. 11 Per Öberg, *A DAE Formulation for Multi-Zone Thermodynamic Models and its Application to CVCP Engines*, 2009.

No. 12 Johan Wahlström, *Control of EGR and VGT for Emission Control and Pumping Work Minimization in Diesel Engines*, 2009.

No. 13 Anna Pernestål, *Probabilistic Fault Diagnosis with Automotive Applications*, 2009.

No. 14 Erik Hellström, *Look-ahead Control of Heavy Vehicles*, 2010.

No. 15 Erik Höckerdal, *Model Error Compensation in ODE and DAE Estimators with Automotive Engine Applications*, 2011.

No. 16 Carl Svärd, *Methods for Automated Design of Fault Detection and Isolation Systems with Automotive Applications*, 2012.

No. 17 Oskar Leufvén, *Modeling for Control of Centrifugal Compressors*, 2013.

No. 18 Christofer Sundström, *Model Based Vehicle Level Diagnosis for Hybrid Electric Vehicles*, 2014.

No. 19 Andreas Thomasson, *Modeling and control of actuators and co-surge in turbocharged engines*, 2014.

No. 20 Emil Larsson, *Model Based Diagnosis and Supervision of Industrial Gas Turbines*, 2014.

No. 21 Andreas Myklebust, *Dry Clutch Modeling, Estimation, and Control*, 2014.

No. 22 Tomas Nilsson, *Optimal Engine Operation in a Multi-Mode CVT Wheel Loader*, 2015.

No. 23 Daniel Jung, *Diagnosability Performance Analysis of Models and Fault Detectors*, 2015.

No. 24 Martin Sivertsson, *Optimal Control of Electrified Powertrains*, 2015.

No. 25 Peter Nyberg, *Evaluation, Generation, and Transformation of Driving Cycles*, 2015.

No. 26 Kristoffer Lundahl, *Models and Critical Maneuvers for Road Vehicles*, 2016.

No. 27 Vaheed Nezhadali, *Modeling and Optimal Control of Heavy-duty Powertrains*, 2016.

No. 28 Xavier Llamas, *Modeling and Control of EGR on Marine Two-Stroke Diesel Engines*, 2018.

No. 29 Sergii Voronov, *Machine Learning for Predictive Maintenance*, 2020.

No. 30 Victor Fors, *Autonomous Vehicle Maneuvering at the Limit of friction*, 2020.

No. 31 Fatemeh Mohseni, *Decentralized Optimal Control for Multiple Autonomous Vehicles in Traffic Scenarios*, 2021.

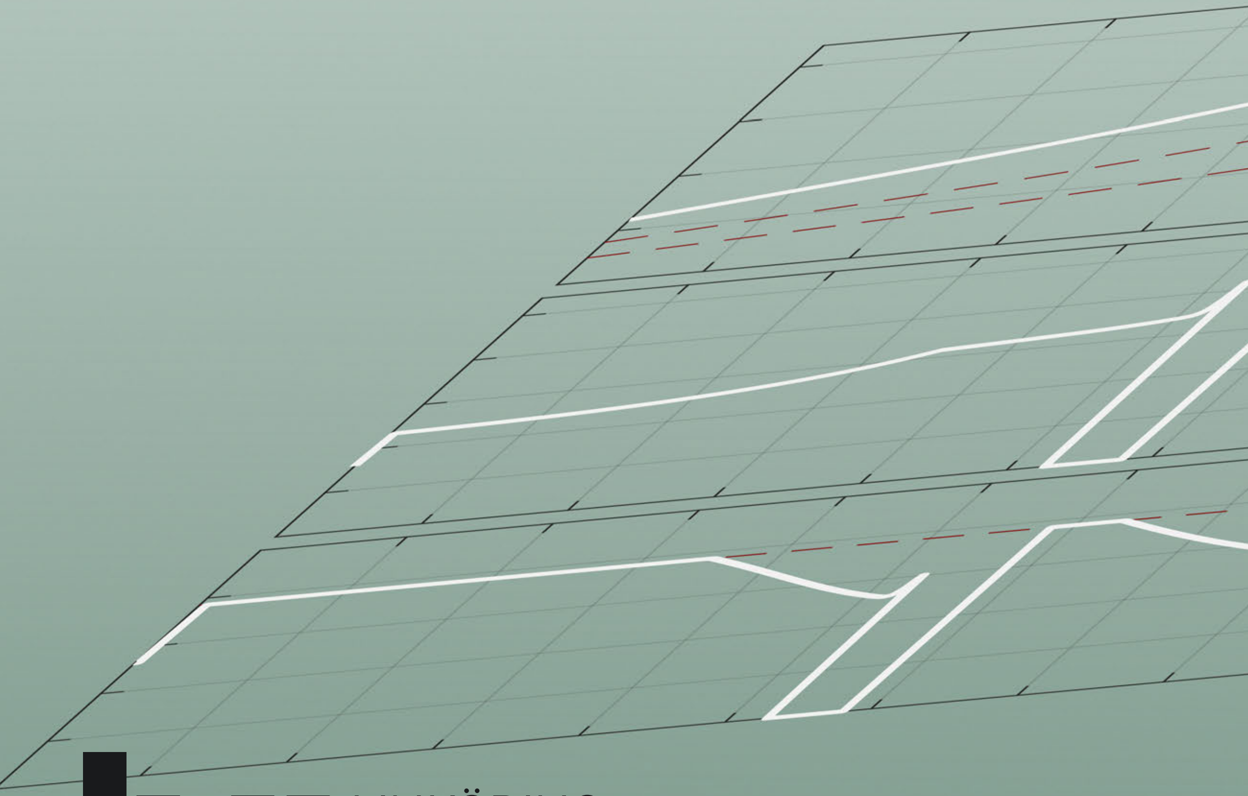
No. 32 Mahdi Morsali, *Trajectory Planning for an Autonomous Vehicle in Multi-Vehicle Traffic Scenarios*, 2021.

FACULTY OF SCIENCE AND ENGINEERING

Linköping Studies in Science and Technology
Dissertations No. 2145, 2021
Department of Electrical Engineering

Linköping University
SE-581 83 Linköping, Sweden

www.liu.se



LINKÖPING
UNIVERSITY