Analysis and Simulation of Fuel Consumption and Energy Throughput on a Parallel Diesel-Electric Hybrid Powertrain

Master of Science Thesis

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Abstract

The aim of this master thesis is to study the energy throughput and fuel consumption of a parallel diesel-electric hybrid vehicle. This has been done by utilising a software model of such a vehicle to simulate the results of alterations of variables believed to affect energy throughput and fuel consumption as well as other parameters of interest. These parameters are selected depending on their relative importance when it comes to hybrid technology and the power sources of such a vehicle; the diesel engine, the electric machine and also the battery.

For obvious reasons it is important to focus on reducing fuel consumption but in an overall perspective it is also vital to understand how parameters related to the battery state can be affected and how the battery lifetime can be increased. Thus the key parameters in this study are energy throughput, fuel consumption, battery state of health (SOH) and state of charge (SOC), powertrain modes and drivability. Further, analyses of total used energy, costs and CO_2 emissions have been made. The alterations have been made to dataset variables mainly affecting the torque distribution between the diesel engine and the electric machine and to other variables believed to affect the selected key parameters.

The results show that for most variable alterations a weighting needs to be done as to the relative importance of reducing either the energy throughput or the fuel consumption since these most often change in opposite directions as the altered variables are simulated. The results can nevertheless be used as indications for how certain vehicle data alterations affect the above mentioned key parameters. It is shown that the alterations lead to reduced energy throughput more often than they lead to reductions in fuel consumption. One variable alteration however leads to decrease of both these two main key parameters, namely reduced maximum torque from the electric machine (EM). When it comes to sustainable development and CO_2 emissions it can be concluded that the main source of emissions are from the diesel fuel consumption.

Keywords: Heavy-duty vehicles, hybrid powertrain, diesel-electric hybrid, diesel engine, electric machine (EM), energy storage system (ESS), lithium-ion battery, model simulation, SIL, energy throughput, fuel consumption, SOH, SOC, drivability, CO_2 emissions, torque distribution, SOC target, SOC window, EM torque curve, battery charge/discharge power, start SOC, sustainable development.

Acknowledgements

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The project has both been incredibly interesting and very rewarding. I have learnt much; not only about hybrids, simulations and other thesis related topics but also about myself and about working with the one colleague whom I will forever work very closely with: me.

There are always people to thank when project like this is accomplished. Without their help and support the results would not had not been achieved.

First and foremost would like to express my deepest thanks to my excellent supervisor at Volvo Powertrain Corporation, Kristoffer Rydquist. Without his support, encouragement and expert knowledge in the area the project would not have been possible to complete. I would also very much like to thank my examiner and supervisor Torbjörn Thiringer and my supervisor Jens Groot without whom I would have had too many unanswered questions to finish the project in a satisfactory way. Also, the author of this thesis owes great thanks to the ever so knowledgeable Martin Engström at Volvo Powertrain Corporation who somehow always knows the answer and always takes time to help me in spite of actually having no time.

I would also like to thank my co-workers and managers at Volvo Powertrain Corporation. Not only did I experience a wonderful summer here but I also got to come back and finish my Master of Science degree. Everyone I have been in contact with at the department of Control Systems are just great and have given me support and also much needed diversions from the thesis work.

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All in all, everyone that has been involved in this project has been great company and has given me a high job satisfaction.

I would last but certainly not least like to thank Martin, my family and my friends for never-ending support during the project progress and for being my largest and most important source of well-needed diversion from the master thesis work. They are always there to remind me of what really is important in life.

Thank you all,

Johanna
Göteborg, July, 2009

Preface

About Volvo Powertrain Corporation

Volvo Powertrain Corporation is a business unit in the Volvo Group and serves to coordinate driveline operations thereby being responsible for developing and manufacturing heavy diesel engines, gearbox and driveshafts. Volvo Powertrain Corporation is also responsible for supplying the Volvo Group with drivelines for medium-heavy applications.

The Volvo Group has common engine platforms that fulfil the latest environmental requirements, a more focused research and development program, more efficient production and a more focused supplier structure.

Volvo Powertrain Corporation supports seven business areas within the Volvo Group; Volvo Trucks, Renault Trucks, Nissan Diesel, Mack Trucks Volvo Construction Equipment, Volvo Buses and Volvo Penta. The business unit has operations in Sweden, France, and North and South America employing approximately 8,000 people in total.

The Control Systems department works with development and design of electronic control systems for Volvo's heavy and medium duty diesel engines and gearboxes. Control Systems produces the software engineering for all in-house engine projects, AMT (automated manual transmission) gearbox and complete hybrid system control including start-up, driving modes, torque distribution, engine braking, brake blending etc. with the exception of the code for electric motor control, the battery control which is done by external companies but specified by Volvo. The department consists of about 150 people in eleven groups.

The master thesis purpose concerns issues involved in the P3610 project which supplies diesel-electric hybrid powertrains to Volvo 3P (Renault Trucks, Volvo Trucks and Mack Trucks) and Volvo Bus. Two internal Volvo Powertrain departments are involved in the project; Hybrid and Control Systems.

Environmental work at the Volvo Group

The president and CEO of the Volvo Group, Leif Johansson, has very ambitious visions concerning the environmental responsibility and actions of the corporation. The concept of sustainable development is divided into three focal areas; environmental, economic, and social responsibility. The motivation for the environmental work lies among others in the adverse effects of increased global warming and the diminishing amount of available oil. Both important since more than 98 % of the energy use in the transport sector comes from fossil fuels; 97 % comes from crude oil. (The Volvo Group, 2008).

The aspiration of the company is to be a driving force for environmental work within the transportation industry which is to be accomplished by for instance taking on a product life cycle perspective and actively researching new technology with less environmental impact. (AB Volvo, Environmental policy, 2004).

The most important environmental principles include resource efficiency, the precautionary principle and studies of environmental performance. A lot of research is focused on developing alternative drivelines and fuels, for instance the diesel-electric hybrid and dimethyl ether (DME) powered vehicles (Volvo Truck Corporation, 2007c). In 2007 Volvo Trucks introduced the world's first CO_2-neutral automotive factory in Ghent, Belgium. The factory is supplied with energy from three wind turbines, biomass and bio-oil heating plants, and solar panels in order to decrease the emissions of CO_2 and to reduce energy consumption (Volvo Truck Corporation, 2007a).

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Nomenclature and abbreviations

Abbreviations

BMU	Battery Management Unit
C@SS	Charge at Stand Still
CBC	Charge Balance Control
DLL	Dynamic-Link Library
DME	Dimethyl Ether
DOD	Depth of Discharge
EBS	Engine Brake System
(E)ECU	(Electronic) Engine Control Unit
EGR	Exhaust Gas Recirculation
EM	Electric Machine
EMS	Engine Management System
ESS	Energy Storage System
ET	Energy Throughput
EV	Electric Vehicle
FAME	Fatty Acid Methyl Ester (the main component of biodiesel)
FC	Fuel Consumption
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
HIL	Hardware in the Loop
HPCU	Hybrid Powertrain Control Unit
ICE	Internal Combustion Engine
LCA/I	Life Cycle Assessment (Analysis)/Inventory
NO_X	Mono-Nitrogen Oxides (NO and NO_2)
OCV	Open Circuit Voltage
PM_{10}	Particulate Matter (with aero dynamical diameter smaller than 10 μm)
PMU	Powertrain Management Unit
SCR	Selective Catalytic Reduction
SD	Sustainable Development

SEK	Swedish Krona
SIL	Software in the Loop
SOC	State of Charge
TD	Torque Distribution
TECU	Transmission Electronic Control Unit
USD	US Dollars

Symbols

A	Ampere (unit of current)
A_f	Frontal area of the vehicle
Ah	Ampere-hour (unit of electric charge)
c_d	Aerodynamic drag coefficient
c_r	Rolling friction coefficient
d_{cycle}	Distance of cycle
DOD_OCV_{index}.	Index over the depth of discharge
$E_{charge,\ diesel}$	Diesel energy used to charge the battery
$E_{diesel,}$	Energy content of diesel fuel
$E_{discharge,\ battery}$	Energy output from the battery for vehicle propulsion
$Emissions_{battery}$	Total emissions associated with the battery use
$Emissions_{diesel}$	Total emissions associated with the diesel fuel use
$E_{prop,\ diesel}$	Energy for vehicle propulsion provided by diesel fuel
$E_{SOC,diff}$	Energy difference in SOC from start to end of cycle
ET	Energy throughput
FC	Fuel consumption
$FC_{SOCComp}$	Fuel consumption (SOC compensated)
g	Gravitational acceleration
h	Height above sea level
J	Joule (unit of energy)
K	Kelvin (unit of temperature)
kWh	Kilowatt-hour
$LCE_{battery}$	Life cycle emissions associated with the battery
LCE_{diesel}	Life cycle emissions associated with diesel fuel

m_v	Vehicle mass
Nm	Newton-metre (unit of torque)
n_{series}	Number of battery cells in series
$n_{strings}$	Number of battery series
P_{aux}	Auxiliary power
P_{bat},	Battery power
P_{fric}	Friction power
PI	Proportional-integral
P_{kin}	Kinetic power
P_{pot}	Potential power
P_{prop}	Propulsion power
rpm	Revolutions per minute (unit of frequency of rotation)
SOC_{end}	End SOC
SOC_{start}	Start SOC
$SOH_{AS,end}$	End SOH for the simulation with altered settings
SOH_{change}	Change of SOH during a cycle
$SOH_{org,end}$	Start SOH for the simulation with original dataset settings
$SOH_{org,start}$	End SOH for the simulation with original dataset settings
t_{cycle}	Time of cycle
$U\_OCV_{discharge}$	Discharge voltage of the battery
v	Vehicle speed
V	Volt (unit of voltage)
v_{act}	Actual vehicle speed
v_{avg}	Average vehicle speed
v_{dem}	Demanded vehicle speed
v_{diff}	Difference in vehicle speed
W	Watt (unit of power)
$\eta_{diesel/el}$,	Efficiency of conversion from diesel energy to electricity
η_{ICE}	Diesel engine efficiency
µ	micro (prefix equal to 10^{-6})
ρ_{air}	Air density

1 Introduction

One of the biggest problems the world is facing today is the steadily deteriorating climate, which, to a great extent, is a result of our large and increasing usage of energy (WWF, 2005). Today, most energy is produced from non-renewable energy sources such as oil, coal and other fossil fuels as well as from nuclear power (Ekonomifakta, 2006). During the past few years, research on alternative fuels and energy sources has increased dramatically and scientists all over the world make great efforts to develop more sustainable solutions and technologies (Oberhand, 2001).

There are several different reasons to replace and reduce the use of fossil fuels with alternative and more sustainable energy sources and increased energy efficiency. The most acute reason is to decrease anthropogenic climate impact, primarily by reduction of greenhouse gas (GHG) emissions (Miller, 2007). Diesel fuel exhaust contains not only such gases, but also particulate matter that is listed as carcinogenic (EPA, 2005). In fact, heavy-duty diesel vehicles emitted almost 15 % of the entire U.S. inventory of particles smaller than 10 μm in diameter (PM_{10}) (Oberhand, 2001) There are also economic driving forces behind the development of alternative fuels; decreasing amounts of available oil leads to increasing oil prices and even to oil crises[1]. This is of additional importance for companies within the transportation industry; in the case of the Volvo Group, fuel can be accounted for about one third of the customers' costs (AB Volvo, Sustainability report, 2008).

There are many alternatives to conventional fossil fuels such as biodiesel, hydrogen and fuels cells, and various hybrid vehicles (Oberhand, 2001). This study focuses on heavy-duty diesel-electric hybrids, which have been on the market since the mid-nineteen hundreds (Roan, 1978). Today they are seen as an important step on the way towards a sustainable society (Oberhand, 2001).

Some of the most important components in such a hybrid vehicle are the diesel engine, the electric machine (EM), and the energy storage system (ESS). In such a vehicle propulsion energy does not only come from diesel fuel but also of energy stored in the ESS, which most often is a battery. The consumption of diesel fuel is often lowered since it may be replaced by the provision of for example regenerated brake energy (Guzzella and Sciarretta, 2007). The battery does not have an eternal life length but will need to be exchanged as the capacity has decreased below a certain level. Some parameters affecting the battery state of health (SOH) include among others the energy use, both through charging and discharging (Piller, Perrin, and Jossen, 2001) and the battery temperature (Coleman, Lee, and Hurley, 2006).

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[1] An example of an oil crisis what occurred between in 1979 when the oil price rose from $13.62 per barrel in January to $24.20 in November that same year. It was considered to be the results of a conflict between the oil producing countries Iran and Iraq (Smil, 2005).

1.1 Previous work

Hybrid and diesel-electric hybrid vehicles and their performance have been extensively studied and their functionality has been a prominent field of research for many years. The main attraction of such vehicles, and thus also the focal point of most studies, is the possibilities to decrease fuel consumption and the size of the internal combustion engine and to reduce emissions as compared to conventional vehicles (see appendix A for examples of such studies).

When it comes to simulation and modelling of such hybrid vehicles and components more recent work include optimising strategies with the purpose of creating more efficient control strategies. Such studies have previously mainly been focused on fuel consumption reduction. (Banks, 1999; Zhu et al. 2004; Johannesson and Egardt, 2008; Sambeat, 2008).

1.2 Problem description

The purpose of the master thesis is to study the performance of a diesel-electric hybrid powertrain. The focus lies on studying energy throughput of the energy storage system (ESS) i.e. the battery and how this is related to fuel consumption of the internal combustion engine (ICE). The main purpose of such a study is to improve the usage of both the ICE and the ESS.

For obvious reasons it is important to focus on reducing fuel consumption but in an overall perspective it is also vital to understand how the health of the ESS varies with different parameters such as the so called state of charge (SOC) window and energy throughput. The health and the life length of the ESS are directly related to each other, which is why it is important to study all parameters affecting ESS health. Previously a lot of hybrid torque distribution model simulation and analysis have been based on optimal regulation of diesel engine operation (see section 1.1). Missing however is inclusion of battery health and life time studies. In this thesis the focus is thus extended to also include battery life length and battery energy throughput as key parameters in addition to the more traditional fuel consumption studies.

1.2.1 Purpose of the project

The objective of the project is essentially to study how different parameters affect the ESS and diesel engine usage in the form of energy consumption. A more detailed description of the problem formulation is given in the list below:

- Simulation of a defined parallel diesel-electric hybrid vehicle powertrain, specifically aimed at studying the usage of an ESS in the form of a battery and the associated energy throughput during a number of typical driving cycles. The aim of the simulation is to study how the energy throughput varies with the fuel consumption of the diesel engine.
- Extended study of energy throughput and fuel consumption e.g. an optimisation.

- Suggest and perform different analyses of the energy throughput and diesel fuel consumption that can be used to compare the resulting energy throughput with the fuel consumed in the ICE. The analyses should include comparisons of e.g. the environmental impact of the different energy sources.

Further the simulation model results should be validated and some form of robustness test of the same should be performed.

1.3 Method and analysis

The study and analysis of vehicles and vehicular components can be performed in many different ways. Measurements can for example be taken in an actual vehicle, on the engine in rig, by hardware in the loop (HIL)[2] simulation or by software in the loop (SIL)[3] simulation. The various levels of analysis provide different advantages and disadvantages. Studies done on levels further from real situations may loose in accuracy and reliability but may instead gain in that it is often less time consuming and simpler when it comes to implementing and testing changes (Choi and Kwon, 1999).

The analysis in this project will be performed on software models and results will be obtained from SIL simulations. To test the robustness of the simulation outputs the simulations will be repeated using another duty cycle.

The project is divided into four different steps, first the modelling stage, followed by the simulations and then an evaluation or analysis step where all simulation results will be evaluated and analysed. Several analyses of the results will be made in which the environmental impacts, the costs and total energy use of the battery usage will be related to that of the fuel consumption in the diesel engine. During these steps continuous verification of the results will be performed.

The modelling step includes an initial overview of a hybrid powertrain model. Modelling an entire vehicle is a complex task, why a previously created model of such a powertrain will be used as a basis for further improvements. When it comes to modelling and analysing vehicle control systems there are several suitable software environments such as Matlab/Simulink® (MathWorks™, 2009) and Dymola (Dynasim AB, 2009). The existing model has been created in the Matlab/Simulink® environment and therefore all modelling and programming in the project will be done using the same program. The model of the different vehicular components is designed in Simulink®[4]; a graphical user interface which is provided with input parameters via

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[2] HIL simulations are performed using the actual electronic control unit hardware. All other vehicle hardware such as e.g. the engine are replaced by computer models (Hanselmann, 1996).

[3] SIL is used for software-based simulations were hardware is replaced by software (Choi and Kwon, 1999).

[4] Simulink® is a MathWorks™ product; a graphical user interface used for simulation of non-linear dynamic systems. The interface enables an easy and comprehensive overview of complex systems (Pärt-Enander and Sjöberg, 2003).

the Matlab®[5] workspace. This makes simulations faster and facilitates for changes in variables. The main task in this step is to prepare this model so that it is can function as a proper tool for the intended purpose.

In the simulation step several parameters are varied systematically to enable analysis of energy throughput and the relation between ET and fuel consumption in the diesel engine. The parameters to be varied include SOC window, torque from the electric motor, and battery charge/discharge power.

The analysis step includes interpretation and presentation of the simulation outcomes and the calculated key parameters. The analysis further includes comparisons of energy throughput and fuel consumption calculated using different approaches such as calculations of CO_2 emissions and cost analysis models.

1.4 Limitations

The analysis is based on simulation results. The simulations are performed using a vehicle model, which in many respects is simplified as compared to reality. The modelling of parameters such as environmental factors, driver behaviour and conditions may differ considerably from actual conditions. Effects of implementation i.e. validation in vehicle is not either included in the scope of this study.

The focus of this study will be factors affecting battery health and fuel consumption. Other factors such as vehicle emissions will not be included even though the results from such studies would be very interesting. This is due to the limitations of SIL simulations; not all parameters can be modelled and simulated. The actual effects of parameters such as emissions will not be studied.

The analysis of CO_2 emissions will be performed based on a reference battery and engine closely resembling those in the simulation model but not identical. The result of this step will not be specific for the studied vehicle but will be used as an indication of the relative environmental impacts. Performing a comprehensive life cycle assessment (LCA) of the actual vehicle would be extremely time consuming and could easily be the subject of a master thesis on its own. Therefore the performed environmental analysis will not be extensive.

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[5] Matlab® is a Mathworks™ product which Simulink is a part of. It is a software environment as well as a programming language created to facilitate calculations and numeric computations, data analysis and algoritm development (Pärt-Enander and Sjöberg, 2003)).

2 Hybrid powertrains

In this section the vehicle type that is the focus of this master thesis will be described regarding for instance components of interest, key terms, and future prospects of the vehicle technology. The vehicle in study is a parallel diesel-electric hybrid and consequently the chapter is focused on this technology. First, a brief history of the vehicle is presented.

Electric vehicles are not a new invention, at least not in the history of automotive vehicles. In fact the very first electrically powered vehicle was introduced sometime between 1832 and 1839 by the Scotsman Robert Anderson (Vancouver Electric Vehicle Association, 2007). The hybrid concept for vehicle propulsion is not as old as the electric counterpart but still it has quite an extensive history to date. Examples of vehicles using various hybrid techniques for propulsion have been in service almost since the mid twentieth century (Roan, 1978). A hybrid vehicle is defined as a vehicle with two or more power sources that can be used for vehicle propulsion. There are many different combinations of such power sources, for instance hydraulic hybrids were a hydraulic circuit assists a conventional drive train and the most common combination today when it comes to heavy duty vehicles; a diesel engine and a battery (Bennett, 2009). Further, there are also different ways to construct a hybrid, for instance the two power sources could either be placed parallel to each other or in series (Guzzella and Sciarretta, 2007). This is called the *vehicle configuration* and will be described in this chapter.

Hybrids have many advantages over conventional vehicles. Apart from the fact that using an extra power source with alternative fuels instead of fossil fuels reduces emissions contributing to global warming, hybrids reduce the fossil fuel consumption. Further, the different power sources can, for some hybrid configurations, be used simultaneously or consecutively. This enables such effective propulsion as possible. In a diesel-electric hybrid the power can be delivered in three different ways; either from the battery alone, or by torque blending where power is delivered from both the diesel engine and the battery, or purely mechanical with power delivered solely from the diesel engine (Bennett, 2009). For instance, electric energy has the advantage of zero emission locally, which can be combined with the high energy and power density of an internal combustion engine (Guzzella and Sciarretta, 2007). In addition to this they can utilize brake energy and they often contribute to lower vehicular noise levels (Volvo Truck Corporation, 2007b). In a conventional truck most of the auxiliary equipment such as the servo pump, air compressor and power outlets, is driven by the diesel engine. But, in a diesel-electric hybrid vehicle where the supply of electricity is ample small electric motors can instead be used in these purposes. This gives more freedom in the physical placing of the components and also they only consume energy at the moments when they are used[6]. Figure 2.1 shows the torque that can be provided at different speeds depending on which combination of the power sources that is used.

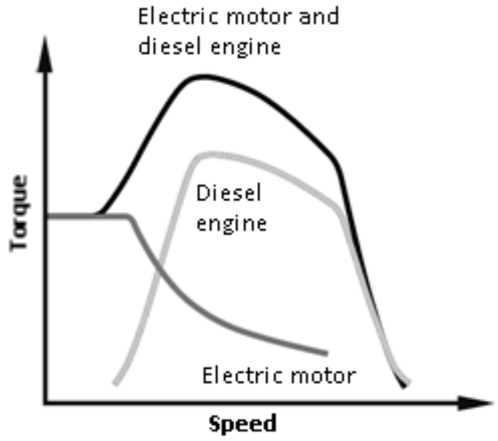

Figure 2.1 Torque demand versus vehicle speed for different power sources. The figure shows how the total torque is increased as the two power sources are combined. The electric motor operates better than the diesel engine at low revolutions while the diesel engine operates best at high revolutions. These properties are can be combined to provide efficient vehicle propulsion. Adapted from Volvo Truck Corporation (Volvo Truck Corporation, 2007b)

One disadvantage of hybrid vehicles is that they are often between 10-30% heavier than conventional vehicles, which may cancel out the fuel consumption savings from the hybrid drive. However, the advantages of hybrid propulsion most often outweigh the drawbacks. (Guzzella and Sciarretta, 2007).

In a hybrid vehicle, the life length of the battery is strongly affected by total energy passing through the battery (Woodbank Communications Ltd, 2005b). The term 'energy throughput' is in this project used to describe how much energy that has been stored and released during a number of typical driving cycles. A more detailed description of the term is given below (see section 2.2.1).

The Volvo Group has, over the last years, developed concept hybrids in the form of refuse trucks, distribution trucks, and city buses operated by diesel-electric hybrid powertrains. The internal combustion engine can be powered either by conventional diesel or by bio-renewable diesel. The business idea mainly revolves around the fuel saving potentials, which are stated to be able to amount to as much as 35% depending on the specific application (Volvo Truck Corporation, 2007c).

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[6] Personal communication with Kristoffer Rydquist, software function developer at Volvo Powertrain Corporation, the 13th of March, 2009.

2.1 Powertrain components

The term *powertrain* is in this thesis used as a collective name for all components that transfer torque to the wheels of a vehicle. The term chiefly comprises the engine, the transmission, the clutch and the driveshaft. Hybrid specific powertrain components here include the electric machine and energy storage system. These components will be described in further detail in this section.

2.1.1 Internal combustion engine

An engine is defined as a machine that converts one form of energy to another for example heat energy to mechanical work. There are many different types of engines, for instance the steam engine and the most common in contemporary society; the internal combustion engine (ICE). The latter is named by the fact that the fuel is combusted inside of a cylinder. Different fuels such as gasoline or biogas can power the engine (Bennett, 2009).

The diesel engine in a hybrid diesel-electric vehicle is normally downsized as compared to the engine of a conventional vehicle. This is mainly because the additional power source provides extra propulsion energy but also to make room for the other power source and associated components. In a hybrid the diesel engine can also be used to charge the battery unit (Guzzella and Sciarretta, 2007).

When it comes to environmental impact, diesel fuel combustion is, as previously mentioned, associated with various harmful emissions such as GHGs, carcinogenic particles, and NO_x (Oberhand, 2001). This will be discussed further in section 2.7.

2.1.2 Electric machine

In a diesel-electric hybrid an electric machine (EM) is used as the secondary power source. The EM can consist of both a motor that provides torque for vehicle propulsion and a generator that charges the battery. There are many different types of motors, e.g. DC motors, induction AC motors and permanent-magnet synchronous motors. The energy supply to the generator can come from either the ICE or from recuperated brake energy. Thus, the EM can operate in three different ways; either by converting electric power from the battery to mechanical power for vehicle propulsion, by converting mechanical power from the diesel engine to electric power recharging the battery, or by recuperating mechanical brake power to generate electric power recharging the battery (Guzzella and Sciarretta, 2007).

Depending on the vehicle configuration (which will be described in more detail below) the motor and generator can either be combined in a single machine as in the case of a so-called parallel hybrid or, for a series hybrid two separate machines are needed (Guzzella and Sciarretta, 2007).

2.1.3 Energy storage system

One of the most important components of a hybrid-electric vehicle (HEV) is the energy storage system (ESS), which is used as the second power source in addition to the ICE. There are many different kinds of energy storage systems such as the supercapacitor[7]. The most common type however is the battery, which will therefore be the focus of this section. In section 2.2 below, all terms involving the ESS that are used in this thesis will be described.

A battery stores chemical energy that can be transformed into electrical energy. The technology has been used as an ESS for hundreds of years, perhaps even longer. In 1800 the Italian physicist Alessandro Volta discovered how to harness electric energy, but some historians believe that this technology may already have been known millennia ago. Archaeological findings dating between 248 BC and 226 AD made near Baghdad, Iraq indicate that ceramic vessels containing cylinders made of copper, lead and iron may have been used as galvanic cells[8] (von Handorf, 2002). Modern battery history did though begin with the voltaic pile; the first electric battery invented by Volta (Nationalencyklopedin, 2009), and today there are many different types of batteries such as nickel-cadmium, lithium-ion, and lead-acid batteries to mention some (Guzzella and Sciarretta, 2007).

Modern batteries consist of several cells. The assembled cells together make up a so-called *battery pack*. Each cell contains three main components; two electrodes (a positive – the anode and a negative – the cathode) and a medium for ion transport called an electrolyte. The metals and compounds that make up the electrodes and the electrolytes are in principal what distinguish the different battery types. For example; the anode of a nickel-cadmium battery consists of cadmium, the cathode of nickel (II) hydroxide ($Ni(OH)_2$) and with potassium hydroxide (KOH) as the electrolyte. The potential difference between the electrodes is transformed into energy in the presence of the electrolyte (ibid, 2007).

Another distinction can be made between primary batteries that are non-rechargeable, and secondary that are rechargeable. In vehicles secondary batteries are used. (ibid, 2007).

The efficiency of a battery can be defined as a ratio between the total delivered energy from a fully charged battery and the energy needed for full recharge of the same. This is sometimes referred to as the global efficiency and depends on whether it is the current or the power that is kept constant during the test (ibid, 2007).

Lithium-ion batteries power the HEV in this study. A lithium-ion battery pack consists of individual cells. The anode consists of carbon (usually graphite), the cathode of lithium oxide and the electrolyte is a lithium salt solution such as a cobalt oxide (e.g. LiCO2). The batteries have

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[7] A supercapacitor stores energy in the electric field created in an electrochemical double layer (Guzzella and Sciarretta, 2007).

[8] One theory is that the batteries were used to plate coins with e.g. gold (von Handorf, 2002).

very high so-called specific power, which is a great feature for energy storage systems to be applied in a parallel hybrid. The cell voltage is typically 3.6 V. However, they are quite expensive and have a relatively short life cycle at present, which means that further development is required. The improvement potential mainly lies in finding superior alternatives for the cathode and the electrolyte (ibid, 2007).

Yet there are still some differences in the requested properties of batteries intended to be used in purely electric vehicles (EV) and hybrid electric vehicles (HEV). The former need the battery to store enough energy to provide all propulsion torque to the vehicle; they need to store around 35 kWh. To keep the battery weight at an acceptable level EVs need batteries with maximised energy density[9] or specific energy[10]. Lithium-ion batteries produced as so-called high-energy batteries are generally very expensive, more than ten times as expensive as the batteries needed for the HEVs where the battery only works to support the ICE. In this case the desired quality is rather maximized power density or specific power. Such batteries are correspondingly called high-power batteries (Gaines and Cuenca, 2000).

The cost for a high-energy lithium-ion cell (as part of a complete vehicle) was about 250 USD/cell (100 Ah) in the year 2000. The corresponding price for a high-power cell was then about 20 USD/cell (10 Ah) (ibid, 2000).

2.2 Hybrid terminology

In this section some terms for the hybrid and the ESS important in this study will be introduced and described briefly, these are here called key parameters. Many are directly related to the aim of the thesis. These are all thus presented in the results.

2.2.1 Energy throughput

The term energy throughput is, as previously mentioned, used to describe how much energy [kW] that has been stored and released in the battery when the vehicle is in operation. The average energy throughput [kWh/h] is a measure of the energy that in average is stored and released during a duty cycle. The throughput describes the total usage of the EM. Further the value is correlated to the battery lifetime and is therefore here of paramount interest (Woodbank Communications Ltd, 2005a). One aim of the project is to study the relation between energy throughput and fuel consumption of a diesel-electric hybrid vehicle.

Several other terms also affect the energy throughput; these include battery charge/discharge power[11], the target value for battery charge (SOC), the minimum level of battery discharge and

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[9] Battery *energy density* is the energy that can be stored per battery volume (Gaines and Cuenca, 2000).

[10] Battery *specific energy* is the energy that can be stored per battery mass (Gaines and Cuenca, 2000).

[11] Personal communication with Jens Groot, PhD student at Chalmers University of Technology and R&D engineer at Volvo Technology, the 9th of April, 2009.

the maximum level of charge[12], the size of the EM and also of the battery[13], the current and power, and the internal temperature of the battery[14].

2.2.2 State of health

The state of health (SOH) of a battery is a parameter that provides information on the general condition or the remaining lifetime and performance of a battery. It is a measure of the residual full charge capacity of the battery as compared to the nominal capacity. The battery SOH is mainly affected by continuous charging and discharging causing the chemical composition of the battery to degrade. The SOH is an important factor in the process of battery management to optimise the battery use (Coleman, Lee, and Hurley, 2006). The lifetime of a battery is often defined as the number of charge/discharge cycles a battery can complete before the capacity falls below 80 % of the initial capacity (Woodbank Communications Ltd, 2005a).

There are many different ways of determining the SOH of a battery. One method is to use electrical pulses to measure the change in the so-called terminal voltage of the battery, another is to compare the maximum available capacity with the rated or nominal capacity of a battery (Coleman, Lee, and Hurley, 2006). Still, it is hard to monitor SOH, which is why predictive methods have been developed. These rely on generic models of the battery to determine various parameters such as the ability to store charge and the resistance of the battery, which are used to predict the SOH (Bhangu et al., 2005).

2.2.3 State of charge

The state of charge (SOC) of a battery is, simply put, the remaining battery capacity or, the remaining battery charge at a certain point in time. As a battery is charged or discharged the SOC changes accordingly. SOC is denoted as a percentage, ranging from zero to a fully charged battery at 100%. One definition states that the full SOC has been reached when the battery current has been constant for 2 hours[15] (Piller, Perrin, and Jossen, 2001).

The SOC is an important parameter for many reasons. The SOC, being a measure of the battery charge level related to the maximum discharge capacity, is vital to know at each point in time in order to avoid overcharging or a too deep discharging of the battery. The battery capacity, to complicate matters further, is not necessarily constant over the battery lifetime. It may vary due

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[12] Personal communication with Hanna Bryngelsson, design engineer at Volvo Powertrain Corporation, the 13th of May, 2009.

[13] Personal communication with Torbjörn Thiringer, professor at the division of electric power engineering, Chalmers University of Technology, the 17th of March 2009.

[14] Personal communication with Kristoffer Rydquist and Martin Engström, software function developers at Volvo Powertrain Corporation, the 16th of March, 2009.

[15] At constant voltage and temperature.

to various issues such as for example corrosion of the conductors etc. (ibid, 2001). This is termed the battery state of health (SOH), which was described above.

There are many different ways of determining battery SOC; depending on the battery type and application certain methods may be more suitable than others. One of the most common ways is to count the ampere-hours. This method is based on the fact that the current is directly related to the charge and discharge of the battery. The actual SOC is calculated from a start SOC and the integral of the current[16] . This method can only be used for simulation outcomes or for EVs; not for HEVs (ibid, 2001).

2.2.4 Powertrain modes

The powertrain mode is an important parameter when it comes to how much torque that should be distributed from each power generator. There are often many different such modes, when it comes to parallel hybrids the most important are the so called *ICE only* mode, *electric only* mode, *hybrid* mode, and the *charge at standstill* (C@SS) mode. The first three are easy to grasp the meaning of; either the ICE alone provides the torque, the EM alone or both together as in the third mode. The C@SS mode is launched when the battery is at very low SOC levels. This mode means that the ICE will not shut down when the vehicle stop but keep running to charge the battery (Engström, 2007).

2.2.5 Current, power and voltage

Current and power are two terms that are very important when it comes to battery performance. Electric current [A] is simply charged particles, i.e. electrons, in motion. The more freely the charged particles can move around in a material the better the conductivity of the same. The current can vary with time. Power [W] can be described as the work that is done during a certain time as current flows with a certain resistance. The resistance is constant for a certain material[17], which means that the power varies with the current. (Borgström, Jönsson and Kullberg, 1996). The power of a battery could vary during a discharge may vary and decrease the more the discharge continues (Woodbank Communications Ltd, 2005b)

Voltage [V] is an electrical potential difference; the amount of work that a unit charge flowing from one point to another can perform. Battery voltage varies with the current, temperature etc. (Borgström, Jönsson and Kullberg, 1996). When it comes to the voltage of a battery it is determined by the chemical reactions, battery polarisation and other such parameters. Further, it may vary depending on when it is measured. Since voltage varies with current, one way of measuring voltage is when the battery is disconnected i.e. not supplied with any current. The nominal voltage of a battery is a sum of the voltage in each cell and is calculated during some

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[16] Certain factors such as losses of supplied current need also be taken into account when performing such calculations.

[17] At a certain temperature.

form of equilibrium conditions. The nominal voltage of a battery is generally a typical value close to the voltage during actual use. This is a common way to describe battery capacity and a customary way to classify different battery types. The voltage during for instance charging and discharging may vary (Woodbank Communications Ltd, 2005b).

2.3 Vehicle control units

Several different electronic control units (ECU)[18], containing controller software, are used to manage the powertrain. The control units are provided with data input from for instance hardware sensors carrying information on e.g. engine temperature, vehicle speed, or the driver's pedal position. This data (which can be analogue or digital) is processed by the control unit software that uses the input to make calculations and eventually decisions on for instance cooling fan speed and gear selection, which are then broadcasted as outputs. The outputs are sent forth as input to other control units or ultimately converted into action by e.g. switching units (Bennett, 2009). The main control units are listed below together with a brief description.

- **Engine Electronic Control Unit (EECU)**[19]. The EECU is usually physically located on, or near the engine where it governs most signals involved in engine operation. Most importantly the EECU manages the engine fuelling (Bennett, 2009).
- **Transmission Electronic Control Unit (TECU).** The TECU controls signals to the gearbox on for instance the gear switching strategy. In a parallel hybrid vehicle it also controls the clutch (see figure 2.2 below)[20].
- **Hybrid Powertrain Control Unit (HPCU)**. This control unit manages the hybrid abilities, functions controlling the previously mentioned electric only mode, monitors the SOC etc.[20]

Within the hardware of the control units lie, as previously mention software functions containing logical programming used to produce outputs controlling vehicle operation. These functions need the above-mentioned inputs, but they also require input in the form of numbers carrying important information on how the inputs should be interpreted to produce the proper output (Engström, 2007). These are called *dataset parameters* and are described in brief in section 2.6.1 below.

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[18] An ECU is also sometimes referred to as an electronic control module (ECM) (Bennett, 2009).

[19] An EECU is also commonly referred to as an engine management system (EMS) (Bennett, 2009).

[20] Personal communication with Kristoffer Rydquist, software function developer at Volvo Powertrain Corporation, June 2008.

2.4 Level of vehicle hybridisation

There are many different types of hybrid vehicles and concerning how much the vehicles make use of the hybrid functionality several different types can be distinguished, some of which are described briefly below:

- **Micro hybrids** are the lowest level of hybridisation. Here the EM and battery are used only during automatic vehicle start and stop. (IDAE, 2009).
- **Mild hybrids** are parallel hybrids where the main traction energy is supplied by the ICE and the EM, which is often very small, provides torque mainly during vehicle take-off and boost for example during uphill driving. Also, energy can be recuperated in a small scale. The battery is not required to have very high capacity either. The ICE can however be downsized as compared to the engine of a conventional vehicle (Guzzella and Sciarretta, 2007).
- **Full hybrids** are vehicles that can be driven longer distances using only the EM to provide torque i.e. utilizing both power sources to a greater extent than a mild hybrid. The EM generates electric energy mainly from the ICE but may also generate electricity from recuperated brake energy (IDAE, 2009).

The higher the level of hybridisation the smaller the ICE can be, implying that the fuel consumption decreases. The backside is that the EM needs to be correspondingly increased in size (Guzzella and Sciarretta, 2007).

2.5 Hybrid vehicle configurations

A hybrid vehicle makes use of more than one power source. This implies that more than one configuration of the various components is possible. A diesel-electric hybrid can be configured in three different ways; as parallel, series or combined hybrids. The parallel and series configurations will be described in further detail below. The combined hybrid is a cross between the previous two configurations; in closest resemblance to a parallel hybrid but with certain characteristics of a series hybrid. (Guzzella and Sciarretta, 2007).

2.5.1 Parallel hybrid configuration

In a parallel hybrid vehicle all power sources, i.e. both the diesel engine and the electric motor in the case of a diesel-electric hybrid, operate on the same driveshaft. This means that they can power the vehicle simultaneously or individually. This allows for an optimisation of the power distribution i.e. using the most optimal power source in a certain situation; either diesel engine power alone, electric power alone or both together. A normal situation for parallel hybrids is that the diesel engine is turned off when it normally would be idling e.g. during stops and also during vehicle take-off. During acceleration or when driving uphill the electric motor can assist the diesel engine (Guzzella and Sciarretta, 2007). An example of a parallel diesel-electric hybrid powertrain is shown in figure 2.2.

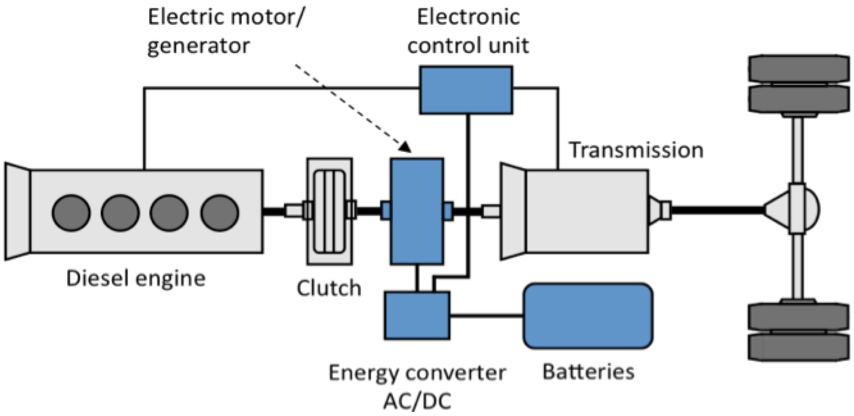

Figure 2.2 The main components of a parallel hybrid powertrain. The clutch and the EM, which can be used as both a motor and a generator, are the components specific for a parallel hybrid. Adapted from Volvo Truck Corporation (Volvo Truck Corporation, 2007b).

As can be seen in figure 2.2 above a parallel hybrid requires the presence of a clutch to disconnect the diesel engine from the driveshaft when using electric power only. The EM in this case can be used as both a motor to provide torque to the wheels and as a generator to charge the battery. This charging energy can be supplied either from the diesel engine or from recuperated brake energy. In spite of the fact that the overall weight of the powertrain is increased by the addition of the EM, clutch etc. the final result is a gain in system efficiency as compared to a conventional vehicle. The main reasons for this are the above mentioned power distribution optimisation, brake energy recuperation, diesel engine shutdown at e.g. idling, and also because of the fact that both the ICE and the EM can be downsized as compared to how big they would have needed to be had they powered the same vehicle by themselves (ibid, 2007).

2.5.2 Series hybrid configuration

A series hybrid is in principal an electric vehicle using an ICE to provide steady state auxiliary power to charge the ESS. The torque for vehicle propulsion is thus produced solely by the electric motor and the diesel engine is only used to provide energy to charge the battery. In this case the EM needs to be divided in two separate units; the generator converts power from the diesel engine into electricity to charge the battery whereas the motor is located further downstream of the motor converting the electric output from the battery into mechanical torque (Guzzella and Sciarretta, 2007). A schematic overview of a series diesel-electric hybrid powertrain is depicted in Figure 2.3.

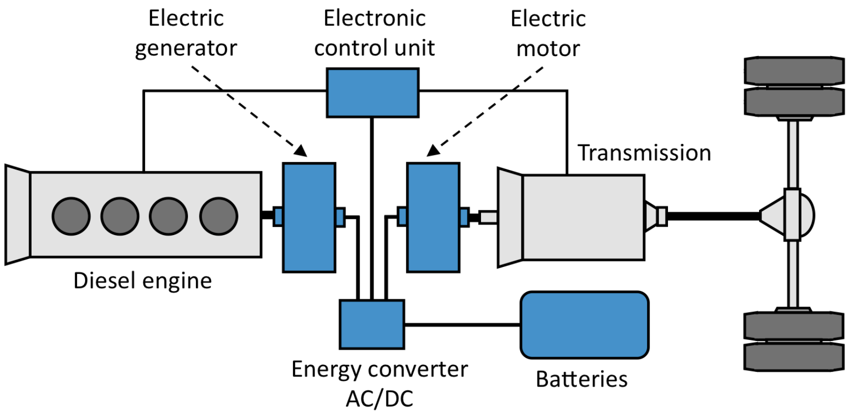

Figure 2.3 The main components of a series hybrid powertrain. The diesel engine serves only as an auxiliary power unit used to charge the battery. Adapted from Volvo Truck Corporation (Volvo Truck Corporation, 2007b).

Since energy can be regenerated from braking and stored in the battery the electric motor also needs to be able to function as a generator like the EM of the parallel configuration. Another advantage of the series hybrid as compared to a conventional vehicle is the fact that the engine can operate as efficiently as possible regarding emissions and fuel consumption since the energy provided from the ICE is not directly used to power vehicle propulsion. Compared to a parallel hybrid the series configuration has the advantage of not needing a clutch, but instead the disadvantage of needing two electric machines. Also, the electric motor needs to be full sized since it is the sole sources of traction power. The fuel efficiency of a series hybrid is generally worse than of a parallel although the emission levels from a series hybrid may be lower (Guzzella and Sciarretta, 2007).

2.6 Torque distribution

The torque distribution is controlled by a software function that can be said to be the heart of a parallel hybrid vehicle. It is the function that decides how the torque should be split between the different power sources and it is, for the Volvo hybrid, located in the EECU. In the case of a diesel-electric hybrid the function governs the distribution of torque between the diesel engine and the EM when the clutch (see Figure 2.2) is engaged (Engström, 2007).

The torque distribution function consists of many sub-functions, each carrying information on strategies regarding areas such as when to charge the battery, when to use battery power etc. One of them governs almost all parameters that are used to study energy throughput, fuel consumption and other key parameters in this study, namely the *charge balance control* (CBC) function (ibid, 2005). This sub-function will therefore be described in the following section.

2.6.1 Charge balance control

The main task for the CBC function is to control the charge balance of the ESS, i.e. the battery. The function evaluates several inputs regarding battery condition such as the SOC, the vehicle speed etc. and outputs restrictions regarding e.g. the EM speed and torque. The outputs are in turn interpreted by other sub-functions within the torque distribution function and ultimately affect the physical components to operate the vehicle in the required way (Engström, 2007).

The CBC function also requires knowledge of certain so-called *dataset parameters*, as previously mentioned. These parameters are basically thousands of constants used as inputs to all software functions governing the entire vehicle. Examples of such parameters are the maximally allowed discharge of the battery and the engine temperature at which the cooling fan needs to start. These dataset parameters are determined through extensive tests and optimisation processes but are relatively easy to modify and very accessible. For this reason the thesis analysis is focused on these. Most of the dataset parameters that are studied in this thesis reside within the CBC function (ibid, 2005).

2.7 Hybrids and sustainable development

Achieving a level of development that is sustainable is one of the greatest challenges facing humankind today. Most scientists agree that changing our ways of life and developing technology that is more in harmony with nature is an extremely urgent matter and even though some changes have already taken place the progress pace must still be increased and sustainability needs to be incorporated in our every decision. The concept *Sustainable Development* was first coined in the report *Our Common Future* published in 1987 by the *World Commission on Environment and Development*, the definition of the concept according to the commission is:

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*
> (World Commission on Environment and Development, 1987).

Conventional vehicles are in many ways not very sustainable. The exhaust contains not only greenhouse gases like for instance CO_2 and N_2O but also particulate matter that are toxic and some even listed as carcinogenic (EPA, 2005). Heavy-duty diesel vehicles emitted almost 15 % of the entire U.S. inventory of particles smaller than 10 µm in diameter (PM_{10}) (Oberhand, 2001). However, even though the aggregated emissions and fuel consumption of heavy-duty diesel vehicles carrying weighty loads may be very high, the emissions and fuel consumption per transported mass or volume is most often much lower than those of conventional passenger cars powered by gasoline.

Although it is a well known fact that combustion of fossil fuels in vehicles are a major source of environmentally harmful emissions, this is in fact only one of many sources of emissions when considering the entire life time of a vehicle. Recently, the focus when it comes to environmental issues has been shifted from small-scale studies towards a so-called life cycle perspective where all environmental aspects that arise during a products life are considered. This means that not only the environmental effects associated with the use phase of a product are taken into account but also the emissions from raw material extraction, refining, production, transportation etc. are included in the analysis, commonly referred to as a life cycle assessment (LCA) (Baumann and Tillman, 2004).

The following two sections will address the sustainability of the two vehicle components in focus when studying energy throughput and fuel consumption of a parallel diesel-electric hybrid powertrain; the battery and the diesel engine.

2.7.1 Batteries and sustainable development

As previously mentioned, batteries need to be replaced when the remaining capacity no longer is sufficient. Energy throughput is one of the most important parameters when it comes to battery life length. An increased use of a rechargeable battery, i.e. increased energy throughput means decreased lifetime.

A battery is made up of many different materials, in a life cycle perspective most of these are produced from raw materials that need to be extracted, processed and transported before they can be assembled into the final product. Some of the materials may be produced from recycled products, which reduces the need for virgin material but still these products need to be disassembled and the recycled material has to be extracted and purified (Råde, 2001). For many of these different phases in the life of a battery energy input is required. This energy may originate from many different sources; most commonly the energy comes from either fossil fuel or electricity. When calculating the total or life cycle environmental impact of a product all these energy sources as well as materials need to be included (Baumann and Tillman, 2004).

When it comes to batteries and battery usage there are many different factors that are important considering sustainability issues. Many batteries are made of raw materials that may be very energy demanding to extract and may generate much waste generating a large so-called ecological rucksack. They may also be scarce and sometimes even toxic. Lithium-ion batteries contain, besides lithium, for instance nickel or cobalt all for which the material stocks are constrained and exhaustible, a fact that will be even more evident as HEVs, EVs and other battery products gain market shares in the future (Råde, 2001). Considering battery usage the source of the energy that is stored in the battery may be included in a life cycle assessment (LCA). This source may be diesel fuel, regenerated brake energy or, in the case of a plug-in hybrid, electricity. In the latter case the electricity production mix needs to be considered, i.e. from which sources the power originates from. This may be anything from hydro- and wind power to nuclear power and coal power plants (Baumann and Tillman, 2004).

A life cycle inventory (LCI) of lithium-ion batteries indicate that the CO_2 emissions associated with production of such energy storage systems are about 75 kg CO_2/kWh or 20.8 kg CO_2/MJ (Ishihara et al. 2006).

2.7.2 Diesel engines and sustainable development

As in the case of the battery, several different aspects need to be accounted for when analysis the total environmental impact associated with diesel engine use during the entire lifetime of the product. For instance material and energy required for production of the engine hardware need to be accounted for as well as the diesel fuel emissions during combustion if such a life cycle scope is selected for analysis (Baumann and Tillman, 2004). In a hybrid vehicle the diesel engine can be downsized which often means lower environmental impact since the amount of raw material needed to produce the engine and also the emissions and fuel consumption may be reduced (Weststart, 2001).

As previously mentioned diesel fuel combustion is associated with emissions of greenhouse gases, NO_X, particulate matter and other environmentally harmful substances. However, internal combustion engines (ICEs) have a huge advantage in that they have been studied and developed over a long period of time and used on a large scale. The performance of transport vehicles is also often regulated in for example governmental legislation on emissions standards etc. (European Communities, 2009). Advanced diesel engines are also often associated with low emission levels. Advanced technological development has resulted in very fuel-efficient vehicles. Emission reduction techniques such as exhaust gas recirculation (EGR), selective catalytic reduction (SCR)[21] and particle filters as well as cleaner fuels with e.g. low sulphur content all contribute to reduce the environmental impact of ICEs. Advanced diesel engines have a high efficiency and low emissions. Further, most diesel engines can also be fuelled by biodiesel without having to make any modifications (Weststart, 2001).

Heavy-duty vehicles are most commonly powered by diesel fuel. The emissions and fuel consumption of such vehicles needs to be related to parameters such as haulage in terms of vehicle weight, amount of transported cargo and, when considering public transportation vehicles, the number of passengers. Taking all these parameters into account such vehicles may be considered to be both fuel efficient and low emitting (ibid, 2001).

An LCI of the CO_2 emissions associated with diesel fuel indicates that combustion during the use phase contributes to the highest percentage of the emissions (86.5%). Further the study shows that emissions from the oil refinery process contributes to 9.8% of the total life cycle emissions while crude oil production and crude oil transport represent the third largest source of CO_2 emissions of diesel fuel. Overall, the LCI showed that diesel fuel is associated with emissions of 0.633 kg CO_2/horsepower-hour or 0.236 kg CO_2/MJ (Sheehan et al. 1998).

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[21] EGR and SCR are techniques used to reduce NO_X emissions. The first works by recirculating some of the ICE exhaust gas into the engine cylinders while the latter uses a catalytic substance to convert NO_X into nitrogen (N_2) and water (Weststart, 2001).

2.8 The future of hybrid vehicles

The future is one thing human kind can never have total knowledge of or control over. Yet the future is one of the areas that receive most of our attention (although extensive dwelling on past events is fairly common as well). Scientists and businessmen spend their lives trying to foresee future development in all areas possible, so also, and quite naturally too, the future of fossil fuels and alternative transportation technologies.

As previously mentioned, much research is currently being made on various alternatives to conventional fossil fuelled vehicles. Such alternatives include biodiesel, fuel cell technology, electric vehicles and various types of hybrids. In fact there are so many different options for future transportation fuels that some scientists believe that future there will be an interim period with many different types of fuels. Diesel-electric hybrids and similar vehicles are believed to come to play an important role in a future society. The retail price of these vehicles is believed to decrease due to factors such as economy-of-scale, technology development, public acceptance and governmental regulations on vehicle and emission standards. Consequently, such and other hybrid vehicles are likely to increase in number (Dell and Rand, 2001; Weststart, 2001).

Other important issues well worth mentioning when it comes to the future of hybrid vehicles is the availability and consequent constraints of scarce metals for the energy storage systems. The resources are limited and may be exhausted rapidly should the HEVs and EVs increase greatly in number. This, however, may be counteracted for example by clever battery recycling schemes (Råde, 2001).

2.9 The vehicle model in the study

The Volvo Group have for some years been researching and developing many different kinds of so-called alternative drivelines. These include vehicles powered by renewable fuels such as dimethyl ether (DME)[22] and biodiesel (FAME) (Volvo Truck Corporation 2007c). Several companies within the Volvo Group have also developed different hybrid vehicles, some of which are currently sold on the market. Some examples of Volvo hybrids are shown in Figure 2.4, below.

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[22] DME can be produced from both fossil and renewable raw materials (Volvo Truck Corporation, 2007).

Figure 2.4 Different Volvo vehicles with a diesel electric hybrid driveline. From left to right: *Volvo FE Medium Duty distribution vehicle*, *Renault Premium Distribution Hybrys*, *Volvo 7700 hybrid city bus* and *MACK ® TerraPro™ Low Entry refuse truck* (The Volvo Group, 2009).

Most of the hybrid vehicles developed within the Volvo Group are parallel diesel-electric hybrids, which are therefore used as a basis for the vehicle model in the study. More specifically, the vehicle model is based on a parallel diesel-electric hybrid bus meaning that the diesel engine and the electric motor can deliver torque separately as well as collectively. The EM is used in the same extent as a mild hybrid. This means that the electric motor serves three purposes; to drive the car forward together with the diesel engine, to function as a generator when the vehicle brakes, and to serve as the starter motor for the diesel engine. When the vehicle starts running the electric motor is used as the sole driving force until the vehicle gains some speed. Then the diesel engine starts, and takes over the propulsion. As the vehicle then stops at for example a bus stop the diesel engine is shut down as the vehicle comes to a halt. The electric motor serves as an engine brake and the energy from the deceleration charges the battery. Further, when the vehicle is being driven up a slope the electric motor can help the diesel engine by providing extra power. The EM in this case thus consists of both a motor that provides torque for vehicle propulsion and a generator which charges the battery, either with energy from the ICE or recuperated brake energy (Volvo Bus Corporation, 2008). The most important vehicular components are described below.

The 4-cylinder, 5-litre ICE runs on diesel and is called the Volvo D5E diesel engine. It produces 210 hp. The EM is called I-SAM[23], functioning both as a motor and as a generator. The permanent magnet motor can be run on alternating current. The ESS consists of a battery that is, as previously mentioned, of lithium-ion type. A DC/DC energy converter converts the electricity from the lithium-ion battery from 600V to 24V. The lead-acid battery of conventional vehicles is included also in the hybrid. The transmission is automatic and called Volvo I-Shift. It interacts with the hybrid system and is mainly optimised for city driving (ibid, 2008).

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[23] I-SAM stands for *Integrated Starter Alternator Motor*

3 Simulation environment

This chapter describes the background of and environment for the studies carried out in this thesis. To be able to study and analyse variables important in the operation of such a vehicle it is useful and practical to utilize a simulation model. One definition of the concept of simulation is that “ [s]imulation is the imitation of the operation of a real-world process or system over time [involving] the generation of an artificial history of the system […] used to describe and analyze the behavior of a system […]” (Banks, 1999).

The advantages of simulating in a computer environment as opposed to measuring in an actual vehicle are many and include for instance reduction of the time as compared to tests in reality, implementing and studying effects of changes quick and easy, facilitated problem diagnosis, studies requiring constant in data, and facilitated constraint identification (ibid, 1999)

A simulation model to be used for analysis of a parallel diesel-electric hybrid vehicle was originally created several years ago in Matlab/Simulink®, as previously mentioned[24]. The first task in the project was to update and expand the model for compliance with later control strategies so that it could serve as an accurate model of more modern hybrid vehicles. In connection with this updating procedure the model needed continuous troubleshooting.

Since the simulations in this project aims primarily at studying the usage of the energy storage system (ESS), i.e. the battery, and the associated energy throughput during a number of typical driving cycles the model should facilitate studies of how the energy throughput in the battery can be weighted towards fuel consumption of the internal combustion diesel engine. These features where thus implemented in the model design.

Further, the model is accompanied by several data files[25] providing simulation parameters such as model constants, initial values etc. These files also needed to be updated to perform in accordance with the actual vehicles.

3.1 Simulation model

The simulation model has been created in a Matlab/Simulink® environment and is a representation of a complete vehicle including for instance a driver model and a road model which enable simulations of the performance of an actual hybrid vehicle. The topmost level of the simulation model is presented below in Figure 3.1.

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[24] The model was originally created by Martin Engström, software function developer at Volvo Powertrain Corporation. The incorporated battery model was created by Jens Groot, PhD student at Chalmers University of Technology and R&D engineer at Volvo Technology.

[25] Most of these data files are Matlab® files, which are called upon by the simulation model.

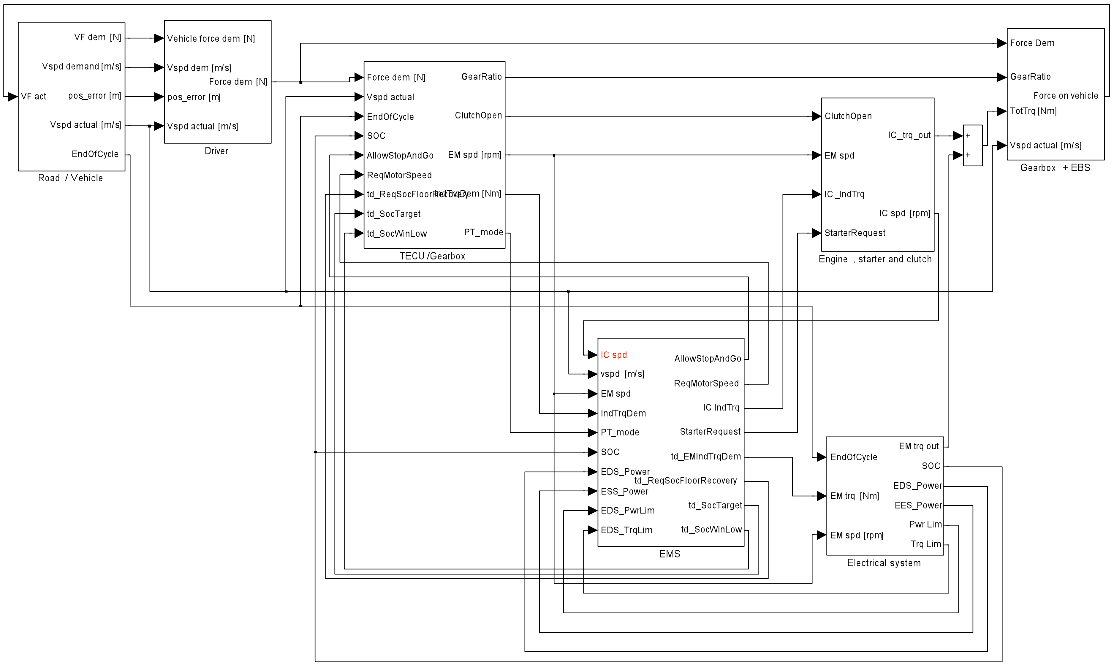

Figure 3.1 The simulation model. The figure shows the topmost level in the simulation model in which the subsystems form separate blocks.

The different sub-models used to simulate the vehicular components are listed below:

- Driver model
- Electrical system
- EMS
- Engine, starter and clutch model
- Gearbox and EBS model
- Road and vehicle model
- TECU and gearbox model

Within the sub-models simulation blocks define components of the vehicle such as the ICE, the electric machine, the battery, transmission, and driver behaviour. The model includes all EMS software in the form of a dynamic-link library (DLL) file, which has gathered all information on how to handle certain input signals from the actual EMS software and thus produces the same outputs as would the software in the actual vehicle. The seven sub-models in the simulation model are presented in more detail in the following sections.

3.1.1 Driver model

The driver is designed as a simple *PI*-controller and utilises inputs of demanded vehicle force [N], demanded and actual vehicle speed [m/s], and position error [m], which are outputs from the road and vehicle models. The inputs are used to generate one output signal; the force demand [N], which is used in the two models related to the gearbox.

3.1.2 Electrical system

The inputs to the electrical system consist of information on the EM, namely speed [rpm] and torque [Nm]. The system outputs the SOC, the energy to be used for electric drive and battery charging/discharging [J], and also restrictions on EM torque [Nm] and power [W].

The electrical system is made up of three sub-models, two containing information on the electric drive system (EDS) functionality that e.g. produces information on the EM temperature [K] and power [W]. The third model is one of the most important for this thesis; the battery model. The inputs here are the current [A] to the battery; positive value for battery charge and negative for discharge, and the outdoor temperature. The model processes these signals to calculate e.g. battery resistance, SOC, SOH etc. by using logical programming as well as input constants defined in supplementary ESS files. These parameters are logged and studied in the results.

3.1.3 EMS

The heart of the EMS sub-model is the previously mentioned dynamic-link library (DLL) file containing information on all functions of the actual EMS software. The inputs are manifold and include for instance vehicle speed [km/h], SOC, powertrain mode, and EM speed [rpm]. The outputs are also multiple including e.g. the SOC target, the engine brake torque [Nm] and information that is used to calculate fuel consumption [litre/s]. The EMS also contains a function that evaluates key position, i.e. if the ignition is turned on or not.

3.1.4 Engine, starter and clutch model

This sub-model represents the ICE or diesel engine, clutch and all mechanical power auxiliaries. It uses signals carrying information on EM speed [rpm], ICE torque from the EMS [Nm], and whether the clutch is open or not and processes these to produce outputs of ICE speed [rpm] and torque [Nm] from the modelled ICE or diesel engine. The outputs are in turn passed on to the EMS model and one of the gearbox models.

The ICE and the clutch are modelled using look-up tables that perform linear interpolation of the inputs. The data for these tables is called upon by the model and enclosed in several Matlab® files. They also use the inputs in modelled formulas to calculate the outputs. The data on the energy needed for the mechanical power auxiliaries is also read from supplementary files and is used to calculate the remaining ICE torque available for vehicle propulsion.

Within this model several important parameters are calculated; they include the total propulsion energy provided by the ICE [J], the total ICE brake energy [J], and total ICE friction energy [J]. Some of these are further used to calculate key parameters in the study.

3.1.5 Gearbox and EBS model

The *gearbox and engine brake system* (EBS) model is one of two gearbox models. It utilises inputs from the driver, the vehicle and the ICE such as actual vehicle speed [m/s], force demand [N], gear ratio, and total vehicle torque [Nm] to produce the actual vehicle force, which is calculated as the sum of the force from the powertrain and the braking force. Data on the wheel radius and rear axle length is fetched from external files.

This sub-model also performs calculations of important parameters such as total propulsion energy and total brake energy [J].

3.1.6 Road and vehicle model

This sub-model in turn consists of several sub-models, each used to calculate parameters related to the vehicle and driving environment. The only input comes from the *gearbox and EBS* model in the form of the actual vehicle force [N]. This is used, along with several look-up tables, to calculate the vehicle friction force, potential force from information on driving altitude, kinetic force, and position [m] of the vehicle. The latter is used together will e.g. vehicle speed [m/s] and force to calculate the position error used by the driver model to increase or decrease speed to catch up. The model also outputs information on the actual vehicle speed [m/s] and demanded vehicle force.

The requested vehicle speed, position, altitude etc. is loaded from the file containing information on the duty cycle and used as input vectors in the mentioned lookup tables.

Also this sub-model performs calculations of important parameters. These contain information on e.g. the number of starts and stops the vehicle has made and how long time the vehicle has stood still [s]. Further, the total cycle length turnout [m] is calculated.

3.1.7 TECU and gearbox models

The *TECU and gearbox* model is the most extensive of all sub-models. It decides the gear switch strategy, the powertrain (PT) mode, the clutch status and whether charge at standstill (C@SS) is required or not. The inputs are many; actual vehicle speed [m/s], force demand [N], requested EM speed [rpm], SOC, SOC target etc. The outputs are gear ratio, indicated torque from the ICE and EM [Nm], EM speed [rpm], PT mode, and clutch status.

The sub-model is very complex, not only does it require data from several external files, it also contains a multitude of tuneable parameters. The latter are constants set in the model deciding like for example the start gear depending on the SOC and values for the minimum allowed time between two gearshifts.

Statistics on the various PT modes is gathered within this sub-model. These are presented in the results.

3.2 Duty cycle

One of the inputs to the simulation model is a so-called duty cycle, which consists of data on for example altitude above sea level and vehicle speed and position. The duty cycle used in this study is an urban driving cycle characterized by low vehicle speed, low accelerations and repeated stops. The cycle data is most often based on real measurements.

Different duty cycles have been used in this project as simulation input. The cycle that has been used the most is sampled in London on the route for bus 159. The velocity profile is presented in Figure 3.2 below.

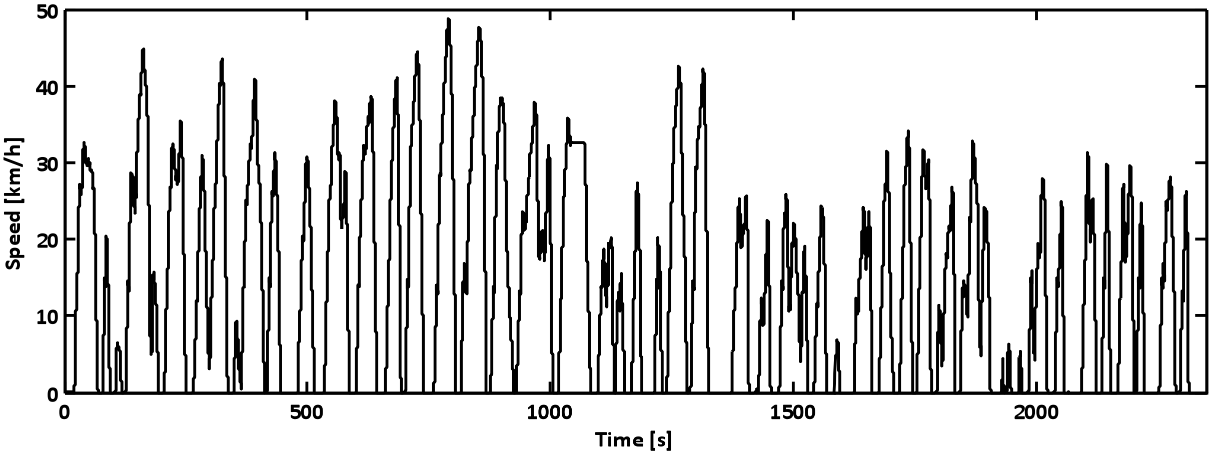

Figure 3.2 The velocity profile of the duty cycle *London route 159*. The figure clearly shows the many starts and stops of the duty cycle.

Other duty cycles have mainly been used for testing and validation of the simulation model and the results. The one that has been used the most in this project is a cycle called *SORT 1* (Standardised On-Road Test), which was developed by the International Association of Public Transport (UITP)[26] for heavy driving urban mode. This cycle has been used to test the robustness of the results. The SORT 1 cycle consists of three starts and stops, followed by acceleration to a certain speed which is held for a couple of seconds before the vehicle brakes again. Some key numbers for the different duty cycles are presented in Table 3.1 below:

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[26] The UITP is an international network for various actors including public transport authorities and operators, policy decision-makers, scientific institutes and also the public transport supply and service industry (UITP, 2008).

Table 3.1 Key values for the duty cycles used in the simulations. The data comes from the files containing information on the duty cycles, which also are used as a basis for the simulations.

Duty cycle	**Time [s]**	**Total distance [km]**	**Average speed [km/h]**	**Maximum speed [km/h]**	**Maximum acceleration [m/s^2]**	**Maximum deceleration [m/s^2]**	**Number of stops**
London route 159	2281	8.97	14.2	49	1.50	2.20	56
SORT 1	153	0.520	12.6	40	1.03	0.80	3

3.3 Reference vehicle

The simulation model requires inputs in the form of vehicle parameters such as vehicle mass, engine size, wheel radius, battery type etc. The model obtains these parameters from supplementary Matlab® files as previously mentioned. The vehicle in this study is a parallel diesel-electric hybrid single deck bus corresponding to one of the bus models produced by Volvo Buses. Some other specifications for the vehicle model have been presented in section 2.9 above.

Further information on vehicular specifications that is not presented in this thesis may be confidential and can therefore not be revealed or reproduced in this context.

4 Model verification

The simulation model is, as previously described, very complex and extensive, albeit it, at the same time, is a simplified representation of a real hybrid vehicle. This means that both the model as well as the results need to be verified in some way in order to assess their accuracy. The robustness test of the results will be described in the following chapter.

The results of these calculations and tests had to be made before the actual project simulations could be initiated. Therefore the results and the analysis of the model verifications are presented in this section.

First, verification of the model is described. In this purpose several calculations, test simulations as well as literature comparisons of parameters such as resistance etc. have been performed. Also, several simulations using different duty cycles have been performed and the results verified visually regarding plausibility of e.g. ICE and EM speed and torque, SOC level, and gearshifts. The verifications of fundamental character are accounted for in the sections below.

4.1 Calculation of fuel consumption

Calculations of fuel consumption both through by-hand calculation and using the simulation model have been done and the results compared. The hand-calculations were based on the following equation (Guzzella and Sciaretta, 2007):

$$P_{prop} = P_{fric} + P_{aux} + P_{pot} + P_{kin} \tag{1}$$

In this equation, P_{prop} is the propulsion power, P_{fric} friction power, P_{aux} is the power needed for the electrical auxiliaries and is assumed to be 4400 W[27], P_{pot} is the potential power, and P_{kin} the kinetic power. The three other terms are in turn calculated using the following equations (Guzzella and Sciaretta, 2007):

$$P_{fric} = v \cdot \left(\left(m_v \cdot g \cdot c_r \right) + \left(\tfrac{1}{2} \cdot c_d \cdot A_f \cdot \rho_{air} \cdot v^2 \right) \right) \tag{2}$$

Here, v is the vehicle speed, m_v the vehicle mass, g the gravitational acceleration, c_r the rolling friction coefficient (assumed to be constant here for simplicity), c_d the aerodynamic drag coefficient (also assumed to be constant for the same reason), A_f the frontal area of the vehicle, and, finally, ρ_{air} is the density of air.

$$P_{pot} = \frac{d}{dt}\left(m_v \cdot g \cdot h \right) \tag{3}$$

---

[27] The value of 4400 W was assumed in consultation with Jens Groot, PhD student at Chalmers University of Technology and R&D engineer at Volvo Technology.

The *h* in this equation is driving altitude or height above sea level. This equation is equal to zero since the altitude is set to be constant.

$$P_{kin} = \frac{d}{dt}\left(\tfrac{1}{2} \cdot m_v \cdot v^2\right) \tag{4}$$

The fuel consumption [litre/100 km] is then calculated from P_{prop} by multiplying with cycle duration time, t_{cycle}, and dividing by the engine efficiency, η_{ICE} and the efficiency of conversion from diesel energy to electricity $\eta_{diesel/el}$, the energy content of diesel fuel per litre $E_{diesel,}$ and by the length of the duty cycle or distance travelled, d_{cycle}, according to the equation below:

$$FC = \frac{P_{prop} \cdot t_{cycle}}{\eta_{ICE} \cdot \eta_{diesel/el} \cdot E_{diesel} \cdot \left(d_{cycle} \cdot 10^{-5}\right)} \tag{5}$$

The vehicle speed was set to be 10 m/s, the cycle length to 5000 m and the vehicle mass to 14 500 kg. The calculations amounted to a value for the fuel consumption of 15.5 litre/100 km. This was then to be compared to the results from simulations using the project model. These simulations were made based on three different vehicles; one hybrid vehicle with a 5-litre engine (the same as the project hybrid), one conventional diesel-only vehicle, also with a 5-litre engine, and finally another conventional vehicle but with a 7-litre engine. The results are presented in the following table:

Table 4.1 Results of the fuel consumption model verification.

Source/vehicle	**By-hand arithmetics**	**Hybrid, 5-litre engine**	**Conventional, 5-litre engine**	**Conventional, 7-litre engine**
Fuel consumption [litre/100 km]	15.5	12.3	13.8	14.0

From the results it can be seen that the fuel consumption for both the by-hand calculation and the three simulations are fairly similar to each other. The difference in the simulation results of the two conventional vehicles is a consequence of the difference in engine size, i.e. the bigger the engine the more the fuel consumption. This is true also for the hybrid vehicle, which, in addition to a smaller engine, also has an extra power source in the form of an electric motor, which reduces the fuel consumption even more.

4.2 Literature verifications

Further verifications were made in which certain simulation output parameters where compared to literature values of the same. The most important of these verifications is presented in the following sections.

4.2.1 Fuel consumption comparisons

A general literature study of fuel consumption values for various heavy-duty vehicles was initially performed to see within which ranges the fuel consumption of the project simulations could be expected to be. Several references stated that the fuel consumption was around 60 litre/100 km but values as low as 23 and up to 98 litre/100 km where also found (King et al. 1995; Badin et al. 1996; Folkesson et al. 2003; M.J. Bradley & Associates, 2006; Navarro, 2009). The conclusion of this study is that the fuel consumption of the model hybrid should end up somewhere within this range, most likely in the lower parts since the modelled vehicle is a hybrid with an additional power source and also since several of the studies found are quite dated and the technology is assumed to have developed in the time that has past since then. This finding was used in the process of upgrading the simulation model.

4.2.2 Comparison of idle fuel consumption

A simulation was performed in which the vehicle speed in the previously described duty cycle file was set to zero, while the engine was running, i.e. the vehicle was in idle mode. The fuel consumption was then calculated from the simulation outputs and compared to literature reference values. For confidentiality reasons no absolute numbers can be given but this analysis was used when tuning the model parameters.

4.2.3 Comparison of battery resistance values

Literature values for battery resistance, and even values for lithium-ion batteries in specific were found and used to verify the plausibility of the modelled battery resistance that was calculated from several simulations. Also in this case, for confidentiality reasons, neither the literature values nor the simulations output of this parameter can be given, but the results were anyhow used to verify the results.

4.3 Plausibility simulations

Simulations of two different vehicles with two different duty cycles have been performed in the purpose of comparing the relative fuel consumptions and assessing the plausibility of the results. The two duty cycles that have been used are London 159 route and SORT 1. The vehicles are first a hybrid with a 5-litre engine, then also a diesel powered heavy-duty vehicle with a 7-litre engine, which is the corresponding conventional vehicle. The idea is to calculate the fuel consumption and make comparisons based on the following hypotheses:

a. The fuel consumption [litre/100 km] for both cycles should be fairly similar for the same vehicle since they both include starts and stops and have approximately the same average speed etc. (see Table 4.2 for a comparison).

b. The fuel consumption for the conventional vehicle with a 7-litre engine is expected to be higher than for the 5-litre hybrid. This both because the hybrid engine is smaller and also because the hybrid has an additional power source in the electric motor.

c. Further development of hypothesis b, above, is that the ratio of the fuel consumption for the hybrid and the conventional vehicle should be under 35 %, which is the figure presented as the maximum possible savings from hybrid propulsion.

For confidentiality reasons, all numbers are normalised based on a set value of 50 litre/100 km for the fuel consumption of the hybrid in the London 159 route.

Table 4.2 Results of the model fuel consumption plausibility study.

Engine/vehicle type	Hybrid, 5-litre engine	Conventional, 7-litre engine	Hybrid fuel savings [%]
FC (London 159) [litre/100 km]	50	65.40	23.5
FC (SORT 1) [litre/100 km]	54.96	66.26	17.1

The conclusion that can be draw in this case is that the results confirm the theories presented in the hypotheses above. This shows that the model outputs are plausible and that the values are within reasonable limits. This in turn indicates that the project results are equally likely to be plausible and applicable to reality.

4.4 Result verification

In connection with the simulations simple ocular verifications of the results were made. Several selected outputs were studied in order to make an initial examination of the accuracy or status of the simulation. This was done directly after every simulation (after both the initial simulations and the optimisation) and included studies of vehicle speed, gear selection, the speed [rpm] and the demanded and actual torque [Nm] of both the IC engine and the EM including the electric brake torque, the SOC and target SOC. This study gave an important implication of the simulation outcome and indicated for instance if the engines could provide sufficient torque to complete the duty cycle in a satisfactory manner. For instance, during the optimisation simulations several cases where the vehicle only had completed a part of the entire cycle could be identified and the results evaluated accordingly.

5 Implementation

In this chapter the actual execution of the simulations is presented. The aim of the simulations according to the project objectives was to produces outputs enabling studies of various components of the hybrid powertrain such as the ESS and the diesel engine through parameters like e.g. battery energy throughput, fuel consumption battery SOH etc.

The implementation phase of the project thus started with research in the purpose of finding which hybrid variables that could be altered to study the parameters of energy throughput and fuel consumption, and then further, which of these variables that were of interest. The variable research was made within the previously described CBC and torque distribution models, by means of literature reviews and personal interviews with several experts at function development, battery technology, hybrid control among others[28]. It was decided that the focus should lie on so-called *calibratable*[29] *variables* that are defined in the dataset. These have the advantage of being easy to modify and implement in the simulation, which was one of the reasons why the focus was placed here. The extensive research process was initially focused on finding so-called *focal areas*, i.e. a selected number of areas under which the variables could be categorized. This resulted in the selection of five such areas, which are presented below. After consultation with software developers at Volvo who have expert knowledge of the hybrid vehicles and torque distribution function[30] the ultimate outcome of the research was both nine different variables, all believed to affect the key parameters of the study, and also a decision on how to alter them in order to study just how they affect these parameters. It was further decided that the initial simulations should be based on adjustments of the selected variables as explained in the following section.

5.1 Focal areas

The nine parameters were grouped into the five different focal areas *SOC target*, *SOC window*, *EM torque curve*, *ESS charge/discharge power* and *Start SOC*. These are described below in further detail. The nine selected variables to alter in the simulations are also described in the context of their respective focal area (they can also be found in appendix B together will the selected alterations). The actual values of the parameters will not be presented due to confidentiality reasons. However, the interesting analysis is not how the key parameters are affected in absolute numbers but rather the general trends.

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[28] Personal communication with Kristoffer Rydquist, Martin Engström, and Hanna Bryngelsson, engineers at Volvo Powertrain Corporation and Jens Groot, PhD student at Chalmers University of Technology and R&D engineer at Volvo Technology, March-July, 2009.

[29] Parameters that are possible to calibrate are here named *calibratable*.

[30] Personal communication with Kristoffer Rydquist and Martin Engström, software function developers at Volvo Powertrain Corporation, the 16th of March, 2009.

5.1.1 SOC target

The SOC target is, simply put, the SOC value towards which the hybrid control functions attempt to regulate the SOC. This target depends on the current vehicle mass and speed. In a specific vehicle it is thus the speed that determines the SOC target; the higher the speed the lower the target to ensure that as much space for regenerated brake energy is available in the battery as it is assumed that the vehicle speed sooner or later will be reduced to a standstill (Engström, 2007). The only variable that will be altered within this area is the *SOC target* variable, which will be both raised and lowered by 5 units. Since the SOC target is mapped towards both vehicle mass and speed all the mapped values will be raised or lowered at the same time.

5.1.2 SOC window

The SOC window is the space between the minimum allowed SOC level and the maximum SOC level, i.e. a restriction of the range within which the SOC is allowed to be before the battery either needs to be charged by force or discharged or at least not charged any further by force. The SOC window thus has a lower limit and an upper limit. The SOC window is set to be much smaller than the full capacity of the battery in order to increase the lifetime of the battery (Engström, 2007). As previously mentioned a too deep discharge or overcharging of a battery may affect the health profoundly.

Within this focal area also only one variable, namely the *SOC window* variable, has been altered. In this case however, six different alterations have been made. Both the lower and the upper limit have been increased and also decreased by five units; a total of four alterations. Finally the lower and upper limits are increased or decreased at the same time changing the window by a total of ten units, for each of the two alterations respectively. In order to increase the understanding of how the SOC window is altered with the different settings a representation of the window size is shown in figure 5.1 below.

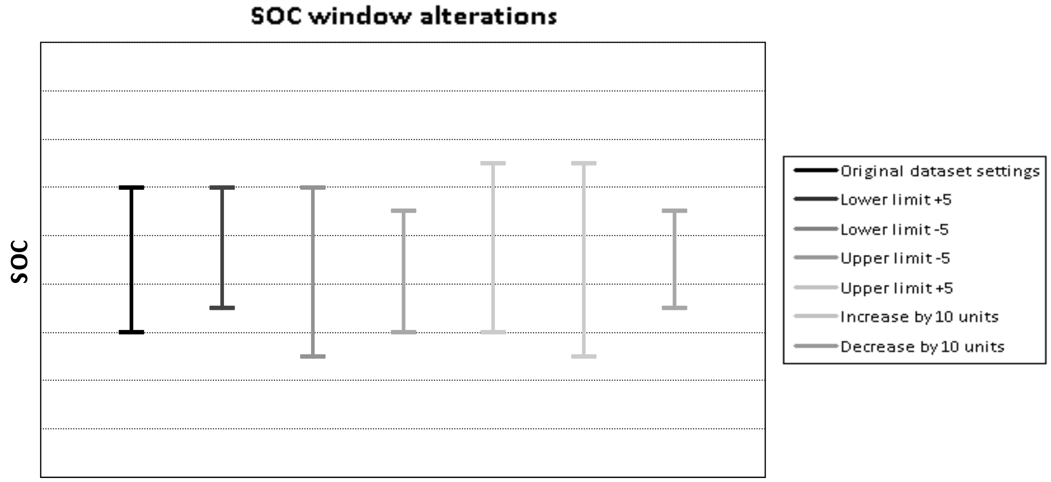

Figure 5.1 A graphic representation of the SOC window alterations. All six variations are shown in addition to the original dataset SOC window, which is included for comparison.

5.1.3 EM torque curve

The EM torque curve defines which torque that is to be provided from the EM at a certain vehicle operation point, i.e. both positive torque from the electric motor and negative torque from the generator. The curve thus both governs the EM during electric drive mode as well as the hybrid mode where the electric motor may work as a complement to the diesel engine providing extra boost (Engström, 2007).

Here five variables to be altered in simulations have been selected. The first two, named *maximum EM torque* and *minimum EM torque*, are mapped against the speed of the electric motor. They define the maximum positive torque for the motor and the maximum negative torque for the generator. These two variables have both been decreased to 90 % and increased to 110 %. Further, the same alterations (90 % and 110 %) have been made to a variable called *ED reference torque*. This variable is used as a reference value for the indicated torque from the electric propulsion system included since it may control the EM torque in certain driving conditions. The final two altered variables within this focal area regulate the maximum added boost to the diesel engine from the electric motor and the maximum electric generator regeneration, respectively. They are called *maximum added boost* and *maximum added regeneration*, and are both also decreased to 90 % and increased to 110 %.

These tests decrease or increase the EM torque capacity and are thus in a sense implications of what the results would be if the EM size was correspondingly decreased or increased.

5.1.4 ESS charge/discharge power

The calibratable variables associated with the ESS charge/discharge power focal area regulate the maximum discharging power (through the so-called *battery power high* variable) and the minimum charging power, (through the so-called *battery power low* variable) (Engström, 2007). The parameters are altered to 50 % and 90 % of the original dataset settings in the initial simulations.

5.1.5 Start SOC

The *start SOC* variable is the only variable that is not a dataset parameter. Instead it is a parameter set in one of the Matlab® files that provides the hybrid model with information. It decides the level at which the SOC is when the simulation starts. Normally the battery SOC level as a vehicle is started is either the same as it was when the vehicle was shut off or altered by plug-in charging of the vehicle as it is parked. This test thus shows the possible gains from having a plug-in hybrid, i.e. raising the start SOC as the vehicle is parked. It also indicates the trends of how the key parameters are affected by a start SOC at a lower or higher level. The start SOC is raised by 5 units or lowered by the same as compared to the start SOC for all other simulations.

5.2 Calculation of key parameters

The key parameters were selected with foremost consideration to what would fulfil the project aim, but also what would be interesting to study, what was possible to study considering that the vehicle is but modelled, and finally what could be included within the time frame of the project.

Energy throughput and fuel consumption are two obvious key parameters. So is also the SOH, which, even though it is directly related to the energy throughput, is implemented in the model and thus easily measured. Further, the intention is also to use the SOH in the calculation of two other key parameters; the cost and CO_2 difference in the comparative analysis. Other key parameters included in the study are SOC and powertrain modes. The final key parameters are related to vehicle drivability, which is a parameter that is interesting to try to study since the hybrid model cannot actually be taken for an actual test drive.

Many of the equations contain the figures $1e^5$ and 3600. The former is included in the calculations to refer to the parameters per 100 km. The latter constant of 3600 is used to convert from the unit of kilowatt-hours [kWh] into the unit of joule [J] ($1\ kWh = 3600\ kJ$).

Calculation or estimation of all key parameters is described in the following sections and the results of the calculation in chapter 5.

5.2.1 Energy throughput

The energy throughput is calculated using several different simulation outputs. The key parameter has been calculated both in the most commonly used unit [kWh/h] but also in [kWh/100 km] in an attempt to increase the comparability with the key parameter fuel consumption which is measured in [litre/100 km]. The following two equations are used to calculate the energy throughput, *ET*:

$$ET = \frac{\left(\left|P_{bat}\right|\right)_{avg}}{t_{cycle}} \tag{6}$$

$$ET = \frac{\left(\left|P_{bat}\right|\right)_{avg} \cdot 1e^5}{d_{cycle} \cdot 3600} \tag{7}$$

The average battery power [kW] calculated over the entire cycle is denoted P_{bat}, the time of the cycle is t_{cycle} and the distance travelled d_{cycle}. All equation parameters are logged during the simulations.

5.2.2 Fuel consumption

The diesel fuel consumption is the second main key parameter. In order to calculate the parameter SOC the difference in the level of SOC at the end of the duty cycle compared to that of the start needed to be calculated. So-called SOC compensation of the fuel consumption is necessary in order to make the results from the different simulations comparable. The deviation in SOC at the end of the cycle and in some cases at the start of the cycle differ for each of the selected simulations. Thus the fuel consumption is adjusted so the SOC ends at the same level as it had at the start of the drive. The energy of the SOC difference, $E_{SOC,diff}$, [J] is calculated using the following equation:

$$E_{SOC,diff} = \left(\frac{SOC_{end} - SOC_{start}}{100}\right) \cdot n_{series} \cdot n_{strings} \cdot Ah \cdot 3600 \cdot \int \left(U\_OCV_{discharge}\right) \cdot d(DOD\_OCV_{index}) \qquad (8)$$

In this rather complicated equation, SOC_{end} and SOC_{start} denote the end and start SOC, respectively. n_{series} is the number of battery cells in series and $n_{strings}$ is the total number of such parallel series. Ah is the electric charge, the discharge voltage of the battery $U\_OCV_{discharge}$ is integrated w.r.t. the depth of discharge[31], DOD_OCV_{index}. The parameters are either obtained as simulation outputs or found in the Matlab® files accompanying the model.

Using this SOC difference the SOC compensated fuel consumption, $FC_{SOCComp}$, is calculated from the actual fuel consumption, FC, using the following equation:

$$FC_{SOCComp} = \frac{FC - \frac{SOC_{diff}}{E_{diesel} \cdot \eta_{diesel/el} \cdot \eta_{ICE} \cdot \eta_{EM}}}{d_{cycle} \cdot 1e^{-5}} \qquad (9)$$

Here E_{diesel} is the energy content of diesel fuel, η_{ICE} the diesel engine efficiency, $\eta_{diesel/el}$, is the efficiency of conversion from diesel energy to electricity, and d_{cycle} is the distance travelled. In the results and in this section the key parameter is simply called fuel consumption. However, what is referred to is always the SOC compensated fuel consumption, if nothing else is explicitly stated.

5.2.3 SOH

The SOH is calculated as an algorithm within the model. The calculations in the model are fairly complicated. The cycle depth is calculated from the DOD and the battery temperature etc. A lookup-table reads information from external data files on the number of cycles remaining until the battery end of life as a function of the DOD and temperature.

The change in SOH, denoted SOH_{change}, for the simulations with altered settings as compared to the SOH change for the simulation of the original dataset is calculated using the following equation:

$$SOH_{change} = \frac{SOH_{AS,end} - SOH_{org,end}}{SOH_{org,start} - SOH_{org,end}} \qquad (10)$$

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[31] The depth of discharge (DOD) is the inverse of the SOC, i.e. $DOD = 1 - SOC$.

Here $SOH_{AS,end}$ is the end value of the SOH for the simulation with altered settings. $SOH_{org,start}$ and $SOH_{org,end}$ are the end and start SOH, respectively, for the simulation with original dataset settings.

5.2.4 SOC

The SOC is, like the SOH, calculated as an algorithm within the model. It depends on parameters such as current and temperature. The SOC is the simply logged during the simulations.

5.2.5 Powertrain modes

The powertrain modes are also obtained as simulation outputs, and are logged in the model. Information on which mode the vehicle is in is decided in the EMS, by the actual engine software where the decision on mode based on several different parameters and logical programming is made. The relative frequency of each powertrain mode is calculated within the model.

5.2.6 Comparative calculations

The comparative calculations included in this thesis are three in number; comparisons of the total energy, cost, and CO_2 emissions. They were made in order to be able to compare the relative gains or losses in energy throughput to those of the fuel consumption. The calculations of these are presented here.

When it comes to comparing energy throughput and fuel consumption caution needs to be applied. It is important to keep in mind that these two parameters are not interchangeable, meaning that the consumption of diesel fuel can be described as energy consumption [MJ/100 km] whereas the energy throughput is not only energy consumed by the EM and used for vehicle propulsion but also the energy that is recuperated by the generator. This means that as they are both recalculated to [MJ/100 km] the latter parameter is in a sense a double-count of the energy as compared to the fuel energy consumption. In a way this means that the parameters cannot be compared as to the total energy consumption. Still, it is interesting to get an idea of how a battery *kWh* is correlated to a *litre* of diesel fuel. Also, the main objective of an optimisation would be a lowering of both parameters. Therefore a calculation of the so-called total energy has been made.

The total energy was calculated in [MJ/100 km] based on the energy throughput and fuel consumption. The conversion from [kWh/100 km] and [litre/100 km] was made using the conversion factor $(1\,kWh = 3.6\,MJ)$ and the energy content of diesel, E_{diesel} [MJ/litre], respectively. The total energy was calculated as the sum between the energy throughput [MJ/100 km] and fuel consumption [MJ/100 km].

The cost analysis that is performed is very crude and does not go into detail on e.g. investment costs, inflation, and opportunity costs etc. Further, only costs of the battery and of the diesel fuel will be included in the calculations. This reduces the analysis to more of guideline than of information on the absolute costs.

The battery used in the studied vehicle is assumed to be of a high-power type (see section 2.1.3 for further detail on this area). As previously mentioned, such a battery costs about 20 USD/cell (Gaines and Cuenca, 2000). Further, the number of cells in a general heavy-duty hybrid-electric parallel vehicle is approximated to be 400[32]. This means that the total cost of the battery when it is assembled in a complete vehicle is about 8000 USD[33]. The cost has to be partitioned over all the years the battery is in operation. Since the changes of the selected parameters result in either improved SOH development or worsened as compared to the original dataset, this will be the parameter that will influence the cost. The cost is namely calculated per 100 km.

The cost comparison figures for the battery were thus calculated using the SOH. It is assumed that the battery will last until the nominal capacity has fallen below 80 % of the initial value. Thus, the maximum distance that the vehicle could travel before the SOH fell to 80 % was calculated using the SOH_{change} parameter and the distance travelled during the duty cycle. The total price of the battery was divided by this maximum distance and then normalized to a cost per 100 km.

The corresponding cost for the diesel fuel was also calculated per 100 km. The price of buying diesel varies constantly, but it is approximated to be 1,74 USD/litre[34] (The Automobile Association Limited, 2009).

When it comes to CO_2 emissions the comparative calculations are not based solely on the emissions from the use phase but on the total amount of CO_2 emitted during the entire lifetime of both a lithium-ion battery and diesel fuel. As previously described, such a life cycle inventory is based on the accumulated emissions from the initial process of raw material extraction, through phases such as refining and transportation to the final end use of the product, which could for example be recycling or landfill disposal. The calculations are rather straightforward. However, some issues related to allocation of the associated emissions arise. The diesel fuel is used to provide torque to the vehicle directly, but also to charge the battery via the EM. It was decided that the emissions associated with the diesel fuel used directly for vehicle propulsion would be allocated to the diesel fuel and that the emissions associated with the fuel used to charge the battery would be allocated to the battery. This decision was made based on the fact that the comparison is made on emissions related to the use of the fuel and battery and the ultimate purpose of that use is considered to be the provision of propulsion torque.

The following equations show how the total life cycle CO_2 emissions associated with the diesel fuel and the battery, respectively, are calculated:

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[32] The number of 400 has been assumed since passenger HEVs use battery packs containing around 200 high-power cells and it is approximated that a heavy-duty HEV would need about twice as many cells.

[33] 8000 USD corresponds to approximately 57 900 SEK (Forex Bank, 2009).

[34] 1.74 USD/litre corresponds to approximately 12.60 SEK/litre (Forex Bank, 2009).

$$Emissions_{diesel} = \frac{E_{prop,\,diesel} \cdot 1e^{5}}{\eta_{diesel} \cdot \eta_{ICE} \cdot d_{cycle}} \cdot LCE_{diesel} \tag{11}$$

$$Emissions_{battery} = \frac{E_{charge,\,diesel} \cdot 1e^{5}}{\eta_{diesel} \cdot d_{cycle}} \cdot LCE_{diesel} + \frac{E_{discharge,\,battery} \cdot 1e^{5}}{d_{cycle}} \cdot LCE_{battery} \tag{12}$$

In the two equations above, $Emissions_{diesel}$ and $Emissions_{battery}$ are the total emissions associated with the product [MJ/100 km]. $E_{prop,\ diesel}$ is the energy used for vehicle propulsion provided by diesel fuel. $E_{charge,\ diesel}$ is the diesel energy used to charge the battery, while $E_{discharge,\ battery}$ is the energy output from the battery used for vehicle propulsion. The terms LCE_{diesel} and $LCE_{battery}$ are the life cycle emissions associated with the battery and the diesel fuel, respectively.

The results of these calculations are presented in chapter 6 along with all other simulation results.

5.2.7 Driveability parameters

Drivability, or vehicle performance is a parameter that preferably comes from taking the actual vehicle for a ride while trying to, totally empirically, get a feeling for what the vehicle is like to drive, for example concerning the smoothness of the drive and pedal response[35]. In this case, no such tests have been performed. When it comes to measuring or estimating drivability from software simulations there are many different ways to accomplish this, none of them the ultimate way. An attempt to answer the question of the vehicle performance will be made through the calculation of several parameters approximated as drivability parameters. The criteria for these are further that they must be able to be calculated from the simulation results.

Three different parameters were selected to describe the vehicle drivability; vehicle speed, acceleration, and the total number of gearshifts made during a duty cycle.

When it comes to vehicle speed drivability issues, two different calculations are made. First, the average speed, v_{avg} is calculated from the speed the vehicle has when in motion, using the following equation:

$$v_{avg} = \frac{d_{cycle}}{t_{cycle}} \tag{13}$$

Second, a calculation of how many percent of the duty cycle the actual vehicle speed differs from the demanded speed made. It was decided that a speed slower than 3 km/h of the demanded speed would be considered a noticeable difference; thus the calculation shows in how many percent the actual vehicle speed differs from the demanded speed by more than 3 km/h. This difference

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[35] Personal communication with Lars Walfridsson, software function developer, Volvo Powertrain Corporation, June, 2009.

mainly arises as the vehicle accelerates, which is why the parameter to a certain extent also can be seen as a measure of acceleration performance. The difference in vehicle speed, v_{diff}, was calculated using the following equation:

$$v_{diff}(d) = v_{dem}(d) - v_{act}(d) \tag{14}$$

Here v_{dem} is the driver's demanded vehicle speed and v_{act} the actual speed. The percent of this difference that is larger than 3 km/h is then calculated using logical algorithms programmed in Matlab®.

Finally, a calculation of the number of gearshifts that is made during a full duty cycle was made. This is used a measure of drivability with the motivation that the more gearshifts, the less smooth the driving will feel[35]. The number of gearshifts is calculated in the simulation model as the sum of the times the gear is changed during a simulation. Figure 5.2 shows how it is calculated in Simulink®.

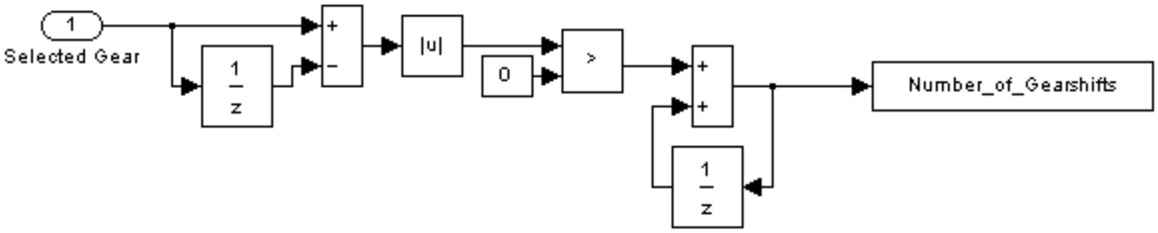

Figure 5.2 Calculation of the number of gearshifts in Simulink®. The figure shows the part of the model created to calculate this key parameter.

5.3 Program operation

The designed flowchart for the main simulation program is show in figure 5.3. The figure illustrates how constants, initial values, etc. are imported into the Matlab® workspace as the program is executed.

The program starts with a couple of selections; of simulation parameters, duty cycle, which focal area and variable to simulate etc. Then all these parameters are read into the Matlab® workspace from which they can be accessed by the simulation model when executed in the next step. The most important simulation outputs are then saved to a data structure[36] specific for the selected simulation settings. When all simulations have been performed the key variables are calculated and plotted to be presented as the project results.

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[36] A data structure is an efficient way to store a lot of computerized data.

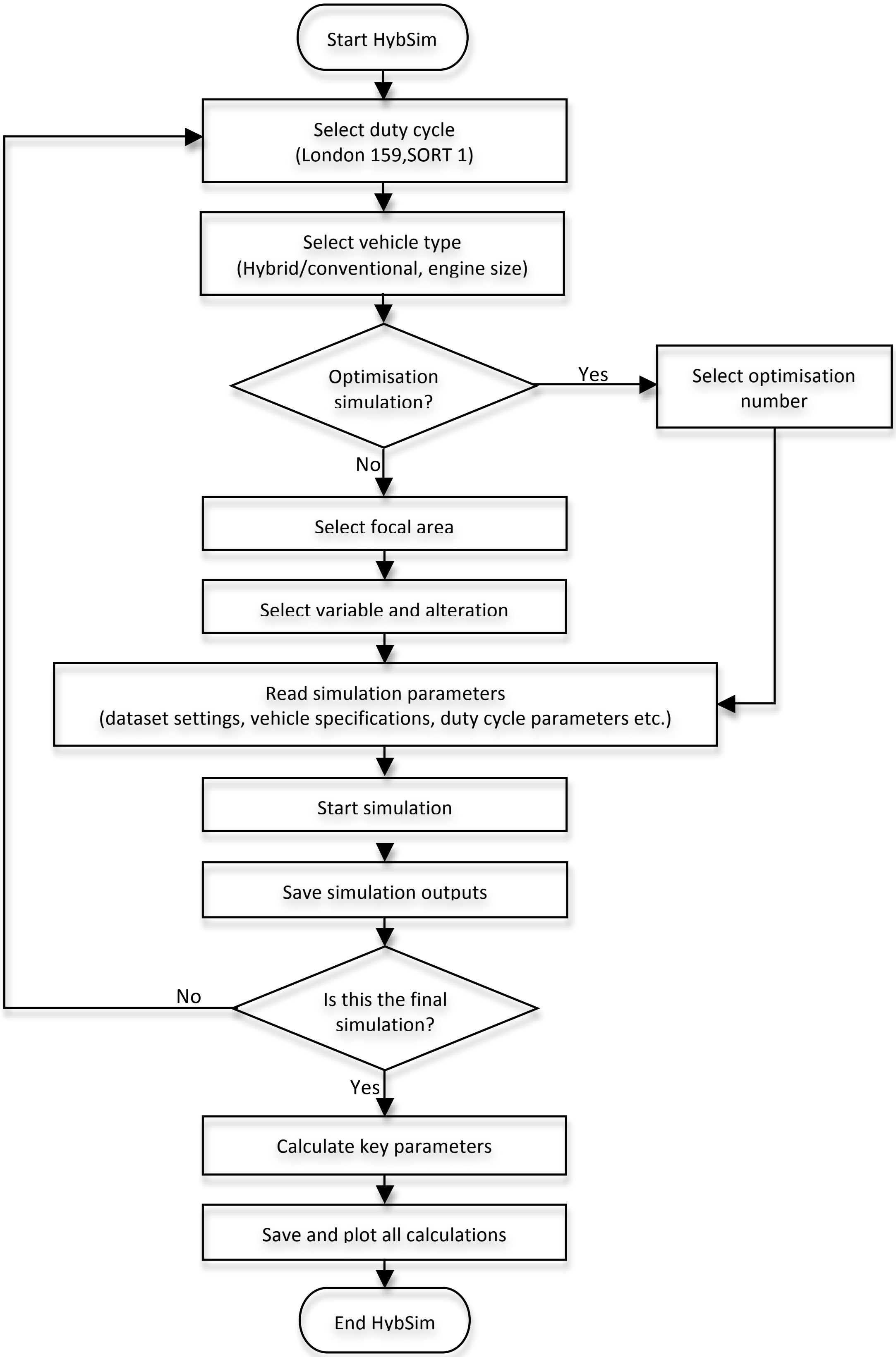

Figure 5.3 Simulation program flowchart. The figure shows how the HybSim program is designed to function. Adapted from Honda et al. 1979.

5.4 Optimisation

The optimisation part of the project is performed to further study the effects of the variable alteration to see if any trends can be discerned. In order to reduce the number of simulations in the optimisation phase a selection of the most interesting simulation settings had to be made. Several different ways to make such a choice were considered, ultimately it was decided that then comparison of total energy was to be used in this purpose.

The calculations of the total energy [MJ/100km] were thus used, and from these values it was decided that the simulations resulting in a decrease of total energy of more than 0.02 MJ/100 km as compared to the original dataset total energy. Further decisions that were taken concerned which alterations that should be made to the selected variables. The optimisation simulations are to be continued with stepwise alterations of the selected variables, either until some point corresponding to an optimum is reached or until other factors prohibit further alteration of a parameter. All these variables along with the alterations are presented in chapter 6, and can also be found in appendix C.

5.5 Robustness test

The previous chapter treated verification of the simulation model. Similar validation tests are also important to do on the simulation results. Such a robustness test has been performed, with the main purpose of investigating the universality of the results. The calculated key parameters and thus the simulation results are all based on the London 159 route. When it comes to the analysis of these results it is essential to know whether the discussion only is valid for the specific simulation conditions or if the analysis possibly also could be generalised.

The robustness test thus comprises a repetition of all the simulations of the London 159 duty cycle with all altered variables as well as the original dataset, however, this time the SORT 1 cycle is used instead. The idea is to study the results of this test and compare them to the results of the ordinary simulations and look for trends or patterns equal for both duty cycle results. This comparison is made using the main key parameters; energy throughput [kWh/h] and fuel consumption [liter/100 km].

6 Results

In this chapter the results from first the initial simulations and then from the optimisation simulations will be presented. The calculated key parameters such as energy throughput and fuel consumption will be represented by various graphs. Other important results include comparisons[37] between the original dataset and the altered settings to show the savings or losses in for example energy consumption and battery state of health (SOH). All results presented in this chapter are generated from simulations of a diesel-electric hybrid vehicle utilising the Matlab/Simulink® model presented in section 3.1.

The simulations from which the results emanate and which are described in this section are, as previously mentioned, based on literature studies and stakeholder interviews. The outcome of this pre-study was the identification of several parameters believed to have significant impacts on both energy throughput as well as state of health of the energy storage system (ESS). The selected parameters are connected both to the performance of the electric machine (EM) and the ESS which are two of the most important components in a diesel-electric hybrid vehicle.

The results are divided into several different parts; presented by the parameters energy throughput and fuel consumption, SOH, state of charge (SOC), powertrain mode, and current and power output. Further, a section deals with the important parameter of driveability in which attempts are made to illustrate how the driver perceives the vehicle performance. Finally, a section in which the results from the so-called optimisation simulations is included in this chapter. This section shows the results in the form of energy throughput, fuel consumption and driveability. In some cases the results are further divided into the above mentioned focal areas; SOC target, SOC window, EM torque curve, ESS charge/discharge power and start SOC for increased clarity (see section 5.1 for additional details on these areas).

6.1 Energy throughput and fuel consumption

Here the resulting energy consumption for all different dataset settings is presented. The parameters are calculated using the equations presented in section 5.2.

The purpose of this project was to study the relationship between energy throughput and fuel consumption, which is why these parameters are presented first in this chapter. In addition to graphs of these, the so-called total energy of the vehicle will also be presented. This latter parameter is determined by calculation of the energy content [MJ] from both the fuel

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[37] In this chapter all comparisons made on the results from the simulations with altered settings are with the results obtained from the simulation in which the original dataset was used. The simulation outcomes based on the original dataset are thus used as references.

consumption [liter/100km][38] and the energy throughput [kWh/100km][39], which are added to give the total energy parameter [MJ/100km]. Again, it may be worth mentioning that the parameters cannot be compared as to the total energy consumption but that the total energy is still included since, for both parameters, a lowering is considered to be beneficial and an increase negative.

Figure 6.1 and Figure 6.2 nedan show the energy throughput [kWh/100km] and fuel consumption [liter/100km] change as compared to the original settings (the black bar to the far left in the respective graphs). The values written alongside the bars represent this change in units of percent. When no value is written on the bars the changes are very small (less than 0.01 %) or nonexistent. Here the results are presented with a separate graph for each focal area. The results from the simulations of start SOC has been separated from the rest since these changes have not been done to the dataset parameters (see section 5.1.5 for further detail).

In the figures it can be seen that both the energy throughput of the battery and the fuel consumption of the internal combustion (IC) engine may vary with the tested settings. Further, the two parameters may increase or decrease independently of each other. A decrease of both parameters means less energy throughput in the battery and less fuel consumption, vice versa is true in the case of an increase.

Figure 6.1 shows graphs for the SOC target, SOC window, EM torque curve, and charge/discharge power. The SOC target graph shows that as the SOC target is increased by 5 units both the energy throughput and fuel consumption increase; by 2.59 % and 0.46 % respectively. As the SOC target is lowered the energy throughput decreases by 4.45 % while the fuel consumption increases by 0.08 %, which is a relatively small increase.

The SOC window graph shows an increase in both energy throughput and fuel consumption for a smaller SOC window; both for the case with a raised lower limit as well as for a decrease of both limits by totally 10 units (by 2.16% for energy throughput and 1.80% for fuel consumption, for both settings). Further it can be seen that two settings lower the energy throughput (by 2.82% and 2.89% respectively) and only slightly increase the fuel consumption (by 0.23% and 0.02% respectively), namely reducing the lower limit and increasing both the upper and lower limits by a total of 10 units. Both two cases correspond to a larger SOC window. Remaining are the alterations of only the upper limit by 5 units, up and down, which give no significant change neither in energy throughput nor in fuel consumption.

When it comes to the simulations with altered EM torque curves most settings resulted in quite small or insignificant changes in both parameters. Still it may be worth to mention some of these results in more detail. As the maximum EM torque is lowered to 90% both the energy throughput

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[38] The unit of [liter/100km] is used since it is common to denote reference values for fuel consumption of heavy-duty vehicles per 100 km.

[39] The unit for energy throughput is presented as kWh per 100 km so it corresponds to the fuel consumption values.

and the fuel consumption are decreased (by 0.19% and 0.03%). The opposite case, where the maximum EM torque is raised to 110% both parameters instead increase (by 0.29% and 0.01%). Three settings result in somewhat larger changes; 110% maximum added boost increased both energy throughput and fuel consumption by 1.04% and 0.07%. As for changes in the maximum added regeneration, a decrease (to 90%) resulted in less energy throughput (-2.31%) but more fuel consumption (+1.26%) while, in opposite, an increase (to 110%) resulted in a higher level of energy throughput (+1.64%) and less fuel consumption (-0.61%).

The last graph in Figure 6.1 depicts the results for the charge/discharge power simulations and shows decreases in energy throughput and small but not entirely insignificant increases in fuel consumption.

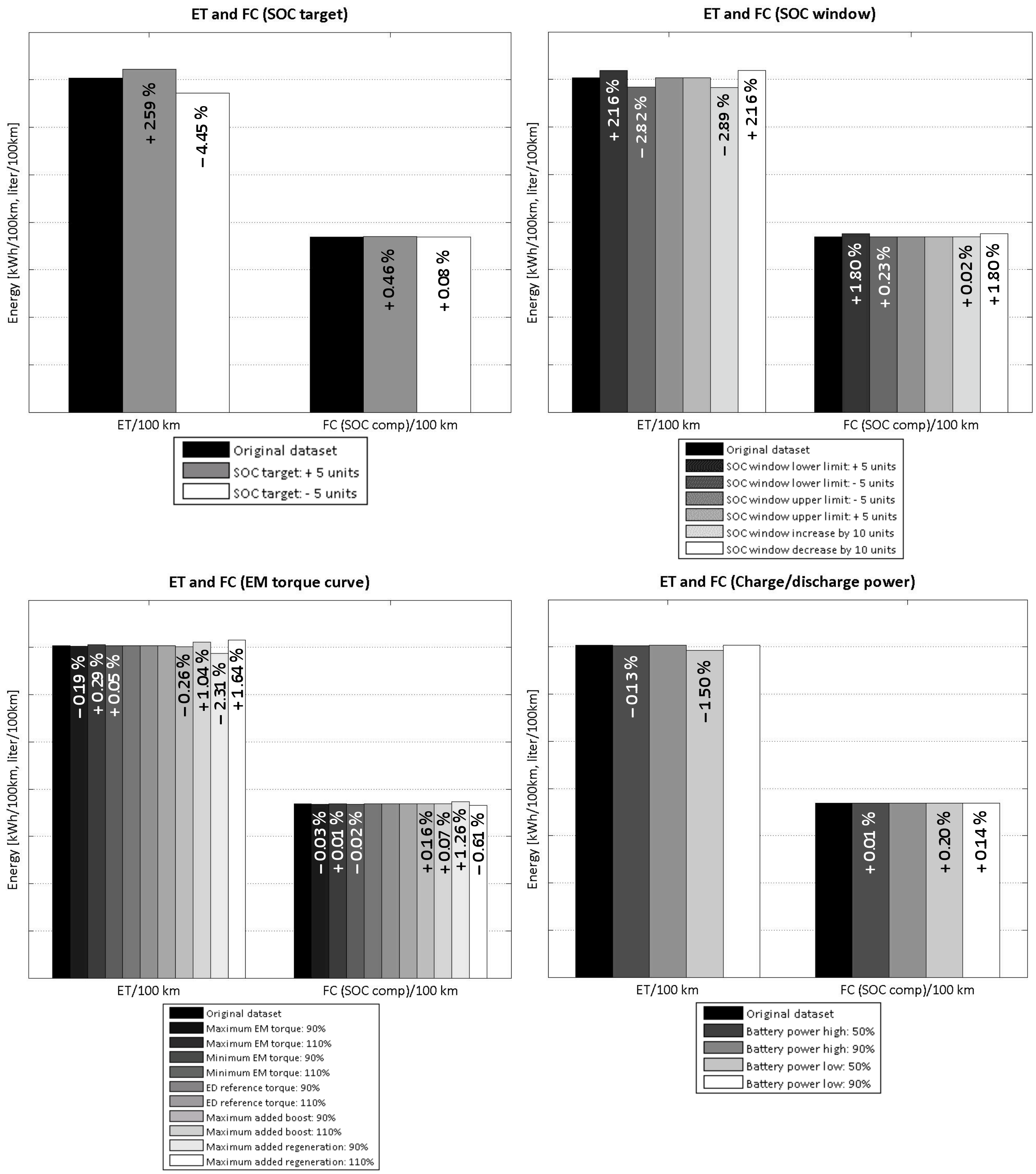

Figure 6.1 Graphs of the energy throughput and fuel consumption outputs for the first four focal areas. The different graphs represent the first four selected focal areas and the bars represent the various simulation settings. The black bar represents the results from the reference simulation and the values represent the change in percent relative to this reference. No value means that no significant change could be observed.

Figure 6.2 shows the energy throughput and fuel consumption in the cases where the start SOC has been either increased or decreased. In the case of a higher start SOC the energy throughput decreases by 2.79% but the fuel consumption increases by 0.61%. The opposite is true when it comes to a lower start SOC, energy throughput increases by 3.09% while the fuel consumption is lowered by 0.64%.

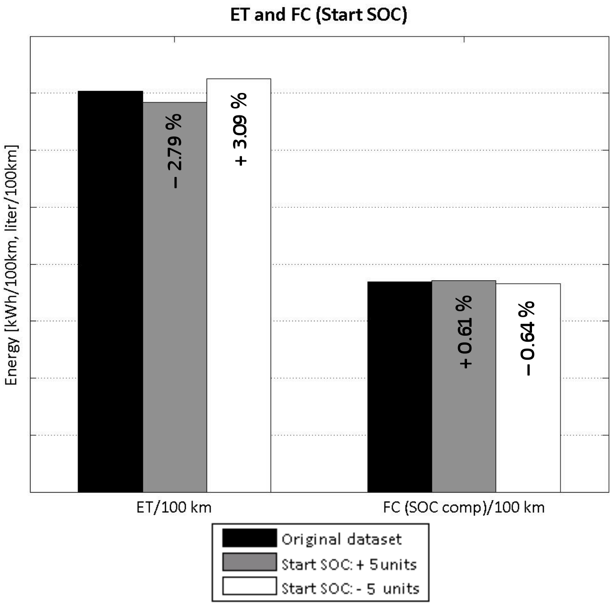

Figure 6.2 Energy throughput and fuel consumption outputs for the focal area of start SOC. The different bars represent the energy throughput and fuel consumption of the various simulation settings for the focal area *Start SOC*. The black bar represents the results from the reference simulation and the values represent the change in percent relative to this reference. No value means that no significant change could be observed.

It is also of interest to compare all results in one single graph as opposed to dividing them depending on focal area which is done in the two figures above. Figure 6.3 nedan shows the energy throughput [kWh/h][40] calculated from the simulation outputs for all different settings as well as for the original dataset. The axis does not start from zero[41], which is done to clarify the differences between the bars since the changes in energy throughput are more interesting than the absolute length of the bars. It can be seen that the energy throughput is lowered in nine cases and increased in the same amount of cases. Six simulations resulted in no change as compared to the energy throughput of the original dataset settings. The settings resulting in lower energy throughput are, in order of lowest to highest energy throughput savings, SOC target -5 units, SOC window increase by 10 units, start SOC increased by 5 units, lower limit of the SOC window lowered by 5 units, 90% maximum added regeneration, 50% battery power low, 90% maximum added boost, 90/ maximum EM torque and finally 50% battery power high.

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[40] The unit of kWh/h is used at Volvo Powertrain Corporation when it comes to providing guidelines and restrictions for energy throughput limit values.

[41] This is represented by the axis break in the lower left corner of the graph.

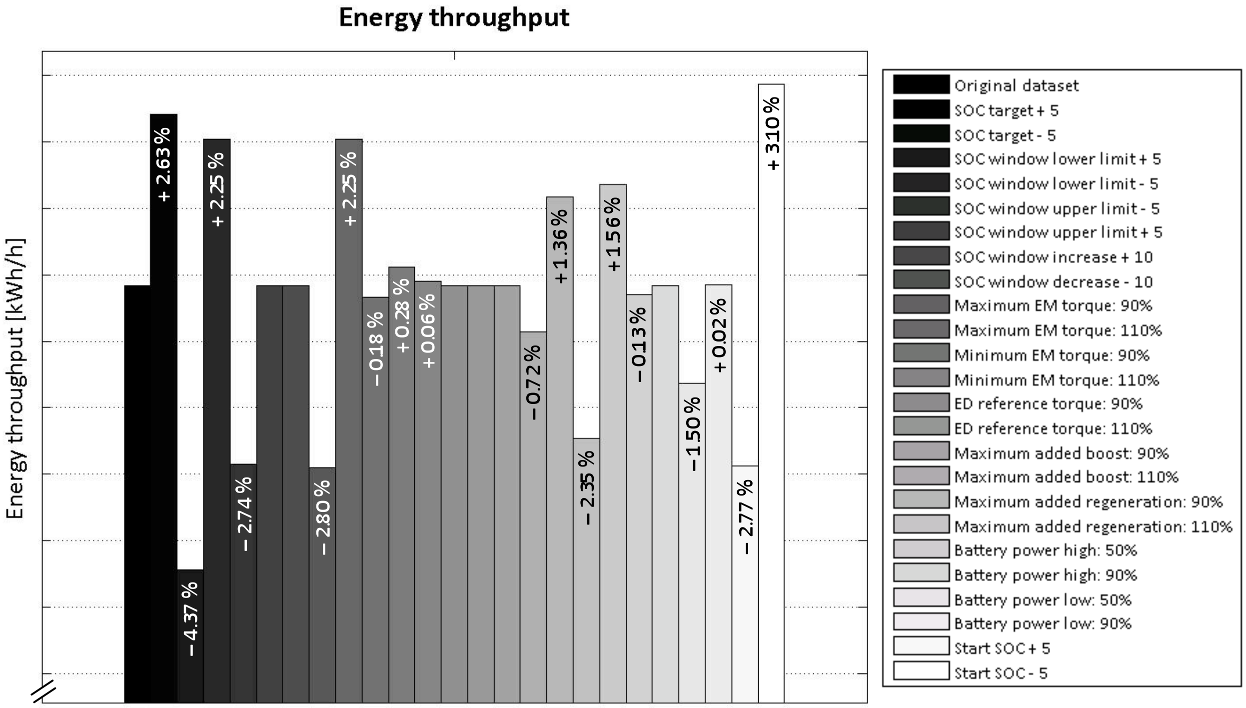

Figure 6.3 Energy throughput [kWh/h]. The black bar represents the results from the reference simulation and the values represent the change in percent relative to this reference. No value means that no significant change could be observed.

Figure 6.4 shows the bars of the calculated fuel consumption [liter/100km] for all the different simulations. As with the energy throughput graph in Figure 6.3 the axis does not either start from zero for the same reasons as mentioned before. It can be seen that most of the results are fairly similar to the reference simulation, though some indicate an increase in fuel consumption. Only two simulations, the first for the setting of increased maximum added regeneration (110%) and the other for lowered start SOC value (-5 units), show visible decrease in fuel consumption. All in all, four settings result in lowered fuel consumption. In addition to those previously mentioned; these are also 90% EM torque both maximum and minimum. As much as 14 settings resulted in worsened fuel economy while six resulted in no change at all.

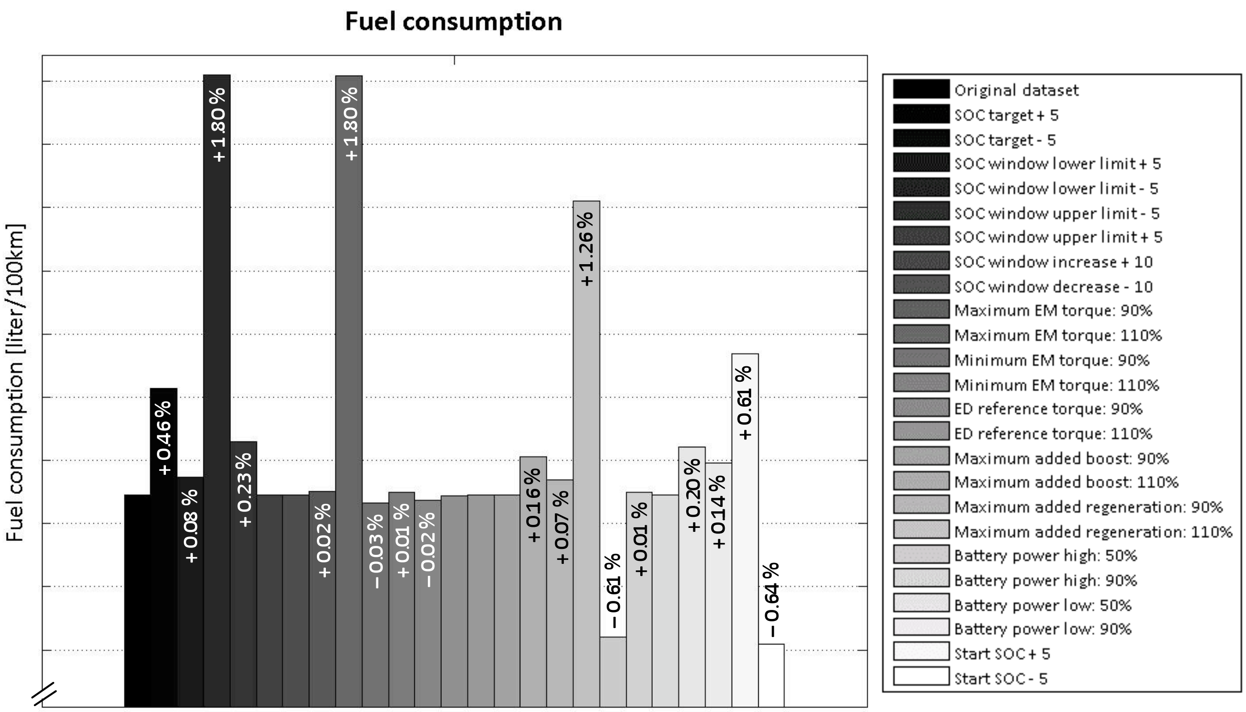

Figure 6.4 Fuel consumption [MJ/100km]. The black bar represents the results from the reference simulation and the values represent the change in percent relative to this reference. No value means that no significant change could be observed.

It is interesting to compare the two graphs of energy throughput and fuel consumption. For instance, both display six settings resulting in no change. As it happens, these are the same for both parameters, namely both increase and decrease by 5 units of the upper limit of the SOC window, 110% maximum EM torque, 90% and 110% ED reference torque, and 90% battery power high. Further, there is only one setting leading to reductions in both energy throughput and fuel consumption and that is 90% maximum EM torque. Six simulations show the opposite, worse results for both parameters. These are SOC target +5, increase of the SOC window lower limit by 5 units, decrease of both limits of the SOC window by a total of 10 units, 110% maximum EM torque, 110% maximum added boost and 90% battery power low.

In order to compare the relative gains or losses in energy throughput to those of the fuel consumption several different ways of calculating the relationship between the two parameters was used. The results of the first comparison will be presented here, while the results from two other comparisons will follow in a subsequent section.

First then, a calculation of the energy consumption in units of MJ/100km was made. The following two figures describe the outcome of these calculations. In Figure 6.5 the bars show whether the simulation settings either improved or worsened the energy throughput and fuel economy as compared to the original or reference settings. A value larger than zero indicates an increase and a value smaller than zero correspondingly a decrease. The figure shows the same results as does Figure 6.3 and Figure 6.4 but makes it easier to see which settings either reduce or increase the two parameters.

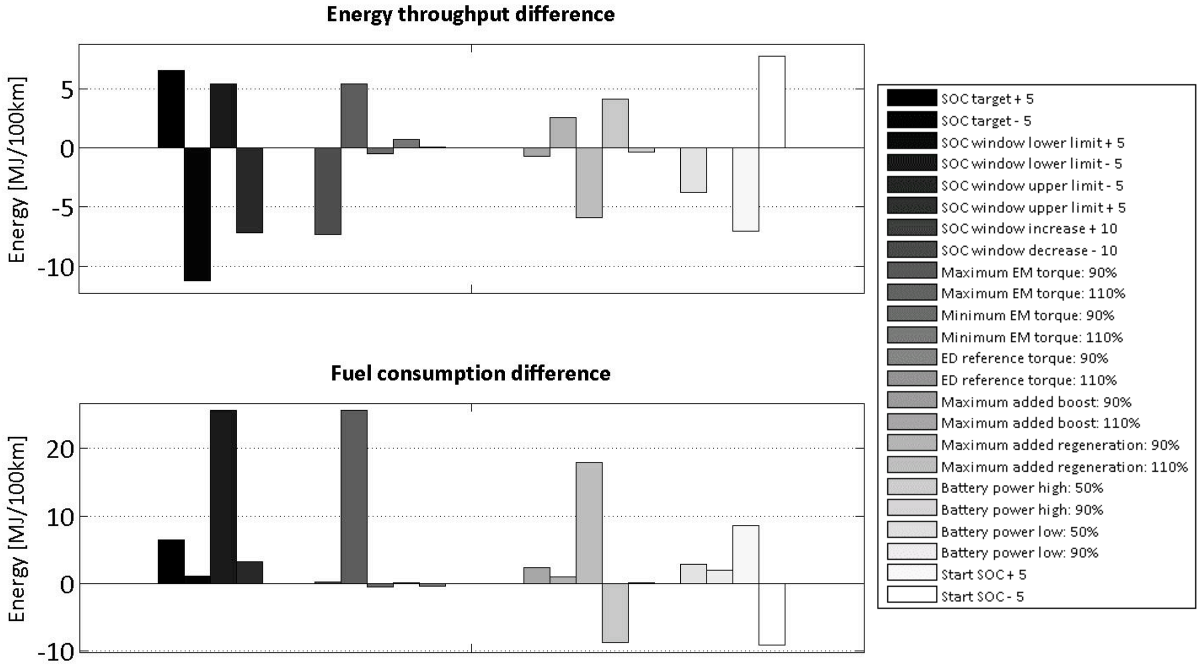

Figure 6.5 Difference in energy consumption for the altered settings compared to the reference dataset. The first figure shows the difference in energy throughput. A bar above zero indicates an increase and a bar below zero a decrease in energy throughput. The same is valid for the second graph, which shows the relative difference in fuel consumption.

Figure 6.6 shows the total energy difference, which is calculated as the difference between the total energy for the simulations with altered settings and that of the original dataset simulation. The bars thus represent the possible savings or losses in energy as compared to the original settings. As in the previous case a positive value indicates increased energy consumption whereas a negative value indicates potential savings. In total, 15 settings resulted in lower values of the energy sum than the original dataset settings.

The result of this calculation was to be used as a basis for the optimisation, and in order to limit the number of parameters to evaluate it was decided that only the simulations resulting in an absolute value of energy consumption savings larger than 0.1 MJ/100km would be included in the optimisation step. This resulted in a selection of nine different simulation settings, at least one from each focal area, evident from Figure 6.6, namely the following, presented in falling order of the magnitude of the total energy:

- SOC target -5
- SOC window increase +10
- Maximum added regeneration: 110%
- SOC window lower limit -5

- Start SOC -5
- Maximum EM torque: 90%
- Battery power low: 50%
- Minimum EM torque: 90%
- Battery power high: 50%

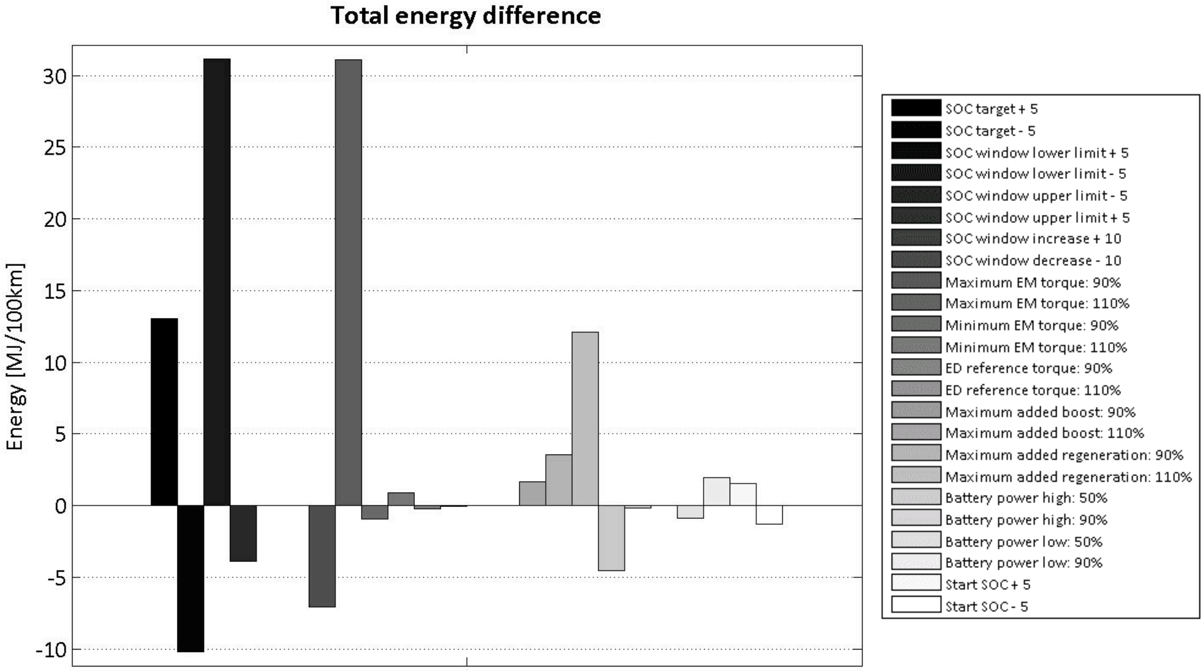

Figure 6.6 Total energy difference. The bars show the aggregated value of the energy i.e. the sum of the energy throughput and fuel consumption differences for the different simulations. A bar above zero indicates an increase and a bar below zero a decrease in total energy.

The results of the optimisation step will be presented in section 6.7 nedan.

6.2 State of health

The state of health (SOH) of an energy storage system, in this case the battery, is a parameter important to study since it conveys information on the life length of the ESS. The SOH is related to various factors such as for instance energy throughput (for further detail, see section 2.2.2 above). SOH will decrease continuously as the battery is used, inevitably heading for the end of the battery life. In this case the various simulation settings give rise to SOH curves with different slopes. It is perhaps not as interesting to study the changes of SOH with time as it is to see how the different settings affect the SOH decline as compared to the SOH decline of the original dataset settings. This is thus presented in the following figure; Figure 6.7 describes how much, in percent, the various settings either lead to a decreased or an increased change of SOH loss. The results are calculated using equation (10), which means that a value above zero implies an improved SOH curve while the opposite is true in the case of a negative value. From the figure it can be seen that 11 settings resulted in improved SOH change, 7 in worsened and 6 (the same as previously, for energy throughput and fuel consumption) in no change.

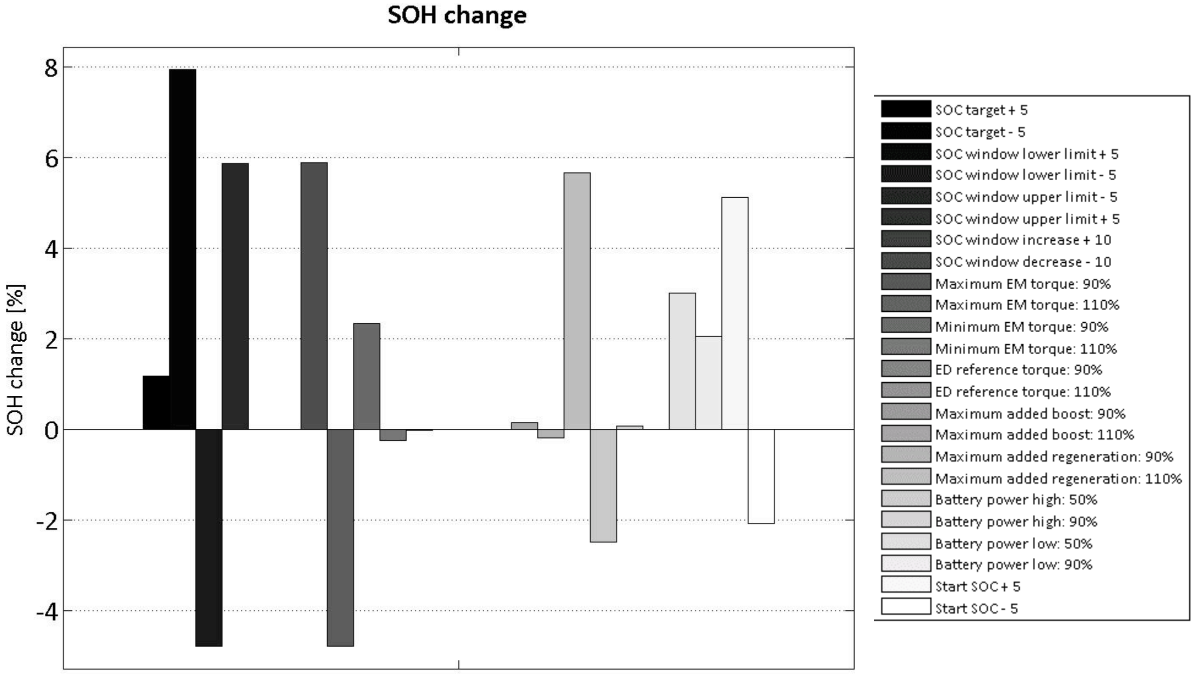

Figure 6.7 SOH change relative to the original dataset SOH change. A bar extending above zero indicates an improved SOH change, while a bar below zero indicates a turn for the worse in terms of battery life time as compared to the original dataset SOH.

6.3 State of charge

The state of charge (SOC) in a battery reflects the level of charge a battery carries at the moment. The parameter is described in further detail in section 2.2.3 above. When it comes to visualisation of the results the same is valid in the case of SOC as in the case of SOH. It is perhaps not that interesting to study the changes of SOC with time. These curves change very little compared to the original dataset SOC curves for the focal areas EM torque curve and battery charge/discharge curve. The other three focal areas all involve direct changes of SOC parameters, which has direct consequences for the SOC curves. Still, to give an idea of what the SOC curves may look like they are presented in the figure nedan, see Figure 6.8. The graphs are shown without legends since the purpose is not to show the results in detail but to give a general idea of the appearance of the SOC curves.

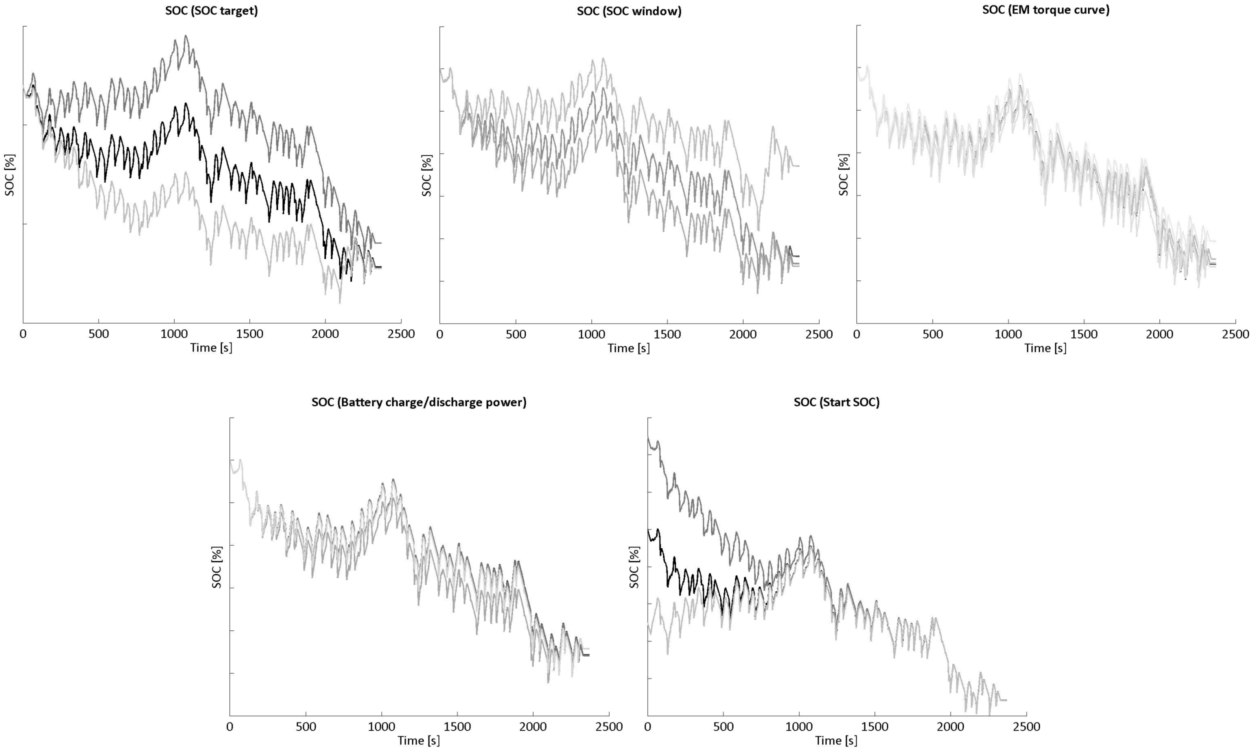

Figure 6.8 SOC curves. The different graphs show the SOC variations with time during a complete duty cycle.

There are many other ways to visualise battery SOC. One way is to make histograms of the SOC to show how long time the SOC stays at different levels of charge during the duty cycle. The figures[42] below show such histograms. The SOC histogram for the original dataset has been included in the above every column of graphs to facilitate visual comparison.

Figure 6.9 shows the SOC histograms for the simulations where the SOC target has been altered. It is evident from the figure that as the SOC target is increased the SOC stays at higher levels of charge for a longer time and vice versa for the case when the SOC target is decreased as compared to the original dataset.

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[42] A histogram is a graphical way of showing how large proportion of the studied parameter (on the y-axis) that belongs to a certain category (the x-axis), and is a way of depicting data density. The bars in the histogram may be of varying width. This is because the width has not been set as constant but rather the number of bars (10 bars per histogram).

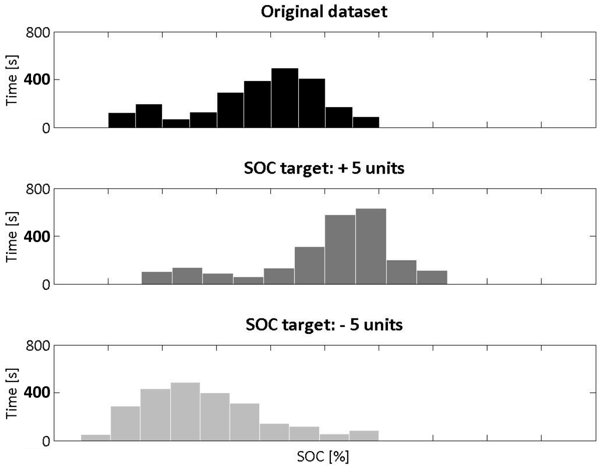

Figure 6.9 SOC histograms for the focal area SOC target. The histogram shows at which values the level of battery charge is during a duty cycle; the bar height indicate how often the charge level is at a certain SOC.

Figure 6.10 shows the SOC histograms for the simulations done when altering the SOC window. From the figure it can be seen that as the upper limit of the SOC window is changed the resulting SOC histograms are the same as for the original dataset. This correlates to the results obtained for energy throughput and fuel consumption above. Different results are found for the cases in which the lower limit has been altered. The shape of the histogram for an increase in the SOC window, either by lowering the lower limit by 5 units or by increasing both limits by totally 10 units are roughly the same. Furthermore, by comparison to the original dataset it can be seen that the SOC is more evenly spread for the two altered cases. Also the two histograms where the lower limit has been raised to a higher level either by raising the limit by 5 units or by decreasing both limits have roughly the same distribution. The SOC is here more concentrated around higher values of SOC than for the original dataset.

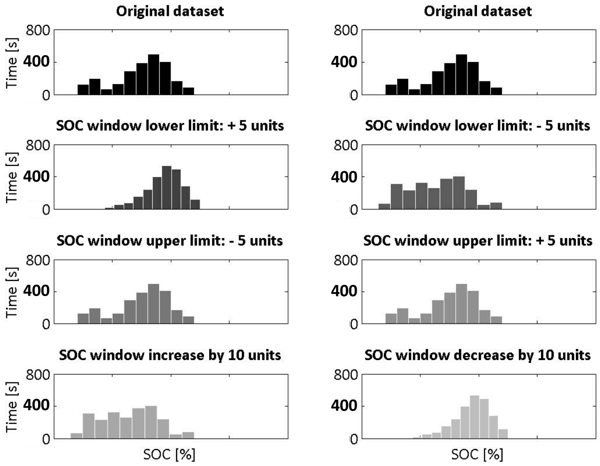

Figure 6.10 SOC histograms for the focal area SOC window. The histogram shows at which values the level of battery charge is during a duty cycle; the bar height indicate how often the charge level is at a certain SOC.

Figure 6.11 shows the SOC distribution for the alterations related to the EM torque curve. As far as can be seen all histograms are similar, to each other as well as to the histogram of the original dataset.

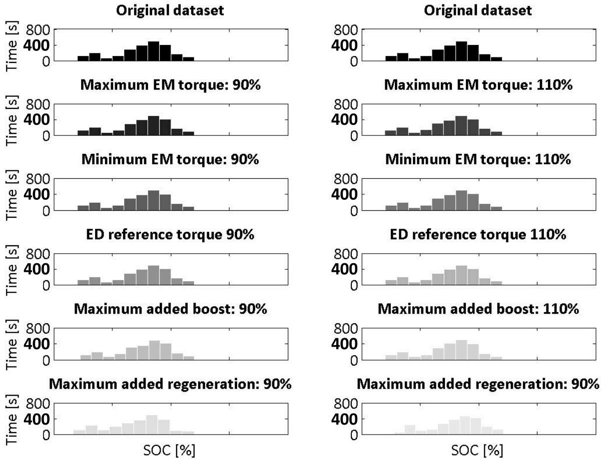

Figure 6.11 SOC histograms for the focal area EM torque curve.

Figure 6.12 shows the histograms for the focal area charge/discharge power. Also in this case it is evident that most curves are similar to the original dataset, with one exception; as the low battery power is decreased to 50% of its original value the SOC distribution becomes more even and less bell shaped than the other curves. It further implies that the SOC is more often at lower levels than for the other cases.

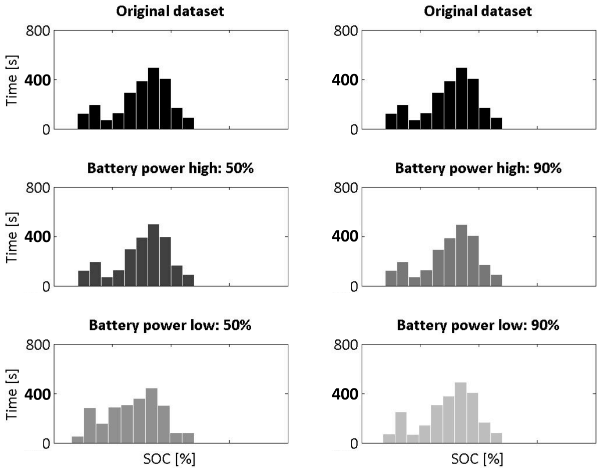

Figure 6.12 SOC histograms for the focal area charge/discharge power. The histogram shows at which values the level of battery charge is during a duty cycle; the bar height indicate how often the charge level is at a certain SOC.

Finally, Figure 6.13 shows that as the start SOC is changed, the SOC level spreads out more over a wider range for an increased start SOC and that the histogram for a decreased start SOC is fairly similar to that of the original dataset.

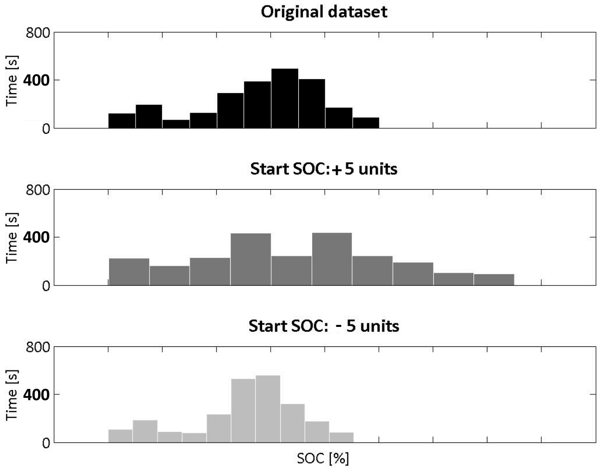

Figure 6.13 SOC histograms for the focal area start SOC. The histogram shows at which values the level of battery charge is during a duty cycle; the bar height indicate how often the charge level is at a certain SOC.

6.4 Powertrain modes

There are several different so-called powertrain (PT) modes for vehicle operation as explained in section 2.2.4 above. These decide the configuration by which the vehicle is to be propelled. Examples of such modes include for instance the start-up mode as the key is turned and the so-called *electric only* mode when the vehicle is provided by torque from the EM alone, for example during take off. All modes are not relevant to present in the context of this thesis; some are never used, and some, such as the previously mentioned start-up mode, are mandatory and thus equal for all different dataset settings. The following five figures show the amount of time that is spent in the various modes during a duty cycle. Like for the first two figures of this chapter the results are presented with separate graphs for each focal area and the results from the simulations of start SOC has again been separated from the rest.

Both Figure 6.14 and Figure 6.15 below show that the time is mainly spent either in the electric or in the hybrid mode. A shorter time is spent with both the EM and the diesel ICE idling in the *electric/diesel idle* mode. On the whole it is clear that the time the vehicle spends in the different modes does not change dramatically as compared to the original dataset simulation in any case. Still, some differences are noteworthy. Perhaps the most evident change happens in the two cases of SOC window lower limit +5 units and decreased SOC window by 10 units. Here a fourth PT mode is introduced, namely the *charge at standstill* (C@SS) mode. As explained previously this mode is undesirable since it the efficiency at C@SS is very poor and it causes the diesel engine to run during stops. Further it can be noted that while the idling phase stays fairly constant an exchange is made between the electric and the *hybrid* modes. As one is increased the other decreases by more or less the same amount of time and vice versa. It appears there is a correlation between these to modes.

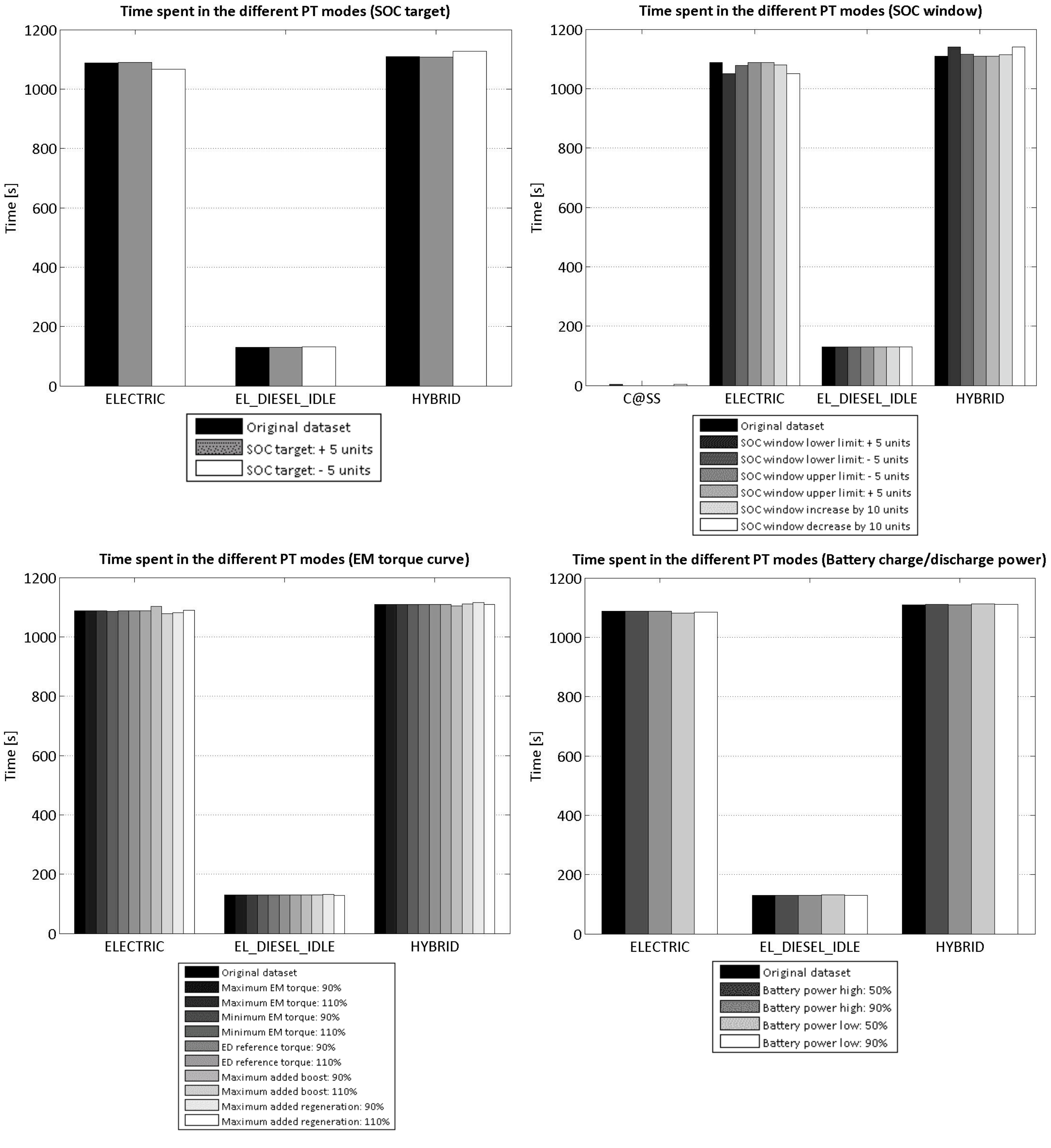

Figure 6.14 Time spent in the different PT modes for the first four focal areas. The graphs represent the first four selected focal areas and the bars represent the various simulation settings. The black bar represents the results from the reference simulation included for comparison. No value means that no significant change could be observed.

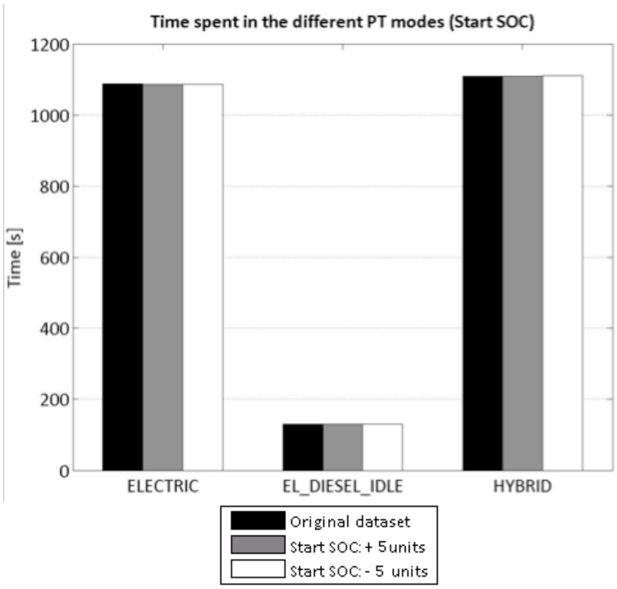

Figure 6.15 Time spent in the different PT modes for the focal area of start SOC. The different bars represent the energy throughput and fuel consumption of the various simulation settings for the focal area *Start SOC*. The black bar represents the results from the reference simulation included for comparison.

6.5 Analysis of costs and environmental impact

Other comparisons between the outcome of the energy throughput and fuel consumption have been made, apart from the previously presented energy comparisons. Both cost analysis and environmental impact comparisons are highly relevant and interesting for the aim of this project. These two analyses have been described in section 5.2.6 above, and the results will be presented below.

6.5.1 Cost analysis

The results of the battery cost analysis shows that the vehicle could travel a distance of approximately 2 000 000 km[43] before the battery SOH is reduced to 80 %. It is important to note that battery replacement is very expensive[44]. The cost per 100 km for both the battery and the diesel fuel per 100 km has also been calculated. The results show that the fuel cost is more than 150 times higher per 100 km than the corresponding cost of the battery. What is interesting though is the comparison between the costs associated with the original dataset and those associated with the altered dataset simulations. The cost analysis thus also includes a calculation of the relative costs for the battery and the diesel fuel respectively as compared to the costs of driving using the original dataset as well as a comparison of the aggregated cost for both energy sources.

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[43] This corresponds to just over 2 years of driving 24 hours a day at a speed of 100 km/h.

[44] Personal communication with Jens Groot, PhD student at Chalmers University of Technology and R&D engineer at Volvo Technology, September, 2009.

Figure 6.16 shows the results of the comparison of costs for the respective energy sources as compared to those of the original dataset. The bars extending above zero indicate the potential costs savings as compared to the original dataset costs. The variable alterations resulting in increased battery cost (bars below zero in the graph indicating the value of the loss) are the SOC target alterations, for the SOC window lower limit lowering and upper limit increase (both by 5 units), for the 110 % maximum EM torque, 110 % maximum added boost, and 110 % maximum added regeneration. Also all battery power alterations except 90 % battery power high indicate lower battery costs as well as the lowering of the start SOC. Six simulations indicate higher battery costs than the original dataset; SOC window lower limit +5 units and upper limit -5 units, 90 % maximum EM torque, 110 % minimum EM torque, 90 % maximum added boost (the three latter show very small cost increase), 90 % maximum added regeneration, and also a raised start SOC. The other simulations show no change in battery cost as compared to the corresponding original dataset costs.

Considering the cost difference for the diesel fuel, most simulations indicate increased costs; up to more than 1 USD/100 km in loss. Several simulations indicate no change in fuel cost, or small savings as can be seen in the graph. These are alteration of the SOC window upper limit and SOC window increase of both limits, all alterations of both maximum and minimum EM torque as well as both alterations of the ED reference torque, 110 % maximum added boost, and also both alterations of the battery power high. The two simulations resulting in cost savings when it comes to fuel consumption are 110 % maximum added regeneration and a lowered start SOC.

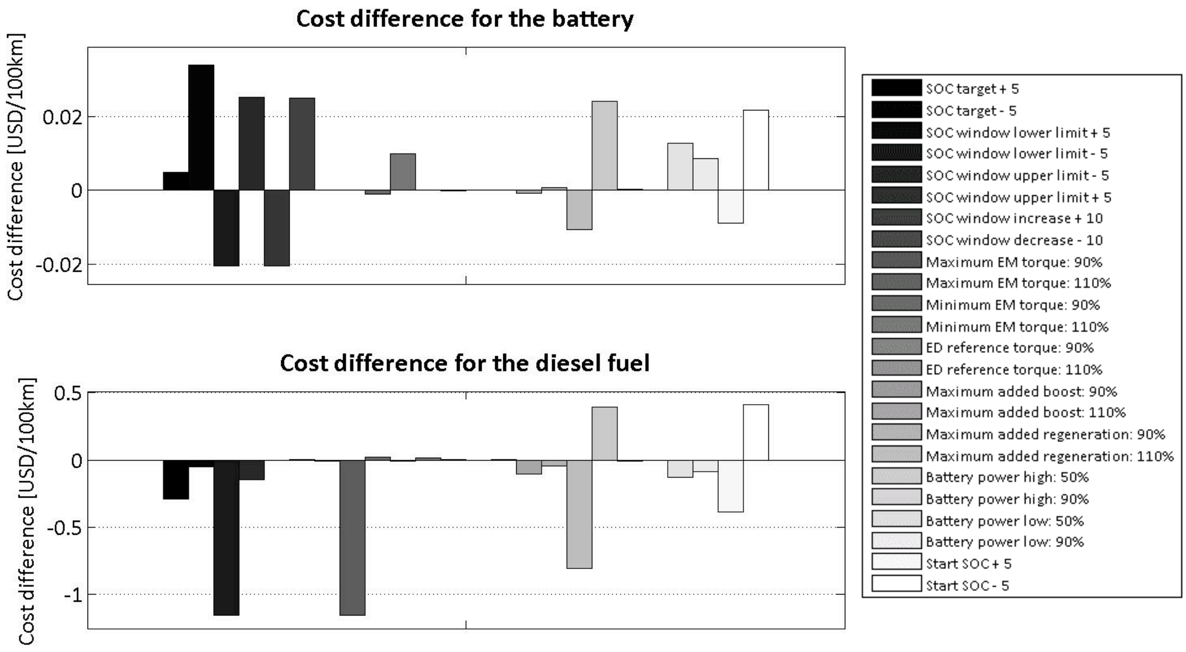

Figure 6.16 The cost difference as compared to the costs of the original dataset. The figure shows the cost savings (bars above zero) and losses (bars below zero) for both the battery and the diesel fuel.

Figure 6.17 shows the results of the comparison of total or aggregated costs for both energy sources as compared to those of the original dataset. This graph is perhaps even more interesting than the previous two. It shows that most alterations indicate larger costs. A few simulations show no change of the total costs; both alterations of the ED reference torque and 90 % battery power high. The simulations resulting in cost savings are all alterations of both maximum and minimum EM torque, the cost savings are relatively small for these, larger yet for 110 % maximum added regeneration and start SOC -5.

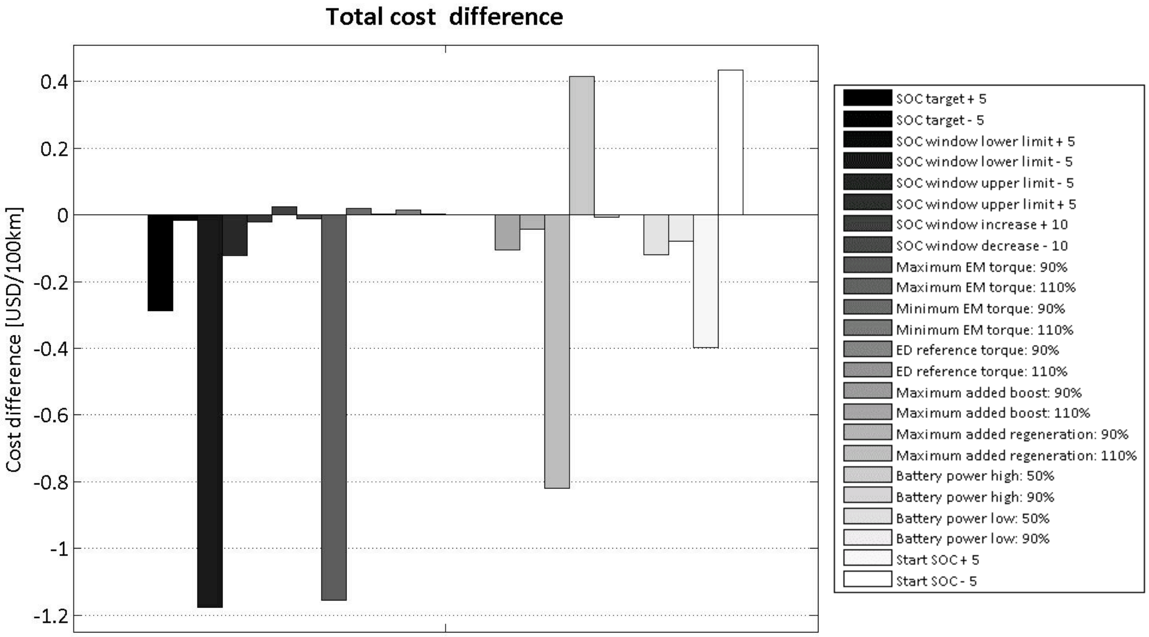

Figure 6.17 The total cost difference as compared to the total costs of the original dataset. The figure shows the cost savings (bars above zero) and losses (bars below zero) for the aggregated sum of both the battery and the diesel fuel costs.

6.5.2 CO_2 emissions analysis

A life cycle analysis is, as previously mentioned, a good way of studying the total environmental impact of a product. In this study a limited environmental analysis has been performed, which focuses on CO_2 emissions. Calculation of these emissions associated with the battery and with the diesel fuel over the entire lifetime of the two products has been performed. The difference between the emissions for the simulations with altered variables and the simulation with original dataset settings have also been calculated. Also, calculation of the total CO_2 emissions i.e. the sum of the battery and diesel fuel emissions have been made, as well as a corresponding total CO_2 emission difference calculation with comparison to the original dataset emissions.

Figure 6.18 shows the CO_2 emissions from the battery use and from the diesel fuel use [$kgCO_2$/100 km]. The emissions from the diesel fuel used for vehicle propulsion are slightly higher than those of the battery use. Further, it is worth to mention that the much of the emissions associated with battery use can be attributed to the diesel fuel used to charge the battery. The uppermost graph shows that the emissions from the battery use are affected to a greater extent than the same simulations for the diesel fuel by the first few alterations of SOC target and SOC window.

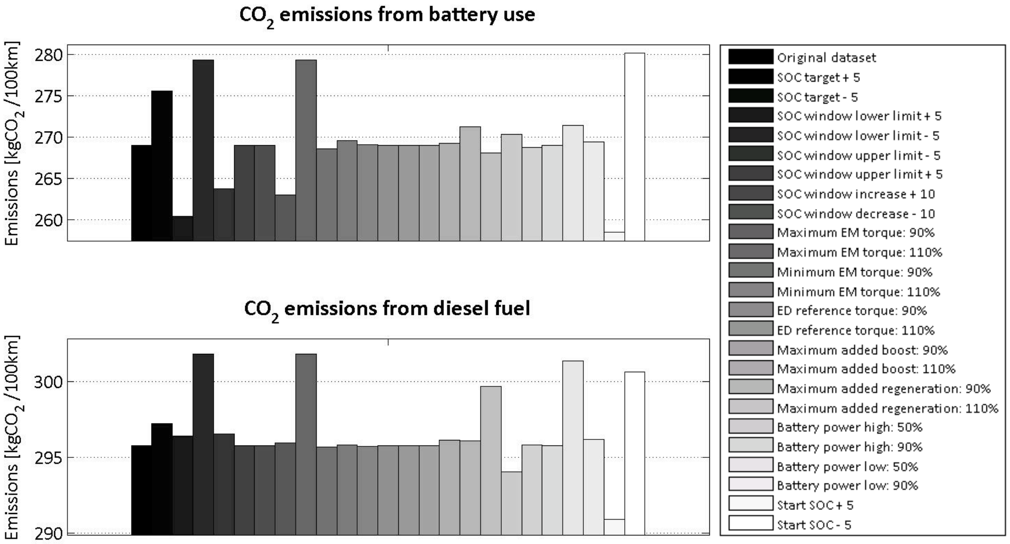

Figure 6.18 CO_2 emissions associated with the battery and diesel fuel lifetimes. The emissions are calculated as [kgCO_2/100 km] and presented for all simulations.

Figure 6.19 shows the difference in CO_2 emissions. The trends are the same for both the battery and the diesel fuel. The parameter start SOC +5 results in significantly lowered emissions for both the battery and the diesel fuel use.

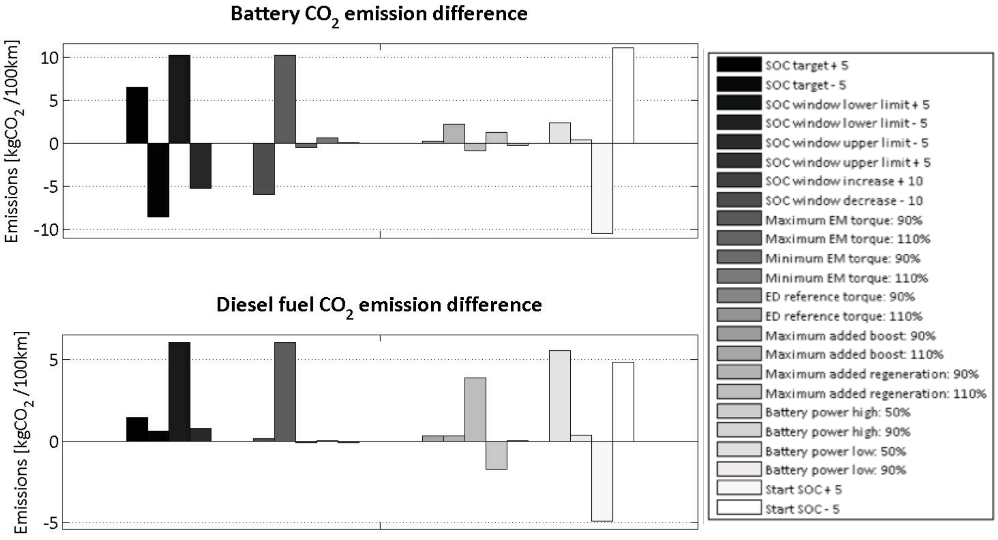

Figure 6.19 CO_2 emission difference for the battery and diesel fuel. The graphs show the difference in emissions between the simulations with altered variables and those of the simulation with original dataset settings. A bar below zero indicates a reduction of CO_2 emissions while a bar above zero indicates an increase. No visible bar means no significant difference.

Figure 6.20 shows the sum of the emissions for the battery and diesel fuel use. Since the patterns for both products are fairly similar the total emissions also show the same trends. The emissions are all in the region of 560 kg CO_2 per 100 km. The difference in CO_2 emissions is shown more clearly in the next figure where the emissions of the simulations with altered variables are compared to those of the original dataset simulation.

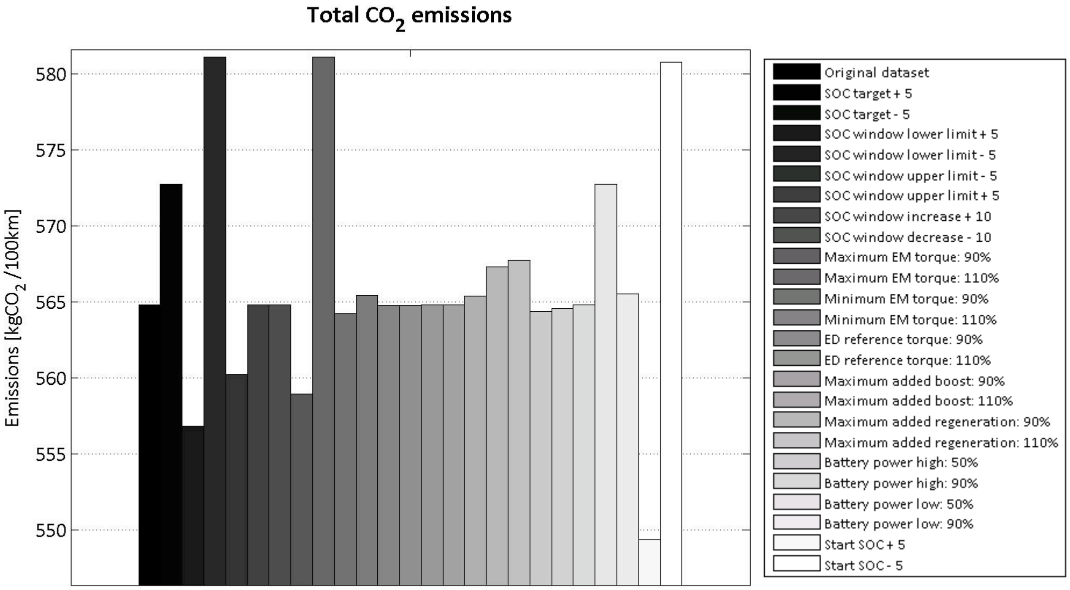

Figure 6.20 Total CO_2 emissions associated with the sum of the battery and diesel fuel emissions. The emissions are calculated as [$kgCO_2$/100 km] and presented for all simulations.

Figure 6.21 below shows the difference in total CO_2 emissions. Here it is evident that SOC target -5, SOC window lower limit -5, SOC window increase +10, and start SOC +5 reduce the total CO_2 emissions significantly. Four additional simulations indicate slightly decreased emissions; 90 % minimum EM torque, 90 % maximum EM torque, 110% maximum added regeneration, and 50 % battery power high. However, most simulations result in increased emissions; a few result in unchanged amounts. The latter are the alterations of the SOC window upper limit, 110 % minimum EM torque, both alterations of the ED reference torque, and finally 90 % battery power high.

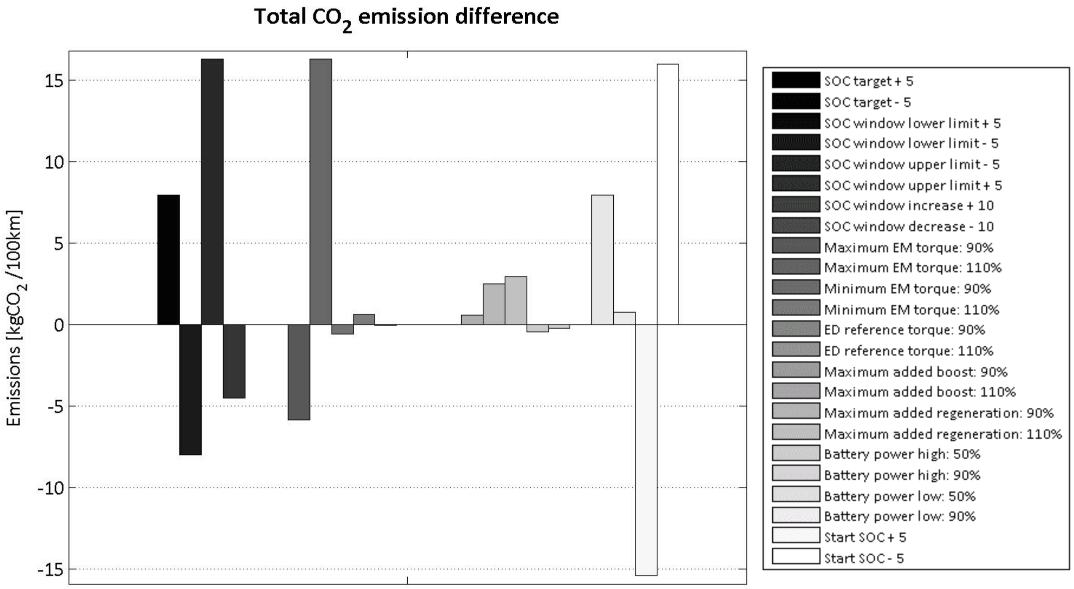

Figure 6.21 Total CO$_2$ emission difference. The graph shows the difference in emissions between the simulations with altered variables and those of the simulation with original dataset settings. A bar below zero indicates a reduction of CO$_2$ emissions while a bar above zero indicates an increase. No visible bar means no significant difference.

6.6 Performance and drivability

When it comes to measuring or estimating the vehicle performance and drivability from software simulations there are many different ways to accomplish this. Drivability is very hard to estimate. As previously mentioned, the best, but still quite subjective, way of measuring drivability is by taking the actual vehicle for a ride. Since this has not been performed, instead, drivability will be estimated by the calculation of several parameters.

When it comes to vehicle speed, two parameters were calculated, namely the average speed and the percentage in which the actual speed differs from the demanded speed by more than 3 km/h. The results from the calculations of average speed are shown in Figure 6.22 nedan. From the left hand side graph it can be seen that the average speed is similar for all simulations, around 21.4 km/h and all less than 0.35% different from the original dataset average speed. When, on the other hand, studying the enlarged, right hand side graph some small differences can be discerned. The largest differences in average speed can be seen in the two cases where the maximum added boost has been altered. As the boost is decreased to 90% the average speed decreases (to 21,08 km/h or 98.7% of the original dataset average speed) and conversely, as the boost is increased to 110% the main speed also increases to 21,55 km/h or 100.87% of the original dataset average speed).

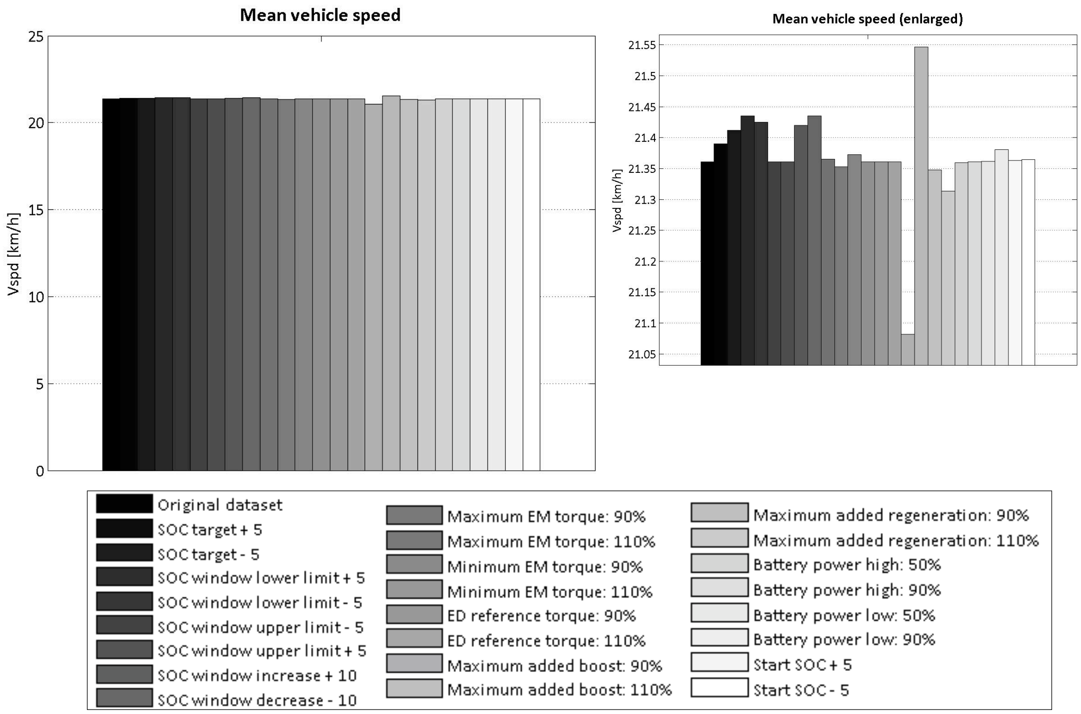

Figure 6.22 Average speed. The graph to the right is an enlargement of the left hand graph depicting the same thing but in closer detail for clarification. N.B. that the axis of the enlarged graph does not start from zero.

Further, calculations of the percentage difference between the actual and the demanded speed were made. The actual vehicle speed is never exactly the same as the demanded vehicle speed, but the simulation model of the driver is constructed so that when the vehicle is slower than the demanded speed the driver will try to compensate or catch up by driving faster after the period of slow speed. This is exemplified in Figure 6.23 nedan, which clearly shows how the speed oscillates between too slow (below zero) and too fast (above zero).

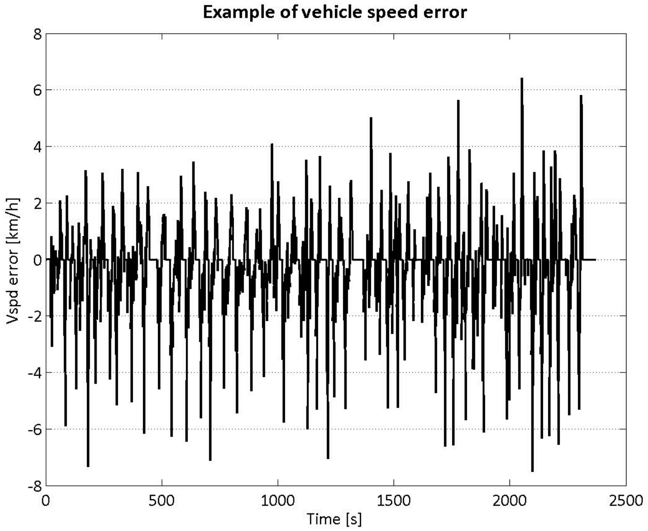

Figure 6.23 Example of vehicle speed error for the original dataset simulation. The figure shows the constant fluctuations in vehicle speed as the driver tries to correct for differences in demanded and actual vehicle speed.

When it comes to drivability, what will be noticeable while driving is the occasions when the vehicle cannot deliver enough torque to meet a certain speed request from the driver. This is measured by calculating the percentage of the time when the actual vehicle speed is 3 km/h below the demanded speed. Figure 6.24 nedan shows this time percentage, named error percentage, for the different simulations. As is evident from the graph on the left hand side, all simulations, including that based on the original dataset, demonstrate a lack of consistency when it comes to the demanded and actual speed. The main issue here is whether the altered settings give rise to improved or worsened conformity, but it is also interesting to note that the original dataset is more than 3 km/h slower than the demanded speed in about 3.9% of the total time of duty cycle.

As can be seen in the right hand side graph the altered settings improve the drivability when it comes to speed conformity as compared to the original dataset in most cases. A total of five cases worsen the error percentage, four only slightly (equal to or less than 0.01%). These are 90% maximum EM torque, 90% minimum EM torque, 50% battery power high, and start SOC +5. The case where the error is increased by 2.1% is for 90% maximum added boost. Four cases result in an error equal to that of the original dataset, namely the changes of the SOC window upper limit (both by -5 and +5) and ED reference torque (both 90 and 110%). The rest, i.e. 15 cases, resulted in improved error percentages. Notably, 110% maximum added boost resulted in 1.2% improvement. The second and third best were 90% maximum added regeneration (-0.46%) and SOC window lower limit -5 (-0.45%). The remaining improved the error by between 0.002 to 0.27%.

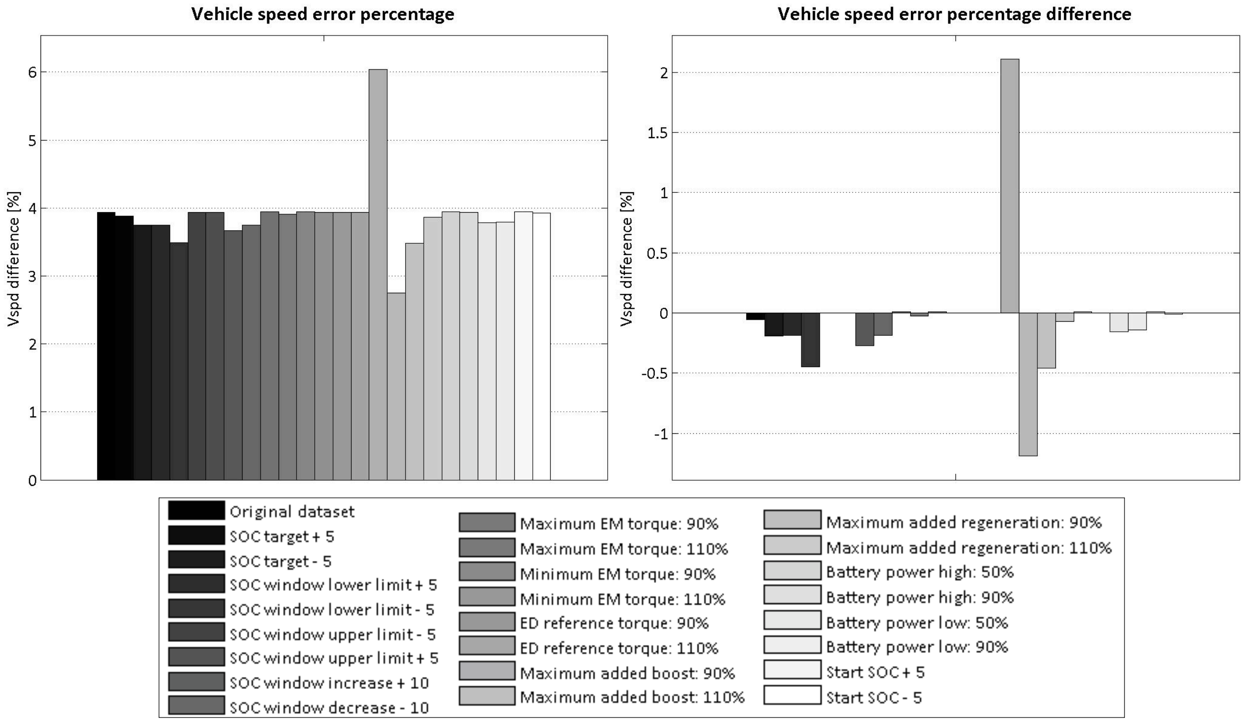

Figure 6.24 Vehicle speed error percentage. The left figure shows the error [%] for each simulation including the original dataset simulation. The right figure shows a comparison between the original dataset and the altered settings. A value of zero (no visible bar) means no difference in error percentage from the original dataset. A value above zero means a larger error while a value below zero indicates a smaller error than the original dataset simulation.

The smoothness of the drive is illustrated by the number of gearshifts. The comparison is made to the number of gearshifts of the original dataset simulation, which was 242. The calculations showed that most simulations gearshifts resulted in the same number of gearshifts, i.e. 242. Six simulations resulted in more gearshifts, meaning that the drivability for these settings is worse than for the original dataset settings, at least when it comes to this parameter. These settings are SOC target -5 (245 gearshifts), SOC window lower limit -5, (245 gearshifts), SOC window upper limit + 5 (245 gearshifts), 110% maximum added boost (247 gearshifts), 110% maximum added regeneration (244 gearshifts), and 50% battery power low (245 gearshifts). Only one simulation resulted in a lower number of gearshifts; the setting of 90% maximum added boost resulted in 241 gearshifts.

6.7 Optimisation

The outcome of the simulations presented in the sections above indicated that certain dataset settings resulted in lower total energy calculated as described in section 5.2.6. The selection of which parameters to optimise was made based on the total energy savings as compared to the results from the simulation based on the original dataset settings. The settings that resulted in savings larger than 0.02 MJ/100 km were included in the optimisation step. These are listed again below:

- SOC target -5
- SOC window increase +10
- Maximum added regeneration: 110%
- SOC window lower limit -5
- Start SOC -5
- Maximum EM torque: 90%
- Battery power low: 50%
- Minimum EM torque: 90%
- Battery power high: 50%

The settings used in the optimisation step were chosen based on the previous simulation outcomes; on the values of total energy savings and the SOH change (both as compared to the results from the simulation based on the original dataset settings), calculated with equation (10), see section 5.2.3 above. The simulations settings were thus continuously altered until either the total energy savings or a drastically changed SOH indicated that the setting no longer led towards a more optimal simulation outcome. The optimisation simulation results for total energy, energy throughput, fuel consumption, and SOH are presented in appendix C.

The optimisation process finally resulted in one setting that improved the total energy the most for each selected test case. These settings are named the *best* settings and are presented in the list below:

- SOC target -9
- SOC window increase +48
- Maximum added regeneration: 205%
- SOC window lower limit -24
- Start SOC -4
- Maximum EM torque: 1%
- Battery power low: 10%
- Minimum EM torque: 90%
- Battery power high: 35%

In the case of 90% minimum EM torque the optimisation procedure showed that this setting, i.e. the first alteration, was the best among those tested. The results from the simulations based on this setting have are presented above, why this setting is not included in the optimisation result presentations following in this section.

Figure 6.25 nedan shows the final results of the total energy calculations for the remaining eight so called best cases. The graph shows that six cases resulted in significantly improved values of the total energy while two cases, namely start SOC -4 and 35% battery power high, only resulted in minor improvement of this parameter (-1.75 and -0.80 MJ/100 km, respectively). Three cases showed improvements of approximately 35 MJ/100 km. These are target SOC -9, SOC window increase by +48 units, and SOC window lower limit -24. The setting that showed the most improvement in total energy is increased maximum added regeneration by 205%. The total energy savings in this case amounts to 68.3 MJ/100 km.

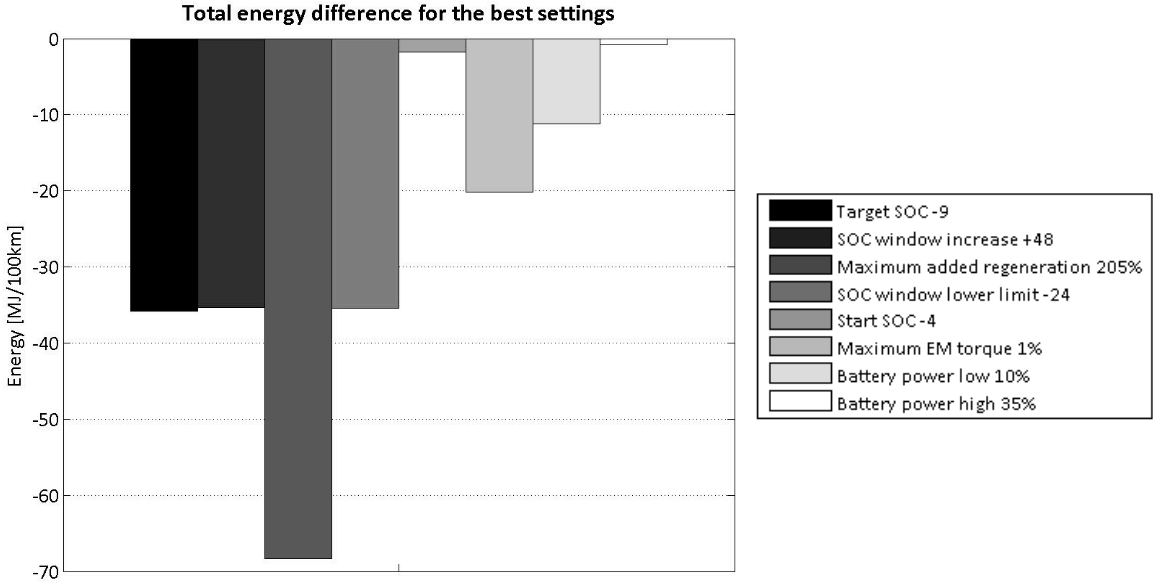

Figure 6.25 Total energy difference for the so-called *best* settings. The graph shows the calculated energy saving [MJ/100 km] as the sum of the energy throughput and fuel consumption compared to the original dataset.

In a few of the cases there was some ambiguity as to which result should be considered the best of the different settings. This ambiguity arose when the total energy savings and the SOH change were not both increasing for a simulation.

For the case of alterations of the start SOC, there was some ambiguity as to which of the three cases -8,-7, and -4 that gave rise to the most optimal energy savings considering also the SOH change. Start SOC -8 gave the most energy savings (-3.35 MJ/100 km) but also the worst SOH change from the original dataset (-7.19%). A start SOC of -4 gave the least energy savings of the three (-1.75 MJ/100 km) but instead the least bad SOH change (-2.13%). A start SOC of -7 gave a result in between the two previously mentioned (-2.61 MJ/100 km and -5.79%). It was decided that the most optimal results were obtained from start SOC -4 since it was estimated that an SOH deterioration of 5% or more was not acceptable.

Further, the settings corresponding to a maximum EM torque of 0% proved to be more optimal than 1% as regarding to total energy savings but since the difference was very small (1.7 MJ/100km) and the SOH change was better for the 1% case, this was selected as the more optimal one.

It was decided that the optimisation tests should be terminated either when the vehicle could not complete the duty cycle (this was evident from the calculation of the simulated length of cycle) or when the vehicle was unable to reach the demanded speed (evident from the simulated actual torque). This was also manifested in the SOH, which either dramatically decreased or did not decrease at all compared to the SOH from the original dataset.

Below the results for the above-mentioned nine best cases will be presented and studied in more detail.

6.7.1 Energy throughput and fuel consumption

Figure 6.26 nedan shows the resulting energy throughput and fuel consumption difference for the above mentioned eight best cases[45]. It can be seen that the greatest differences (up to a reduction of 99.6 MJ/100 km) are achieved for energy throughput. Further, it can be seen that most results show decrease of the parameter. Only two cases lead to increased energy throughput, namely maximum added regeneration of 205% (by 31.27 MJ/100 km or 8.69 kWh/100 km) and a start SOC of -4 (by 6.22 MJ/100 km or 1.73 kWh/100 km). Three cases; target SOC -9, SOC window increase by +48 units, and SOC window lower limit -24, show reduction in energy throughput of about 42 MJ/100 km or 12 kWh/100 km. The case with the greatest reductions is 10% battery power low where the savings amount to 65.13 MJ/100 km or 18.09 kWh/100 km.

Most results when it comes to fuel consumption lie between an increase of 7 MJ/100 km (corresponding to 0.18 litres/100 km) to a decrease in consumption by 8 MJ/100 km (corresponding to 0.21 litres/100 km). Two cases excel; firstly a decrease in fuel consumption by 99.57 MJ/100 km (2.58 litres/100 km) for a maximum added regeneration of 205%, and secondly an increase in fuel consumption by 54.96 MJ/100 km (1.40 litres/100 km).

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[45] The ninth case of 90% minimum EM torque is left out again, for reasons mentioned previously.

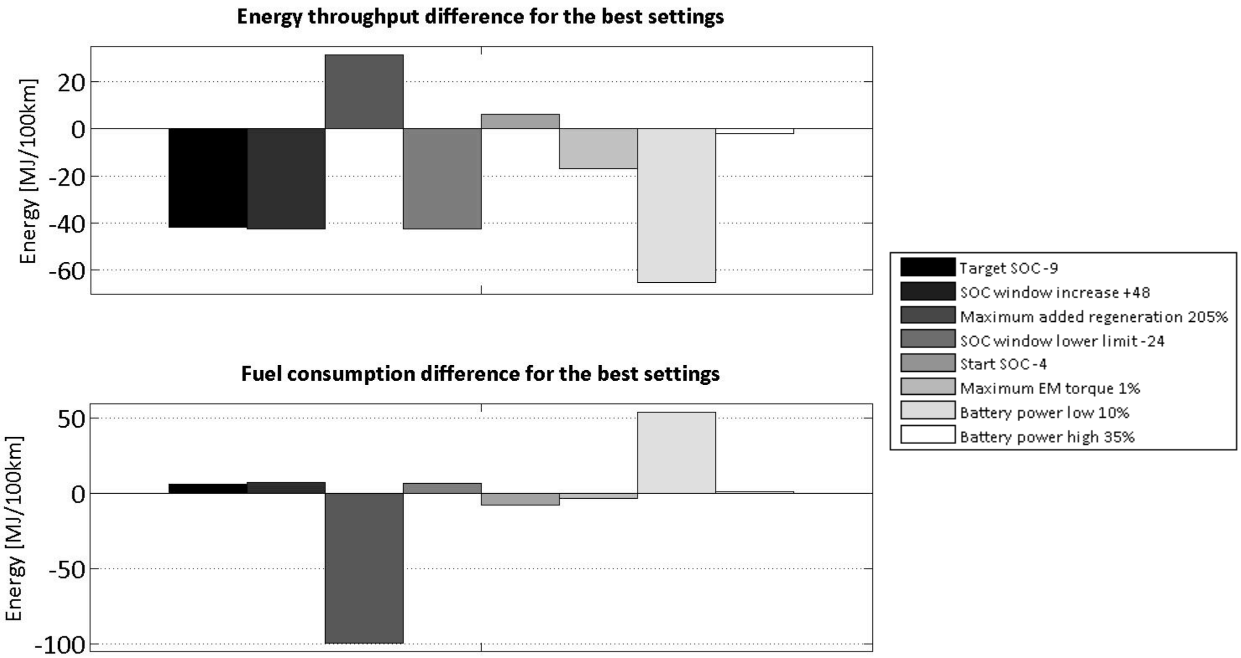

Figure 6.26 Energy throughput and fuel consumption difference for the best settings. The first figure shows the difference in energy throughput. A bar above zero indicates an increase and a bar below zero a decrease. The same is valid for the second graph, which shows the relative difference in fuel consumption.

6.7.2 Performance and drivability

The drivability will be presented for the eight above-mentioned best settings. Figure 6.27 shows the average speed in two graphs, the right hand side graph an enlargement of the left hand side graph. The figure shows that the average speed of the vehicle is fairly constant, regardless of the different settings, around 21.4 km/h. The enlargement shows the small differences, mainly for the last three cases; 1% maximum EM torque (decrease to 21.28 km/h or 99.63% of the original dataset average speed), 10% battery power low (increase to 21.52 km/h or 100.72% of the original dataset average speed), and finally 35% battery power high (decrease to 21.29 km/h or 99.66% of the original dataset average speed).

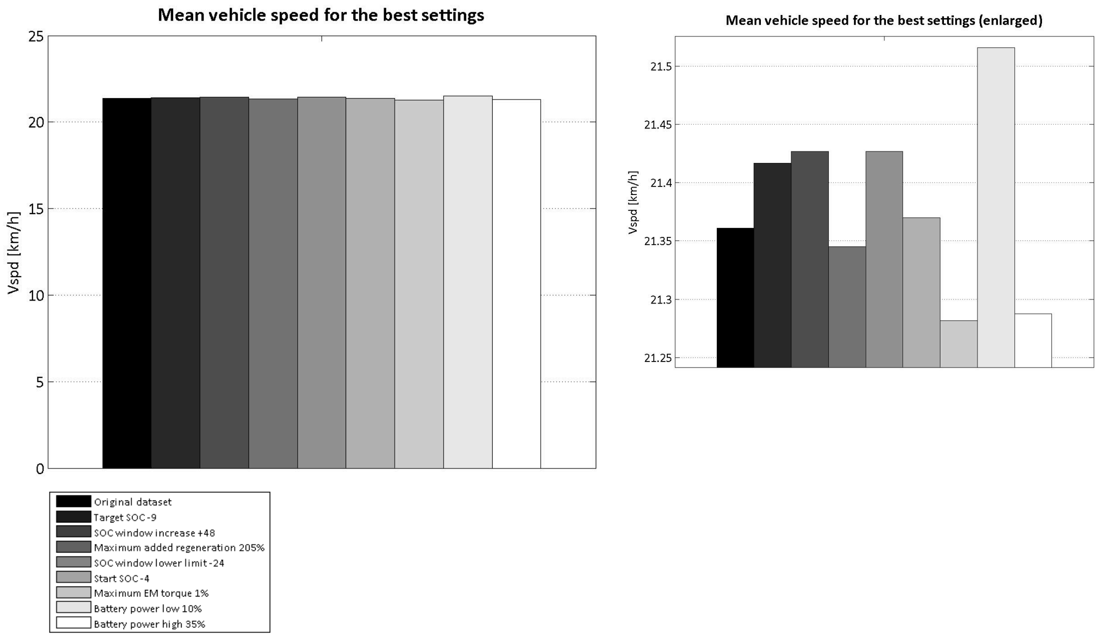

Figure 6.27 Average speed for the best settings and the original dataset settings. The graph to the right is an enlargement of the left hand graph depicting the same thing but in closer detail for clarification. N.B. that the axis of the enlarged graph does not start from zero.

Figure 6.28 nedan shows the percentage of the time when the actual vehicle speed is 3 km/h below the demanded speed, named the error percentage, for the best settings and with the original dataset error percentage included for comparison. The graph on the left hand side shows that all simulations demonstrate a lack of consistency between demanded and actual speed. The right hand side graph shows that the altered settings improve the drivability when it comes to speed conformity as compared to the original dataset in all but two cases; these two are 1% maximum EM torque and 35% battery power high.

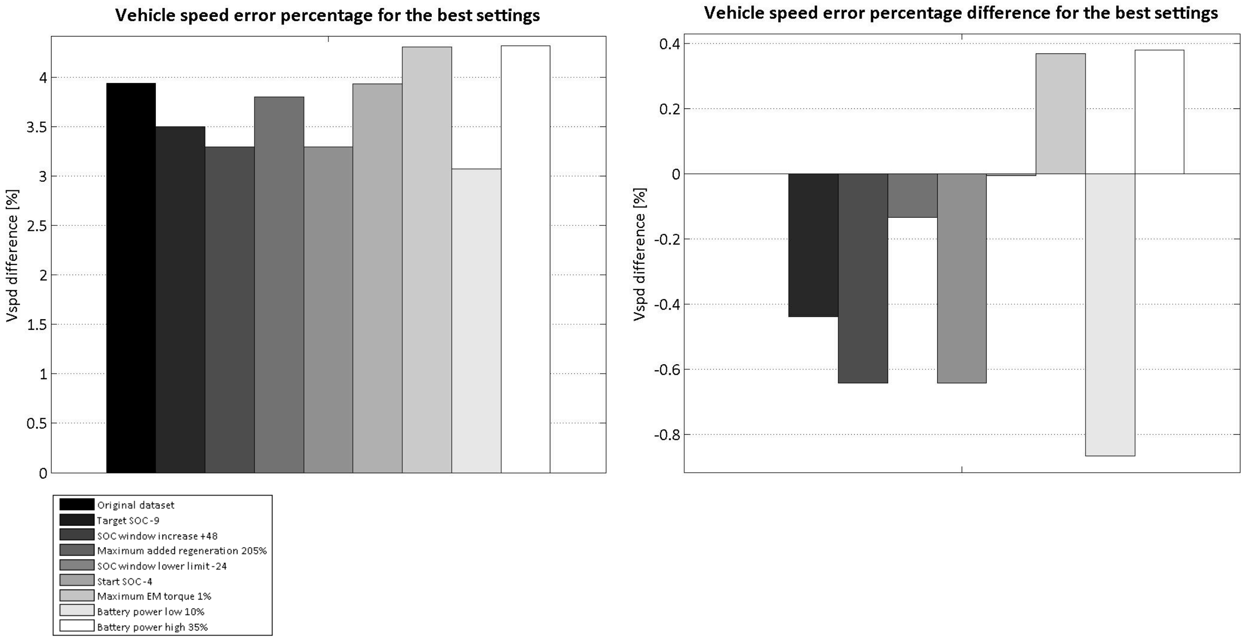

Figure 6.28 Vehicle speed error percentage for the best settings and the original dataset settings. The left figure shows the error [%] for each simulation including the original dataset simulation. The right figure shows a comparison between the original dataset and the altered settings. A value at zero means no difference, a value above zero means less vehicle speed error while a value above zero means increased error percentage as compared to the original dataset.

When considering the number of gearshifts used as a parameter to reveal the smoothness of the drive all but one (start SOC -4 has 242 gearshifts) of the so-called best settings show a different number of gearshifts than the original dataset simulation. The simulation with a SOC target of -9 units gives rise to 249 gearshifts, SOC window increase +48 to 248, 205% maximum added regeneration to only 240 (an increase of the smoothness and thus improvement of drivability), SOC window lower limit -24 to 248 gearshifts, 1% maximum EM torque to 243, the simulation with 10% battery power low gives rise to 246 gearshifts, and 35% battery power high to 247 gearshifts. This means that all but two settings result in worsened drivability considering only this parameter.

6.8 Results of the robustness test

The simulations of the London 159 route need to be verified as to the universality of the results when it comes to the different focal areas and there impact on the selected key parameters. In this purpose simulations of exactly the same settings but with a different duty cycle, namely the previously mentioned SORT 1, have been performed. The results of these simulations are presented in this section. The expectations are, in this case, not to see the same values as in the case of the London 159 route since the two cycles are not entirely similar (see section 3.2 for further detail), but to look for patterns showing similarities in trends. The comparison is made for the parameters energy throughput [kWh/h] and fuel consumption [liter/100 km].

Below the figures showing the graphs as results of these calculations are presented, first for the London 159 route and then for the SORT 1 duty cycle. Again, it is stressed that the comparison will not be of absolute values but of the general trends for the two duty cycles.

Figure 6.29 shows the energy throughput [kWh/h] and fuel consumption [liter/100 km] for all the initial simulations (not the optimisation simulations). When it comes to the two graphs of energy throughput they are fairly similar when it comes to the cases were the parameter either increases or decreases as compared to the original dataset. It can be seen that most bars that are higher than the original dataset bar for the London 159 simulations correspond to bars that are taller than average in the same graph for the SORT 1 duty cycle. The same general trend can also be seen in the cases where the bars are lower than the original dataset bar (for London route 159) or lower than average (for SORT 1).

Concerning the two graphs in Figure 6.29 showing fuel consumption the trends are perhaps not as obvious. Yet, it is still possible to see some similarities. The tall bars number 2, 4, 9 and 24 in the top graph (of London route 159) correspond to bars that are higher than average for the SORT 1 fuel consumption. Also, the last bar (number 25) and bar number 19 are among the shortest bars for both duty cycles.

Finally, it can be interesting to note that in the case of the SORT 1 duty cycle, which is much shorter with much less starts and stops than the London 159 route, the energy throughput increases in almost all simulations with altered settings as compared to the original dataset. Also, the fuel consumption decreases in almost all cases in the same comparison.

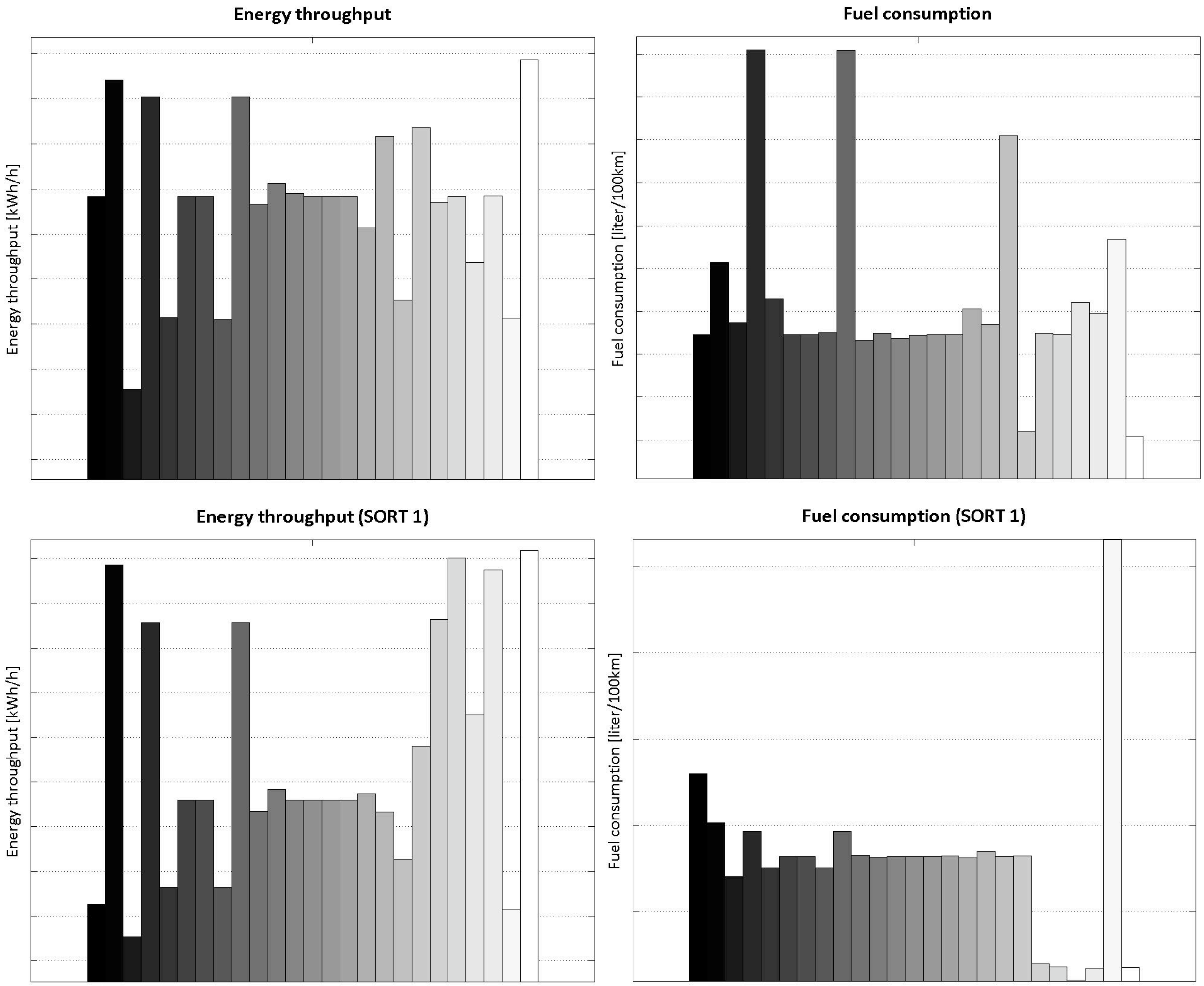

Figure 6.29 Energy throughput and fuel consumption for London route 159 (on top) and SORT 1 (below). The comparison is to be made between the two graphs that are on top of one another.

7 Discussion

In this chapter the results presented in chapter 6 will be analysed in further detail. In chapter 6 the simulation results were presented for the different key parameters. In this chapter the analysis will be made for each focal area in order to examine how these areas affect the key parameters in study. The discussion will mainly focus on the two key parameters energy throughput and fuel consumption to reconnect to the aim of the master thesis, though other parameters such as drivability will also be included. Further, the results of the so-called optimisation simulations will not be considered separately but instead in the context of the respective focal areas.

7.1 SOC target

The results for the simulations with altered SOC target will be discussed based on the calculations of parameters concerning energy, both for the battery and for the diesel engine. These parameters are energy throughput, fuel consumption, and SOC of the battery. Also, a discussion of the results from the drivability calculations will be made.

When it comes to energy throughput the changes in SOC target has quite substantial impact; raising the SOC target increases the energy throughput while a decrease of the SOC target results in decrease of the energy throughput. The latter statement is true for both a SOC target decrease by 5 units and, from the optimisation step, for a decrease by 9 units. Further, the energy throughput is reduced more as the SOC target is decreased. The simulations with SOC target -5 showed a decrease of the parameter by 11.28 MJ/100 km, which was further decreased by 41.85 MJ/100 km for the simulations with SOC target -9 as compared to the original dataset.

The fuel consumption on the other hand increases, both for increased and decreased SOC target; even though the increase is smaller for a lowering of the SOC target than for a raise of the same. This difference is reduced as the SOC target is further lowered; as the SOC target is lowered from -5 to -9 the fuel consumption difference as compared to the original dataset increases, from a difference of +1,10 MJ/100 km to +6.06 MJ/100 km. The CO_2 emissions are increased for both cases while the costs are decreased. The costs decrease mainly because the battery costs are lowered; the fuel costs are increased in both cases.

The simulations results show that in the case of an altered SOC target the two parameters energy throughput and fuel consumption are not consistent in their response to the altered settings. Yet there are certain observable trends. A raised SOC target has a negative effect on both parameters while a lowered target has a positive effect on the energy throughput but a negative effect on the fuel consumption (though not as bad as for a raised SOC target). The SOH change is better than for the original dataset for both simulations; around 1 % better for the raise of the SOC target and as much as 8 % better for the opposite case.

It is perhaps not surprising that a higher SOC target increases the energy throughput. Figure 6.8 shows that the SOC mainly is at low levels rather than at high. Therefore, the energy throughput increases as the EM increases the charge of the battery aiming for the higher SOC target. It is however interesting to note that this increase is not counteracted by a decreased discharge of the battery. The EM functions more as a generator than a motor in this case, thus increasing the need for torque provision from the diesel engine, which means increased fuel consumption. In the case of a lowered SOC target the energy throughput decreases for the opposite reason; the EM does not need to charge the battery as much, which again is not totally counteracted by an increased discharge. This means that the fuel consumption increases, albeit not as much as for the raised SOC target.

The differences when it comes to SOC and the amount of time that is spent on either higher or lower levels of charge are fairly obviously related to the target of the same. As the target is increased it is only natural that the SOC is at higher levels and vice versa when the target is lowered.

When it comes to drivability issues the average speed increased for all alterations of the SOC target, both a SOC target increase and decrease indicate decreased performance. The other speed parameter in study, the error limit, showed the opposite. As compared to the original dataset, the simulations of altered SOC target all showed better results as to the conformity of the actual speed with the demanded. The improvement increased in the case of a lowered as compared to a raised target and was the best in the case of a SOC target of -9 units. Finally, a decrease in SOC target implies the smoothness of the drive may be lowered since the number of gearshifts increase; from 245 for a SOC target of -5 to 249 for a target lowered by 9 units. No difference in the number of gearshifts was seen in the case of an increased SOC target.

7.2 SOC window

The results of the energy throughput calculations shows increased values for two variable alterations, unaltered values for two, and for the last two alterations; decreased energy throughput. Further it is interesting to note that both simulations with increased energy throughput increase by the same amount. The parameters with decreasing energy throughput are also fairly similar in percentage. Therefore it may be of interest to see if any commonalities between them can be found, that could account for the increase or decrease.

The variable alterations resulting in increase of the parameter are lower limit +5 units and SOC window decrease by 10 units (where the upper limit has been lowered while at the same time the lower limit has been raised). What they both have in common is obviously a raise of the SOC window lower limit.

Further, the simulations leading to unaltered energy throughput are those where the upper limit has been changed. The conclusion that can be drawn from this observation, together with the previous, is that alterations of the upper limit of the SOC window do not affect the energy throughput. The reason for this is most probably that the SOC never rises to such high levels so that it is comes near the upper SOC limit. This can also be seen when studying Figure 6.8; the

SOC rarely rises above even the start level. This fact implies that a raise of the SOC window lower limit is the cause of the above-mentioned increase in energy throughput.

When it comes to the two simulations for which a decrease of the parameter has occurred, their common feature is a lowering of the lower limit, i.e. the opposite for the case where the energy throughput increased.

The conclusion here is thus that a lowering of the SOC window lower limit decreases the energy throughput, while a raise of the same limit increases the energy throughput. Alterations to the upper SOC limit do not affect the parameter significantly. Therefore the discussion in this section will mainly focus on the alterations of the lower SOC window limit.

When it comes to fuel consumption almost similar trends can be observed. Altering the upper limit results in unaltered fuel consumption, i.e. no gains can be made by changing this parameter. Raising the lower limit by 5 units result in an increased fuel consumption of 1.8 %. In the case of lowering the lower limit there is no reduction in fuel consumption but instead a slight increase (by 0.23 and 0.02%) even though this increase is not as large as that of the lower limit rise. The optimisation tests include two cases in which the SOC window has been altered; in both cases the optimal simulation included a decrease of the SOC window lower limit by 24 units. Both resulted in decreased energy throughput and total energy but increase in fuel consumption, further emphasis the conclusion drawn above. Also, the decrease in energy throughput for the optimisation simulations is much larger and so is the increase in fuel consumption indicating that the findings are in fact trends.

Here it is interesting to analyse the results from the calculations of the total energy difference. Even though this parameter is no exact measure of the energy consumption it is an attempt to compare the relative worth of the energy throughput changes versus those of the fuel consumption changes. For the SOC window alterations, the total energy shows the same as the two previously mentioned parameters for all simulations except for those were the energy throughput was decreased but the fuel consumption was increased slightly (i.e. for a lowering of the lower limit by 5 units); the total energy is decreased as compared to that of the original dataset.

The total CO_2 emissions are increased for all alterations except for the alterations of the upper limit by -5 and +5. The emissions are increased extra much for the two alterations where the lower limit is raised by 5 units. The cost analysis indicates losses for all cases, especially for the same two alterations. One simulation, of raised upper limit, however indicates potential for cost savings.

Taking the SOH parameter into consideration, the analysis only confirms the above-mentioned conclusions. The simulations resulting in increase of both energy throughput and fuel consumption are associated with a worse SOH change by around 5 % as compared to the original dataset change. The simulations where only the upper SOC window limit was altered result in no change in the SOH development as compared to that of the original dataset. Finally, the simulations where the lower SOC limit has been lowered by 5 units result in almost 6 % better SOH change than the original dataset. The SOH change is primarily associated with the energy throughput parameter as previously mentioned, which explain the conformity between them.

The SOC histograms are almost similar for all these simulations, with exception again of the two simulations with lowered lower limit. Here the SOC is more evenly spread, and more often residing at the lower levels compared to the rest.

For the simulations of all other focal areas than this, the powertrain (PT) modes are fairly similar, i.e. mainly divided between the electric and hybrid modes with some occasional idling occurring. In this case the vehicle goes into a fourth mode, the charge at standstill (C@SS) mode, for two simulations, namely the case of a raised lower limit by 5 units and a decrease of both limits where the lower limit is raised by 5 and the upper limit lowered by 5 units. Again, it is assumed that the variable affecting the PT mode parameter is the raising of the lower limit. These results imply that as the lower limit is raised the vehicle needs to go into the C@SS limit, which is not desired.

Considering the drivability parameters almost the same trends as those discerned above can be seen, albeit with some differences. The average speed is raised (improved) and the speed error improved for all cases except the two where all other parameters were unaffected; the average speed and speed error are unaltered here as well. The average speed for the two cases where the lower limit is raised by 5 units does result in a slightly higher average speed than for the lowering of the limit. When it comes to vehicle speed error the opposite is true; here the two cases where the lower SOC window limit is instead lowered by 5 units show a larger improvement in speed error than for a raise of the limit. The same trends in drivability can be seen in the two optimisation simulations with a lowering of the lower limit by 24 units. The average speed is not further improved in the optimisation process, which, on the other hand, the vehicle speed error is.

7.3 EM torque curve

The simulations performed for the variables within this focal area are many, and the way the variables affect the EM torque curve are very different. This discussion will thus be quite extensive. The SOC histograms and SOC curves are fairly similar for all simulations settings within this focal area and will thus not be further discussed.

To start with, three simulations lead to no alterations of neither energy throughput nor fuel consumption. Further, neither does the SOH, the SOC curves, PT modes nor any other parameter included in this study. These variable alterations are 110 % minimum EM torque and the two alterations of the ED reference torque. The conclusion to be drawn here is that these parameters are not involved in the charge balance control functionality.

This leaves us with seven variable alterations that have some effect on the key parameters. When it comes to energy throughput, fuel consumption, and maximum EM torque it is interesting to note that 90 % maximum EM torque indicate a decrease of both parameters while 110 % indicates an increase of both. The optimisation results further confirm that a lowering of the maximum EM torque is beneficial for both energy throughput and fuel consumption; the most optimal setting was 1 % maximum EM torque. The maximum EM torque defines the maximum positive torque from the EM, i.e. the electric motor torque. This indicates that the motor should not be used the way that it currently is. Further, the SOH is improved for the 90 % case and worsened for the 110 % setting, while both drivability parameters as well as the PT modes are fairly similar to the original dataset. The total costs and all CO_2 emissions are reduced for 90 % torque while both parameters are increased for a setting of 110 % of the variable. Thus all parameters indicate that a lowered maximum EM torque is favourable.

Continuing with the minimum EM torque, the increase of the variable had no effect on the key parameters as previously mentioned, while lowering the parameter increases the energy throughput while decreasing the fuel consumption. This parameter affects the minimum negative torque, i.e. the maximum torque to charge the battery. One reason for these observations could be that as the maximum negative torque is decreased the battery charging from the diesel engine is decreased or that as the torque is decreased the energy in the battery is used more and the fuel consumption thus lowered. The SOH is slightly worsened due to the increased energy throughput, while the costs are lowered implying that cost savings can be made when decreasing the minimum EM torque. The total CO_2 emissions are also decreased, while the PT mode and the drivability parameters are relatively unchanged.

The maximum added boost parameters indicate lowered energy throughput when the variable is lowered to 90 % and increased energy throughput for 100 % maximum boost. The fuel consumption increases in both cases as compared to the original dataset. The total energy is increased for both alterations even though it is increased more for 110 % than for 90 %. Further, 90 % maximum added boost indicates an improved SOH while 110 % indicates a worsened SOH. The PT mode graphs indicate that, for a decreased boost, the time is spent more in electric mode than in hybrid mode as compared to the original dataset PT mode distribution. Also very interesting to note is that the average speed is significantly decreased for a lowered boost and increased for an increased boost. The vehicle speed error is correspondingly very much increased for the case of 90 % maximum added boost and much decreased for 110 % maximum added boost. The number of gearshifts is decreased for the 90 % case and increased for the 110 % case. For the 90 % case both cost losses and increase of the total CO_2 emissions is shown. The conclusion here is that the maximum added boost may be best kept as it is but that a lowering may reduce the strain on the battery since it will not be used to aid the diesel engine during tough operations. Increasing the maximum added boost only improves the vehicle speed related parameters.

The last variable altered within this focal area is the maximum added regeneration. As the variable is lowered the energy throughput decreases while the fuel consumption increases. The opposite is true for regeneration increased to 110 %. This can be explained by the fact that as the regeneration is increased the battery can provide more torque making the battery use increase while the diesel engine can be relieved of some torque providing duties and does not need to consume fuel for battery charging as much. The reasons for the results of decreased regeneration have the same, but opposite explanation. The total energy is increased for 90 % and decreased for 110 % maximum added regeneration, this because of the fuel savings. The optimisation simulation showed that the optimal setting was 205 % maximum added regeneration. The SOH is greatly affected by these alterations; much improved for the 90 % case and much worsened for the 110 % case. The drivability is improved for both alterations in both average speed and speed error while the number of gearshifts is increased for 100 % maximum regeneration implying a less smooth drive. When it comes to cost and CO_2 emissions the 90 % case indicates cost losses and increased emission while the 110 % case indicate cost savings and emission reductions as compared to the original dataset. These factors are mainly affected by the fuel consumption. In this case energy throughput savings need to be weighted against fuel consumption increase and vice versa.

7.4 Charge/discharge power

The power of the battery, both for charging and for discharging, has been altered in four different ways. Additionally, two simulations related to this focal area have been included in the optimisation process.

Two simulations show decreased energy throughput, the other two an unaltered value as compared to the original dataset. The cases with a decrease of the parameter occur when the high power and the low power have been cut to 50 % of the original value. The fuel consumption increases slightly for these two alterations. In the case of a 90 % battery power low the fuel consumption is increased. The total energy shows a decrease for both cases with the variable at 50 % and an increase for 90 % battery power low. The total costs increase for all alterations, though in the case of 90 % battery power high the fuel costs is decreased. The CO_2 emissions are increased for all cases, particularly for 50 % battery power low.

When it comes to the optimisation, the tests show that the battery power low can be decreased to 10 % before the vehicle cannot complete the cycle and the SOC curve is dangerously low. The energy throughput is further decreased and the fuel consumption further increased as compared to the 50 % case. The total energy is however decreased. The lowering of the battery power high is continued until an optimum of 35 % is reached. However, the decrease in energy throughput and increase in fuel consumption are very small and nearly similar to the case of 50 % battery power high.

In this case it is hard to find any trends. The cases where the power is cut to 50 % seem to be better when it comes to energy throughput. The lowering to 50 % of the battery power high, which is the maximum allowed discharge of the battery does not affect the fuel consumption that much. Further lowering to 10 % shows that the energy throughput is decrease while the fuel consumption increases significantly. The total energy is however decreased. This means that the benefits of lowering the discharge power in the form of reduced energy throughput needs to be weighed against the detriments in the form of increased fuel consumption. For the battery power high parameter, which controls the minimum charge of the battery, the energy throughput decreases the more the power is decreased, however, the fuel consumption increases in both cases. A further lowering to 35 % does not affect the two key parameters more than the case of 50 %. Even though the total energy decreases it can be concluded that also in this case the balance is between decreased energy throughput and increased fuel consumption. These results are perhaps not that strange, lowering these two parameters means that the power to and from the battery is lowered and that the use of the EM will be lowered. This energy reduction still needs to be provided; from the diesel engine. Hence, the fuel consumption is raised.

To add further confusion to the matter, the SOH change is improved for all cases except for the 90 % battery power high case, which is unaltered. The SOC curves for all these simulations are fairly similar to each other.

When it comes to the drivability parameters the average speed is unaltered except for battery power high 90 % where it is slightly improved. The vehicle speed error is also improved for this variable alteration as well as for 50 % battery power high. The optimisation test with 35 % battery power high instead shows a worsened average speed and a larger speed error than the original dataset. The two alterations of the low power result in no visible change in speed error as compared to the original dataset. The optimal simulation, with 10 % battery power low, shows an improved drivability; both higher average speed and smaller speed error. This shows that no trends for the drivability parameters can be seen when it comes to alterations of the charge/discharge power.

In total, the results show that energy throughput decrease needs to be weighted against increased fuel consumption when considering a lowering of the minimum charging power and the maximum discharge power. Other factors that should be included in the decision process is that the SOH improves when lowering to charge/discharge power. The drivability parameter does not provide any input of significant importance to the consideration.

7.5 Start SOC

When it comes to the alterations of the start SOC, an increase of the variable gives decrease in energy throughput but increased fuel consumption. The opposite is true for a lower start SOC. The total energy is increased for a lower start SOC and decreased for a higher value of the parameter. The total energy is however reduced for a lower start SOC. An optimisation where the start SOC was further lowered indicated that the total energy did not change that much with the variable alteration and that a start SOC lowered by 4 units was the most optimal setting.

Battery and diesel fuel costs are increased for a raised start SOC and decreased for a lowering of the variable implying cost saving potential. The opposite is true when it comes to CO_2 emissions a raised start SOC gives reduced emissions and lowered start SOC indicate increased emissions.

Again, the results show that a weighting needs to be done between the energy throughput and the fuel consumption. Raising the start SOC in order to lower the energy throughput can be done by implementing plug-in possibilities for charging as the vehicle is shut down.

The SOH change is improved for a higher start SOC and aggravated for a lower start SOC. Not much needs to be said of the SOC curves other than the fact that they all simulations end up with similar curve variations even though they started at different levels. The drivability is relatively unaltered for both alterations.

One conclusion that can be drawn from these results is that the energy throughput is very much affected by changes of the SOC target, but that the gains of this parameter means losses in fuel consumption and vice versa for gains of the latter parameter. The important thing to remember when analysing the start SOC parameter is that the alterations cannot be simply implemented by changing the dataset parameters.

7.6 Robustness of the results

The SORT 1 duty cycle is much shorter than the London 159 route and only created as a test cycle. Very few, if any, routes are this short in reality. It may be so that some effects of the altered variables do not have time to show up during this time, thus indicating results different from those obtained from the longer cycle.

However, the same trends can be observed for both cases even though the difference of the alterations as compared to the original dataset do not always have the same sign. Six simulations out of 24 are higher than the original dataset for the energy throughput parameter for the SORT 1 simulations but not for the London 159 simulations, and eight out of 24 have higher energy throughput than the original dataset for the SORT 1 simulations while they are equal to the original dataset in the London 159 simulations. Ten simulations show the same difference in the comparison. The fuel consumption is lowered for almost all simulations with the SORT 1 cycle as compared to the original dataset. The discrepancies may be explained by the above-mentioned fact that the SORT 1 cycle is much shorter than the London 159 route. The relative differences between the altered variables hold however.

8 Conclusive analysis and improvement suggestions

In this chapter the discussion presented in the previous chapter is summarised in lucid dot lists, one for each focal area. Further a discussion of the reliability of the results is presented as well as a short analysis on the limitations of the results. Finally, some suggestions for further work on the area are given.

8.1 Conclusions from the results

The main conclusions that have been drawn from the results and presented in chapter 7 are summarised in this section. The summaries are divided per focal area.

The alterations of the *SOC target* indicate that:

- Raised SOC target is negative for energy throughput and fuel consumption. The drivability is improved when it comes to keeping up with the demanded speed.
- Lowered SOC target beneficial for energy throughput, but negative for fuel consumption. The drivability is improved when it comes to keeping up with the demanded speed but reduced in smoothness.
- The CO_2 emissions are increased for both cases while the costs are decreased indicating unwanted effects of both alterations.

Alterations of variables affecting the *SOC window* show that:

- Alterations to the upper SOC limit do not affect the key parameters significantly.
- A lowering of the SOC window lower limit decreases the energy throughput, only slightly increases the fuel consumption and improves the SOH, while a raise of the same limit increases energy throughput and fuel consumption and worsens the SOH.
- The total CO2 emissions are increased for all other alterations, extra for the two alterations where the lower limit is raised by 5 units.
- The cost analysis indicates losses for all cases, especially for the two alterations where the lower limit is raised by 5 units.
- The vehicle goes into charge at standstill (C@SS) mode, for the simulations where the lower SOC limit is raised.
- Drivability is improved for most cases.

The main conclusions that can be drawn from the *EM torque curve* simulations are:

- All parameters indicate that a lowered maximum EM torque is favourable.

- 110 % minimum EM torque and the two alterations of the ED reference torque are not involved in the charge balance control functionality
- The maximum added boost might be best kept as in the original dataset, even though a lowered value reduces the energy throughput. Increasing the maximum added boost only improves the parameters related to vehicle speed.
- As the maximum added regeneration is increased the energy throughput increases while the diesel engine fuel consumption decreases. The opposite is true for decreased maximum added regeneration. This means that a weighting of the relative importance of energy throughput lowering versus fuel consumption reduction needs to be done.

Considering the simulations with altered *charge/discharge power* variables the main conclusions are the following:

- For both parameters the benefits of reduced energy throughput needs to be weighed against increasing fuel consumption.
- In the case of a lowered charging power the benefits of reduced fuel consumption in throughput need to be weighed against increase in fuel consumption.
- The total costs and the CO_2 emissions increase for all alterations.
- The SOH is improved for all cases.
- The drivability is indicated to be unaffected by the alterations.

Finally, the most important conclusions that can be drawn from the *start SOC* alterations are:

- An increase of the start SOC gives decrease in energy throughput but increased fuel consumption. The opposite is true for a lower start SOC.
- The energy throughput is very much affected by changes of the SOC target
- Gains for one of the two main key parameters means losses for the other main key parameter; a weighting is needed.
- It is also important to remember that the alterations cannot be simply implemented by changing the dataset parameters.

In summary, the alterations lead to reduced energy throughput more often than they lead to reductions in fuel consumption. One variable alteration however leads to decrease of both these two main key parameters, namely 90 % maximum EM torque.

When it comes to sustainable development and CO_2 emissions it can be concluded that the main source of emissions are from the diesel fuel consumption. Reducing this parameter correspondingly reduces the greenhouse gas emissions.

8.2 Reliability of the results

The accuracy of the model and model simulations have been tested in many different ways and the conclusions are that the model has a high compliance with the reference cases. However, a validation of the results in reality is missing.

When it comes to the universality of the results there are some uncertainties. The relative savings and gains of the key parameters for the altered simulations as compared to the original dataset simulation are not always the same for different duty cycles. However, these discrepancies may depend on the fact that the other tested duty cycle is very short and that the full effect of the variable alterations may not have sufficient time to fully appear. The relative differences between the altered variables nevertheless hold.

The conclusion of the above-mentioned tests is that the results should mainly be looked upon as indications and not as absolute results.

8.3 Limitations of the results

The simulations have mainly been performed on a model hybrid bus. Preferably the variable alterations should be tested in real vehicles and also in different vehicle types with different duty cycles.

8.4 Suggestions of improvement ideas for the present hybrid control

The work with the master thesis has been very extensive and very interesting. The main suggestion involves further work that would be interesting to do one the subject. Firstly, it would be of great interest to study even more variables that were not possible to study because of time restrictions. These include for instance studies of battery efficiency, of different battery types and battery current and power use.

Further work suggestions also include testing more variable alterations and creating a more structured optimisation process, where the optimising could e.g. be done with respect to several parameters such as energy throughput and fuel consumption at the same time.

One of the most important suggestions for further work is to find a good and structured way of comparing the two main key parameters of this study; energy throughput and fuel consumption. The main conclusion of the thesis was that in many cases a weighting between the relative importance of reducing energy throughput versus reducing fuel consumption was needed since the two parameters often changed in the opposite directions of one another. An extensive analysis of the possible ways to compare the two parameters should be done and a well-structured method for this should be developed.

Also it would be very interesting to do a model verification test by comparing the simulations to data logged from actual drives or by implementing the results in an actual vehicle. Further, it would be of interest to do even more studies of the result robustness to test the universality of the results even more.

The study of the relative environmental impacts of the two energy sources, i.e. the battery and the diesel fuel is very interesting and highly relevant. It would be of great interest to do an LCA of these two products, however, the workload would be huge and call for an entire master thesis of its own.

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Appendix

Appendix A: Previous studies

Table D.1 Previous studies. The table lists some of the literature written on studies of hybrid vehicles. Here, FC is short for fuel consumption.

Title	Authors	Year	Abstract	Focus	Additional information
A Diesel-Electric Hybrid Bus	Roan, Vernon, P.	1978	Designed with computer aid (simulation). Results confirm feasibility of system including significant advantages in the areas of exhaust emissions and fuel consumption.	FC Emissions	Society of Automotive Engineers – Technical Paper Series Warrendale, Pennsylvania
Efficiency Studies About Daihatsu Engine/ Electric Hybrid system	Honda Shoji; Hoshino, Chisato; Kawakatsu, Shiro; Tsukano, Hiromichi; Yamamoto, Toshikazu; and Iida, Mikio	1979	Computer simulation analysis to study efficiency. Results are accurate fuel consumption.	FC	SAE – Technical Paper Series Warrendale, Pennsylvania
The Future of Heavy-Duty Powertrains		2004	Current view on alternative powertrain technology (alternatives to diesel engines) with respect to technical and market viability in the quest for reduced heavy vehicle fuel consumption and emissions.	Future market FC Emissions	Position Paper - Alternative Powertrain Technology Outlook, 2007 – 2020 Global Insight, Inc. and TIAX, LLC: Lexington and Cambridge, USA
Control of Hybrid Electric Vehicles with Diesel Engines	Jonasson, Karin	2005	Improve electric hybrid vehicles with respect to fuel consumption and to fulfil the future intended NO_X emission regulations.	FC Emissions	Media-Tryck, Lund University: Lund

Appendix B: Simulation plan

SOC target	SOC window	EM torque curve	Charge/discharge power	Start SOC
SOC target +5	Lower limit +5	Maximum EM torque 90%	Battery power high 50%	Start SOC + 5
SOC target -5	Lower limit -5	Maximum EM torque 110%	Battery power high 90%	Start SOC -5
	Upper limit -5	Minimum EM torque 90%	Battery power low 50%	
	Upper limit +5	Minimum EM torque 110%	Battery power low 90%	
	SOC window increase +10	ED reference torque 90%		

	SOC window decrease -10	ED reference torque 110% Maximum added boost 90% Maximum added boost 110% Maximum added regeneration 90% Maximum added regeneration 110%		

Appendix C: Optimisation

Table C.1 Optimisation settings and results

Test no	Test parameter	Result Total energy difference [MJ/100 km]	Result SOH change [%]	Comments
1	SOC target -10	-61.7621	44.3043	Did not complete cycle (77%)
2	SOC target -4	-6.8086	7.9350	
3	SOC target -6	-11.7914	8.7415	
4	SOC target -7	-19.9701	11.2229	
5	SOC target -8	-29.1840	18.9690	
6	SOC target -9	-35.7923	24.0794	
7	SOC target -9.5	-69.4572	35.9064	Did not complete cycle (89%)
8	SOC window lower limit - 10	-12.8857	14.5187	
9	SOC window lower limit - 15	-25.4212	19.2052	
10	SOC window lower limit - 20	-31.8585	20.3630	
11	SOC window lower limit - 25	-64.0711	32.2787	Did not complete cycle (89%)
12	SOC window lower limit - 21	-31.5010	22.4056	
13	SOC window lower limit - 22	-33.1002	22.5875	
14	SOC window lower limit - 23	-34.4019	22.7776	
15	SOC window lower limit - 24	-35.3460	22.8839	
16	Maximum added regeneration: 150%	-33.3267	-1.7981	
17	Maximum added regeneration: 170%	-51.4771	5.9852	
18	Maximum added regeneration: 190%	-63.7115	8.3531	
19	Maximum added regeneration: 250%	-73.6456	-138.1965	SOH -138%
20	Maximum added regeneration: 200%	-66.9186	5.6572	
21	Maximum added regeneration: 210%	-69.3242	-127.8155	SOH -128%
22	Maximum added regeneration: 205%	-68.3038	3.2307	
23	SOC window increase + 20	-12.8959	14.5187	
24	SOC window increase + 30	-25.4209	19.2052	

25	SOC window increase + 40	-31.7640	20.3630	
26	SOC window increase + 50	-64.0692	32.2787	Did not complete cycle (89%)
27	SOC window increase + 48	-35.4360	22.8840	
28	Start SOC - 10	-2.7903	-134.3128	SOH -134%
29	Start SOC - 9	-3.0964	-10.8817	
30	Start SOC - 8	-3.3499	-7.1869	
31	Start SOC - 7	-2.6092	-5.7928	
32	Start SOC - 4	-1.7493	-2.1330	
33	Maximum EM torque: 70%	-1.4574	0.7632	
34	Maximum EM torque: 50%	-5.2219	5.9883	
35	Maximum EM torque: 30%	-8.6370	6.5308	
36	Maximum EM torque: 10%	-14.0673	6.9317	
37	Maximum EM torque: 1%	-20.1398	4.7107	
38	Maximum EM torque: 0%	-21.8763	4.6604	
39	Battery power low: 40%	-5.8411	3.0589	
40	Battery power low: 20%	-7.3763	10.9406	
41	Battery power low: 10%	-11.1677	46.0457	
42	Battery power low: 1%	-42.6912	100.0000	Very bad SOC
43	Battery power low: 5%	-21.2472	88.0970	Did not complete cycle (89%)
44	Minimum EM torque: 70%	-0.0398	0.0039	
45	Minimum EM torque: 80%	-0.0455	0.0002	
46	Minimum EM torque: 85%	-0.0470	0.0016	
47	Minimum EM torque: 95%	-0.0285	0.0025	
48	Minimum EM torque: 89%	-0.2326	-0.0122	
49	Minimum EM torque: 91%	-0.2109	-0.0118	
50	Battery power high: 40%	-0.4921	0.5170	
51	Battery power high: 20%	-0.2355	7.4480	
52	Battery power high: 10%	-43.1813	-82.2069	Not enough torque provided
53	Battery power high: 30%	0.1932	1.8811	
54	Battery power high: 35%	-0.8039	3.0591	
55	Battery power high: 45%	-0.4748	0.1841	

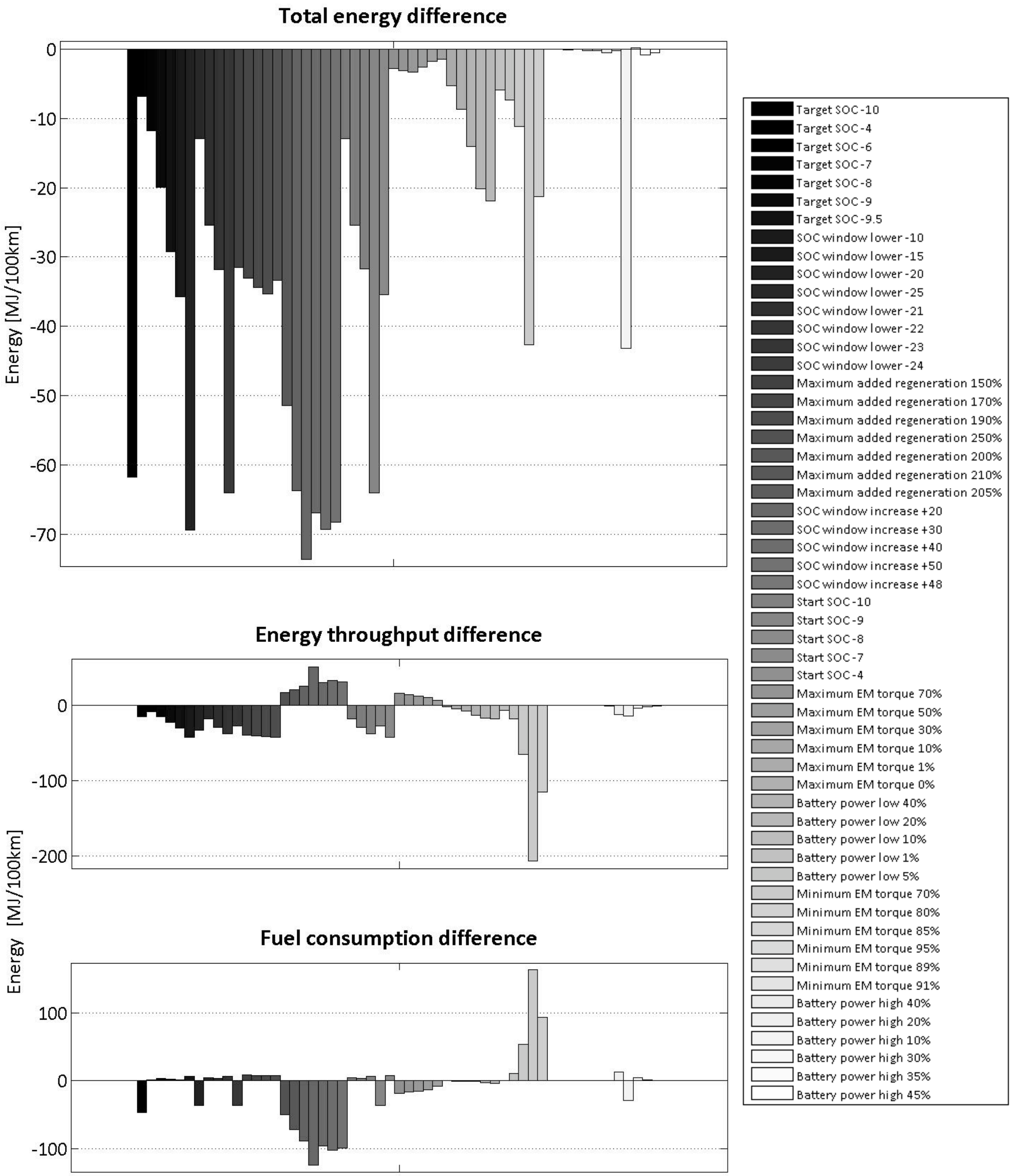

Figure C.1 Results from the optimisation simulations. The topmost graph shows the total energy difference from all optimisation simulations as compared to the original dataset simulation. Likewise, the middle and the bottom graphs show the energy throughput and fuel consumption difference, respectively.

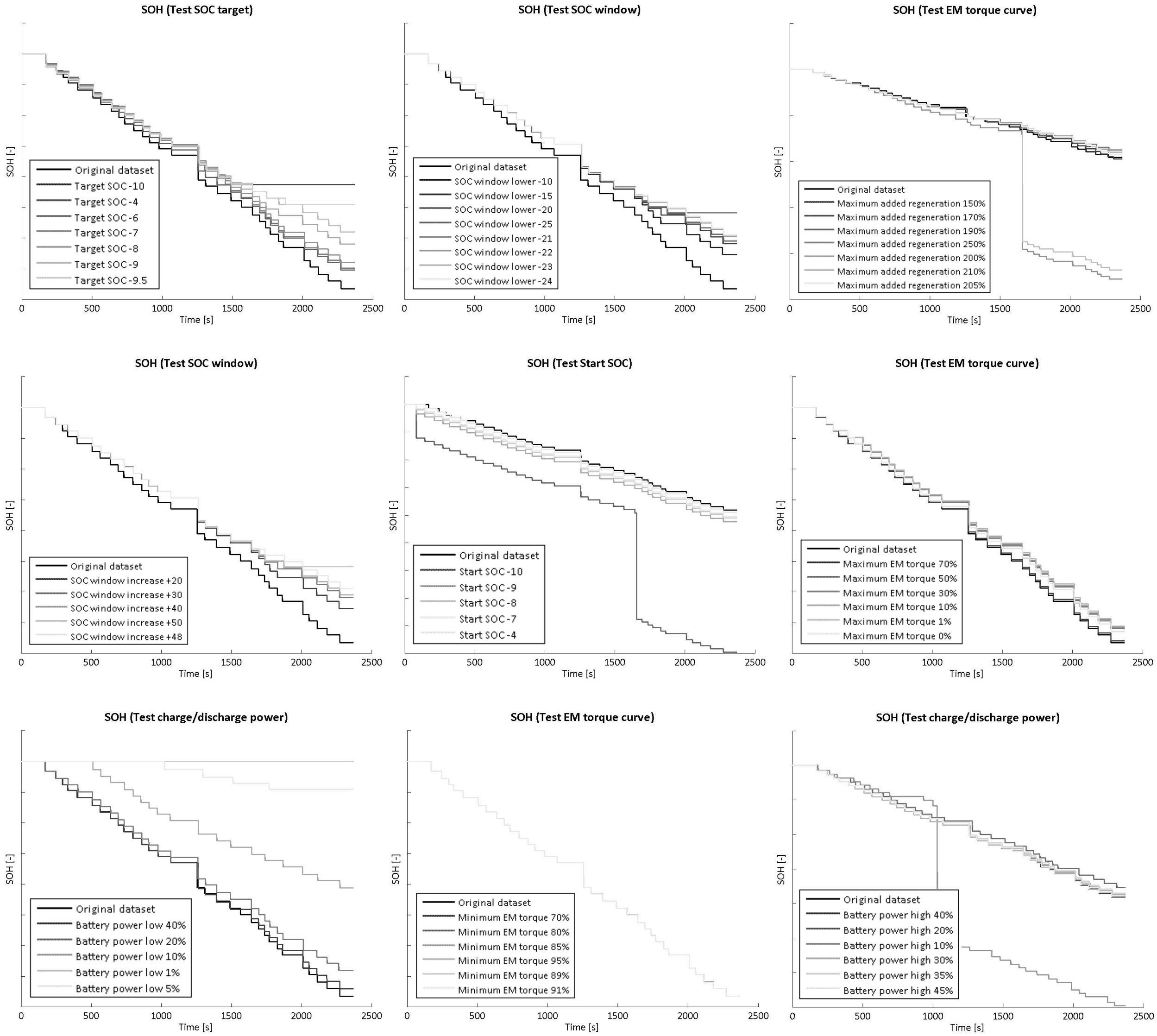

Figure C.2 The SOH change with time for the different optimisations. The original dataset SOH curve is always represented by a black line.