Thesis for the Degree of Doctor of Philosophy

A Methodology for the Design of Cost Effective Hybrid and Fuel Cell Powertrains

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Christofer, my son, I hope you, your generation and our planet will benefit from alternative transportation systems.

Abstract

This thesis deals with system design of cost effective hybrid and fuel cell vehicles. Today (2004) the major disadvantages of these vehicles are increased complexity and component costs. However, the decrease in cost of electrical components and the environmental concern make these vehicles more and more competitive. To make hybrid and fuel cell vehicles cost effective, a sensible system design plays a decisive role. Configuring, choosing, sizing and energy management of vital powertrain components determine how cost effective a system is. The powertrain is the system in a vehicle that develops and transmits traction power. A cost effective powertrain system is both fuel efficient and cheap in component cost. On the road and in the showroom today, hybrid vehicles are powered by both a small gasoline engine and an electric machine. By using the electric machine in combination with an energy buffer, braking energy can be regenerated. Thanks to the power assisting buffer, the engine can also be smaller in size. Energy management is a specific and crucial problem in hybrid vehicles; it determines how power is distributed between the buffer and the primary power unit. The primary power unit can be a combustion engine, a fuel cell or a high capacity battery.

A computer tool THEPS has been developed by the author. THEPS uses simulation and optimization to propose a powertrain concept from requirements and conditions. An example of a requirement is the desired top speed of the vehicle. Some conditions are fuel price and interest rate. The approach is to regard the output from a simplified vehicle model as a function of design variables. Characteristics defined by the design variables are: type of powertrain, type and size of vital components and directives for the energy management. The intention is to minimize the operating cost of the vehicle, i.e. the sum of component, fuel and component wear cost. An evolutionary algorithm is utilized for optimization. For the complex nonlinear optimization problem, which exists in THEPS, such an algorithm is suitable because the solution space contains numerous local minima and is discontinuous.

Another contribution is a library including powertrain models. The library is developed in the modeling language Modelica and includes models that are more detailed than the models used by THEPS. The objective with the library is to analyze hybrid powertrains proposed by THEPS. The thesis also describes the development of a scaled, hybrid electric, model car prototype. The primary power unit of the model car is a lead-acid battery and the buffer of the model car is a high-power super capacitor. Traction and steering of the car are radio remote controlled.

Three case studies using THEPS are also included. In the first case study a powertrain is adapted to an existing city bus route in the Swedish city of Göteborg. The second case study deals with a waste disposal truck and the third case study deals with a taxi car. The case studies indicate that new powertrain technologies can be competitive from a cost perspective, in some applications, already at present time. It is for example reasonable to equip heavy vehicles running in urban areas with hybrid powertrains. The case studies also indicate that hybrid and/or fuel cell cars can be a more cost effective choice than conventional cars in a near future (2015). Another indication is that it will not be clear for a customer which powertrain concept to choose. The reason is that many cost effective powertrain concepts will be offered. The best choice will depend on the application.

Keywords: Hybrid Vehicle, Hybrid Electric Vehicle, Fuzzy Logic, System Engineering, Optimal Design, Evolutionary Algorithms, Genetic Algorithms, Alternative Powertrain, Fuel Cell Vehicle, Modeling, Simulation, Model car.

Outline of Thesis

The thesis is divided into two major parts. The first part gives a background to the problem of the thesis, a description of the problem and an explanation how it is solved. This part contains the most important results and can be read separately from the second part. The second part is a collection of three published papers, one submitted paper and two reports. Acronyms, terms and symbols frequently used in the first part of the thesis are listed in Appendix A.

The thesis consists of following papers and reports:
Paper A:
J. Hellgren and B. Jacobson, "A Systematic Way of Choosing Driveline Configuration and Sizing Components in Hybrid Vehicles", Presented at the SAE Future Transportation Technology Conference, SAE Paper 2000-01-3098, Costa Mesa, USA, 2000. Also published in SAE 2000 Transactions. Journal of Passenger Car - Mechanical Systems.

Paper B:
J. Hellgren, "Conceptual Powertrain Design and Energy Management of Hybrid Electric Vehicles Using Evolutionary Algorithms and Sugeno Fuzzy Logic", Submitted to IEEE - Vehicular Technology, 2004.

Paper C:
J. Hellgren and K. Jonasson, "Comparison of Two Control Algorithms for the Energy Management of Hybrid Powertrains", Nordic Workshop on Power and Industrial Electronics, Trondheim, Norway, 2004.

Paper D:
J. Hellgren, "Modelling of Hybrid Electric Vehicles in Modelica for Virtual Prototyping", Internal Report, Machine and Vehicle Systems, Chalmers University of Technology, Göteborg, Sweden, 2004.

Paper E:
J. Hellgren and M. Åsbogård, "Improved Energy Management of Hybrid Powertrains by Coordinated Energy Management of Auxiliary Systems", AVEC '04 Conference, HAN-University, Netherlands, 2004.

Paper F:
J. Hellgren, L. Laine, J. Sjöberg, M. Rönnberg, D. Enry and A. Abuding, "Systematic Design and Development of a hybrid Electric Scale Model Car", Internal Report, Machine and Vehicle Systems, Chalmers University of Technology, Göteborg, Sweden, 2004.

Other relevant papers and reports, not included in the thesis, are:
Paper G:
J. Hellgren and M. Wahde, "Evolving Finite State Machines for the Propulsion Control of Hybrid Vehicles", Advances in Signal Processing and Computer Technologies, ISBN 960-8052-37-8, WSES, 2001.

Paper H:
L. Laine, J. Hellgren and M. Rönnberg, "Proposing and Implementing The Control Architecture of a Scale Model Hybrid Car", Internal Report, Machine and Vehicle Systems, Chalmers University of Technology, Göteborg, Sweden, 2004.

Paper I:
J. Hellgren, L. Laine, M. Åsbogård and J. Sjöberg, "Specification of a Hybrid Electric Garbage Truck", Internal Report, Machine and Vehicle Systems, Chalmers University of Technology, Göteborg, Sweden, 2003.

Paper J:
L. Laine, J. Hellgren, M. Åsbogård and J. Sjöberg, "Specifications of a Hybrid Electric Taxi", Department of Machine and Vehicle Systems, Chalmers University of Technology", Sweden, 2003.

Paper K
J. Hellgren and B. Jacobson, "A Systematic Way of Choosing Driveline Configuration and Designing Hybrid Cars", Product Models, ISBN 91-7219-870-2, Linköping, Sweden, 2000.

Paper L:
J. Hellgren, "Modelling of Hybrid Electric Vehicles in Modelica for Virtual Prototyping", 2nd International Modelica Conference, Munich, Germany, 2002.

Paper M:
M. Åsbogård, F. Edström, J. Bringhed, M. Larsson and J. Hellgren, "Evaluating Potential of Vehicle Auxiliary System Coordination Using Optimal Control", AVEC '04 Conference, HAN-University, Netherlands, 2004.

Division of work between authors:
Paper A:
Hellgren did the modelling work and the majority of the report writing in the paper. Jacobson gave constructive guidance.

Paper B-Paper E:
Hellgren did the majority of the work related to these papers. Sjöberg gave constructive guidance for the report writing of Paper B. The work load was fairly evenly distributed in Paper C.

Paper F and Paper H:
The work load was fairly evenly distributed between the authors of the papers.

Paper G:
Hellgren did the modelling work and the majority of the report writing in the paper. Wahde gave constructive guidance.

Paper K-Paper L:
Hellgren did the majority of the work related to these papers.

Paper M:
Åsbogård did the majority of the work related to this paper.

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The author wishes to thank all peoples involved in this project, which was performed at the department of Machine and Vehicle Systems at Chalmers University of Technology, for interesting discussions, data and ideas during the work. Prof. Mart Mägi, Assoc. Prof. Bengt Jacobson and Prof. Jonas Sjöberg have supervised the project. Bengt and Jonas deserve special thanks for their engagement. Also Assoc. Prof. Mattias Wahde, acting as co-advisor, has been important for the progress of this work.

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This work would not have been possible to perform without the initiative and support from the industry. Björn Kristiansen at Volvo Buses has been the link between Chalmers and Volvo in the beginning of the project. Other persons from the industry assisting with ideas or information are: Joachim Lindström, Kristian Niklasson, Pedro Roel and Johan Herland. VINNOVA (a Swedish Agency for Innovation Systems), Volvo, Scania and Saab supported the work financially. Also, thanks to my mother Margit for her careful reading of the manuscript and her support during a demanding time. Last but not least I would like to thank friends and family.

Contents

Chapter 1

Introduction

This chapter gives a background to the problem treated in the thesis, a problem description, an overview of related work and main contributions

1.1 Transportation and the Environmental Concern

Each region on Earth produces more than it consumes of some goods and services and less than it consumes of others. Through transportation, goods are moved from where there are surpluses to where there are shortages. Improved transportation has extended the areas in which various goods can be profitably marketed. From this one can say that transportation gives people and goods greater value. The ability to inexpensively move goods and people is a fundamental link in the economic chain.

The automobile industry is nowadays one of the world's major manufacturing industries. By the early 1990s more than 50 million automobiles were manufactured worldwide annually [1]. If global trends in transportation are projected to year 2100, the world will need 10 times more energy than today [2]. The greatest increase in transportation energy consumption will occur in the developing world. By year 2010, India is expected to have 36 times more cars than in 1990 [2]. Nearly 40% of the world's energy now comes from petroleum, and another 21% comes from natural gas [2]. The world's oil reserves-to-production ratio was 41 years in 2003 [3]. This ratio has been fairly constant the last 20 years [3]. Both proved reserves and production have increased since 1989: by 12.5% and 20% respectively [3]. The majority of the oil reserves, 63.3%, are located in the Middle East [3]. From the the facts recently presented, it is difficult to predict when oil prices drastically will increase in the future.

In addition to limited access, there is an environmental concern surrounding the use of fossil fuels. Environmental pollution caused by humans is already so great that some scientists question whether the Earth can continue to support life unless immediate actions are taken. The transportation sector has a poor environmental record: it impoverishes local air quality, causes acidification and is a major emitter of CO_2. In 1990, the transportation sector was responsible for approximately 25% of the world's energy use, and 22% of the global CO_2 emissions [4].

Some alternatives to reduce the impact of transportation are: extend the use of public transport, work closer to home, more frequently work at home, use alternative fuels and use more energy efficient powertrains. The powertrain is the system in a vehicle that develops and transmits traction power. This thesis will focus on the option to use more energy efficient powertrains.

1.2 Renewable Energy Carriers

Since the industrial revolution, humankind has been burning fossil fuel. The result is a rapid buildup of atmospheric carbon dioxide that is unprecedented in the history of human life on earth. No one knows the precise effects, but there is a risk that temperatures will increase and global weather patterns will change.

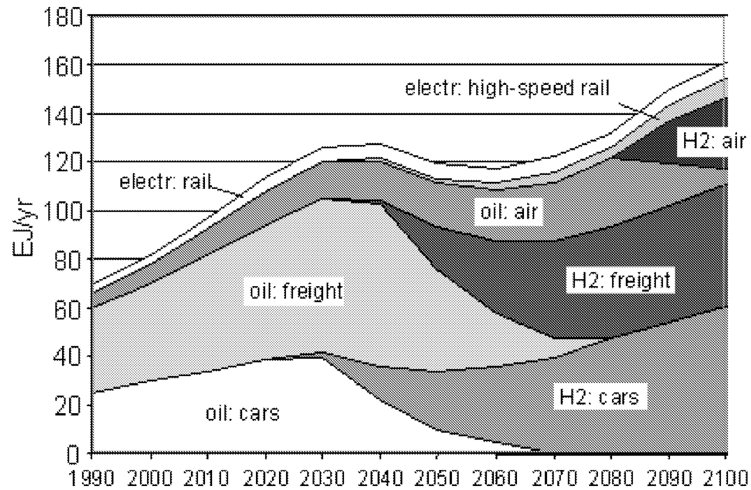


Figure 1.1: *Example of energy source scenario: hydrogen is an important transportation fuel already in the 2030s. The figure illustrates a scenario where low extra component cost for FCVs is assumed. The result of this assumption is an early introduction of hydrogen to the transportation sector. The prediction is from [4].*

Renewable energy carriers are very interesting because they do not influence the amount of atmospheric carbon dioxide.

Examples of renewable energy carriers are ethanol, methanol, hydrogen and electricity stored in batteries. Ethanol and methanol can be based on biomass, hydrogen on biomass or solar energy and electricity on water power, bioenergy or wind power. Renewable energy carriers do not save primary energy, but they are cleaner than gasoline. The challenge of renewable energy carriers is primarily an economic one. If the environmental impact of emissions is valued monetarily, renewable energy carriers become much more competitive. To use electricity directly in automobiles, by charging batteries, is difficult because of the limited operating range that present (2004) battery technology enables. To achieve an acceptable range of a car, the battery needs to be large. So large that it is not feasible from a practical and economical perspective. A revolution in battery technology could however change the picture.

1.3 Alternative Powertrains

The need to save energy and reduce pollution, motivated in Section 1.1, has made alternative powertrains such as *Hybrid Electric Vehicles* (HEVs) and *Fuel Cell Vehicles* (FCVs) more interesting. The challenge in the transportation sector is to reduce emissions and improve fuel economy without sacrificing the vehicle performance.

The main principle in HEVs is to use an energy buffer. Definition 2.3, see Section 2.3, presents how HEVs are defined in this thesis. Characteristic of FCVs is an electrochemical energy conversion. For the customer, this type of vehicles introduce an opportunity to decrease operating cost owing to the potential of lower energy consumption. The fact that electrical power components have become cheaper is also a point in favor of alternative powertrains. Powertrain is defined in Definition 2.1. There will probably be a mix of different powertrains in the future, since the best choice is a function of the applied requirements and conditions. An example of a requirement is the transport task. Some conditions are fuel costs and interest rate. Figure 1.1 illustrates a feasible prediction how the distribution of vehicles propelled by different fuels, i.e. fossils fuel and hydrogen, may vary in time.

In most driving situations, the largest portion of power is generated in the *Primary Power Unit* (PPU). The PPU, see Definition 2.4, can for example be a combustion engine or a fuel cell. The result of using an energy buffer, in a vehicle, is that energy can be stored at braking and later reused. The energy buffer, named buffer in this thesis, can for example be a battery. Another result is that the PPU can be more or less decoupled from the wheels. This makes it possible for the PPU to work efficiently, i.e. close to its optimal point. The control of the PPU becomes much less obvious when a buffer is used. In this thesis, an HEV is defined as a vehicle using a buffer that assists the PPU.

1.4 Objectives

The main objective of this thesis is to develop a methodology for the design of cost effective alternative powertrains. Configuring, choosing, sizing and energy management of vital powertrain components are in focus. The method described in this thesis may be used as a guide for transforming requirements and conditions to suitable powertrains. The objective of this thesis is to give answers to the following questions:

- How should the components of a HEV be chosen and sized in a cost effective and systematic way? The components in focus are those used for generating power, i.e. the PPU and the buffer.
- How should energy flows in a HEV be managed? The energy flows in vital systems like PPU, buffer and auxiliary power units need to be controlled. It is highly desirable to be able to implement the control strategy in a virtual and/or real prototype. Chapter 2 describes vital vehicle systems further.
- How can a proposed powertrain, complete with control algorithm, be evaluated without building an expensive prototype?
- Are there circumstances in which alternative powertrains are suitable from a cost perspective?[1]

1.5 Limitations

To make the questions presented in Section 1.4 possible to answer limitations are necessary. The method of conceptual powertrain design is described in Chapter 3 and Chapter 4. Following limitations are made in the method:

- A specific set of powertrain configurations are examined. These, further desscribed in Chapter 2, are conventional powertrain with stepped gear box, fuel cell powertrain with and wihout buffer, series hybrid powertrain with engine as PPU, parallel and split hybrid powertrains.
- Only a limited number of powertrain component types and sizes are examined. These are presented in Section E.1.
- The *Energy Management Algorithm* (EMA), presented in Chapter 3, considers only the present vehicle status, i.e. it makes no future predictions. EMA is defined in Definition 3.2.
- Driveability, emissions, noice, mechanical vibrations, the cost of component assembly, research and development of new powertrains and the risk of component failure are not considered aspects when examining a powertrain.
- Simplified powertrain models are used. The models are of steady-state type. Steady-state means that input-output relations are not time dependent.
- Stochastic variations in the transport task are not considered.
- The operation of engines is controlled by power. This power corresponds to a prescribed combination, the optimal line, of torque and speed. This is further described in Section 2.5.1.

[1] It is extremely difficult to give a trustworthy answer to whether or not alternative powertrains will be common in the near future. The reason is that it is not only technical challenges that must be overcome. Political decisions and customer opinion may be at least as important as technical progress.

1.6 Related Research and Development Activities

Most of the research and development related to HEVs, describe the development of a prototype or a specific component in an alternative powertrain. Several papers can also be found on simulation tools that analyze a known configuration. According to the knowledge of the author, no report, paper or thesis deals with a method that automatically finds a cost effective powertrain system.

1.6.1 Research Related to Powertrain Design and Energy Management

Research related to the design of the powertrain or development of an EMA using "engineering practice" or systematic methods are presented here. Systematic methods are meant to be a support to the engineer of an alternative powertrain. Characteristic of these kinds of problems is to let a computer search among numerous solutions in a systematic way.

- "Study of the Parametric Optimization for a Parallel Hybrid Electric Vehicle Power Train" [5]. This work presents guidelines on how vital components like engine, battery and electric motor should be sized in a parallel HEV.

- "Mechatronic Design and Control of Hybrid Electric Vehicles" [6]. Guidelines for the design and control of HEVs are given in this paper. *Fuzzy Logic* (FL) is proposed as a control algorithm.

- "Hybrid Vehicle Engine Size Optimization" [7]. This work concludes that both sizes of vital components and the control of the engine are important for the system efficiency of a HEV.

- "CAE tools for quasi-static modeling and optimization of hybrid powertrains" [8]. This work uses optimization to minimize fuel consumption in a fairly simple HEV model.

- "A study of design issues on electrically peaking hybrid electric vehicle for diverse urban driving patterns" [9]. Guidelines to size components of hybrid vehicles such as electric motors, internal combustion engines, transmissions and energy storage devices based on the requirements of different drive cycles are discussed in the paper. It is for example claimed that the size of the PPU is related to the maximum speed of the driving cycle.

- "Analysing Hybrid Drive System Topologies" [10]. In this work a feed-forward Matlab/Simulink model is used to evaluate and compare hybrid powertrain configurations. Design variables, e.g. components sizes, are determined by intuition.

- "How size and performance of hybrid electric vehicle components are influenced by acceleration patterns" [11]. This paper claims that the transport task is very important for the sizing of components in a HEV.

- "Fuzzy Logic Control for Parallel Hybrid Vehicles" [12]. In this paper, a fuzzy logic controller is developed for hybrid vehicles with parallel configuration. The underlying theme of the fuzzy rules is to optimize the operational efficiency of all components, considered as one system. The paper claims that FL is very suitable for EMAs in HEVs.

- "Optimisation of Energy Flow Management in Hybrid Electric Vehicles via Genetic Algorithms" [13]. In this paper the parameters in a FL control algorithm are tuned. A cost function is formulated in such a way that fuel consumption and emissions are minimized.

- "A Novel Design of Energy Management System for Hybrid Electric Vehicles Using Evolutionary Computation" [14]. Using an *Evolutionary Algorithm* (EA), the FL control algorithm of a HEV is optimized. Both the rules and membership functions are considered in the optimization.

- "Route Adaptation of Charge Strategies for Hybrid Vehicles" [15]. This Ph.D. thesis deals with how the ultimate potential of a hybrid powertrain, using optimal control sequences, is found. The result can be used to evaluate a control algorithm.

- "Optimization strategy for design and control of a hybrid vehicle" [16]. In this paper the energy flows in a parallel hybrid vehicle are optimized by optimal control theory.
- "Equivalent consumption minimization strategy for parallel hybrid powertrains" [17]. Optimal control is used to minimize the fuel consumption of a parallel hybrid car.
- "Integrated drive cycle analysis for fuzzy logic based energy management in hybrid vehicles" [18]. In this paper, the concept of a driving situation awareness driven EMA for parallel hybrid vehicles is proposed. The idea is to extract the driving information from the past to classify the type of roadway and the way the driver handles the vehicle.
- "ADVISOR 2.1: A User-Friendly Advanced Powertrain Simulation Using a Combined Backward/Forward Approach" [19]. The popular and widespread simulation package Advisor is described in this paper. The special approach, combining forward- and backward-facing simulation, is in focus.
- "Integrated simulation of vehicle dynamics and control tasks execution by Modelica" [20]. This paper describes HEV models developed in Modelica[21]. The approach is to use a realistic control architecture and dynamic models to enable development of real time EMAa.
- "Regeneration of power in hybrid vehicles" [22]. This paper deals with the issue of power regeneration in HEVs. It is highlighted that the braking force must be distributed on both the rear and the front axle for a stable and safe braking. The battery should accept the high power introduced in a braking sequence to maximize brake energy regeneration.

1.6.2 Research and Development Related to a Prototype Vehicle with a Hybrid Powertrain

Some papers and reports that use computer simulation or a real prototype to evaluate a configuration are presented here.

- "Drive force control of a parallel-series hybrid system" [23]. This paper describes some technical issues in the development of Toyota Prius.
- "Nasa's Involvement in Technology Development and Transfer The Ohio Hybrid Bus Project" [24]. A prototype of a series HEV bus is described in this report. The bus is claimed to offer double the fuel economy.
- "Real life testing of a Hybrid PEM Fuel Cell Bus" [25]. A prototype of a series HEV bus is described in this paper. A 50 kW PEM fuel cell and a NiMH battery are included in the powertrain. The paper claims that hybrid fuel cell buses have a big potential, but there are still many issues to consider prior to full-scale commercialisation of the technology. These are related to durability, lifetime, costs, vehicle and system optimisation and subsystem design.
- "Integrated Energy Transducer Drive for Hybrid Electric Vehicles" [26]. This thesis describes simulation and development related to a hybrid vehicle using an integrated energy transducer.
- "Analysis of a Gas Turbine Driven Hybrid Drive System for Heavy Vehicles" [27]. This thesis deals with the simulation and development of a hybrid city bus propelled with a gas turbine.

1.6.3 Reports Dealing With the Technical Status of Hybrid and Fuel Cell Technology

There are many reports that survey the present technical status of alternative powertrains. The authors often summarize the efforts of companies.

- "Fuel Options for the fuel cell vehicle: hydrogen, methanol or gasoline?" [28]. The economical impact on different fuels are compared. The authors claim that pure hydrogen is the most cost-effective choice.

- "Utveckling och produktion av el-, hybrid- och bränslecellsfordon i Japan" [29]. The development of HEVs in Japan is surveyed and discussed in this report. The report is only available in Swedish.
- "Fuel cell powered vehicles" [30]. This report compiled by SAE (Society of Automotive Engineering) describes fuel cells in general and surveys the technical status and progress of FCVs.

1.7 Outline of the Thesis

This section gives an overview of the chapters in the thesis. People who have experience in automotive technology are advised to glance through Chapter 2.

- Chapter 1 gives a background to the problem, a literature survey, objectives and main contributions.
- Chapter 2 deals with the structure of an automobile. The major parts, i.e. body, chassis and powertrain, are illustrated. A vital part of this chapter is the explanation of different types of powertrains and powertrain components.
- Energy management in hybrid powertrains is handled in Chapter 3. An *Energy Management Algorithm* (EMA), see Definition 3.2, based on *Fuzzy Logic* (FL) is also proposed in the chapter.
- Chapter 4 describes how simulation and optimization can be used in powertrain design. The idea to use *Evolutionary Algorithms* (EAs) and simplified vehicle models, for designing powertrains, is introduced and exemplified.
- In Chapter 5 the results of three case studies are presented.
- Chapter 6 summarizes the papers included in this thesis.
- In Chapter 7 the work presented in this thesis is discussed and conclusions are summarized. It is for example discussed when an automated design process can be useful.
- Chapter 8 presents possible problems, related to the work presented in this thesis, to investigate in the future.

1.8 Main Contributions

The main contributions of the thesis are:

- The simplified and generic powertrain model introduced in Paper B. Generic means that the model can be used to model numerous types of powertrains by changing its parameters. Because of the simplicity of the model, a simulation is performed fast. Section 4.7.2 describes the model further.
- The EMA introduced in Paper B. The algorithm, based on FL, is further described in Chapter 3.
- The computer tool THEPS[2]. THEPS uses an EA to optimize the design variables with respect to the operating cost (€/km) of a vehicle. The design variables correspond to the powertrain layout and EMA of the vehicle.
- The case studies presented in Chapter 5. Three types of vehicles, a bus, a garbage truck and a taxi car are investigated. Both present (2004) and future (2015) circumstances are assumed.
- A library, developed in Modelica, for modeling and simulation of HEVs. The library is described in Paper D. Modelica [21], is a language for modeling physical systems. It has been proposed as a standard by an international association. Modelica can handle problems in different areas, e.g. mechanics, electricity, chemistry, fluid dynamics and control theory.

[2]THEPS is an abbreviation of Tool for Hybrid Electric Powertrain Synthesis

- An algorithm, introduced in Paper E, for the control of auxiliary systems in HEVs. Both fuel consumption and component wear can be reduced using the algorithm.

- The initiation and development of a HEV prototype. The prototype has the size of a scale model car. A scaled model car has shown to be a cost effective prototype. The prototype strenghten the practical relevance of this thesis.

Chapter 2

Vehicle Propulsion Technology

This chapter describes vehicle technology. Current technology (2004) is in focus.

2.1 The Structure of an Automobile

In general an automobile consists of the body, the chassis and the powertrain. The powertrain develops and transmits traction power. Figure 2.1 shows the structure of an automobile.

The body of an automobile normally encloses the powertrain, the chassis and the driver and passengers. The term body does not include the engine, transmission, chassis or frame.

The propulsion system or powertrain is in this thesis defined as follows

Definition 2.1. *The powertrain is the system in a vehicle that generates and transforms the power necessary for propulsion.*

Examples of components that can be involved in a powertrain are *Internal Combustion Engines* (ICEs), mechanical transmissions, drive shaft, differential gear and electric machines. The components can be arranged in numerous ways.

The under portion of an automobile, generally excluding the powertrain, is called the chassis. The chassis consists of the frame, springs, shock absorbers, axles, brakes, wheels, tires, and steering mechanism.

The frame supports the powertrain. The frame is supported by the suspension system, and that in turn is supported by the axles and wheels. The frame must be sufficiently stiff and strong to resist severe twisting and bending. Heavy vehicles normally have separate bodies and frames, but cars are usually built with the frame and body integrated.

Auxiliary systems are normally defined as all sub-systems within a vehicle not directly necessary for propulsion. Examples of auxiliary systems for safe vehicle operation are:

- Lightning and windshield wiper systems.
- Air compressor. Pneumatic systems, e.g. the kneeling system in a bus and braking systems of heavier vehicles, use compressed air. The air compressor is normally very power consuming.

Examples of auxiliary system for increased convenience are:

- Air conditioning system. Specially in hot countries it is motivated to cool the air. The air conditioning system is normally very power consuming.
- Sound and navigation systems.
- Power windows and power sunroof.
- Brake and steer assisting systems.

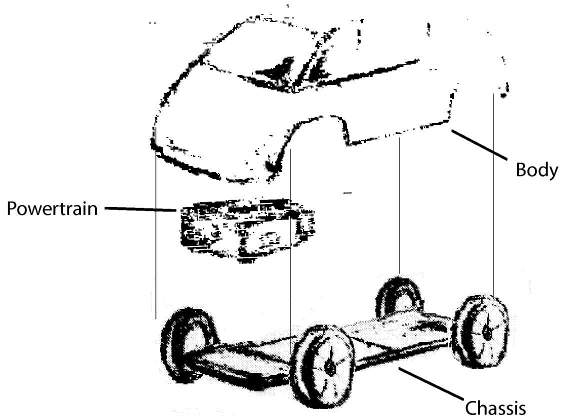


Figure 2.1: *The structure of an automobile. This thesis focuses on the powertrain, i.e. the system providing propulsion power. Auxiliary systems are not located on a specific region in the vehicle. Rather they are located both in the chassis, the body and the powertrain. Auxiliary systems can be defined as all sub-systems within a vehicle not directly necessary for propulsion.*

The supply and demand of electrical power will probably increase dramatically in future automobiles. Many of the mechanical, hydraulic and pneumatic auxiliary systems of today will be replaced with electro-mechanical systems in future. The door opening system in buses, normally pneumatic today, is an example of a system that might be electro-mechanical in future. One advantage with electro-mechanical systems is improved functionality. Energy in electrical from can be used in more applications than for example pneumatic energy. Products for increased convenience, like for example refrigators, micro wave ovens and hair dryers, are possible to run if electric power is available. Another aspect is that a mechatronic system can be modularised far more than a purely mechanical system, since the power and information flow can be transferred on electrical wires which are more flexible than mechanical transmissions.

2.2 Conventional Powertrains

Today (2004), conventional vehicles are the dominating vehicle type because of advantages such as simplicity and engineering experience. Figure 2.2 shows the layout of different types of conventional vehicles. Torque is generated in an ICE. The ratio between the torque from the engine and the torque to the driving axle is controlled by a transmission. In a conventional vehicle the power produced in the ICE is always equal (except for losses) to the power necessary for propelling the vehicle[1]. In a vehicle with a fixed-step transmission or an automatic transmission the ratio between the engine and the wheels is limited to a finite set of values. The ratio is continuous within a limited range in a *Continuously Variable Transmission* (CVT). Fixed-step transmissions have been the dominant technology on the market but CVTs are becoming more and more attractive.

The dilemma with conventional vehicles is to combine high performance with low fuel consumption. High performance requires a powerful ICE to handle power demanding accelerations. If the ICE is large it will operate on a low specific power, when traveling at constant speed. ICE engines, of today, have a low efficiency at part load. The conclusion is that it is a contradiction, in conventional vehicles, to combine low fuel consumption with high acceleration requirements.

2.3 Hybrid Powertrains

Following definition of a hybrid vehicle is made in this thesis:

[1]Some exceptions exist, e.g. braking, then the propulsion power is negative. Negative power demand normally corresponds to an idling engine.

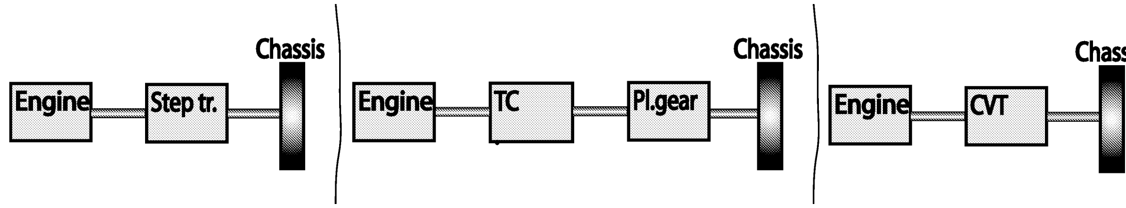


Figure 2.2: *Layout of some conventional powertrains. TC stands for torque converter, Pl. gear for planetary gear, Step tr. for stepped transmission and CVT for Continuously Variable Transmission.*

Definition 2.2. *A hybrid vehicle is a vehicle, that combines two or more sources of power for propulsion. A hybrid vehicle includes a buffer, that can store energy, in its powertrain.*

Examples of power sources are ICEs, fuel cells and muscle power. The pure electric vehicles are still not, on a big scale, ready to conquer the market. Today (2004), the main reason is the shortcoming of the batteries. The energy capacity of a battery is simply not enough for longer trips. A hybrid vehicle gives the possibility to combine the range of a conventional vehicle with the benefits of an electric vehicle. This results in a vehicle with improved fuel economy and lowered emissions. The main drawback with a *Hybrid Electric Vehicle* (HEV) is the normally higher capital cost. The reason to the higher capital cost is that more components are involved in a hybrid powertrain. A HEV is in this thesis defined by

Definition 2.3. *A HEV is a hybrid vehicle including electrical propulsion components.*

The buffer in a HEV enables regeneration of energy. For example, there is much energy to regenerate when the vehicle brakes. The energy in the buffer can later be used when the power demand is high, e.g. at acceleration. The power assistance of the buffer makes the workload of the *Primary Power Unit* (PPU) more independent of the driving condition. The result is that the PPU can work in an efficient way. A PPU is in this thesis defined by

Definition 2.4. *The PPU is the power unit that, in a long time frame, provides the majority of the traction power in a hybrid vehicle. In a conventional vehicle it provides all power. The PPU can for example be a combustion engine or a fuel cell.*

and the buffer by

Definition 2.5. *The buffer is the power unit in a hybrid vehicle that can provide traction power and store energy. The buffer can for example be a NiMH battery.*

The components in a HEV can be chosen and arranged in numerous ways. Figure 2.3 shows examples of how HEVs can be configured. One way to categorize hybrid powertrains is to use the definitions of series (number 1 and 2 in Figure 2.3) and parallel (number 3) HEVs. In contrast to a parallel HEV, a series HEV has no mechanical connection between the engine and the wheels.

The split HEV (number 4) is even called complex, dual or combined hybrid vehicle. A planetary gear, described in Section 2.5.5, connects the two electrical machines and the ICE. When driving, some of the energy flows from the ICE to the wheels via the gearbox as in the parallel powertrain, and some energy flows via the electrical path as in the series powertrain. The proportion between these two energy flows is speed dependent. At higher speeds it works more as a pure parallel hybrid.

An *Integrated Energy Transducer* (IET) is an electrical machine in which both the stator and rotor rotate. The configuration using an IET (number 5) is further described in [26]. An *Integrated Starter and Generator* (ISG) can be regarded as an oversized start engine that has the ability to assist the engine. Vehicles with an ISG are further described in [31]. Configuration 3 is a HEV with a post-transmission (the motor torque is added after the CVT) and configuration 6 is a HEV with a pre-transmission (the motor torque is added before the stepped transmission). Another way is to use the terms mild and strong HEVs. Mild corresponds to a small buffer and strong to a large buffer. A large buffer is able to deliver a moderate power for a fairly long time (1-10 minutes). Different hybrid powertrains are further described in [32][29].

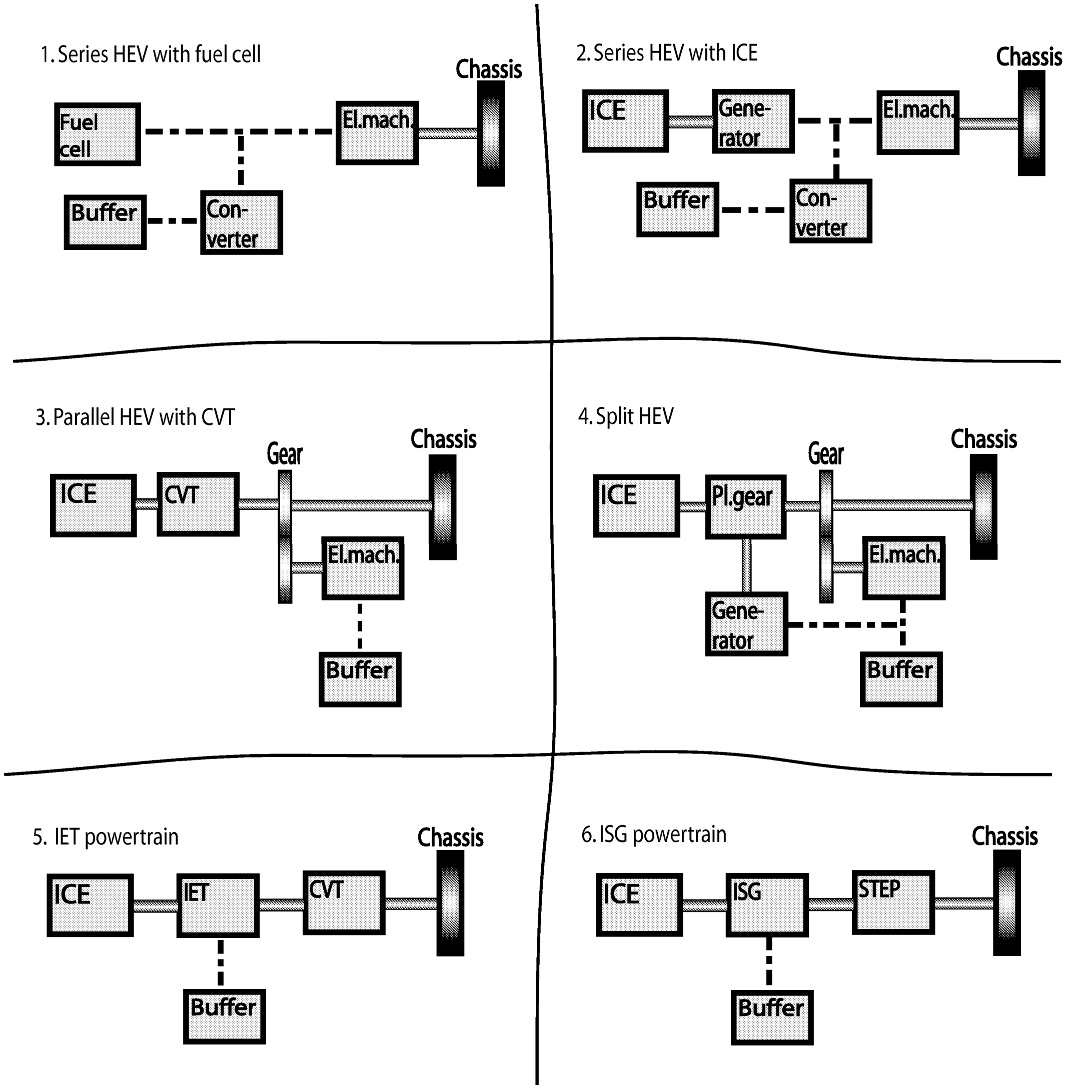


Figure 2.3: *Some hybrid powertrains. Dashed lines represent electrical connections and solid lines represent mechanical connections.*

Table 2.1 presents advantages and disadvantages of some hybrid powertrains. If the advantages and disadvantages are summarized, the conclusion is that a powertrain including few power transformations will result in a higher efficiency. Many components involved will also result in an increased vehicle price. The thumb of rule in engineering "make it as simple as possible" also seems to be relevant for hybrid powertrains. One other important observation is that series hybrid powertrains are normally more suited to regenerate braking energy. On the other hand, parallel powertrains normally have higher efficiency when cruising, i.e. driving at constant speed. These statements indicate that series hybrid powertrains are more suitable when driving in urban conditions, i.e. stop and go driving, and parallel hybrid powertrains are more suitable when cruising, i.e. constant speed driving. General conclusions are however very difficult to achieve.

Many companies and universities have been constructing HEV prototypes for quite a number of years. However, it was not until 1997, with the Toyota Prius I, that HEVs became available to the public market. The Toyota Prius is a split HEV with a gasoline engine and a NiMH battery. Figure 2.4 shows a picture of the Toyota Prius II and its split hybrid propulsion system. Toyota Prius II was released 2004. Other HEVs, available on the commercial market in the year 2004, are Honda Insight (small passenger car), Honda Civic Hybrid (passenger car) and Toyota Estima Hybrid (mini van). In the year 2004 approximately 100 000 HEVs

Table 2.1: *Advantages and disadvantages of some hybrid powertrains.*

Powertrain	Advantages	Disadvantages
Series	• The working point of the PPU is completely independant of the traction power. • The PPU can be mounted in a flexible way, i.e. separately from the wheels. • No driveline oscillations are introduced when the PPU is turned on. • Much energy can be regenerated because the electric machine(s) is largely sized. •A non mechanical connection between the PPU and the wheels gives the potential to remove the differential.	• Many energy conversions result in a low system efficiency with power electronics of today. • The electric machine(s) needs to be largely sized because it must handle all traction itself.
Parallel	• The electric machine and the transmission enable the PPU to work more or less independant of the traction power. • A high efficiency is achieved because the PPU is mechanically connected to the wheels.	• A less flexible powertrain is achieved because the PPU and the wheels must be mounted together. • Limited regeneration capacity because of a normally, relatively small electric machine. • There is a risk that the ICE cannot work on its optimal torque speed combination (the gearbox is not able to set up a suitable ratio).
Split	• The same as for the parallel powertrain.	• The same as for the parallel powertrain. • There is a risc that a power vicious circle can occur, resulting in low efficiency. • A fairly complex system with many components.

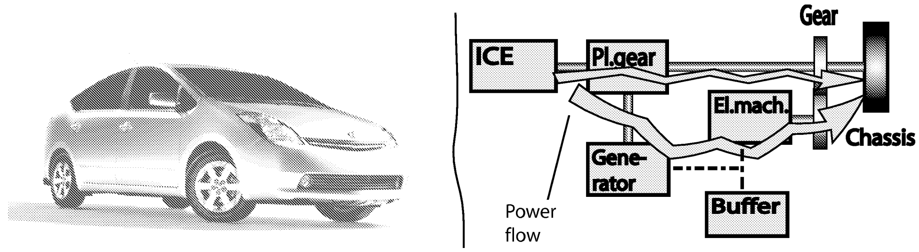


Figure 2.4: *Toyota Prius II [23] and its split hybrid propulsion system. The right-hand picture shows a cruising driving situation. The arrows represent power flows. One portion of the ICE power directly drives the wheels and the rest of the power goes through the electrical (lower) path.*

are sold annually.

Compared to heavy vehicles, cars are of course lighter. Another difference is that they normally travel a shorter distance during their life-time. These aspects should make hybrid powertrains less advantageous in cars than in heavy vehicles. Despite this hybrid powertrains have first been commercialized in cars. Drivability might be one explanation of this.

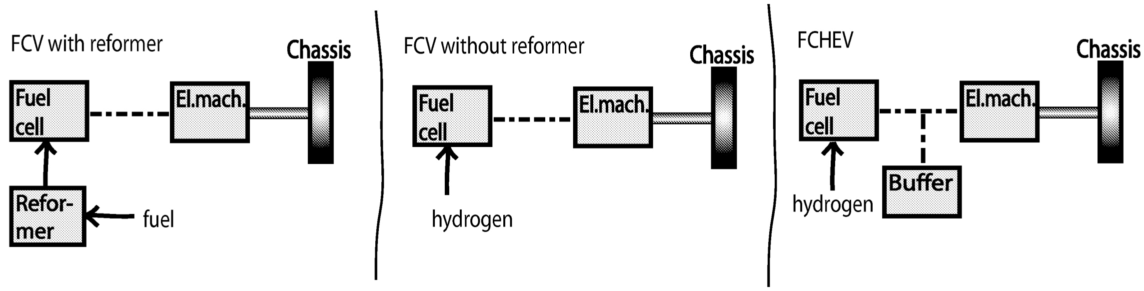


Figure 2.5: *Fuel cell powertrains. A reformer enables the use of a liquid fuel. Unfortenately energy is lost in the reformer, decreasing the total efficiency. There is also an extra capital cost of using on-board reformers. FCHEV stands for fuel cell hybrid electric vehcile.*

2.4 Fuel Cell Vehicles

Strong efforts are being made by several companies to develop *Fuel Cell Vehicles* (FCVs). It is possible that FCVs will replace, at least partly, vehicles using an ICE. A major reason for this is that FCVs offer the potential for extremely low direct emissions. The only substance emitted from the tailpipe is water vapor. The emissions from generating hydrogen may pose a problem. Other reasons are simple packaging and the use of a non-petrochemical fuel. There is a risk that the oil sources will be more limited in the future or that political crises will jeopardize access to oil. Another interesting advantage of fuel cells is modularity, i.e. it is fairly easy to change the size of an existing fuel cell.

Major disadvantages of fuel cells, at present, are high capital cost and difficulties in handling the fuels on-board and in the infrastructure of hydrogen distribution. For example, hydrogen, gasoline and methanol are proposed as fuel. If a non-hydrogen fuel is used, a reformer is normally needed. This converts a fuel (normally liquid) into hydrogen, although this conversion is unfortunately related to emissions and energy losses.

The principles of a fuel cell have been known for many years. For example, fuel cells have been used in the American space shuttle program to efficiently and safely produce auxiliary power. There are currently (2004) no FCVs available on the public market but several companies have built prototypes. It is only a matter of time until FCVs will become commercial. Figure 2.5 shows how FCVs can be configured.

Some believe in the use of a reformer specially with respect to cars, since the storage of hydrogen normally takes a great deal of space and a new infrastructure for handling hydrogen has not yet been designed. Others, e.g. [28], believe that excluding the reformer is the most cost-effective solution. Advantages of using a reformer are presented below.

- Liquid fuels can be used. If methanol is used it can be reformed at relatively low temperatures [28] [2].
- The bulky hydrogen tank is avoided. This is not relevant if hydrogen storage technology is improved by e.g. metal alloy hydrides.

Some disadvantages of using a reformer are:

- An additional conversion is introduced. Energy is lost in the reformer, decreasing the total efficiency.
- The existing electrical power grid cannot be used to distribute the fuel. By installing small scale methane reformers, or small scale electrolyzers at the local fueling station, the hydrogen production can be distributed.
- There is a high capital cost of using on-board reformers that are used only occasionally. Stationary reformers have a much higher duty-ratio.

[2]Methanol can be reformed at 260 °C, compared to 600°C - 900°C for other fuel choices such as gasoline, ethanol, methane, etc.[28]

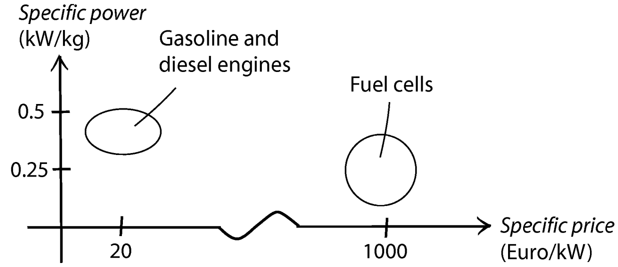


Figure 2.6: *Characteristics of some PPUs today (2004). Specific power is with tank system included. The data on fuel cells are especially uncertain.*

2.5 Vital Systems and Components Used in Powertrains

The choice of component types in a HEV is far from obvious. One reason is that capital cost and performance vary in time. For example, the cost of fuel cells and non-petrochemical fuels will probably decrease drastically in the future. The objective with this section is to give an overview and comparison of components used in HEVs. The reason is that it is necessary to know the characteristics of different components to understand the complexity of configuring, choosing and sizing components in a hybrid powertrain.

2.5.1 Primary Power Units

The purpose of the PPU in a HEV is to transform a fuel into power. The power produced is mechanical for an ICE and electrical for a fuel cell. Figure 2.6 relates some PPUs to specific power (kW/kg) and specific cost (€/kW). The numerical values in the figure are from [30].

Figure 2.7 shows how the efficiency varies with normalized power for some PPUs. As the plots show, the efficiency of gasoline engines and fuel cells are highly dependent on requested power. The maximum efficiency for most ICEs can be found at high torque and about the middle of the engines operating speed range. So in order to minimize the fuel consumption, the ICE should be sized in such way that it frequently operates within this region. Another aspect, when it comes to sizing of combustion engines, is that larger engines normally have a higher efficiency , compared to smaller engines. To conclude, sizing of PPUs is not a simple problem.

Internal Combustion Engines

ICEs are currently the dominant PPUs in vehicles, because of their acceptable performance and low price. A major disadvantage is the generation of emissions. The levels of emissions generated increase greatly in correspondence of abrupt ICE accelerations. HC, NO_X and CO are examples of emissions generated at imperfect combustion[3].

In all ICEs auxiliary sub systems are necessary. The reason is that the ICE needs cooling and lubrication. These systems decrease the efficiency of the ICE because they consume power. Especially at low power demands, auxiliary systems have a negative affect on the efficiency of an ICE. Auxiliary sub systems in an ICE are:

- Cooling pump. The working principle of a cooling system is to let water be cooled in a radiator. A cooling pump makes the water circulating.
- Air pump. This pump drives the fan on the radiator.
- Oil pump. This pump is necessary for lubrication of the engine.

[3]At combustion, with a deficiency or surplus of oxygen, HC is to be formed. The hydrocarbons are poisonous to humans and can cause cancer. Oxygen and nitrogen in the air react at high temperatures and forms NO_X. The NO_X reacts with water and causes acid rain, which is detrimental to the environment. CO is formed at imperfect combustion. CO outlet blocks the ability to absorb oxygen in any air-breathing body.

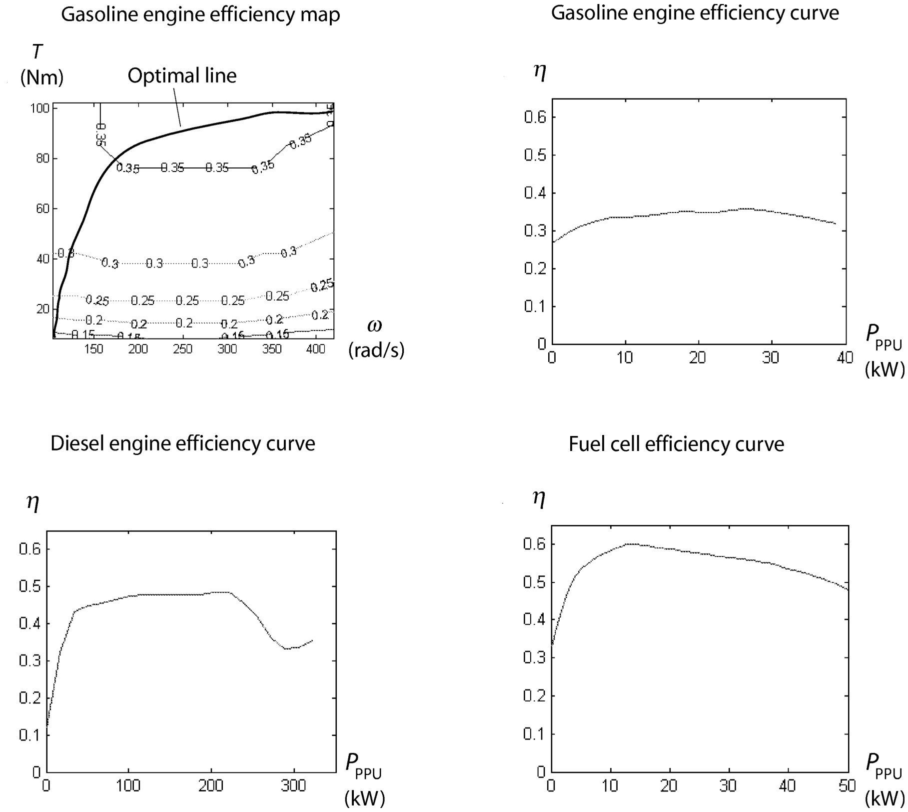


Figure 2.7: *Efficiency curves. For the efficiency curve of the gasoline and diesel engine it is assumed that the engine works on the optimal line. The optimal line represents the combination of torque and speed that gives the highest efficiency. Data for these curves is from Advisor [19].*
- Upper left plot: Contour plot of the efficiency map for the ICE in Toyota Prius I. The ICE has a maximum power of 40 kW. It is clear that the efficiency highly depends on torque.
- Upper right plot: Efficiency as a function of power for the ICE in Toyota Prius I.
- Lower left plot: Efficiency curve of a large diesel engine. The cylinder volume of the ICE is 12.7 liter and the maximum power is 330 kW. Detroit Diesel Corp developed the ICE. At most operating points the diesel engine has a higher efficiency compared to the gasoline engine.
- Lower right plot: Efficiency of a fuel cell system. Power consumption of auxiliary systems, exemplified in Section 2.5.1, are included in the efficiency. The 50 kW fuel cell system is developed by International Fuel Cells. The fuel cell has the highest peak efficiency of all presented PPUs.

Diesel engines are internal-combustion engines in which air is compressed to a temperature sufficiently high to ignite fuel injected into the cylinder. It converts the chemical energy stored in the fuel into mechanical energy. Diesel engines are normally used to propel freight trucks, large tractors, locomotives and ships. Diesel powered cars have become more and more popular in recent years (1990-2004), especially in Europe. One advantage is the high efficiency of these engines, and high torque capability, even at low speed, is another advantage. A drawback of diesel engines is pollution, especially particulate emissions.

Diesel engines are sometimes called compression-ignition engines because initiation of combustion relies on air heated by compression rather than on an electric spark. In a diesel engine, fuel is introduced as the piston approaches the top dead center of its stroke. The fuel is introduced under high pressure. Precise control of fuel injection is critical to the performance of a diesel engine. Since the entire combustion process is controlled by fuel injection, injection must begin at the correct piston position, i.e. crank angle.

Addition of a turbocharger and after cooler can enhance the performance of a diesel engine both in terms of power and efficiency. The most outstanding feature of the diesel engine is its efficiency. In contrast to spark ignition engines, diesel engines do not suffer from preignition problems. Consequently higher theoretical cycle efficiencies, when compared to the latter, can often be realized. Furthermore, the idling and reduced power efficiency of the diesel is far superior to that of the spark-ignition engine. The principal drawback of diesel engines is their emission of air pollutants. These engines typically discharge high levels of particulate matter (soot) and reactive nitrogen compounds often named NO_X.

Gasoline engines are ICEs that generate power by burning a liquid fuel with ignition initiated by an electric spark. Gasoline engines are a common type of ICEs in cars. Compared to diesel engines gasoline engines are normally cheaper.

Internal-combustion engines running on compressed natural gas and blends derived from methanol and ethanol are being studied. The fuels are interesting because they may be produced from readily available biomass sources and have potential for lean burning, high efficiency, and lower emissions. Their problems relate to the large pressurized fuel tanks required because of the lower energy density of the fuel, their poor cold-starting characteristics, and in the case of alcohols, the corrosive character of the fuel.

Gas Turbines

Gas turbines are another type of PPU that use the principle of combustion. Gas turbines have been tested extensively and have good torque characteristics, operate on a wide variety of fuels, have high power-to-weight ratios, have low emissions and offer quiet operation. Compared to diesel engines and fuel cells they are unfortunately inefficient and have a slow response. Gas turbines dominate commercial and military aircraft propulsion. They also dominate aircraft auxiliary power units and auxiliary power units and large military tank propulsion. But when it comes to commercial and personal vehicles such as buses, trucks and passenger cars, gas turbines are in their infancy. The working principle of a gas turbine is fairly simple. Air is compressed in a compressor, heated in a recuperator and then expanded in a turbine. The turbine drives the compressor and a generator. The electricity produced in the generator can be used as an energy source for HEVs.

Fuel Cells

Fuel cells convert chemical fuel directly into electricity. For traction applications, the Polymer Electrolyte Membrane (PEM) cell is the most promising technology, although other fuel cells (e.g. alkaline fuel cells) have been tested as well. At present, fuel cells are far too expensive to be used in cars. For instance, fuel cells cost some 1000 €/kW [30], and this would translate into a total vehicle cost well above 80 000 €(assuming a capacity of 80 kW). But research and development efforts by universities and companies, as well as mass production is expected to bring down costs significantly. Fuel cells operate without combustion, and are thus virtually pollution free. In theory a fuel cell can operate at much higher efficiencies than ICEs, but auxiliary systems reduce the efficiency. Nevertheless, as a whole, a fuel cell system normally has higher efficiency than an ICE. Approximately 20% [33] of the total power is consumed by auxilary systems. Examples of such systems, in a fuel cell, are:

- Air compressor. To handle enough oxygen to the fuel cell the air neeeds to be compressed.
- Coolant pump and fan cooler. A fuel cell also needs cooling.
- Control equipment. The control is realized via electronics consuming power.

There are several possible storage technologies, e.g. compressed gas, liquid hydrogen (cooled hydrogen), metal alloy hydrides and absorption in carbon materials.

Advantages and Disadvantages of Some Primary Power Units

Table 2.2 summarizes advantages and disadvantages of different types of PPUs.

Table 2.2: *Advantages and disadvantages of some PPUs.*

PPU	Advantages	Disadvantages
Diesel engine	• Well known technology. • High torque capability at low speed.	• Petrochemical fuel. • Emissions, especially particulate.
Gasoline	• Compared to a diesel engine the efficiency is normally lower for a gasoline engine.	• A gasoline engine is normally cleaner compared to a diesel engine due to more advanced after-treatment systems.
Alternative ICEs (Compressed Natural Gas and Alcohol)	• Biomass fuel, i.e. renewable. • High efficiency. • Low emissions.	• New technology. • Low energy density of the fuel.
Gas turbines	• Well known technology. • Good torque characteristics. • Low emissions. • Operate on a wide range of fuels.	• Inefficient compared to diesel and gasoline engines. • Slow response.
Fuel cells	• No emissions. • Low noise. • Enables modularity, i.e. simple simple size changing.	• Expensive (2004). • Safety requirements due to hydrogen fuel. • New technology.

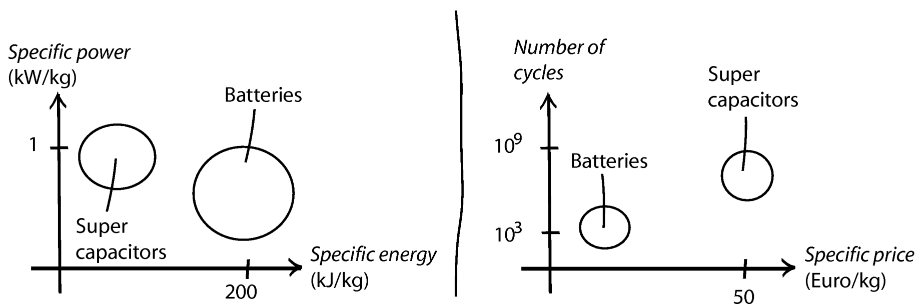


Figure 2.8: *Characteristics of some types of buffers today (2004). The number of cycles reflects how long the buffer can be used before it loses performance and needs replacement. All data are approximative.*

2.5.2 Energy Buffers

The purpose of the buffer in a HEV is to temporarily store energy. The technical motivations to use a buffer in vehicles are explained in Section 2.3. One problem associated with the use of a buffer is energy losses. Other disadvantages are added weight and extra capital cost. Figure 2.8 shows the characteristics of super capacitors and buffers.

Super Capacitors

In a way, a capacitor is a little like a battery. Although they work in completely different ways, capacitors and batteries both store electrical energy. In contrast to a battery, chemical reactions do not occur in a capacitor. One difference between a super capacitor and a conventional capacitor is that a super capacitor can store more energy. Super capacitors are an energy storage technology ideally suited for applications that need repeated bursts of power for fractions of a second to several minutes. High specific power, high specific price and low specific energy are typical characteristics of super capacitors, if compared to batteries. Their specific price will probably decrease significantly in the future if mass production is initiated.

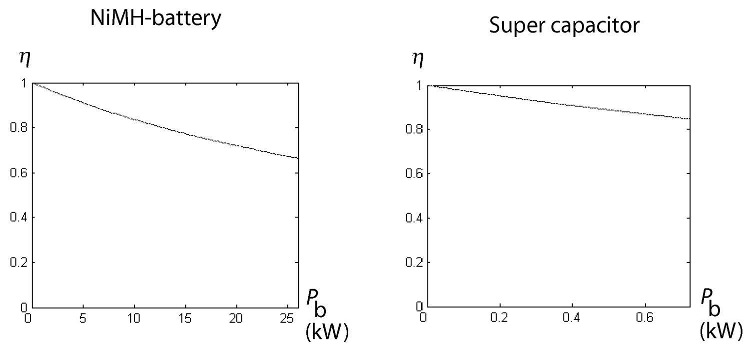


Figure 2.9: *Efficiency curve of NiMH battery (left panel) and super capacitor (right panel). The 25 kW battery is from Panasonic [34] and the 700 W super capacitor is from Maxwell [35]. The battery is similar to the battery in Toyota Prius I. Both efficiency curves are based on resistive losses. Super capacitors normally have higher efficiency due to lower inner resistance.*

Batteries

There are numerous different battery technologies. Some examples of battery types are lead acid batteries, NiMH batteries and lithium batteries. NiMH batteries are popular in HEVs because of such characteristics as high specific power, long lifetime and positive experience in industrial applications. A comparison of NiMH batteries with super capacitors shows that NiMH batteries normally have a shorter lifetime but higher specific energy. As shown in Figure 2.9 super capacitors normally have higher efficiency than NiMH batteries.

Alternative Energy Buffers

Alternative devices for the temporary storage of energy are flywheels and hydro pneumatic buffers. Flywheels work by the principle that the energy is stored in a disc that rotates at a high speed. In the case of a hydro pneumatic buffer, energy is stored through compressing a gas, e.g. nitrogen. Flywheels and hydro pneumatic buffers are rarely used in HEVs at present.

Advantages and Disadvantages of NiMH-batteries and Super Capacitors

Table 2.3 summarizes advantages and disadvantages of NiMH-batteries and super capacitors.

Table 2.3: *Advantages and disadvantages of NiMH-batteries and super capacitors. The table is based on technology of year 2004.*

Buffer	Advantages	Disadvantages
NiMH-battery	• High specific energy. • Industrial Experience.	• Price. • Fairly limited lifetime.
Super capacitor	• Long lifetime. • High specific power.	• Price. • Low specific energy.

2.5.3 Electric Machines

When using an electric machine, one of the primary advantages, is the possibility to let the electric machine handle the transient changes and thereby reduce requirement on the fast dynamics in the ICE. When an electric machine is used as a motor, it converts electric power into mechanical power. If the machine converts mechanical power into electrical power it is a generator. In a HEV an electric machine is often used as both motor and generator. For series HEVs the electric machine generates all the necessary torque on the wheels. Hence an electric machine normally needs to be larger in a series HEV than in a parallel HEV. As a whole,

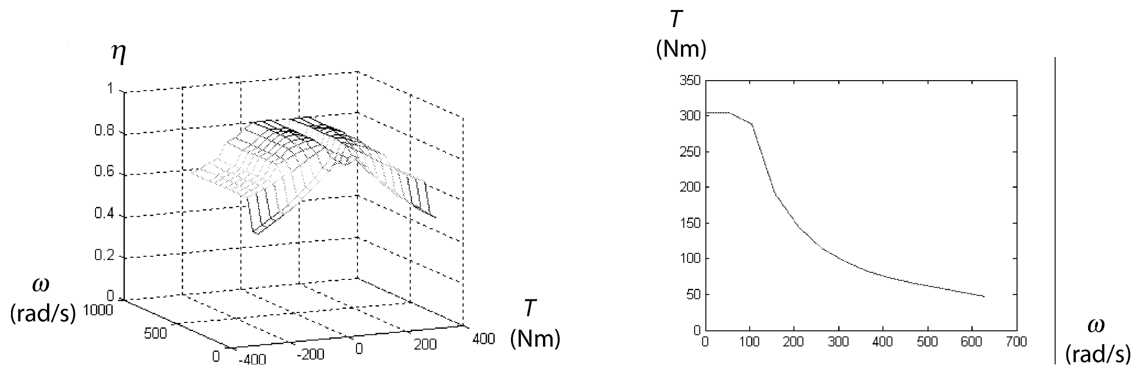


Figure 2.10: *Characteristics of the electric machine used in Toyota Prius I.*
- Left panel: Efficiency of electric machine, with power electronics included, as a function of torque and speed.
- Right panel: Maximum torque curve of electric machine. In contrast to an ICE, an electric machine can handle high torque at low speeds.

there are many different electric machines. Some relevant machines for HEVs are PM machines, induction machines (also called AC machines) and reluctance machines.

Induction machines are suitable for electric vehicles because of their low cost, simple construction and low maintenance. A comparison of PM machines with induction machines indicates that induction machines normally have lower efficiency.

Reluctance machines are less common but an interesting type of electric machine. Characteristics such as reliability, high specific power and the possibility to use low cost materials make reluctance machines a serious candidate. As can be seen in Figure 2.10 an electric machine can, in contrast to an ICE, handle high torque at low speed.

2.5.4 Electrical Converters

The purpose of an electrical converter is to transform one form of electricity to another, more suitable, form. Unfortunately, this power transformation is related to losses. Following forms of electricity normally occur in a HEV:

- Electricity with alternating current (AC). This type of electricity often occurs in PM and induction machines.
- Direct current (DC) with high voltage. Wires that transmitt much energy often use high current to decrease losses.
- Direct current (DC) with low voltage. Some components must simply operate on a fairly low voltage. Many components in auxiliary system use a low voltage, e.g. lights and radio.

There are two major types of converters, namely AC/DC and DC/DC converters. AC/DC converters convert alternating current into direct current. This may be necessary in a HEV with a battery as a buffer because batteries use direct current. DC/DC means that a direct current is transformed into a direct current with another voltage and current. This is often necessary in a HEV because the operating voltage may distinguish between power units. The power from/into an electric energy buffer can be controlled using a DC/DC converter.

2.5.5 Mechanical Transmissions

Most mechanical transmissions function as a rotary speed controller. The ratio of the output speed to the input speed may be constant or variable. In transmissions the speeds may be variable in discrete steps (as on most cars of today) or they may be continuously variable within a range. Fixed-step transmissions usually

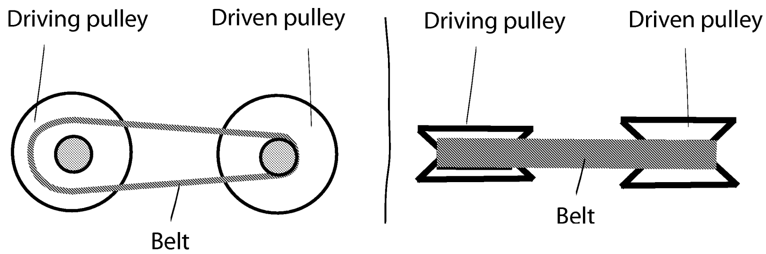


Figure 2.11: *A belt CVT. Side view (left panel) and top view (right panel). By moving the pulleys, in a direction perpendicular to the belt, the ratio is changed.*

employ form-conditioned mechanism, such as gears or chains, and provide fixed speed ratios with no slip. Contionous, i.e. step less, transmissions use either belts, chains or rolling-contact bodies.

As stated in Section 2.5.1 the efficiency of an ICE is highest when the torque on the ICE is high. It is important to use a transmission that can make the ICE operate in a adequate combination of speed and torque, i.e. close to its optimal line. The transmission is installed between the crankshaft of the ICE and the driving wheels. This permits the ICE to operate at a higher speed when its full power is needed and to slow down to a more economical speed when less power is needed.

Types of Mechanical Transmissions

The simplest automobile transmission is the sliding-gear type with four or more forward speeds and reverse. The desired gear ratio is selected by manipulating a shift lever that engages the various gears. This type of transmission is very common in Europe.

The automatic transmission was developed to ease the operation of gear shifting. Most automatic transmissions employ a hydraulic torque converter, a device for transmitting and amplifying the torque produced by the engine. In addition to the hydraulic torque converter, compound planetary gear trains have been designed to provide the speed change. Unfortunately, the energy losses of automatic transmissions are normally higher compared to manual transmissions. Automatic transmissions are very common in USA.

CVTs use either belts or rolling-contact bodies. Figure 2.11 shows a belt CVT, a widely used and inexpensive contionous drive. The sides of the pulleys are conical on the inside, moving them closer together causes the belt to move outward from the center of the pulley and to operate on a larger effective circle. This movement changes the speed ratio. Such drives depend on friction and are subject to slip. Today, the belts are made of steel plates or rubber band. CVTs employing rolling-contact bodies are known as traction drives.

Table 2.4 summarizes advantages and disadvantages of stepped and continuously variable transmissions.

Table 2.4: *Advantages and disadvantages of stepped and continuously variable transmissions.*

Transmission	Advantages	Disadvantages
Fixed step transmissions	• High efficiency. • Well known technology.	• Fixed gear ratios. • Complex operation for the driver.
Continuously variable transmissions	• Continuously variable gear ratio. • High combustion efficiency of engine.	• Low efficiency of transmission. • Sound effects, gearshifts without. changing ICE speed might be confusing for the driver.

Planetary Gears and The Differential Gear

Planetary gears can be defined as an assembly of meshed gears consisting of a sun gear, a ring gear and one or more planet gears supported on a revolving carrier, see Figure 2.12. A planetary gear can be configured

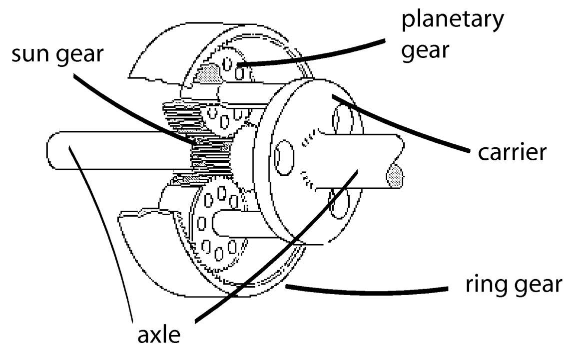


Figure 2.12: *Components in a planetary gear. In the Toyota Prius (split powertrain) the traction motor is connected to the ring gear, the generator to the sun gear and finally the ICE is connected to the carrier*

in several ways, i.e. the number of axles and gears can be different. They are typically used in applications in which the power is split, see Figure 2.3.

The differential gear is a gear arrangement that permits power from the ICE to be transmitted to a pair of driving wheels. The differential divides the force equally between them but permits them to follow paths of different lengths, as when turning a corner. When turning a corner the outside wheel will turn faster than the inner wheel if unrestrained. On a straight road the wheels rotate at the same speed. A Frenchman, Onési-phore Pecqueur, invented the conventional automobile differential in 1827. The torque, turning moment, transmitted to the two wheels with the Pecqueur differential is the same. Consequently, if one wheel slips, as in ice or mud, the torque to the other wheel is reduced. This disadvantage can be overcome somewhat by the use of a limited slip differential or an electrical machine on each driving wheel. Using an electrical machine on each driving wheel requires a sophisticated traction control system.

Chapter 3

Energy Management in Hybrid Powertrains

This chapter explains the problem of energy management in hybrid powertrains and proposes an energy management algorithm based on fuzzy logic.

As stated in Chapter 2, the buffer, see Definition 2.5, in a *Hybrid Electric Vehicle* (HEV) makes the operation of the *Primary Power Unit* (PPU) less dependent of the driving situation. HEV and PPU are terms defined in Definition 2.3 and Definition 2.4 respectively. If the buffer is large the power from the PPU can, in theory, be chosen arbitrarily for a specific situation. This implies that it is not obvious how the energy flows in a HEV should be controlled. The desire is often to control the powertrain in such way that the fuel consumption is low. At the same time the vehicle must handle the driving situation, e.g. meet the desired acceleration. The primary task of the *Energy Management Algorithm* (EMA), see Definition 3.2, is to split the instantaneous vehicle power demand between the PPU and the buffer with regard to following objectives:

- Operate vital powertrain components at high efficiency. To get a low fuel consumption it is not enough to consider only the operation of the PPU. The reason is that high energy losses can also occur in other components. For example, resistive losses in a battery are directly related to current. For HEVs it is relevant to minimize the sum of power losses from each individual powertrain component, i.e. the PPU, the buffer and the electric machine. This is clearly an added complexity not found in conventional vehicles. Figure 3.9 shows how different components can be operated during a driving cycle.

- Not sacrifice vehicle performance. The PPU in a HEV is often smaller in size compared to the PPU in a conventional vehicle. To handle power demanding situations, e.g. accelerations, it is therefore necessary to let the buffer assist. This implicitly means that the EMA must ensure an adequate level of energy in the buffer.

- Minimize component wear. If a component is used carelessly its lifetime may be dramatically shortened. The buffer of a HEV is today (2004) a critical component because it may eventually wear out and need to be replaced. The lifetime of a battery is normally shortened if it is frequently charged with a high power.

- Minimize emissions. The emissions of *Internal Combustion Engines* (ICEs) normally increase if the power changes rapidly.

In practice, critical situations might occur and then the EMA should be overruled by a complementary functionality. Such a situation can be that the driver wants to overtake another vehicle despite a low *State of Charge* (*SoC*). *SoC* is defined in Definition 3.1. For safety reasons, it is at overtaking more important to meet the drivers request, i.e. maximize the PPU power P_{PPU}, instead of manage the energy flows in an energy efficient way. In [36] the EMA is complemented by a "vehicle motion control" functionality. In critical situations the "vehicle motion control" functionality overrules the default EMA.

In this Chapter SoC, EMA, $P_{\mathrm{b}}^{\mathrm{ref}}$ and P_{b} are important terms that are defined as follows

Definition 3.1. *SoC, State of Charge, is a measure of the energy level in the buffer. In an emptied buffer SoC is zero percent while in a full buffer SoC is one hundred percent.*

Definition 3.2. *An EMA is a set of mathematical instructions that proposes a reference buffer power $P_{\mathrm{b}}^{\mathrm{ref}}$ for a given situation*

Definition 3.3. *$P_{\mathrm{b}}^{\mathrm{ref}}$ is a control signal that the EMA proposes. It does not necessary need to be equal to the physical buffer power P_{b}[1].*

Definition 3.4. *P_{b} reflects the physical buffer power, typically derived from measurements.*

Assume that the power demand P_{dem} is known and that $P_{\mathrm{b}}^{\mathrm{ref}}$ is set, then the PPU power P_{PPU} can be calculated using the powertrain model presented in Section 4.7.2[2]. Therefore the EMA implicitly sets the PPU power P_{PPU}. In practice, the reference signal $P_{\mathrm{b}}^{\mathrm{ref}}$ must be transformed to one or multiple control signals. Such a control signal can be voltage applied on a buffer[3] or the throttle angle[4].

A simple EMA is exemplified, in Figure 3.1, to get a better understanding of Definition 3.2. A mathematical description of the EMA is included in the upper panel of Figure 3.1. In words the EMA can be described with following cases:

- Control the buffer level SoC if the vehicle cruises or stands stills. This is done by setting the buffer power in such a way that SoC changes towards a predefined buffer level SoC^{ref}. This case, characterized by zero acceleration, is represented by phase I, III and V in Figure 3.1.

- Let the buffer power P_{b} be in proportion to the power demand P_{dem} if the vehicle accelerates or brakes. This case is valid for non zero accelerations.

The behavior of the EMA is defined by the parameters K_1, K_2 and SoC^{ref}. If the buffer is small it is appropiate to set K_1 and K_2 as small. The reason is that the buffer power is in proportion to these parameters and a small buffer can only give a small power. The EMA needs three input signals SoC, a and P_{dem}. SoC and P_{dem} are vehicle status signals. The driver's intention to accelerate or brake is reflected in a, a is closely related to the pedal position. According to the lower panel of Figure 3.1 the buffer assists the PPU at acceleration and regenerates energy at braking. The figure also shows that the buffer is charged at phase I, III and V. The reason is that SoC is lower than SoC^{ref}.

3.1 Energy Management Algorithm Using Fuzzy Logic

This section describes the EMA proposed in Paper B and Paper C. The approach is to regard the objectives on an EMA, presented in the beginning of this chapter. An important requirement, in this thesis, is that it should be possible to use the EMA for different powertrains. Section 3.1.3 motivates why it is possible to use the EMA for different powertrains. An EMA is adapted to a specific powertrain by setting its design variables. In this thesis design variables are denoted with ξ. There are design variables both in the long and short-term EMA. An optimization process described in Chapter 4 is used to tune the design variables. Definitions of the long and short-term EMA follows

Definition 3.5. *The long-term EMA handles decisions relevant for a long time frame, in the order of minutes. The output of the long-term EMA is the reference value of the energy level in the buffer SoC^{ref}.*

[1] Due to component limitations, it might occur driving situations, e.g. braking, then P_{b} differs from $P_{\mathrm{b}}^{\mathrm{ref}}$.

[2] In a more realistic case, e.g. in a real vehicle, it might be adequate to set P_{PPU} by formulating a regulator problem. For a regulator problem, it is desired that a specific output of the plant is constant. In this case P_{PPU} is regulated so $|P_{\mathrm{b}}^{\mathrm{ref}} - P_{\mathrm{b}}|$ is minimized.

[3] The applied buffer power, normally controlled by a DCDC-converter, determines the charge or discharge current to a battery or a super capacitor.

[4] The throttle angle affects the combustion process in an ICE.

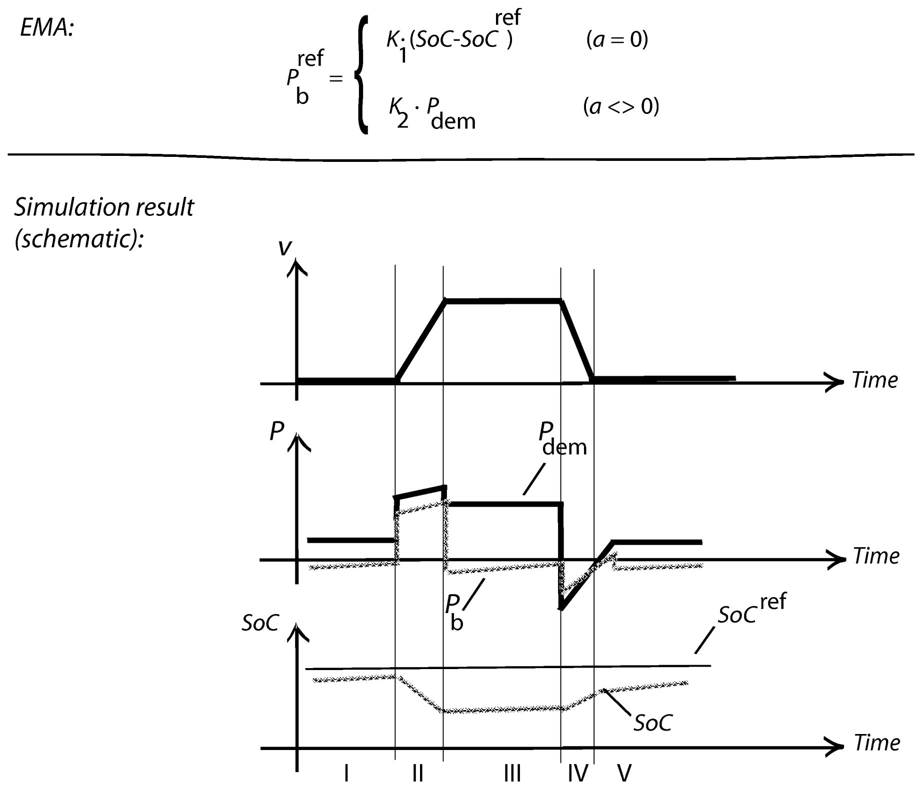


Figure 3.1: *An exemple of an EMA. The power demand from the vehicle is denoted P_{dem}. This power includes both power necessary for propulsion and power consumed by auxiliary systems. The parameters K_1, K_2 and SoC^{ref} define the behavior of the EMA. The upper panel defines the EMA. According to the SoC plot the buffer is charged, reflected by a negative P_{b}, during constant and zero speed. Another simulation result is that braking energy is regenerated.*

Definition 3.6. *The short-term EMA handles decisions relevant for a short time frame, in the order of seconds. $P_{\text{b}}^{\text{ref}}$, the reference value of the power from, or into, the buffer, is the output of the short-term EMA.*

A cascade control structure [37] according to Figure 3.2 is utilized. Cascade control uses the output of the primary controller to manipulate the setpoint of the secondary controller. Characteristic of cascade control is that the secondary loop process dynamics are significantly faster than the primary loop process dynamics. In Figure 3.2 the long-term EMA handles the primary loop and the short-term EMA handles the secondary loop.

As Section 3.1.2 describes, the long term strategy, expressed by SoC^{ref}, only influences the reference buffer power $P_{\text{b}}^{\text{ref}}$ at cruising and when the vehicle stands still. The long term strategy is not relevant at acceleration and braking. According to the mathematical definition of SoC^{ref} in Section 3.1.1, SoC^{ref} is not changed at cruising and when the vehicle stands still. As Figure 3.5 shows $P_{\text{b}}^{\text{ref}}$ changes at these situations. Another way to interpret this is to say that the dynamic of SoC^{ref} is slower than the dynamic of $P_{\text{b}}^{\text{ref}}$, i.e. the secondary loop is faster than the primary loop.

The main motivation to use a cascade control structure is that the EMA can be modified in a straightforward way to regard future predictions. If it, for example, is desirable to charge the buffer in advance to climb a hill it is more intuitive and easy to increase SoC^{ref}, than to control $P_{\text{b}}^{\text{ref}}$ in such a way that SoC is increased. An analogy is the cruise controller in a car. It is normally easier for the driver to set the desired speed compared to manipulating the gaspedal to obtain the desired speed.

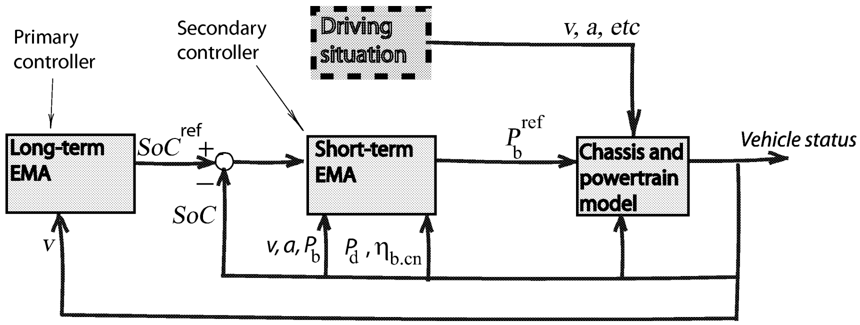


Figure 3.2: *Overview of control structure. A cascade control structure is utilized. The long-term EMA determines how long-term decisions are carried out. These decisions are relevant for a time frame in the order of minutes. While the short-term EMA handles decisions relevant for a time frame in the order of seconds.* SoC^{ref} *is the reference value of the energy level in the buffer and* $P_{\mathrm{b}}^{\mathrm{ref}}$ *is the reference value of the power from, or into, the buffer.* P_{d} *is the power demand of the vehicle including braking power and* $\eta_{\mathrm{b.cn}}$ *is the efficiency between the buffer and the chassis.*

3.1.1 Long Term Energy Management Algorithm

It is normally wise to have an adequate reserve of energy in the buffer. For example, it can be advantageous to have energy available in the buffer when the vehicle stands still. The reason is that an energy and power demanding acceleration will probably occur. The purpose of the long-term EMA, see Definition 3.5, is to set the desired energy level of the buffer, expressed by SoC, in a proper way. A fairly simple long-term EMA is chosen, it is expressed by

$$SoC^{\mathrm{ref}} = 0.5 + \xi_{\mathrm{DoD}} \cdot (0.5 - (\frac{v}{v_{\mathrm{max}}})^{\xi_{\mathrm{vExp}}}) \tag{3.1}$$

where ξ_{DoD} and ξ_{vExp} are design variables further described in Paper B, v_{max} is the required maximum speed of the vehicle. The equation implies that the buffer should be ready to assist with energy if the vehicle has low speed and ready to receive energy if the vehicle has high speed. This is equivalent to a high reference energy level SoC^{ref} for low speeds and a low SoC^{ref} for high speeds. If ξ_{vExp} is two, SoC^{ref} will be in proportion to the kinetic energy of the vehicle[5]. The simplest long-term energy management is to set SoC^{ref} as constant.

3.1.2 Short Term Energy Management Algorithm

The instant power distribution, between the buffer and the PPU, is defined by the short-term EMA. The short-term EMA, see Definition 3.6, determines the operating points of the powertrain components by primarily setting the reference buffer power $P_{\mathrm{b}}^{\mathrm{ref}}$. The sign convention is that a negative buffer power, $P_{\mathrm{b}}^{\mathrm{ref}} < 0$, corresponds to charging of the buffer. The short-term EMA is realized via a rule based controller. In this thesis the rules are formulated by Sugeno *Fuzzy Logic* (FL).

There are two major types of FL methods: Mamdani and Sugeno FL [38]. The phases characteristic of FL, illustrated in Figure 3.3, are described more in detail and exemplified in Appendix C. The two first phases, 'Fuzzification' and 'Rule evaluation', are exactly the same in both FL methods. However, the 'Defuzzification' phase differs between the methods. In Mamdani FL a constant output is related to each rule. In Sugeno FL each rule is associated with a linear function. Because of the linear dependence of each function on the input variables $\boldsymbol{x}_{\mathrm{inout}}$, the Sugeno method is ideal for interpolating multiple linear controllers. A Sugeno FL algorithm resembles a gain scheduler[6] [39].

[5] The kinetic energy of mass m, moving with the speed v, is $m/2 \cdot v^2$

[6] In a gain scheduling controller, a number of operating points are first selected. At each operating point a local linear controller is designed. For intermediate operating points the local linear controllers are interplated or scheduled. The result is a global gain scheduling control low or gain scheduler.

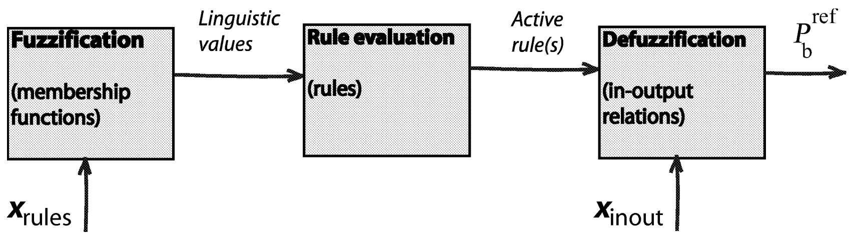


Figure 3.3: *The structure of the Sugeno FL algorithm. Three distinct phases can be identified: 'Fuzzification', 'Rule evaluation' and 'Defuzzification'. $\boldsymbol{x}_{\rm rules}$ are signals used in the 'Rule evaluation' phase and $\boldsymbol{x}_{\rm inout}$ are signals used to evaluate input-ouput relations $P^{\rm ref}_{{\rm b},r}$. Table 3.1 defines $\boldsymbol{x}_{\rm rules}$ and $\boldsymbol{x}_{\rm inout}$ is defined in (3.4)-(3.9).*

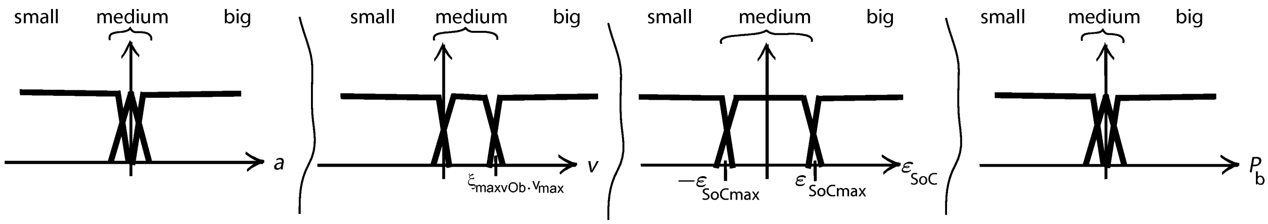


Figure 3.4: *Membership functions used in the Sugeno fuzzy logic regulator. The objective with the membership functions is to convert numerical values to linguistic values. The variables a, v, $P_{\rm b}$ and $\epsilon_{\rm SoC}$ are defined in Table 3.1. $\xi_{\rm maxvOb}$ is further described in Table 3.2. An appropiate value, used in this thesis, of $\epsilon_{\rm SoCmax}$ is 5%.*

Figure 3.3 shows the structure of the Sugeno FL algorithm. Numerical values of $\boldsymbol{x}_{\rm rules} = (a, v, \epsilon_{\rm SoC}, P_{\rm b})^{\rm T}$ are in the 'Fuzzification' phase converted[7] to linguistic values by the membership functions illustrated in Figure 3.4. The linguistic values used are 'small', 'medium' and 'big'. In the 'Rule evaluation' phase linguistic values of $\boldsymbol{x}_{\rm rules}$ are used.

The basic idea with a FL algorithm is to formulate human knowledge and reasoning by if-then rules. The first part of a rule, preceding 'then', specifies the condition for which a rule holds. The second part, following 'then', is the corresponding control action, i.e. a specific input-output relation. Table 3.1 defines the rules used in the EMA. Rule 1-4 define the EMA at cruising, i.e. constant speed. These rules regulate $P^{\rm ref}_{\rm b}$ so that SoC is close to its target value $SoC^{\rm ref}$. This is equivalent to setting $\epsilon_{\rm SoC} = \frac{SoC - SoC^{\rm ref}}{\xi_{\rm DoD}}$ close to zero. The left panel in Figure 3.5 shows schematically how $\epsilon_{\rm SoC}$ can vary in time. The magnitude of the buffer power $P_{\rm b}$ at crusing is defined by design variables $\xi_{\rm DischpCr}$, $\xi_{\rm ChpCr}$, $\xi_{\rm PPUOptCr}$ and $\xi_{\rm PampCr}$. $P_{\rm b}$ is closely related to the time derivate of SoC. In the beginning of the sequence the buffer power is high in order to quickly adjust $\epsilon_{\rm SoC}$. Rule 5 enables the PPU to be shut off when the vehicle stands still and/or at low speeds. The motivation is to avoid inefficient PPU operation. In Section 2.5.1 it is stated that most PPUs are inefficient at low power demand. Design variable $\xi_{\rm MaxvOb}$ defines the upper speed for which the PPU should be shut off. When the vehicle stands still, the algorithm alternates between rule 5 (the PPU is shut off) and rule 2 (the buffer is charged). Rule 6 and its input-output relation makes it possible for both the PPU and the buffer to assist at acceleration. The middle panel in Figure 3.5 shows an example there rule 5 first is active during an acceleration sequence. When the speed is high enough, i.e. $v > v_{\rm max} \cdot \xi_{\rm MaxvOb}$, the input-output relation of rule 6 determines the power split. The input-output relation of rule 7 determines the amount of energy to be regenerated. The PPU is assumed to be shut off during braking so the majority of the not regenerated power is absorbed by the mechanical brakes. As visualized in Figure 3.5, only a part of the kinetic energy can be regenerated. The limitation in buffer power $P_{\rm bmax}$ and vehicle dynamic aspects[8], reflected in $\gamma_{\rm reg}$, explains the limitation.

The input-output relations $P^{\rm ref}_{{\rm b},r}(\boldsymbol{\xi}, \boldsymbol{x}_{\rm inout})$, r corresponds to an index for a rule, are defined by

[7]In version 2 of THEPS, this conversion is realized by if-statements. The reason is to save computational time. In the more accurate Modelica models, described in Paper D a genuine FL calculation is performed.

[8]For front wheel driven vehicles it is always a maximum of regenerated kinetic energy. The reason is that all torque not can be applied on the front wheels.

Table 3.1: *Rules used in the Sugeno FL algorithm. Priority of rule r is denoted p_r. P_b stands for buffer power, $\epsilon_\mathrm{SoC} = \frac{SoC - SoC^\mathrm{ref}}{\xi_\mathrm{DoD}}$ is a measure of how far SoC is from its reference value SoC^ref, v is speed and a is acceleration.*

r, p_r	Rule	Comment
1, 1	If a is medium and P_b is big then output signal is $P^\mathrm{ref}_{\mathrm{b},1}$	Continue to discharge buffer if discharging and driver cruises.
2, 1	If a is medium and P_b is small then output signal is $P^\mathrm{ref}_{\mathrm{b},2}$	Continue to charge buffer if charging and driver cruises.
3, 2	If a is medium and ϵ_SoC is big then output signal is $P^\mathrm{ref}_{\mathrm{b},3}$	Discharge buffer with high power if SoC is high, i.e. far from SoC^ref.
4, 2	If a is medium and ϵ_SoC is small then output signal is $P^\mathrm{ref}_{\mathrm{b},4}$	Charge buffer with high power if SoC is low, i.e. far from SoC^ref.
5, 5	If v is medium and ϵ_SoC is not small and P_b is big then output signal is $P^\mathrm{ref}_{\mathrm{b},5}$	No PPU power if low/zero speed and SoC is not low.
6, 3	If a is big then output signal is $P^\mathrm{ref}_{\mathrm{b},6}$	Let both PPU and buffer assist if vehicle accelerates.
7, 3	If a is small then output signal is $P^\mathrm{ref}_{\mathrm{b},7}$	Regenerate power if vehicle brakes.

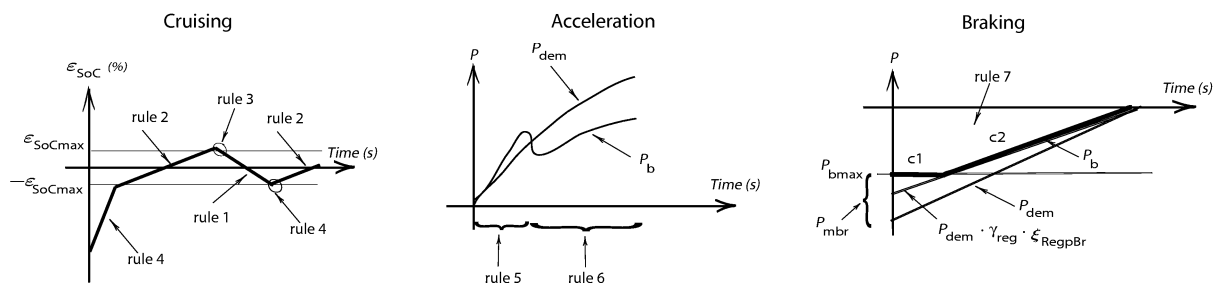


Figure 3.5: *Schematic description of FL input-output relations. In cruising situations, left picture, one of rule 1-4 are active. During acceleration, middle picture, rule 5 or 6 is relevant. At braking rule 7 is active. As illustrated in the right picture only a part of the braking energy can be regenerated. The rest of the power P_mbr is absorbed by the mechanical brakes. In the beginning of the braking sequence 'c1', maximum buffer power P_bmax limits. In the rest of the sequence, vehicle dynamic aspects reflected in γ_reg limits.*

$$[P^\mathrm{ref}_{\mathrm{b},1}, P^\mathrm{ref}_{\mathrm{b},2}, .., P^\mathrm{ref}_{\mathrm{b},R}]^T = \boldsymbol{A} \cdot \boldsymbol{x}_\mathrm{inout} \tag{3.2}$$

where $\boldsymbol{A}$ is defined as

$$\boldsymbol{A} = \begin{bmatrix} \xi_\mathrm{PPUOptCr} & 0 & 0 & P_\mathrm{bnom} \cdot \xi_\mathrm{DischpCr} \\ 0 & \xi_\mathrm{PPUOptCr} & 0 & P_\mathrm{bnom} \cdot \xi_\mathrm{ChpCr} \\ \xi_\mathrm{PampCr} \cdot \xi_\mathrm{PPUOptCr} & 0 & 0 & \xi_\mathrm{PampCr} \cdot P_\mathrm{bnom} \cdot \xi_\mathrm{DischpCr} \\ 0 & \xi_\mathrm{PampCr} \cdot \xi_\mathrm{PPUOptCr} & 0 & \xi_\mathrm{PampCr} \cdot P_\mathrm{bnom} \cdot \xi_\mathrm{ChpCr} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & \xi_\mathrm{AsspAcc} & 0 \\ 0 & 0 & \xi_\mathrm{RegpBr} & 0 \end{bmatrix} \tag{3.3}$$

Table 3.2: *Specification of design variables and parameters used in the short-term energy management. The upper limit of ξ_{PampCr}, denoted B in the table, is a function of buffer properties. A possible value of B is 50.*

Symbol	Description	Possible values
ξ_{DischpCr}	Default normalized discharge power	$[0,1]$
ξ_{ChpCr}	Default normalized charge power	$[-1,0]$
ξ_{PPUOptCr}	Defines the change of buffer power due to a non optimal PPU power. The larger ξ_{PPUOptCr} is the more frequently the PPU will operate in efficient power regions.	$[0,1]$
ξ_{PampCr}	Amplification of buffer power when SoC is to far from its target value	$[1,B]$
ξ_{MaxvOb}	Determines for which speeds only the buffer should propel the vehicle	$[0,1]$
ξ_{AsspAcc}	The fraction of power that the buffer assists with at acceleration	$[0,1]$
ξ_{RegpBr}	The fraction of power that is regenerated	$[0,1]$
P_{bnom}	Nominal buffer power	
P_{ppumax}	Maximum PPU power	
p_{opt}	Normalized optimal PPU power	$[0,1]$
v_{max}	The continuous maximum speed requirement of the vehicle	

Table 3.2 specifies symbols in $\boldsymbol{A}$. The input signals $\boldsymbol{x}_{\text{inout}}$ are defined by

$$\boldsymbol{x}_{\text{inout}} = [\Delta P_{\text{b,dc}}, \Delta P_{\text{b,ch}}, P_{\text{b,ob}}, 1]^T \tag{3.4}$$

The right panel in Figure 3.6 shows two situations where the buffer power is changed in such a way that the PPU works closer to the peak efficiency. $\Delta P_{\text{b,dc}}$, the first item in the vector $\boldsymbol{x}_{\text{inout}}$, can be interpreted as an adequate change[9] in buffer power needed to make the PPU operate closer to its peak efficiency in a buffer discharge situation. Mathematically $\Delta P_{\text{b,dc}}$ is defined as

$$\Delta P_{\text{b,dc}}(t) = \xi_{\text{DischpCr}} \cdot P_{\text{bnom}} \cdot (p_{\text{PPU,dc}}(t) - p_{\text{opt}}) \tag{3.5}$$

where p_{opt} is normalized optimal PPU power, i.e. the power that minimize fuel consumption. The peak efficiency in the upper left panel of Figure 3.9 corresponds to p_{opt}. An estimation of normalized PPU power is included in (3.5); it is defined as

$$p_{\text{PPU,dc}}(t) = \frac{P_{\text{d}}(t) - P_{\text{bnom}} \cdot \xi_{\text{DischpCr}}}{P_{\text{ppumax}}} \tag{3.6}$$

where P_{d} is the power demand of the vehicle including braking power, i.e. $P_{\text{d}} = P_{\text{dem}} - P_{\text{mbr}}$. In (3.6) it is assumed that the buffer power P_{b} is $P_{\text{bnom}} \cdot \xi_{\text{DischpCr}}$. The following equation is similar to (3.5) but is related to charging of the buffer

$$\Delta P_{\text{b,ch}}(t) = |\xi_{\text{ChpCr}}| \cdot P_{\text{bnom}} \cdot (p_{\text{PPU,ch}}(t) - p_{\text{opt}}) \tag{3.7}$$

where

$$p_{\text{PPU,ch}}(t) = \frac{P_{\text{d}}(t) - P_{\text{bnom}} \cdot \xi_{\text{ChpCr}}}{P_{\text{ppumax}}} \tag{3.8}$$

The third item in the vector $\boldsymbol{x}_{\text{inout}}$ is the buffer power needed if only the buffer propels the vehicle. It is defined as

$$P_{\text{b,ob}}(t) = \frac{P_{\text{d}}(t)}{\eta_{\text{b.cn}}} \tag{3.9}$$

[9]The change $\Delta P_{\text{b,dc}}$ is not allowed to be so large that the sign of $P_{\text{b},1}^{\text{ref}}$ changes. If such a change occur an unstable regulator will occur. The reason is that it will not be possible to control SoC towards SoC^{ref} because all "cruising rules" (rule 1-4) will result in an increased SoC. This problem is handled by the third constraint in Section 4.7.4. $\Delta P_{\text{b,ch}}$ suffers from the same problem.

where $\eta_{\mathrm{b.cn}}$ is the efficiency between the buffer and the chassis, i.e. $\eta_{\mathrm{b.cn}} = \eta_{\mathrm{b.bn}} \cdot \eta_{\mathrm{bn.cn}}$. The efficiencies $\eta_{\mathrm{b.bn}}$ and $\eta_{\mathrm{bn.cn}}$ are further described in Section 4.7.2.

From activated rule(s) the output $P_{\mathrm{b}}^{\mathrm{ref}}$ is calculated in the 'Defuzzification' phase according to the calculation procedure given in [40]. Since multiple rules can be active simultaneously, all of the active rules are combined to create the output. Rules with a high priority p_r will have higher influence on the output $P_{\mathrm{b}}^{\mathrm{ref}}$. This is mathematically described by

$$P_{\mathrm{b}}^{\mathrm{ref}} = \begin{cases} \dfrac{\sum_{r=1}^{R} P_{\mathrm{b},r}^{\mathrm{ref}}(\boldsymbol{\xi}, \boldsymbol{x}_{\mathrm{inout}}) \cdot p_r \cdot \alpha_r}{\sum_{r=1}^{R} p_r \cdot \alpha_r} & (\sum_{r=1}^{R} p_r \cdot \alpha_r > 0) \\ 0 & (\sum_{r=1}^{R} p_r \cdot \alpha_r = 0) \end{cases} \tag{3.10}$$

where R is number of rules, p_r is priority for rule r and α_r is the matching degree for rule r. The matching degree reflects how true a rule is.

3.1.3 Reasoning to Why the Energy Management Algorithm can be Adapted to Different Hybrid Powertrains

By changing design variables in the EMA, it can be adapted for different hybrid powertrains. This section exemplifies how EMA design variables are adapted to different powertrains. The following aspects can distinguish between different hybrid powertrains:

- The size of the buffer.
- The lifetime and efficiency of the buffer.
- The size of the PPU.
- The efficiency curve of the PPU, i.e. how the efficiency depends on power.
- The efficiency of energy converting components. Examples of such components are electric machine, converter and mechanical transmission. A more stringent definition of energy converting components is given in Section 4.7.2.

If the buffer is small, the PPU must provide the major part of the traction power during acceleration and the mechanical brakes must absorb much energy during braking. This is fulfilled by setting the design variables ξ_{AsspAcc} and ξ_{RegpBr} as small. These design variables are relevant for rule 6 and 7, described in Table 3.1. The opposite setting of the design variables is possible if the buffer is large. Especially for a small buffer it is advantagous to let SoC^{ref}, reference SoC, vary during the driving cycle. The reason is that the total energy capacity of a small buffer can only be utilized if the energy level varies during the driving cycle. If the energy capacity of the buffer is much smaller than the kinetic energy of the vehicle the buffer must be emptied to maximize the regenerated energy. According to (3.1) SoC^{ref} is determined by the design variables ξ_{DoD} and ξ_{vExp}.

If the buffer has a short lifetime and a low efficiency it is natural to avoid stressing the buffer heavily, i.e. let the PPU provide most of the power during acceleration and let the mechanical brakes absorb a lot of braking energy. In addition, the buffer should be charged and discharged with a small power in cruising situations. This is achieved by setting design variables ξ_{DischpCr} and ξ_{ChpCr} as small, i.e. close to zero. These design variables are relevant for rule 1-4, presented in Table 3.1.

In the case of a small PPU the buffer power must provide the majority of the traction power during acceleration. This is fulfilled by setting the design variable ξ_{AsspAcc}, relevant for rule 6, as large.

The left panel in Figure 3.6 shows a cruising situation for a vehicle incorporating a PPU with a sharp efficiency curve. In this case it can be wise to utilize intermittent PPU operation, i.e. let the PPU operate at two seperated operating points. The reason is that fuel can be saved because more fuel energy is converted at an efficient operating point. This is achieved by tuning the design variables ξ_{DischpCr}, ξ_{ChpCr} and ξ_{PPUOptCr}. These design variables affect the curve plotted in the left panel of Figure 3.5. If ξ_{DischpCr} and ξ_{ChpCr} are large the switching between discharging (rule 1) and charging (rule 2) will be more frequent. It must be

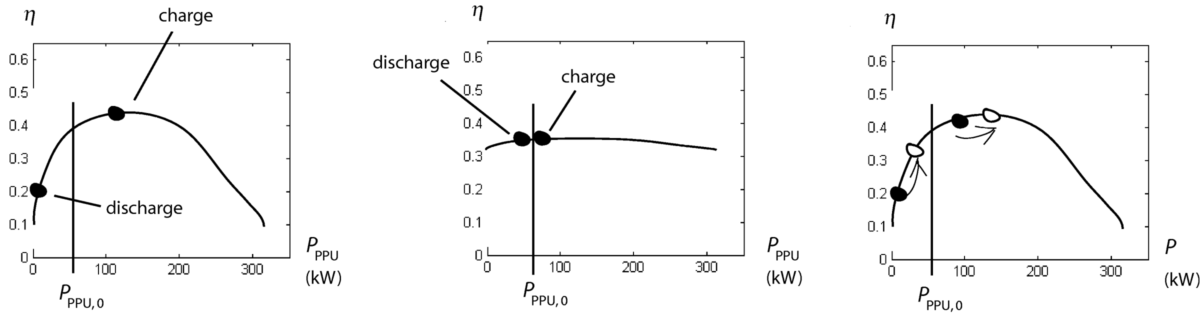


Figure 3.6: *Scematic description of intermittent operation. A HEV runs at constant speed and the PPU power needed to propel the vehicle, with zero buffer power, is $P_{\mathrm{PPU},0}$.*
- Left panel: Intermittent operation is motivated for this PPU efficiency curve. The reason is that fuel can be saved because more fuel energy is converted at an efficient operating point. In this case the buffer stress is significant.
- Middle panel: Intermittent operation is hardly motivated in this case due to the almost flat efficiency curve. The buffer power is almost zero at the operating points.
- Right panel: A change of buffer power makes the PPU operating closer to its peak efficiency. The change from an operating point marked with a dot to an operating point marked with a circle corresponds to an increase of the design variable ξ_{PPUOptCr}.

stressed that intermittent PPU operation is not suitable if the buffer has a short lifetime and a low efficiency. The reason is high power flows through the buffer at such an operation. The result is that an EMA often is a compromise between PPU efficiency and stress of other components. The right panel in Figure 3.6 shows a strategy that is natural for a PPU with an almost straight efficiency curve. In this case intermittent operation is not motivated. The reason is that such an operation will only increase the buffer stress without a significant increase in PPU efficiency.

The efficiency of power converting components will influence the design variables in the EMA. If, for example, the electric machine in a parallel HEV has a low efficiency, intermittent PPU operation will be less beneficial. The reason is that more power losses will occur at buffer charging and discharging.

3.1.4 Simulation of a hybrid Electric Vehicle Using Fuzzy Logic Energy Management Algorithm

To simplify the understanding of the EMA, a simulation, carried out using a Modelica[10] [21] model, is presented in this section. This model is of feed-forward type and more detailed than the model presented in Section 4.7.2. Figure 3.7 shows the layout of the simulation model used in this section. The majority of components in the model are physically modeled. The interpretation of "physically modeled" is that devices, such as resistors, capacitors and inertias, are included in the component models. The model imitates a scaled model car. A fuel cell acts as PPU and a super capacitor is used as buffer.

The left plots in Figure 3.8 shows how power demand varies during the driving cycle. Trends typical for most vehicles are present. High power is needed during acceleration, while superfluous power normally is available during braking. At cruising, i.e. constant speed, the power demand is moderate. The upper right plot in Figure 3.8 shows how the EMA works. In which way active rule depends on driving situation is presented in this plot. Some reflections are:

- The most simple long-term EMA is used, i.e. $SoC^{\mathrm{ref}}(t) = 50\%,\ \forall t \in [0, T]$. T is the time in the end of the simulation.
- The buffer assists with approximately 50% of the propulsion power at acceleration. This is especially clear in the end of an acceleration sequence.
- The PPU operates in distinct power regions during cruising. This is a consequence of rule 1-rule 4.

[10]The object-oriented modeling language Modelica is designed to allow convenient, component-oriented modeling of complex physical systems, e.g., systems containing mechanical, electrical, or control-oriented subcomponents.

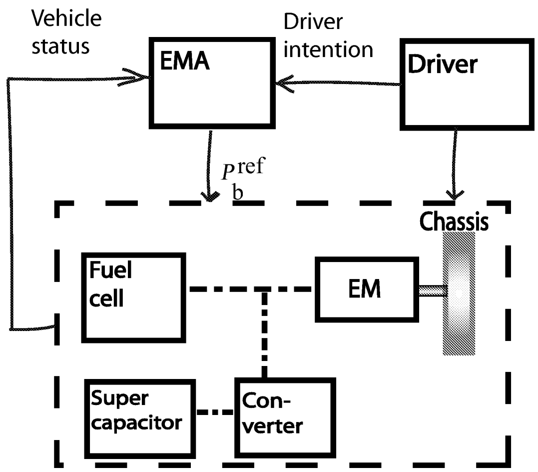


Figure 3.7: *Schematic picture of simulation model of scaled model car. The mass of the car is 12 kg. The fuel cell is able to deliver a power of 120 W and the super capacitor a power of 200 W. The super capacitor, i.e. the buffer, can store 1000 J. The electric machine, EM, is of series direct current type.*

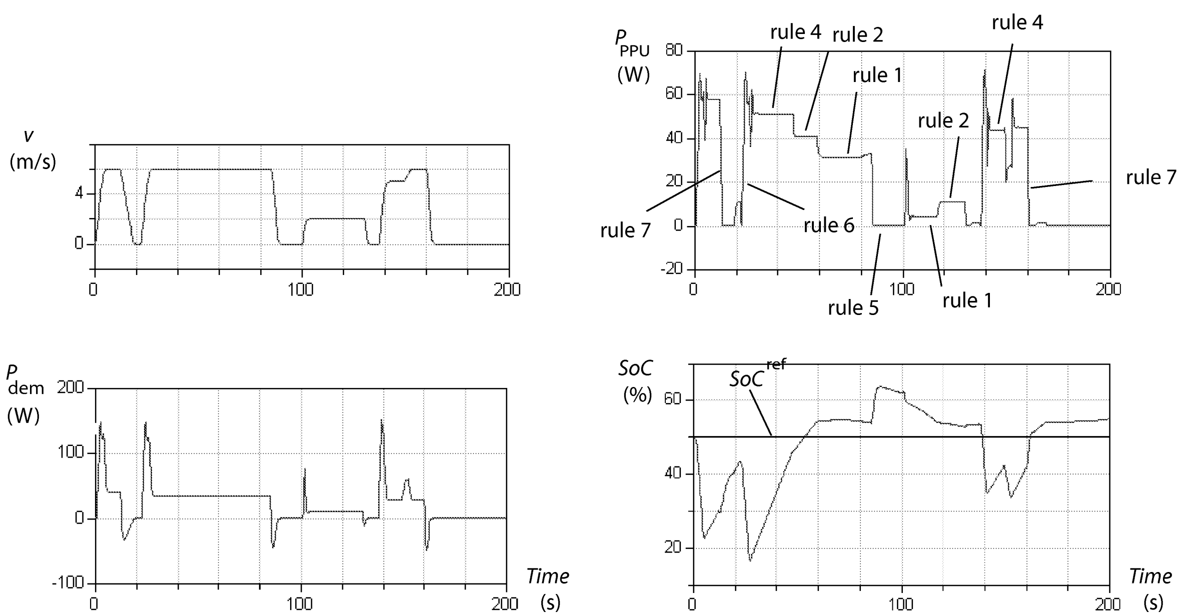


Figure 3.8: *Simulation result. Speed (upper left plot) and power demand (lower left plot) of the scaled model car. The activated rule is presented, at most sequences, in the upper right plot. One of rule 1-4 is active at cruising, rule 5 corresponds to a PPU that is shut off, rule 6 is active at acceleration and rule 7 is active at braking. From the lower right plot it is clear that SoC is far from SoC^{ref} after an acceleration, i.e. when rule 4 is active.*

- The PPU is mostly shut off when standing still. This is a consequence of rule 5.
- The PPU operates at high power directly after acceleration. The reason is that the buffer needs to be fastly charged, i.e. rule 4 is active. This is especially clear in the region $Time \in [30, 85]$.

The simulation result in Figure 3.8 would of course have been different for another setting of the design variables. The appropiate behavior of the EMA, reflected by $\boldsymbol{\xi}$, depends on the powertrain components. The procedure of setting $\boldsymbol{\xi}$ is further described in Chapter 4.

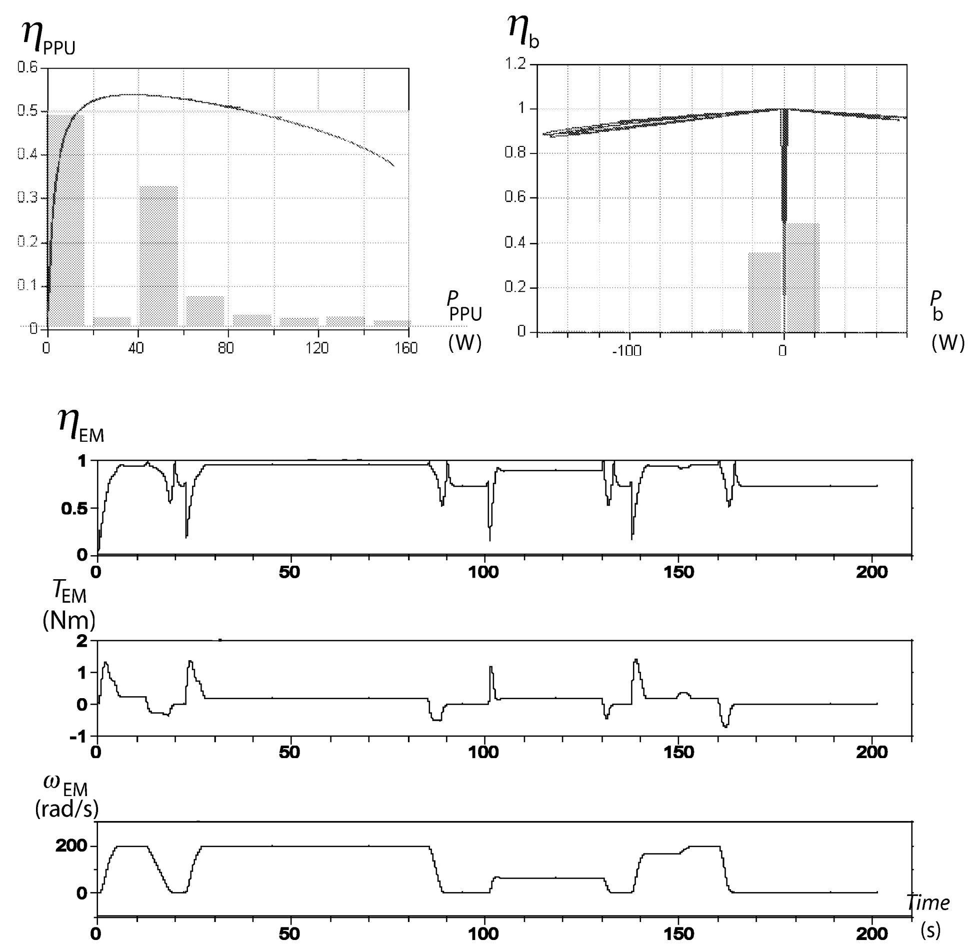


Figure 3.9: *Efficiencies of the PPU, the buffer and the electric machine. The bars represent how frequently, i.e. fraction of total simulation time, the components operates at a specific power. The upper left plot shows that the PPU often is shut off or operated in an efficient power reqion. In approximately 30% of the time it operates close to the peak efficiency. The upper right plot shows that the buffer frequently is operated at low power. The lower plot shows how the efficiency of the electric machine varies during the driving cycle. The efficiency is low when the speed ω is low and the torque is high. The reason is that low speed corresponds to low voltage for the modeled electric machine (series direct current). Resistive losses are higher at low voltage due to higher currents.*

Chapter 4

Using Simulation and Optimization for Powertrain Design

This chapter describes how simulation and optimization can be used as a support during powertrain development.

This chapter is probably the most important part of the thesis because it describes the main contribution: a method for conceptual design of powertrains using optimization and computer simulation. Conceptual design, see Definition 4.1, means that the method is utilized in an early stage of the design process. To introduce the concepts in the method, the design process, concepts in computer simulation of vehicles, optimization techniques and an introductory example for the conceptual design of a motorbike are explained in the beginning of the chapter.

4.1 The Design Process

To understand how simulation and optimization can be used in product development, one must be familiar with the design process. The phase in the design process that this thesis is most related to, is the conceptual design phase, that can be defined as

Definition 4.1. *Conceptual design is the phase, in the product development process, that generates broad concepts. The conceptual design phase is carried out in the beginning of a product development project.*

The phases below are typically performed when a product is designed and developed [41]. It should be stressed that sharp divisions between the phases cannot be drawn and that the phases do not necessarily follow rigidly one after each other. They are often carried out iteratively and the designer often returns to preceding phases.

- Clarification of the problem. Typically, a problem is handed over to the designer from the product-planning department. The designer can now collect information about the problem and specifications are drawn up. The specification defines requirements for the product.

- Conceptual design. Conceptual design is commonly seen to be the most important phase. The decisions made here will influence all subsequent phases. A weak concept can never be turned into an optimum detailed design.

- Embodiment design. In this phase the chosen concept is elaborated into a definitive design. The definitive design defines the arrangement of components and parts. Geometrical shape, dimensions and materials are also determined. Embodiment design is essentially a process of refining concepts generated in the conceptual design phase.

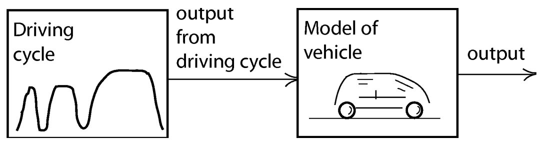


Figure 4.1: *Feed-backward vehicle model. A common approach to define a driving cycle, also used in this thesis, is to express speed as a function of time or position. Some typical outputs of interest, from the feed-backward model, are fuel consumption and component wear.*

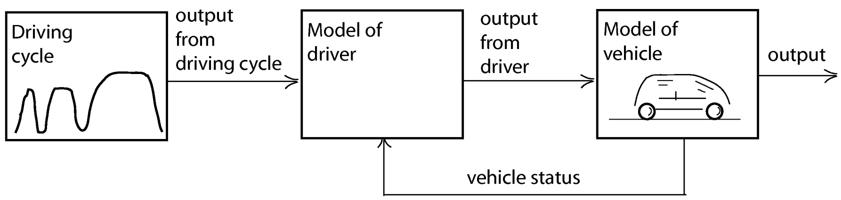


Figure 4.2: *Feed-forward vehicle model. Typically, the driver model follows the reference speed by controlling the traction torque. The reference speed is given by the driving cycle.*

- Detailed design. In this final phase the geometrical shape, dimensions, tolerances, surface properties and materials of all parts of the product are fully specified. Assembly drawings, detail drawings and part lists are made in this phase.

4.2 Computer Simulation of Vehicles

The Latin verb 'simulare' means 'to imitate' or 'to pretend'. In the design process, simulation normally comes between synthesis and evaluation. Simulation has an important function in designing products. During the design process alternative solutions for the design of the new product come into being. One or several solutions are to be chosen for further elaboration. Simulation can be seen as a tool or a guideline for choosing between solutions. The major reason to perform a simulation, according to [41], is to answer following questions:

- Does the product perform as intended, i.e. will it fulfill its functions?
- Can the product be manufactured at an acceptable quality and price?

4.2.1 Feed-backward and feed-forward simulation

When evaluating a powertrain the transport task, normally expressed by the driving cycle, is extremely important for the result. A common approach to define a driving cycle is to express speed as a function of time or position. There are two major types of powertrain models used for evaluation: feed-backward models and feed-forward models.

In a feed-backward model the vehicle is assumed to follow the prescribed speed exactly and therefore no driver model is needed. Figure 4.1 illustrates a feed-backward model. The power demand of the powertrain is calculated backwards from the driving situation. In Section 4.7 it is exemplified how a feed-backward model can be used in an optimization process.

A feed-forward model, illustrated in Figure 4.2, resembles the principle of a physical vehicle. The propulsion power, requested by the driver, gives acceleration and speed. Typical for feed-forward models is the use of a driver model with the purpose of following a reference speed given by the driving cycle. This type of model is especially motivated if dynamic phenomena are of high importance. In Paper D feed-forward models are used for simulation of HEVs.

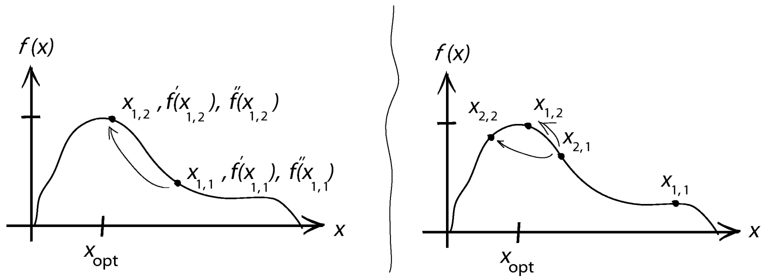


Figure 4.3: *Examples of optimization methods. The left panel shows how a gradient based method can work and the right panel shows the principle of an EA. In $x_{\mathrm{c,i}}$, c stands for candidate index and i for iteration. In the left panel only one solution candidate is present, i.e. c is always one. Normally, solution candidates come closer and closer to x_{opt} for each iteration (i). The arrows indicate a change to a new solution candidate.*

4.3 Using Optimization for Powertrain Design

As mentioned in Section 4.2 simulation can be used as a guideline for choosing between design proposals. Optimization can be seen as the process that automatically finds the best solution, i.e. design proposal. There are many possible criteria to use as a base for judging a technical system. In the case of a vehicle, such criteria can be price, fuel cost, emissions and ride comfort. Some criteria are subjective, like for example ride comfort. Others are easier to measure, e.g. fuel cost. By defining a cost function, it is possible to point out a single solution that will suite our goals better than the others investigated. An optimization process has the objective to minimize a cost function by setting design variables in a proper way. For a vehicle, engine size can for example be a design variable.

One way to perform an optimization is to evaluate all possible combinations. In practice it is normally not possible, from a time perspective, to evaluate all possible combinations. The problem is that an infinite number of solutions exist to a problem with real numbered design variables. Also with a discrete representation of the design variables it is often not realistic to examine all possible cominations. Another aspect is that the number of combinations increases exponentially with the number of design variables. These facts motivate the use of optimization. Optimization techniques can be categorized in two major types:

- Gradient based methods. These methods use a gradient to point out the search direction. The left panel in Figure 4.3 shows the principle of Newton's method. Newton's method [42] uses the first and second derivate of f, i.e. $\frac{\partial f}{\partial x}$ and $\frac{\partial f}{\partial^2 x}$, to find the new solution candidate. An additional candidate is later found from the new solution candidate. This process is iteratively repeated until a satisfactory solution is found.

- Non gradient based methods. If a gradient not is available it is necessary to use alternative techniques. Examples of non-gradient based methods are *Evolutionary Algorithms* (EAs) and Simplex methods. EAs are further described in Appendix B and [43]. The right panel of Figure 4.3 shows how an EA works for a simple optimization problem. Note that $x_{2,1}$ (the second candidate in the first iteration) is choosen for both solution candidates in the second iteration. In EAs new solution candidate(s) are found by probabilistic mechanisms.

Another way to categorize optimization problems is to distinguish between problems including explicit and implicit solutions. When a direct computation of the dependent variables can be made in terms of known quantities, the computation is said to be explicit. Characteristic of explicit solutions is an analytic expression. The problem

$$\begin{aligned} &\text{Min } f(x) \\ &f = sin(x) \end{aligned} \tag{4.1}$$

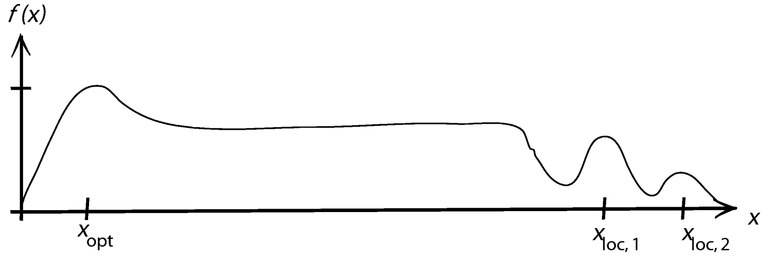


Figure 4.4: *Optimization problem with many local minima. This kind of problem is tricky because it is easy to get stuck in a local minimum. In the figure the global optimum is denoted x_{opt}, local minima are denoted with $x_{\mathrm{loc},1}$.*

subject to the constraint

$$0 \le x \le 2\pi \tag{4.2}$$

has the analytic solution $x = \sin^{-1}(-1) = 3\pi/2$.

A numerical approach is needed if an implicit solution to the system is present. The problem

$$\begin{aligned} &\text{Max } f(x) \\ &f = x - x^5 \end{aligned} \tag{4.3}$$

subject to the constraint

$$0 \le x \le 1 \tag{4.4}$$

has an implicit solution. An approximate solution to (4.3)-(4.4) is $x \approx 0.68$.

A specific problem in optimization is to avoid a solution that is a local minimum. Especially problems with many local minima, exemplified in Figure 4.4 are tricky. Optimization methods using mutliple starting points suits especially well if many local minima are present. Two starting points are present in the EA presented in the rigth panel of Figure 4.3.

4.4 How Optimization is Used in This Thesis

In this thesis, optimization is used to determine the conceptual design of a powertrain. The approach is to regard the output from a simplified vehicle model as a function of its characteristics. Characteristics defined by the design variables are: type of powertrain, type and size of vital components and directives for the energy management. The cost function is represented by a function reflecting the operating cost of the vehicle, i.e. the sum of component, fuel and wear cost. This is described more in detail in Section 4.7.3 and Paper B. To exemplify the idea to use optimization for design, a motorbike is conceptually designed in Section 4.6.

4.5 Motivations for Using an Evolutionary Algorithm

To choose a suitable optimization method is a non trivial task. All optimization methods have advantages and disadvantages. In this thesis an EA is used for the conceptual design of powertrains. The design problem is formulated in Section 4.7. The motivations to use an EA are:

- A non-gradient method is needed because the objective function is non-continuous. A discrete penalty function, defined in Section 4.7, gives a non-continuous objective function.

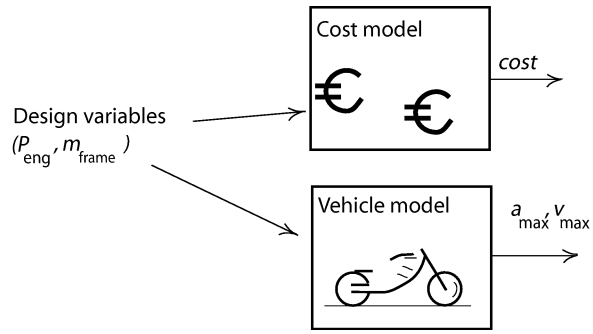


Figure 4.5: *Cost and powertrain model. Both a vehicle model and a cost model are used to determine how appropiate a design proposal is.* P_{eng} *stands for maximum engine power and* m_{frame} *is the mass of the motorbike with engine excluded. Maximum acceleration and speed are represented with* a_{max} *and* v_{max} *respectively.*

- Many local minima exists. An EA normally uses multiple starting points. There is less risk of getting stuck in a local minimum because the space of solutions is searched in parallel. The parallel search of solutions also makes the method suitable for parallel super computers.
- EAs are normally flexible and robust. Even if the objective function or the number of design variables is changed, the same EA can still be used without significant changes.

4.6 An Introductory Example of Conceptual Design Using Evolutionary Algorithms

A fictive company named 'Evolutionary bikes' develops popular racing motorbikes. The key to the success is motorbikes with good performance and a low price. In the following example a very simple powertrain model, a cost model and an EA are used to propose an optimal combination of the design variables vehicle mass and engine size. The term design variable is defined in Definition 4.2.

4.6.1 Cost and Powertrain model

The cost model illustrated in Figure 4.5 implies that a motorbike with a light frame and large engine, i.e. small m_{frame} and big P_{eng}, is the most expensive choice. A light frame is more expansive than a heavy frame because light materials, as for example aluminium, are assumed to be more expansive than heavy materials. Steel is an example of a relatively heavy construction material. The following equation defines the cost c as the sum of frame cost c_{frame} and engine cost c_{eng}

$$c(m_{\mathrm{frame}}, P_{\mathrm{eng}}) = c_{\mathrm{frame}} + c_{\mathrm{eng}} = \frac{1}{m_{\mathrm{frame}}^2} \cdot K_1 + P_{\mathrm{eng}} \cdot K_2 \tag{4.5}$$

where K_1 and K_2 are parameters defined in Table 4.1. P_{eng} is the maximum engine power. It should be noted that the relation between frame mass m_{frame} and frame cost c_{frame} is not well-founded, it is an estimation made by the author. Choosing the cost according to (4.5) is not self evident, one can for example think of including fuel consumption in the cost.

Equations 4.6-4.10 correspond to the box named 'Vehicle model' in Figure 4.5. From these equations are the maximum acceleration a_{max} and the maximum speed v_{max} calculated. The total mass m_{tot} is the sum of frame mass m_{frame} and engine mass or mathematically

$$m_{\mathrm{tot}} = m_{\mathrm{frame}} + \frac{P_{\mathrm{eng}}}{p_{\mathrm{spec}}} \tag{4.6}$$

The frame mass m_{frame} is defined as the mass of the motorbike with engine excluded and p_{spec} is the specific engine power. The maximum speed v_{max} of the motorbike is calculated from

$$F_{\mathrm{tr,cr}} = m_{\mathrm{tot}} \cdot g \cdot f + C_{\mathrm{d}} \cdot A \cdot v_{\mathrm{max}}^2 \tag{4.7}$$

where

$$F_{\mathrm{tr,cr}} \cdot v_{\mathrm{max}} = P_{\mathrm{eng}} \cdot \eta_{\mathrm{t}} \tag{4.8}$$

and g is the constant of gravity, f the coefficient of rolling resistance and $C_{\mathrm{d}} \cdot A$ the air drag resistance. The efficiency of the transmission is denoted η_{t}. $F_{\mathrm{tr,cr}}$ is the total traction force when no acceleration is present. The maximum acceleration a_{max}, specified at a specific speed v_{a}, is defined from

$$F_{\mathrm{tr,acc}} = m_{\mathrm{tot}} \cdot a_{\mathrm{max}} \tag{4.9}$$

where $F_{\mathrm{tr,acc}}$ is the traction force at acceleration. Following equation implies that rolling and air drag forces are assumed as neglectable during acceleration

$$F_{\mathrm{tr,acc}} \cdot v_{\mathrm{a}} = P_{\mathrm{eng}} \cdot \eta_{\mathrm{t}} \tag{4.10}$$

4.6.2 Problem Formulation

In words the optimization problem can be formulated as follows:
Assume that all necessary indata, i.e. other parameters in the model, are known. Minimize the component cost of the motorbike with subject to following constraints:

- The mass m_{tot} of the motorbike may not be too high or too low.
- Three different engine sizes are present.
- The performance of the motorbike must be satisfying. Performance is reflected in top speed v_{max} and acceleration a_{max}.

Mathematically the problem can be formulated as

$$\mathrm{Min}\ c(m_{\mathrm{frame}}, P_{\mathrm{eng}}) \tag{4.11}$$

where m_{frame} is continous in contrast to P_{eng} that is discrete. The cost function c is defined in (4.5). Following bounds on m_{frame} and P_{eng} are introduced to restrict the search space

$$\begin{aligned} &m_{\mathrm{frame,l}} \leq m_{\mathrm{frame}} \leq m_{\mathrm{frame,u}} \\ &P_{\mathrm{eng}} = \{P_{\mathrm{A}}, P_{\mathrm{B}}, P_{\mathrm{C}}\} \end{aligned} \tag{4.12}$$

where P_{A}, P_{B} and P_{C} correspond to different engine sizes. Note that the vehicle model, (4.6)-(4.10), must be solved to achieve m_{tot}, a_{max} and v_{max} in following constraints

$$\begin{aligned} &m_{\mathrm{tot,l}} \leq m_{\mathrm{tot}} \leq m_{\mathrm{tot,u}} \\ &a_{\mathrm{l}} \leq a_{\mathrm{max}} \leq a_{\mathrm{u}} \\ &v_{\mathrm{l}} \leq v_{\mathrm{max}} \leq v_{\mathrm{u}} \end{aligned} \tag{4.13}$$

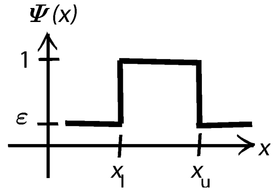


Figure 4.6: *Penalty function used in the new cost function $\tilde{f}$.*

4.6.3 Optimization

To handle the constraints, defined in (4.13), a new objective function

$$\tilde{f} = \frac{c}{\psi_{\mathrm{v_{max}}} \cdot \psi_{\mathrm{a_{max}}} \cdot \psi_{\mathrm{m_{tot}}}} \tag{4.14}$$

with the penalty functions

$$\begin{aligned} \psi_{\mathrm{v_{max}}} &= \psi\left(v_{\max}, v_{\mathrm{l}}, v_{\mathrm{u}}\right) \\ \psi_{\mathrm{a_{max}}} &= \psi\left(a_{\max}, a_{\mathrm{l}}, a_{\mathrm{u}}\right) \\ \psi_{\mathrm{m_{tot}}} &= \psi\left(m_{\mathrm{tot}}, m_{\mathrm{tot,l}} m_{\mathrm{tot,u}}\right) \end{aligned} \tag{4.15}$$

is introduced. If a constraint not is fulfilled, e.g. the maximum speed $v_{\max}$ is too low, the corresponding penalty function $\psi_{\mathrm{v_{max}}}$ is set as small, i.e. $\psi_{\mathrm{v_{max}}} = \epsilon$. An appropiate value of ϵ is 0.1. A fulfilled performance criterion corresponds to a penalty of one. The penalty function is illustrated in Figure 4.6 and defined as

$$\psi\left(x, x_{\mathrm{l}}, x_{\mathrm{u}}\right) = \left(1 + \frac{\epsilon - 1}{1 + e^{(x - x_{\mathrm{l}}) \cdot 100}}\right) + \left(\epsilon - 1 + \frac{1 - \epsilon}{1 + e^{(x - x_{\mathrm{u}}) \cdot 100}}\right) \tag{4.16}$$

Thanks to the new objective function (4.14) the problem can be stated as

$$\text{Min } \tilde{f}(m_{\mathrm{frame}}, P_{\mathrm{eng}}) \tag{4.17}$$

Problem (4.17) is equivalent to (4.11). The difference is that the constraints (4.13) are included in $\tilde{f}$ (4.14) but not in c (4.5).

4.6.4 Results

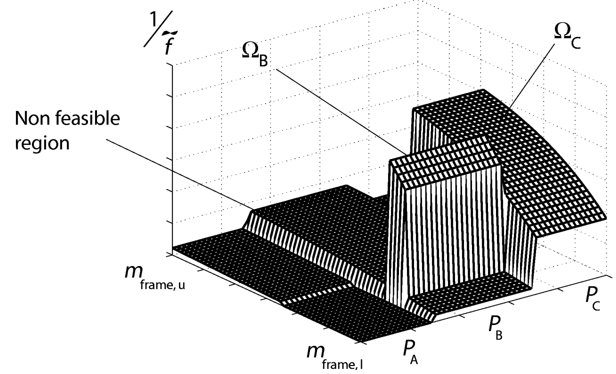
Figure 4.7(a) shows how the inverse of the objective function, $1/\tilde{f}$, depends on the design variables. It is clear that two regions with feasible solutions exist. In the non feasible regions is $1/\tilde{f}$ close to zero. One region Ω_{B} defined by

$$\Omega_{\mathrm{B}} : m_{\mathrm{frame}} \in [m_{\mathrm{frame,l}} + 0.15 \cdot m_{\Delta}, m_{\mathrm{frame,l}} + 0.25 \cdot m_{\Delta}],\ P_{\mathrm{eng}} = P_{\mathrm{B}} \tag{4.18}$$

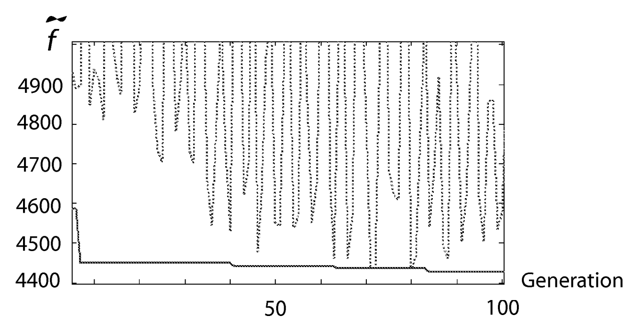
corresponds to a motorbike with a medium sized engine. The mass range m_{Δ} is defined as $m_{\mathrm{frame,u}} - m_{\mathrm{frame,l}}$. Another region Ω_{C} defined by

$$\Omega_{\mathrm{C}} : m_{\mathrm{frame}} \in [m_{\mathrm{frame,l}}, m_{\mathrm{frame,l}} + 0.6 \cdot m_{\Delta}],\ P_{\mathrm{eng}} = P_{\mathrm{C}} \tag{4.19}$$

corresponds to a largely sized engine. The smallest engine, i.e. $P_{\mathrm{eng}} = P_{\mathrm{A}}$, is not adequate because it is too week to meet the performance criterion. Figure 4.7(a) shows that the larger engine allows a heavier frame, than the medium sized engine. The larger engine can, according to (4.19), handle a frame mass of $m_{\mathrm{frame,l}} + 0.6 \cdot m_{\Delta}$. This should be compared to the medium sized engine that, according to (4.18), can handle a frame mass of $m_{\mathrm{frame,l}} + 0.25 \cdot m_{\Delta}$.



(a) Surface plot of the inverse of the new objective function. It is clear that the design variable m_{frame} is discrete and that two feasible regions, Ω_{B} and Ω_{C}, exist.



(b) Evolution process. The solid line represents the best solution, i.e. the individual with lowest cost. The dotted line represents the mean cost of the individuals.

Figure 4.7: *The left panel illustrates the inverted cost as function of the design variables, P_{eng} and m_{frame}. The right panel shows an evolution process. The cost successively decreases with time.*

From motivations stated in Section 4.5 it is appropriate to use an EA to solve (4.17). Figure 4.7(b) shows the progress and the result of the EA. The result is that the minimal price $4.4 \cdot 10^3$ (€), is achieved if $m_{\text{frame}} = m_{\text{frame,l}} + 0.25 \cdot m_{\Delta}$ and $P_{\text{eng}} = P_{\text{B}}$. This corresponds to an engine power of 50 (kW), a top speed of 160 (km/h) and an acceleration of 6.01 (m/s^2). So the answer is that a fairly light motorbike with medium sized engine is the most cost effective solution. Note that the acceleration criterion is barely fulfilled. Table 4.1 defines the indata used in (4.5)-(4.15).

4.7 Conceptual Design of Powertrains Using a Generic Powertrain Model and Evolutionary Algorithms

The major objective with the method described in this section is to be a support in the beginning of the process of developing vehicles, i.e. for conceptual design of vehicles. Definition 4.1 defines conceptual design. As described in Section 4.1 more detailed design needs to be carried out after conceptual design.

The interesting thing, deserving special attention, with the example in Section 4.6 is an automated design process. In the example, an appropriate engine size and frame mass of a motorbike are automatically proposed from requirements. The requirements reflect the customer demands, e.g. the minimum top speed of the motorbike. This approach can make an engineer much more efficient because the computer performs the time-consuming work of comparing different solutions. It can also be an adequate support for a customer

Table 4.1: *Parameters in the introductory motorbike example.*

Parameters for cost model	$K_1 = 8 \cdot 10^3$	(€$\cdot$ kg^2)
	$K_2 = 0.04$	(€/W)
Parameters for powertrain model	$P_\mathrm{A} = 10000,\ P_\mathrm{B} = 50000$	(W)
	$P_\mathrm{C} = 100000$	(W)
	$m_\mathrm{frame,l} = 100,\ m_\mathrm{frame,u} = 400$	(kg)
	$\mathrm{g}\ = 9.81$	(m/s^2)
	$\eta_\mathrm{t} = 0.9, C_\mathrm{d} = 0.5, f = 0.02$	(-)
	$A = 1$	(m^2)
	$p_\mathrm{spec} = 5 \cdot 10^{-4}$	(kg/W)
	$v_\mathrm{a} = 20$	(m/s)
Constraint parameters	$v_\mathrm{l} = 40,\ v_\mathrm{u} = 80$	(m/s)
	$a_\mathrm{l} = 6,\ a_\mathrm{u} = 12$	(m/s^2)
	$m_\mathrm{tot,l} = 250,\ m_\mathrm{tot,u} = 500$	(kg)

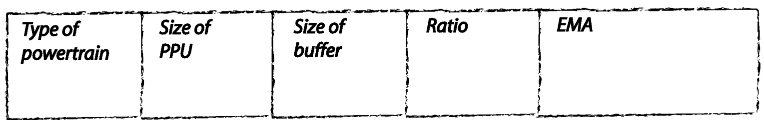


Figure 4.8: *The structure of the genotype. The design variables are defined from the genotype. Both powertrain layout and EMA behavior are included in the genotype. All parts of the genotype consist of one gene except 'EMA' that consists of nine genes. Chapter 3 describes the design variables defining these genes. 'Ratio' is a gene relevant only for split HEVs. The reason is that it determines the gear ratio between the planetary gear and the wheels in a split HEV. This ratio is defined between node 'pn' and node 'cn'.*

to make a wise product choice. The customer can define requirements and the product that best matches the design proposal should be an adequate choice.

Section 4.6 exemplified how optimization of design variables, represented by frame mass m_frame and engine power P_eng, can be used to design a technical system. In this section the set of design variables, denoted by $\boldsymbol{\xi}$, defines the powertrain layout and EMA characteristics of a HEV model. The model can virtually represent a vehicle of any size. In the field of evolutionary biology, genotype is an important term. The genotype is the genetic material of a living being, i.e. its genes. The design variables $\boldsymbol{\xi}$ are defined from the genotype[1]. When developed in a given environment the genotype becomes a phenotype, i.e. the physical and behavioral characteristics of the organism, for example its size and shape. The genotype is mapped to design variables that are mapped to a phenotype or mathematically

$$\textit{genotype} \mapsto \boldsymbol{\xi} \mapsto \textit{phenotype} \tag{4.20}$$

The phenotype corresponds to parameters $\boldsymbol{p}$ used in the generic powertrain model described in Section 4.7.2. In Section E.1.1 it is described more in detail how design variables $\boldsymbol{\xi}$ are mapped into a phenotype in the computer realization THEPS. Figure 4.8 shows the genotype representing the powertrain layout and EMA characteristics of a HEV model. The figure shows that genes for the *Energy Management Algorithm* (EMA) also are included in the genotype. The same genotype can also define a conventional vehicle, in such a case only the first two genes are relevant. Design variable is in this chapter an important term defined as

Definition 4.2. *By optimization, a cost function is minimized by setting design variables. Given a design variable setting, all parameters in a model are determined.*

[1] The genotype is represented by a set of floating point numbers (genes), in the software realization THEPS. Each gene is defined by a number in the interval [0,1].

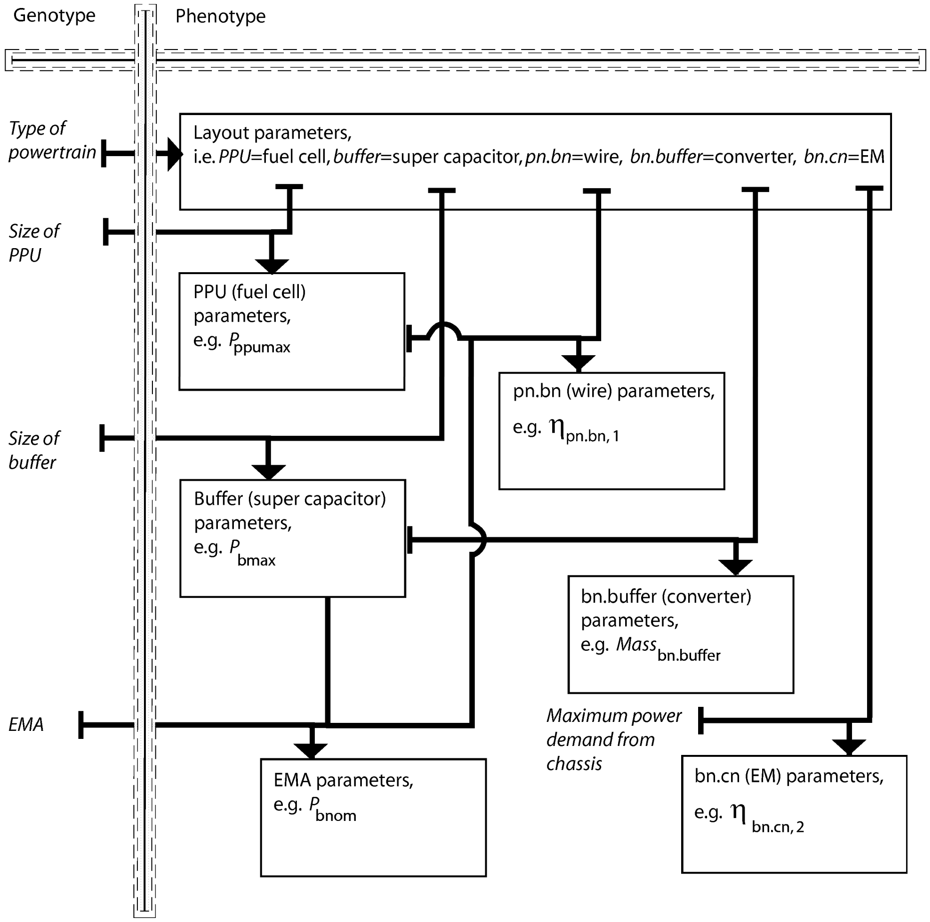


Figure 4.9: *Example of mapping from genotype to phenotype. In this case the phenotype is a series hybrid powertrain with fuel cell as PPU and a super capacitor as buffer. The sizes of the PPU and the buffer are defined by the genes 'Size of PPU' and 'Size of buffer' respectively. PPU stands for Primary Power Unit. The arrangement of the components is given in Figure 4.10.*

Figure 4.9 and Figure 4.10 exemplifies how a phenotype is defined from a given genotype[2]. The mapping to design variables $\boldsymbol{\xi}$ is not represented in the figure. The phenotype is a series hybrid powertrain with fuel cell as PPU and super capacitor as buffer. Figure 4.9 shows that it is an indirect relation between parameters for energy converting components, e.g. the converter, and the genotype. For example, it is possible to define converter parameters, e.g. mass of converter[3], first when buffer parameters are known.

As described in Section E.1.1 the genes 'Type of powertrain' and 'Size of PPU' point out rows in a data base table. Section D describes how the buffer size is achieved. In Section 4.7.5 it is exemplified how the objective function depends on some design variables (genes).

4.7.1 Simulation Procedure

To determine how cost effective a phenotype (powertrain and EMA combination) is, a simulation is needed. The reason is that some parameters, e.g. $P_{\rm dem}$ in the powertrain model, varies in time. Assume that all parameters in the chassis and powertrain model are known. Also assume that the EMA and the transport task are known, then the system in Figure 4.11 can be simulated. Thanks to the chassis model, described

[2]In the software realization THEPS, the transformation from genotype to phenotype is made with a database. A database normally consists of tables and can be seen as a standard of how data should be presented. Appendix E describes THEPS further.

[3]The mass of the converter is the fraction of the maximum buffer power $P_{\rm bmax}$ and the specific power of the converter.

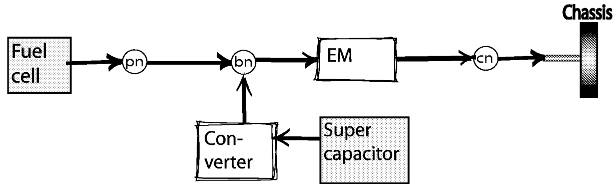


Figure 4.10: *Component arrangement of phenotype. The phenotype represents a series hybrid powertrain with fuel cell as PPU and super capacitor as buffer. This figure shows how the components of the phenotype presented in Figure 4.9 are arranged.*

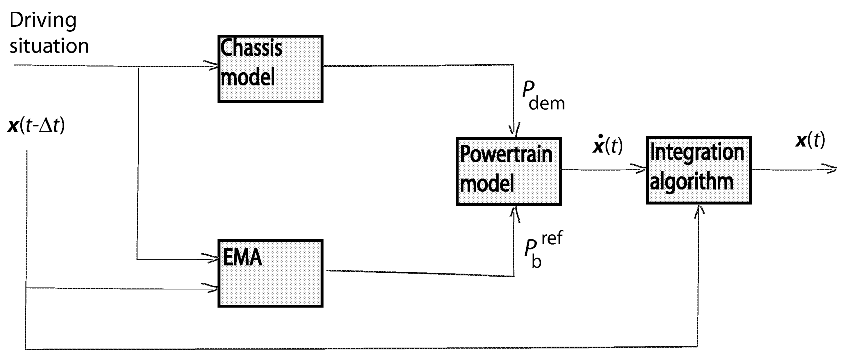


Figure 4.11: *Simulation model. The driving situation reflects desired speed and acceleration at a specific time. PPU power P_{PPU}, power absorbed by the mechanical brakes P_{mbr} and SoC are examples of variables expressing the status of the powertrain. The set of variables at time t is denoted $\boldsymbol{x}(t)$ and at the previous time step $\boldsymbol{x}(t - \Delta t)$.*

in Paper B, the power demand of the vehicle P_{dem} can be calculated for a given driving situation. It should be stressed that the total mass of the vehicle, necessary to calculate P_{dem}, depends on chosen powertrain components. How the EMA determines $P_{\text{b}}^{\text{ref}}$, Definition 3.3, is explained in Section 3.1.

In addition, a numerical integration is needed to evaluate how variables change in time. In the software implementation THEPS, an euler [42] integration scheme is utilized. THEPS is further described in Appendix E. The simulation procedure can be summarized by following statements:

- The powertrain model is represented by a non-linear system of equations. This system is described further in 4.7.2. The EMA is defined according to Chapter 3.1.
- To perform a simulation, i.e. to determine the value of all variables in the powertrain model during the transport task, the system of equations in the powertrain model needs to be solved in each time step. A time step corresponds to a finite time intervall of the simulation[4].

4.7.2 Generic Powertrain Model

The simplifed and generic powertrain model is illustrated in Figure 4.12. Grey boxes and the chassis represent components that generates and/or receives energy. A fuel cell is an example of such a component. Non filled boxes, in Figure 4.12, represent power converting that are defined as

Definition 4.3. *Power converting components, are components in the powertrain that normally do not generate or store energy. These components typically transforms one type of power into a more suitable form. An electric machine is an example of such a component.*

All equations describing the model are given and explained in Paper B. If two variables in the set $\{P_{\text{PPU}}, P_{\text{b}}, P_{\text{dem}}\}$ are known, then the third variable can be calculated using the generic powertrain model. There

[4] In THEPS the time step is set as one second.

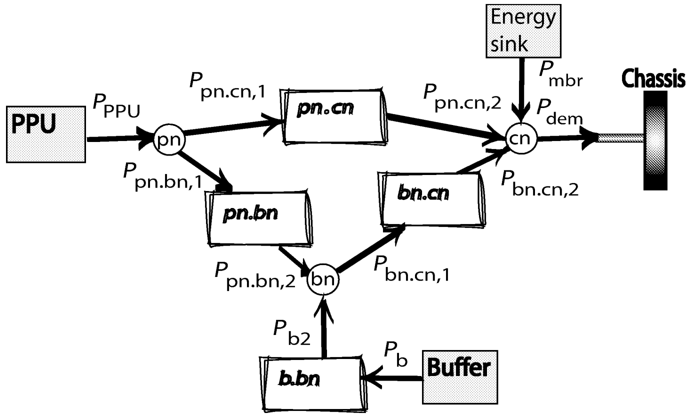


Figure 4.12: *Generic powertrain model. The model can be used for several powertrain types. A component placed between node/component 'x_1' and 'x_2' is named '$x_1.x_2$'. P_{mbr} is the power required for mechanical braking. The energy sink corresponds to heat dissipation from the mechanical brakes to the atmosphere.*

is a non-linear relationship between these three variables. It should be stressed that the mechanical braking power P_{mbr} is calculated by equations included in the powertrain model. These equations imply for example that the mechanical brakes assist the electric machine if the vehicle brakes. The calculation of P_{mbr} is further described in Paper B. One major advantage with the model is that it can be used for several powertrain configurations. This is illustrated in Figure 4.13. The following cases can occur and are exemplified in the figure:

- No buffer is present in the powertrain. In this case, exemplified in the upper left configuration in Figure 4.13, the buffer power P_{b} and the power from the PPU to the lower path $P_{\text{pn.bn,1}}$ are zero. For powertrains without buffer *pn.cn* is the only relevant power converting component.
- The powertrain is of series or parallel hybrid type. In this case the buffer power is given by the EMA. The power from the PPU to the upper path $P_{\text{pn.cn,1}}$ is zero. The relevant power converting components are *pn.bn*, *b.bn* and *bn.cn*.
- The powertrain is of split hybrid type. This is the most complex case because both the buffer power from the EMA and the power split at the node 'pn' needs to be known. In a split HEV the planetary gear, arranging this power split, corresponds to node 'pn'. The power split at 'pn' is calculated from the ratio between the planetary gear and the wheels 'Ratio' (a design variable relevant for split HEVs only), the engine power and the wheel speed. Planetary gears are described in Section 2.5.5. All power converting components in the model are necessary for split HEVs.

Equilibrium equations like

$$P_{\text{PPU}} - P_{\text{pn.cn,1}} - P_{\text{pn.bn,1}} = 0 \tag{4.21}$$

are included in the mathematical description of the generic powertrain model. The equation implies that the sum of power into node 'pn' is equal to the sum of power out from a node 'pn', see Figure 4.12. Also relations and differential equations describing component behavior, exemplified later in this section, are necessary. These relations are of steady type. Steady state means that the relation is not time dependant.

The efficiency of an power converting component determines the relation between power flowing in and out from it. This is mathematically described by

$$P_{\text{x}_1.\text{x}_2,2} = \eta_{\text{x}_1.\text{x}_2}(p_{\text{x}_1.\text{x}_2}) \cdot P_{\text{x}_1.\text{x}_2,1} \tag{4.22}$$

where $p_{\text{x}_1.\text{x}_2} = P_{\text{x}_1.\text{x}_2,1}/P_{\text{x}_1.\text{x}_2,1\ \max}$ is normalized power, $P_{\text{x}_1.\text{x}_2,i}$ (i=1, 2) is power flow into and out from a power converting component. The symbol x_i denotes a node or a component. $P_{\text{x}_1.\text{x}_2,1\ \max}$ is the maximum value of $P_{\text{x}_1.\text{x}_2,1}$, e.g. the maximum power a buffer can handle.

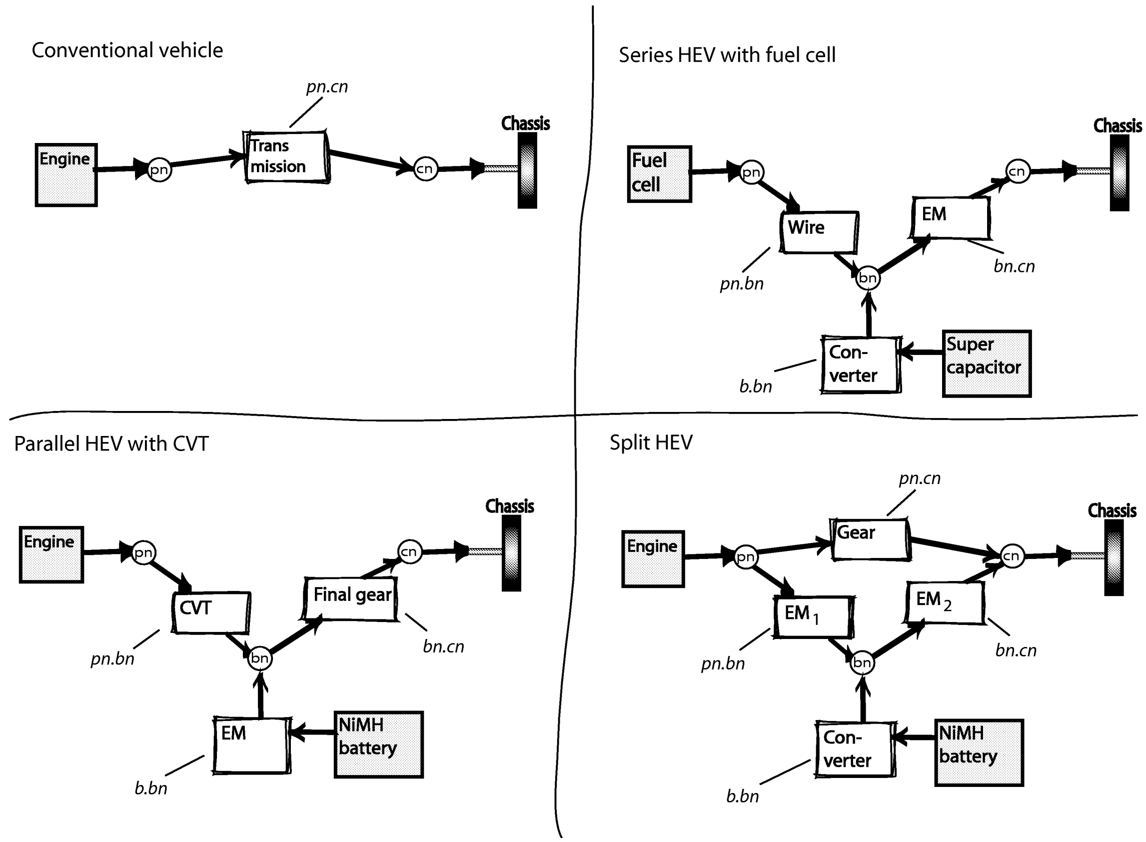


Figure 4.13: *Modeling of some powertrains using the generic powertrain model in Figure 4.12. EM stands for electric machine. The type of powertrain is determined from the gene (design variable) named 'Type of powertrain' in Figure 4.8. From the genes 'Type of powertrain', 'Size of PPU', 'Size of buffer' and 'Ratio' all parameters describing the powertrain components are given.*

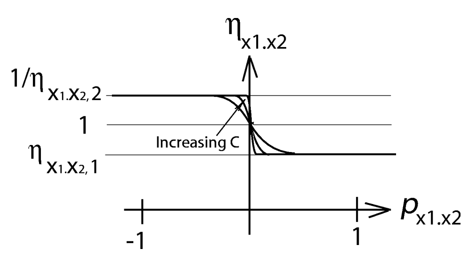


Figure 4.14: *Efficiency function. The efficiency is $\eta_{x_1.x_2,1}$ for positive power and $1/\eta_{x_1.x_2,2}$ for negative power. The influence of parameter C is also illustrated in the figure.*

To make (4.22) valid for power flows in both direction, i.e. for both negative and positive $P_{x_1.x_2,1}$, following equation is introduced

$$\eta_{x_1.x_2}(p_{x_1.x_2}) = \eta_{x_1.x_2,1} + \frac{1/\eta_{x_1.x_2,2} - \eta_{x_1.x_2,1}}{1 + e^{p_{x_1.x_2}\cdot C}} \approx \begin{cases} \eta_{x_1.x_2,1} & (p_{x_1.x_2} > 0) \\ 1/\eta_{x_1.x_2,2} & (p_{x_1.x_2} \leq 0) \end{cases} \tag{4.23}$$

where p is normalized power, also used in (4.22). Figure 4.14 shows $\eta_{x_1.x_2}(p)$ and how its shape depends on the parameter C.

The change of the energy level of the buffer, SoC, depends on the buffer power P_b. The sign convention is that the buffer is charged for a negative P_b. This is mathematically described by

$$\dot{SoC} = -\frac{\eta_\mathrm{b}(p_\mathrm{b}) \cdot P_\mathrm{b}}{E_\mathrm{bmax}} \tag{4.24}$$

where $p_b = P_\mathrm{b}/P_\mathrm{bmax}$ is the normalized buffer power and E_bmax is the energy capacity of the buffer. P_bmax is the maximum buffer power.

Charging and discharging of the buffer is related to losses. These losses are reflected by the efficiency function of the buffer η_b. Typically the efficiency of the buffer decreases with power. This is exemplified in Section 2.5.2.

The equations, the variables at time t, i.e. $\boldsymbol{x}(t)$, and the parameters $\{\boldsymbol{d}(t), \boldsymbol{p}\}$ are included in the powertrain model and forms

$$\dot{\boldsymbol{x}}(t) = f(\boldsymbol{x}(t), \boldsymbol{d}(t), \boldsymbol{p}) \tag{4.25}$$

This system of equations needs to be solved by a numerical approach because it has an implicit solution. The meaning of an implicit solution is described in Section 4.3. For a given set of design variables $\boldsymbol{\xi}$ all parameters $\boldsymbol{p}$ in the model are defined, i.e. $\boldsymbol{\xi} \mapsto \boldsymbol{p}$. This mapping corresponds to the transformation from a genotype to a phenotype described in Section 4.7. The parameters $\boldsymbol{p}$ are not time dependant, i.e. they are constant during the simulation. Examples of such parameters are maximum buffer power P_bmax and depth of discharge ξ_DoD. Due to the transport task, time dependant parameters $\boldsymbol{d}(t)$ reflecting the driving situation also exist. An example of such a parameter is P_dem.

4.7.3 Cost Function

By introducing the cost function

$$c(\boldsymbol{x}, \boldsymbol{p}(\boldsymbol{\xi})) = \sum_{i=\{\mathrm{fuel},\mathrm{capital},\mathrm{wear}\}} c_i(\boldsymbol{x}(t=T), \boldsymbol{p}(\boldsymbol{\xi})) \tag{4.26}$$

the operating cost c of the vehicle can be calculated. Vehicle operating cost is normally dominated by costs due to vehicle value depreciation and fuel consumption. Using a unit that express cost per distance, e.g. €/km, is adequate for an operating cost. Fuel cost, capital cost and component wear cost are included in (4.26). Fuel cost and component wear cost are directly related to the result in the end of the simulation, i.e. $\boldsymbol{x}(t = T)$. Capital cost reflects the value depreciation. This cost is calculated by summing the component cost and spread it over the distance that the vehicle travels during its lifetime. The component cost can be calculated because the type and size of powertrain components are defined from the design variables. The cost calculation is described more in detail in Paper B.

4.7.4 Optimization problem

By using the cost function defined in (4.7.3) an optimization problem can be formulated. The optimization problem is formulated mathematically by

$$\begin{aligned} &\mathrm{Min}\ f(\boldsymbol{\xi}) \\ &f(\boldsymbol{\xi}) = \frac{c(\boldsymbol{x}, \boldsymbol{p}(\boldsymbol{\xi}))}{\psi(\boldsymbol{x}, \boldsymbol{p}(\boldsymbol{\xi}), \boldsymbol{p}_\mathrm{perf})} \end{aligned} \tag{4.27}$$

subject to the bounds

$$\boldsymbol{\xi}_\mathrm{l} \leq \boldsymbol{\xi} \leq \boldsymbol{\xi}_\mathrm{u} \tag{4.28}$$

The penalty function

$$\psi(\boldsymbol{x}, \boldsymbol{p}(\boldsymbol{\xi}), \boldsymbol{p}_{\text{perf}}) = \begin{cases} 1 & (\boldsymbol{\xi} \text{ is feasible} \Leftrightarrow \text{ No constraint is violated}) \\ \epsilon & (\boldsymbol{\xi} \text{ is not feasible} \Leftrightarrow \text{ Some constraint(s) is violated}) \end{cases} \tag{4.29}$$

, where $\epsilon << 1$, resembles the penalty function used in Section 4.6.3. Note that parameters for performance requirements $\boldsymbol{p}_{\text{perf}}$ are only included in ψ. The reason is that performance requirements is only a constraint and do not influence the cost function $c(\boldsymbol{x}, \boldsymbol{p}(\boldsymbol{\xi}))$. An example of a performance requirement is that the top speed of the vehicle must exceed a specific value v_{max}. A design variable proposal $\boldsymbol{\xi}$ is not feasible, i.e. $\psi = \epsilon$, if some constraint is violated. Constraints are typically violated if the powertrain not is designed in a proper way, an example of such a case is a powertrain with a PPU that is too weakly sized. Following constraints are introduced:

- 1. The performance, defined by $\boldsymbol{p}_{\text{perf}}$, of the vehicle must be satisfying. For example must the top speed of the vehicle exceed a specific value v_{max}. Another performance requirement is that there is a maximum acceleration time. The acceleration is defined between two specific speeds. A third performance requirement is gradeability, i.e. the vehicle must handle a specific speed at a specific road grade.
- 2. The absolute value of the buffer power $P_{\text{b}}^{\text{ref}}$ and the PPU power P_{PPU} are not allowed to be too high at any time t. The PPU power P_{PPU} is not allowed to be negative at any time t.
- 3. The SoC is not allowed to be negative or exceed one at any time t.
- 4. The mean difference between SoC and SoC^{ref}, i.e. $\frac{\int_0^T \left| SoC(t) - SoC^{\text{ref}}(t) \right| dt}{T}$, is not allowed to be too high.
- 5. When cruising, the change between charge and discharge is not allowed to be frequent. The motivation is to avoid a frequent switching between high and low PPU power. A frequent switching can be disturbing and stressing for the driver, passengers and propulsion components.
- 6. The change in PPU power is not allowed to be too slow. The response, i.e. the change of power per time unit, of the PPU must be enough to handle the power change at an acceleration. In addition, the time to change from buffer discharge to buffer charge is restricted. This time, that is in proportion to the PPU response, is not allowed to be to long.
- 7. SoC in the end of the transport task must be similar to the SoC in start of the transport task.
- 8. The power split in the planetary gear must be feasible at any time t. This constraint, further described in Paper B, is only relevant for split HEVs.
- 9. During the driving cycle, a switch between charge, rule 2 in Table 3.1, and discharge, rule 1 in Table 3.1, must be present. If no such switch is present, SoC does not follow SoC^{ref} in a satisfying way.

An EA is used to solve this complex nonlinear optimization problem. Motivations to use an EA are presented in Section 4.5. The design process, involving this optimization problem, is exemplified in Chapter 5.

4.7.5 Design Variable Variation

The objective of this study is to achieve a better understanding of how the objective function f (4.27) depends on some design variables. Definition 4.2 defines design variables. The study is based on the powertrain named 'Split HEV: Otto eng., NiMH battery' in Table 5.5. This powertrain is similar to the one used in Toyota Prius I, a medium sized split hybrid car. Section 2.3 describes Toyota Prius more in detail.

Figure 4.15 exemplifies how the objective function f is related to some design variables. A maximum point in the figure corresponds to a minimum point of f because the inverse of f, i.e. $1/f$, is plotted. For each plot, the design variable in relation to its maximum value (%) is presented on the x-axis. The studied design variables are: the type of powertrain $\xi_{TypePtCo}$, the PPU size $\xi_{MassPPU}$, the power that the buffer assists with at acceleration $\xi_{AsspAcc}$ and the upper speed limit for pure buffer propulsion ξ_{MaxvOb}. Some reflections, from Figure 4.15, are:

- Multiple local minima exist in the objective function f. The upper left plot in Figure 4.15 shows that numerous local minima are present then $\xi_{TypePtCo}$ is changed. Motivations to use an EA are presented in Section 4.5. One motivation to use an EA is the presence of numerous local minima. Another interpretation of the plot is that only HEVs with the same PPU and buffer, as the prescribed vehicle, will handle the driving cycle. The reason is that the EMA, in the prescribed vehicle, is adapted for a specific component setup.

- The objective function f is discontinuous. The upper left plot in Figure 4.15 shows that f is discontinuous with respect to $\xi_{MassPPU}$. One motivation to use an EA is a non-continuous objective function. The plot also shows that the engine size not is allowed to differ to much from the prescribed engine size, 39 kW. The reason is that the prescribed EMA is adapted for a specfic engine size.

- The buffer must assist with a moderate power at acceleration. If $\xi_{AsspAcc}$ is to small the requested PPU power will be too large during acceleration, i.e. constraint 2 in Section 4.7.4 will be violated. If $\xi_{AsspAcc}$ is to large, the prescribed EMA will be unable to control SoC. In such a case constraint 3 and/or 4 in Section 4.7.4 will be violated.

- Pure buffer propulsion can not extensively be used in the driving cycle. The reason is that the buffer is drained if it is used frequently. According to the lower right plot in Figure 4.15 there is a upper limit, corresponding to the speed 4.4 m/s, of ξ_{MaxvOb}.

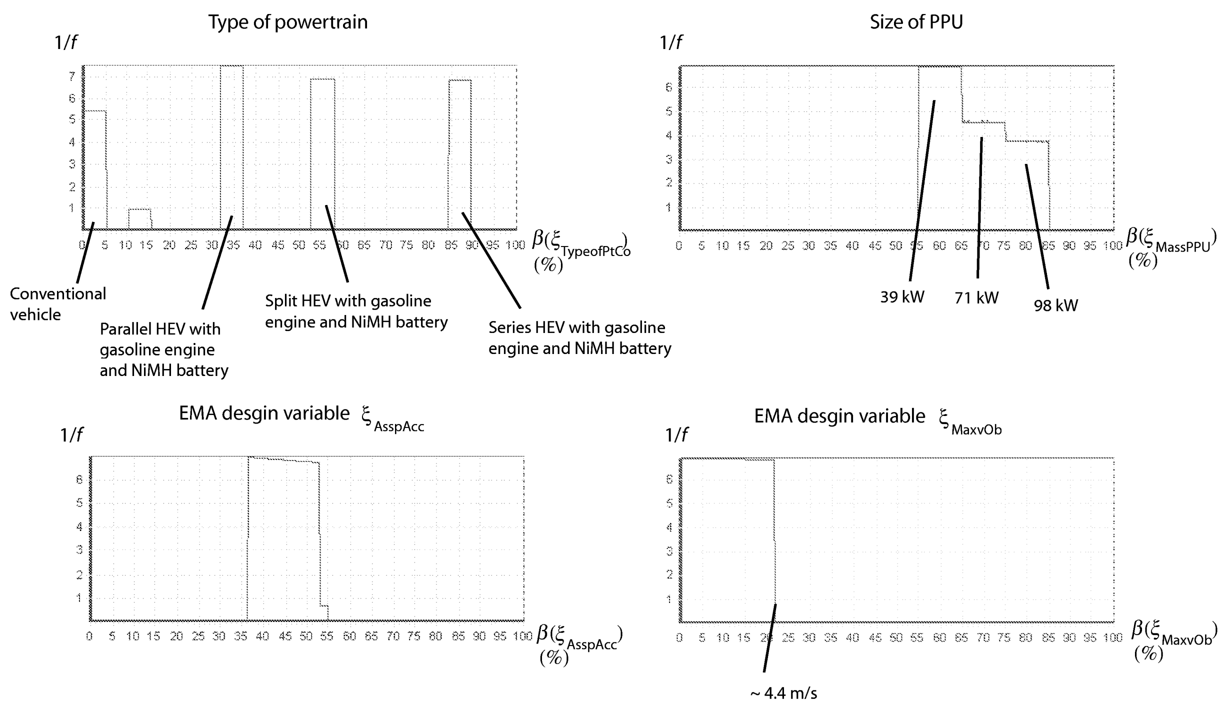


Figure 4.15: *Design variable variation. The function β is defined as $\beta(x) = x/max(x) \cdot 100$, i.e. a design variables is presented in relation to its maximum value.*
- Upper left plot: Numerous local minima are present then $\xi_{TypePtCo}$ is changed.
- Upper right plot: The objective function f is discontinuous with respect to $\xi_{MassPPU}$.
- Lower left plot: The design variable $\xi_{AsspAcc}$ must be in a specific intervall, i.e. the buffer must assist with a moderate power at acceleration.
- Lower right plot: There is a upper limit, corresponding to the speed 4.4 m/s, of ξ_{MaxvOb}, i.e. pure buffer propulsion can not be utilized too often.

Chapter 5

Case Studies

This chapter presents the results of three case studies.

Three case studies, with the major purpose to show what THEPS can be used for, are presented in this chapter. Another purpose is to verify that the outcome from THEPS is reasonable. In all studies circumstances of present time (2004) are compared with assumed future circumstances (2015). The vehicles in focus are a city bus, a garbage truck and a taxi car. The studied powertrain configurations and components are listed in Section E.1.1. Data related to the case studies are presented in Appendix D. Most component data are taken from Advisor [19]. The results should be considered with caution and should be seen more as guidelines. This is explained by limitiations presented in Section 1.5. Another aspect, that makes it crucial to draw general conclusions is that hybrid powertrains can be over adapted. This means that they perform well on driving cycles they are adapted to, but perform worse on others. It is, for example, possible that the fuel consumption of a HEV is higher, compared to a conventional vehicle, when driving on a highway.

The calculation time needed to achieve the result presented in one of the case studies, using a standard PC of year 2004, is 10 to 100 hours[1].

5.1 The Scenarios Evaluated in the Case Studies

Two scenarios are evaluated in each case study. The present time scenario assumes conditions relevant for year 2004. For example, the price of fuel cell systems is very high. In the future scenario, conditions for year 2015 are estimated. In this scenario are for example fossil fuels estimated to be 50% more expensive than today.

5.1.1 Present Time Scenario

At present time (2004) electric propulsion technology is not so common in automobiles. The major reason is the fairly high price of components such as fuel cells, batteries, power electronics and electric machines. Some more important assumptions, described more in detail in Appendix D, made in this scenario are:

- Swedish fossil fuel prices, of year 2004, are assumed. This means that one liter of diesel costs 0.8 € and one liter of gasoline costs 1.125 € [44].
- The prices of petrochemical fuels are lower compared to hydrogen, approximately a factor of two with respect to energy. This means that one MJ of hydrogen is twice as expensive as one MJ of a petrochemical fuel.
- The price of fuel cells (€/kW) is thirty times higher compared to *Internal Combustion Engines* (ICEs), i.e. very expensive.

[1]The calculation time is in proportion to the length of the driving cycle and also depends on computer hardware.

- With respect to power the price of batteries and super capacitors are approximately two times higher compared to ICEs.
- An electric machine, with power electronics included, has a price (€/kW) similar to an ICE and an average efficiency of 0.85.
- The mark-up factor is 1.5 for the heavy vehicles and 2 for the car. For all vehicle types the interest rate is 5%. The mark-up factor reflects that the customer needs to pay more for a component than the manufacturer. Customs and shipping costs are examples of aspects included in the mark-up factor.

5.1.2 Future Scenario

Future (2015) HEVs will probably be more cost effective than they are today. The major reason is the rapid development of electric propulsion components. Both when it comes to price and performance. One example of such a development is the battery pack of Toyota Prius [45]. In the second version, Toyota Prius II, the power density of the battery was increased with 35%, without increasing the price, compared to the first version of Toyota Prius. The first version was released 1997 and the second version 2003. Due to mass production, the price of many electric components will probably have a similar evolution as the battery pack of Toyota Prius. Most assumptions about future (2015) component prices are from the technology goals stated in "FreedomCAR" program [46]. The major mission of the "FreedomCAR" program is to develop more energy efficient and environmentally friendly transportation technologies that enable US to use less petroleum. Some examples of vital assumptions about future conditions are:

- The price of petrochemical fuels are approximately similar to hydrogen, with respect to energy. The explanation of this is 50 % higher prices of petrochemical fuels, compared to the present time scenario, and refined methods to distribute and produce hydrogen. This debatable assumption, also stated in the "FreedomCAR" program, means that 1 MJ of hydrogen has a similar price as 1 MJ of a petrochemical fuel.
- The price of fuel cells (€/kW) is ten times higher, i.e. 250 (€/kW), compared to ICEs, i.e. still very expensive. This is very pessimistic, from a fuel cell perspective, compared to the goal of 30 (€/kW) in the "FreedomCAR" program.
- The price of batteries and super capacitors are approximately five times lower compared to the present time scenario. This agrees well with the goals in the "FreedomCAR" program.
- Electric machines, with power electronics included, in the future scenario have better efficiencies and is cheaper than electric machines in the present time scenario. This agrees well with the goals in "FreedomCAR" program.
- The mark-up factor and the interest rate are the same as in the present time scenario.

5.2 Conceptual Design of the Powertrain in a City Bus

Hybrid and fuel cell powertrains are suitable in city buses. One reason for this is that many starts and stops are present in urban areas, which favor a system that can regenerate braking power. Another reason is the relatively long lifetime of buses compared to cars. The extra capital cost of a hybrid powertrain is spread over more miles for a bus than for a car. A third reason is that packaging is less crucial in buses than in cars. If an alternative fuel, such as hydrogen, is used, centralized fueling also speaks in favor for urban buses.

The purpose with this study is to design the powertrain of a city bus. The bus is assumed to travel a route named "Route 85". The route, which actually exists and is located in the Swedish city Göteborg, is illustrated in Figure 5.1. The corresponding speed profiles are presented in Figure 5.2. The first part, Part 1, of the route is suburban with fairly high speeds and long distances between the stops. The second part, Part 2, is an urban part with low speed, many starts and stops and approximately no slopes. The third part, Part 3, is an urban route with slopes. The speed profiles are derived from measurements presented in [47]. Following performance requirements are made:

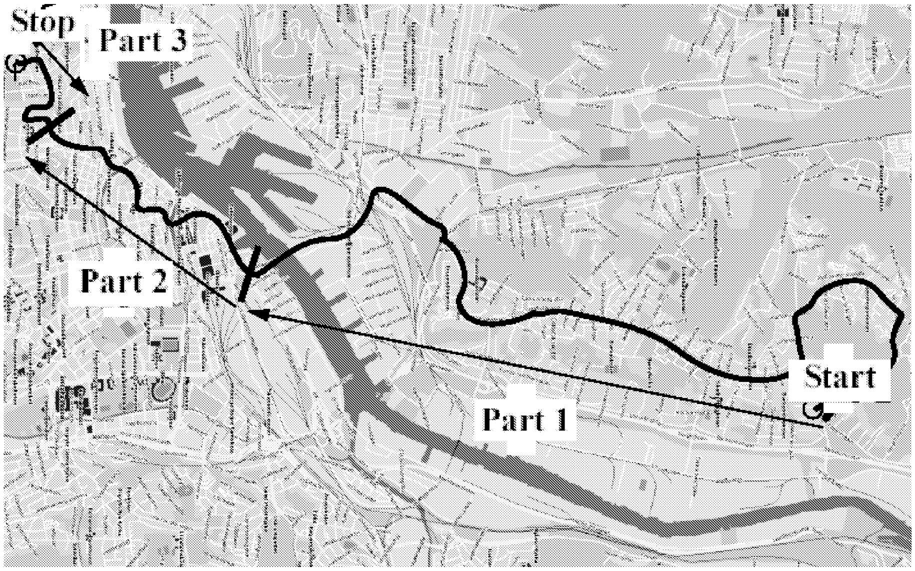


Figure 5.1: *Distribution of bus route 85 in the city of Göteborg. The directions of Part 1 and Part 2 are according to the arrows in the picture. Part 3 stretches from the end of Part 2 to Stop and back to the end of Part 2. The total time of the route, single way, is 60 min and the length is 15 km respectively.*

- The continuous top speed of the bus must exceed 30 m/s, i.e. 108 km/h. It is assumed that no slope is present.

- The maximum time to accelerate from 0 to 10 m/s, i.e. 0 to 36 km/h, is 10 s.

A standard Volvo bus with a mass of 11 000 kg is assumed. The mass excludes powertrain and passengers. The bus is assumed to be half loaded with passengers. More about the bus can be found in Appendix D.

5.2.1 Present Time Scenario

This scenario is based on the assumptions presented in Section 5.1.1. Table 5.1 presents the result. The table claims that hybrid electric buses are a reasonable candidate to conventional buses in the present time scenario. The most cost effective hybrid buses have slightly lower operating cost compared to the most cost effective conventional buses. The *Fuel Cell Vehicles*[2] (FCVs) and *Fuel Cell Hybrid Electric Vehicles* (FCHEVs) are not cost effective at all. Their high capital cost in combination with expensive hydrogen explains this. However, their low energy consumption (MJ/km) shows that they have potential. According to Table 5.1 powertrains with diesel engines are very cost effective. Diesel engines are included in the seven most cost effective powertrains. The low cost of diesel fuel and the high efficiency of diesel engines are the reasons for this. The low operating cost is probably the major reason why most heavy vehicles of today use diesel.

The cost related to buffer wear[3] is high, i.e. 10-20% of the operating cost. In HEVs with a super capacitor[4] the buffer needs, according to THEPS, replacement every 1-2 years. A NiMH battery needs replacement every 1-5 month. This indicates that buffer wear is a significant problem in hybrid city buses of today. The reason is that much energy is regenerated. The buffer wear model is described in Paper B.

[2] Pure hydrogen, stored in pressurized tanks, is assumed as fuel.
[3] Buffer wear cost is not presented in Table 5.1.
[4] Powertrains with a super capacitor as buffer can be considered as mild. The reason is that the energy capacity of a super capacitor is low. A super capacitor can typically handle 2-5 accelerations, without charging in between, before it is emptied.

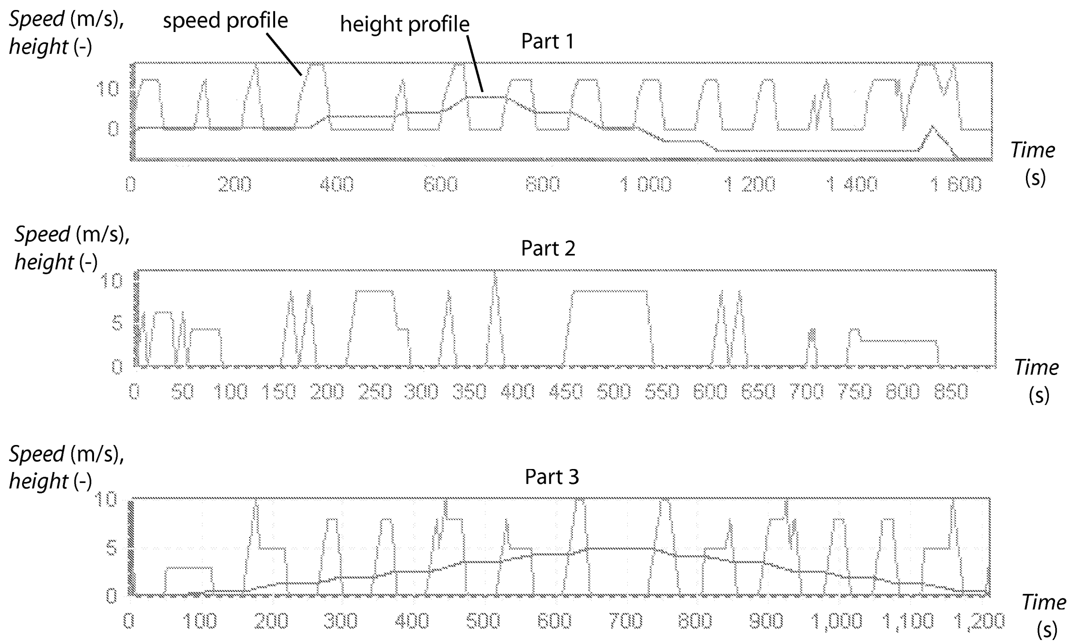


Figure 5.2: *Speed profiles of the parts in city route 85. Part 1 is more of suburban part while Part 2 and 3 are located in urban areas. In Part 1, height varies from 0 to 20 m. In Part 3, height varies from 0 to 70 m.*

5.2.2 Future Scenario

The assumptions presented in Section 5.1.2 are used in this section. Table 5.2 presents the result. A powertrain, including a fuel cell and a buffer, is in this scenario the most cost effective solution for a bus. The explanation is the low hydrogen cost in combination with the energy efficient powertrain of a FCHEV. The FCV, i.e. a fuel cell vehicle without buffer, is not an especially attractive candidate. According to Table 5.1 the capital cost of the FCV is similar to the FCHEV but the fuel consumption is almost the double. This means that it is cost-beneficious to hybridize fuel cell vehicles in this scenario.

HEVs are in this scenario superior to a vehicle without buffer. The HEVs offer approximately 70% lower fuel consumption compared to the non-hybrid vehicles, despite a relatively small increase in component cost. Despite the mean power demand in the driving cycle is fairly low, approximately 20 kW, the chosen PPUs are fairly large (130-230 kW). The reason is that the performance requirements need to be fulfilled. A large PPU is needed if a high continous speed is required. Due to advancements in buffer technology, the time between buffer replacement is approximately 4 times longer in this future scenario.

5.3 Conceptual Design of the Powertrain in a Garbage Truck

Nowadays, in developed countries, the duty to collect waste from households is performed by garbage trucks. Garbage trucks are heavy, approximately 18 000 kg, and frequently need to start and stop. This means that they are suitable for hybrid propulsion.

Data for the chassis of a garbage truck, presented in Appendix D, are derived from [48]. The transport task illustrated in Figure 5.3 is also from [48]. Characteristic for the transport task is that it both includes parts with constant speed and parts with many start and stops. Transportation between residential districts corresponds to constant speed driving. Operation The truck is assumed to run 8 hours per day. 15 kW is assumed to be needed for compression of garbage. In [48] a specification, with industrial relevance, of a garbage truck is made. Following performance requirements are presented in [48]:

- The continuous top speed of the garbage truck must exceed 25 m/s, i.e. 90 km/h.

Table 5.1: *Result of case study with city bus in present time scenario. Cost is defined as operating cost, i.e. the sum of fuel, capital and wear cost per km. Section 4.7.3 describes the cost function further. Price is the total component cost of the vehicle and reflects what the customer should pay. 'Energy' and 'Fuel' is the energy and fuel consumption of the vehicle respectively. The European currency Euro is denoted with €. In Februari 2004 one € corresponds to nine Swedish crowns and 1.4 US Dollar. The densities of the fuels can be found in Appendix D.*

Cost ($\frac{€}{\text{km}}$)	**Type of powertrain**	**PPU size** (kW)	**Buffer size** (kW), (MJ)	**Price** (€)	**Energy** ($\frac{\text{MJ}}{\text{km}}$)	**Fuel** ($\frac{\text{l}}{\text{km}}$)
0.666	Par. HEV: Diesel eng., Super cap.	170	360, 1.4	198 000	12.8	0.327
0.74	Series HEV: Diesel eng., Super cap.	220	400, 1.6	209 000	15.6	0.4
0.741	Split HEV: Diesel eng., Super cap.	220	430, 1.7	212 000	15.5	0.396
0.746	Conventional: Diesel eng.	220	-	163 000	19.9	0.508
0.755	Split HEV: Diesel eng., NiMH battery	220	370, 43	196 000	15	0.383
0.763	Series HEV: Diesel eng., NiMH battery	220	510, 59	203 000	15	0.384
0.788	Par. HEV: Diesel eng., NiMH battery	320	33, 3.8	196 000	14.5	0.371
0.888	Par. HEV: Otto eng., Super cap.	260	230, 1.7	203 000	16.4	0.437
0.946	Series HEV: Otto eng., Super cap.	230	230, 1.7	208 000	18.2	0.484
0.947	Split HEV: Otto eng., Super cap.	260	230, 1.9	210 000	18	0.481
:						
:						
1.15	Series HEV: Fuel cell, Super cap.	180	390, 1.6	450 000	12	6.1

Table 5.2: *Result of case study with city bus in future scenario.*

Cost ($\frac{€}{\text{km}}$)	**Type of powertrain**	**PPU size** (kW)	**Buffer size** (kW), (MJ)	**Price** (€)	**Energy** ($\frac{\text{MJ}}{\text{km}}$)	**Fuel** ($\frac{\text{l}}{\text{km}}$)
0.531	Series HEV: Fuel cell, Super cap.	130	720, 2.9	211 000	10	5.11
0.561	Series HEV: Fuel cell, NiMH battery	150	270, 41	217 000	10	5.13
0.651	Par. HEV: Diesel eng., Super cap.	170	780, 3.1	175 000	10	5.13
0.672	Series HEV: Diesel eng., Super cap.	170	1300, 5	175 000	15	0.38
0.682	Split HEV: Diesel eng., NiMH battery	170	400, 60	175 000	11.9	0.303
0.709	Par. HEV: Diesel eng., NiMH battery	220	630, 94	185 000	11.9	0.306
0.721	Series HEV: Diesel eng., NiMH battery	220	400, 59	178 000	12.9	0.33
0.788	Fuel cell	230	-	230 000	17.8	9.07
0.937	Par. HEV: Otto eng., Super cap.	230	860, 3.4	175 000	14.9	0.398
0.941	Par. HEV: Otto eng., NiMH battery	230	490, 74	177 000	14.4	0.383
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0.962	Conventional: Diesel eng.	220	-	163 000	19.9	0.508

- The maximum time to accelerate from 0 to 15 m/s, i.e. 0 to 54 km/h, is 20 s.

5.3.1 Present Time Scenario

In this case study, only the transport task and vehicle type are different compared to the first case study. According to Table 5.3 it is already in year 2004 reasonable to use hybrid powertrains in garbage trucks. By using a buffer, fuel consumption is reduced by approximately 30% according to the table, without a significant increase in component cost. Like in the first case study, dealing with a city bus, fuel cells are not reasonable to use from a cost perspective.

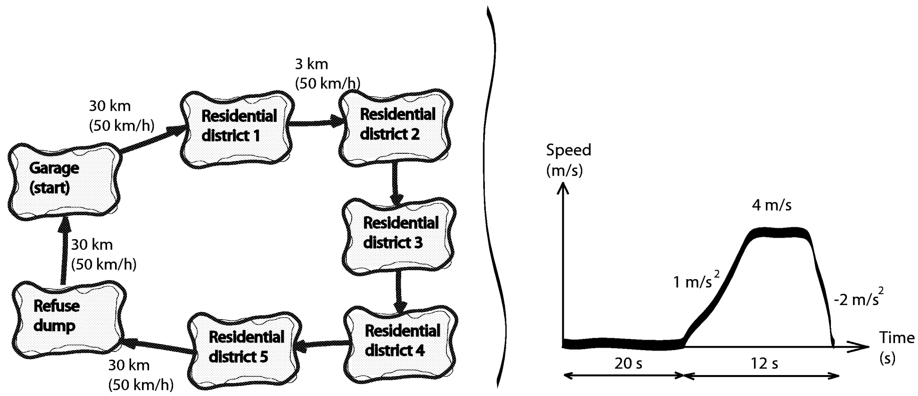

Figure 5.3: *Transport task for garbage truck. The rigth panel shows a sequence in a residential district. The sequence corresponds to the transportation between two houses. A district is estimated to consist of 60 houses.*

Table 5.3: *Result of case study with garbage truck in present time scenario.*

Cost ($\frac{€}{km}$)	**Type of powertrain**	**PPU size** (kW)	**Buffer size** (kW), (MJ)	**Price** (€)	**Energy** ($\frac{MJ}{km}$)	**Fuel** ($\frac{l}{km}$)
0.758	Par. HEV: Diesel eng., NiMH battery	170	150, 18	176 000	13	0.33
0.814	Par. HEV: Diesel eng., Super cap.	170	410, 1.6	203 000	12.8	0.327
0.82	Series HEV: Diesel eng., NiMH battery	170	200, 23	186 000	14.6	0.372
0.824	Split HEV: Diesel eng., NiMH battery	170	350, 41	193 000	14	0.36
0.858	Series HEV: Diesel eng., Super cap.	170	410, 1.6	207 000	14.5	0.372
0.874	Split HEV: Diesel eng., Super cap.	170	540, 2.2	217 000	14.5	0.37
0.894	Conventional: Diesel eng.	320	-	169 000	21.1	0.541
0.963	Par. HEV: Otto eng., NiMH battery	230	200, 23	179 000	15.8	0.423
0.985	Par. HEV: Otto eng., Super cap.	230	310, 1.2	195 000	15.5	0.414
1.02	Split HEV: Otto eng., NiMH battery	230	210, 24	185 000	17.2	0.46
:						
:						
1.28	Series HEV: Fuel cell, NiMH battery	100	280, 32	324 000	12	6.11

Compared to the bus, the buffer of the garbage truck seldom needs replacement. According to THEPS the super capacitor and/or NiMH battery needs replacement 1-5 times during the lifetime of the garbage truck.

5.3.2 Future Scenario

The conditions in this case study are based on the assumptions made in Section 5.1.2. Table 5.4 presents the result. As expected HEVs are more cost effective compared to the present time scenario. FCHEVs with fairly small fuel cells are the best choice in this scenario.

5.4 Conceptual Design of the Powertrain in a Taxi Car

This case study deals with the conceptual design of the powertrain in a taxi car. It is sensible to use a hybrid powertrain in a taxi car, the reason is that taxi cars often travel in cities. This means that regenerative braking is beneficial. Another reason is that taxi cars, compared to many familly cars, travel a long distance

Table 5.4: *Result of case study with garbage truck in future scenario.*

Cost ($\frac{€}{km}$)	Type of powertrain	PPU size (kW)	Buffer size (kW), (MJ)	Price (€)	Energy ($\frac{MJ}{km}$)	Fuel ($\frac{l}{km}$)
0.757	Series HEV: Fuel cell, NiMH battery	130	220, 32	207 000	11	5.6
0.77	Series HEV: Fuel cell, Super cap.	130	790, 3.2	212 000	11	5.62
0.815	Par. HEV: Diesel eng., Super cap.	170	420, 1.7	170 000	11.8	0.303
0.826	Par. HEV: Diesel eng., NiMH battery	170	180, 27	168 000	12	0.306
0.846	Series HEV: Diesel eng., Super cap.	170	460, 1.8	180 000	12.7	0.325
0.857	Split HEV: Diesel eng., NiMH battery	170	200, 29	170 000	13	0.329
0.86	Split HEV: Diesel eng., Super cap.	170	200, 30	169 000	13.1	0.335
0.864	Par. HEV: Otto eng., Super cap.	170	1100, 4.2	180 000	12.6	0.322
1.06	Par. HEV: Otto eng., NiMH battery	230	610, 2.4	172 000	14.1	0.376
1.08	Split HEV: Otto eng., Super cap.	230	300, 45	172 000	14.3	0.382
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1.12	Conventional: Diesel eng.	320	-	169 000	21.1	0.541

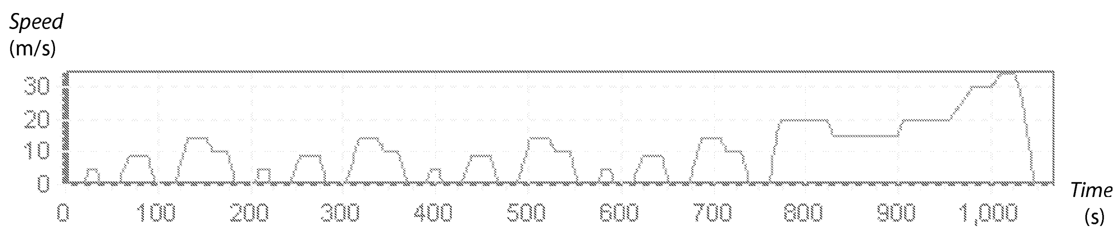

Figure 5.4: *Speed profile of the taxi car cycle. The cycle is named "European Driving Cycle".*

before they are scrapped. The result is that the capital cost is spread over more miles in taxi cars compared to family cars. Following performance requirements are made [49]:

- The continuous top speed of the car must exceed 45 m/s, i.e. 162 km/h.
- The maximum time to accelerate from 0 to 28 m/s, i.e. 0 to 101 km/h, is 12 s.

The transport task is presented in Figure 5.4. The driving cycle, named "European Driving Cycle", is a combined urban and highway driving schedule. This brings out cars that are suitable for both city and highway driving. The car is assumed to be a medium sized car with a mass of 800 kg, powertrain and passengers excluded. In contrast to previous case studies the mark-up factor is set as 2.

5.4.1 Present Time Scenario

In this scenario the economical conditions and technical performance of propulsion components are based on assumptions made in Section 5.1.1. According to Table 5.5 it is a close race between a conventional diesel car and the best HEV. Their operating cost is almost similar. The lower fuel consumption in the HEVs is difficult to motivate because the increase in capital cost, due to additional electrical components. It is very interesting that the configuration "Split HEV: Otto eng., NiMH battery" in Table 5.5 resembles Toyota Prius II. It has the same configuration, type of components and similar component sizes. This is remarkable because THEPS "does not know about" the design of Toyota Prius.

Table 5.5 also claims that NiMH batteries seem to be a more cost effective alternative compared to super capacitors in this scenario. The reason is simply that NiMH batteries are assumed as cheaper than super

Table 5.5: *Result of case study with taxi car in present time scenario. The parallel HEVs use a Continuously Variable Transmission (CVT).*

Cost ($\frac{€}{\text{km}}$)	**Type of powertrain**	**PPU size** (kW)	**Buffer size** (kW), (MJ)	**Price** (€)	**Energy** ($\frac{\text{MJ}}{\text{km}}$)	**Fuel** ($\frac{\text{l}}{\text{km}}$)
0.122	Conventional: Diesel eng.	77	-	20 300	2.77	0.071
0.125	Par. HEV: Diesel eng., NiMH battery	77	13, 1.5	22 700	2.53	0.0647
0.129	Par. HEV: Otto eng., NiMH battery	39	31, 3.5	21 300	2.03	0.0541
0.138	Split HEV: Diesel eng., NiMH battery	77	13, 1.5	25 100	2.62	0.0669
0.141	Series HEV: Diesel eng., NiMH battery	77	13, 1.5	26 300	2.77	0.0709
0.145	Split HEV: Otto eng., NiMH battery	39	31, 3.5	22 500	2.35	0.0627
0.154	Par. HEV: Diesel eng., Super cap.	77	84, 0.34	31 600	2.71	0.0692
0.164	Split HEV: Diesel eng., Super cap.	77	84, 0.34	38 000	2.7	0.068
0.165	Series HEV: Diesel eng., Super cap.	77	84, 0.34	34 000	2.87	0.0734
0.188	Conventional: Otto eng.	71	-	18 600	4.38	0.117
:						
:						
0.397	Series HEV: Fuel cell, NiMH battery	50	13, 1.5	117 000	1.65	0.842

capacitors. The longer lifetime of super capacitors is more motivated in a bus or a garbage truck. In the two first case studies, the cost effectiveness of the powertrains did not highly depend on whether a super capacitor or a NiMH-battery is used as buffer. Another finding is that FCVs not are competitive at all from a cost perspective. Their capital cost is 5-6 times higher, compared to the other configurations. The cost related to buffer wear is 2-5% of the operating cost. In cars with a NiMH battery the buffer needs replacement every 3-10 years according to the calculations made in this scenario. A super capacitor never needs replacement.

5.4.2 Future Scenario

Table 5.6 presents the results of this scenario based on the assumptions presented in Section 5.1.2. It is a close race between the most cost effective hybrid and fuel cell vehicles. However, it is important to note that the capital cost of the FCHEVs is approximately double compared to the HEVs. Someone of the cheaper powertrains is probably a more attractive choice for a customer that drives occasionally.

It is remarkable that the HEVs almost outclass the conventional vehicles in this scenario. If assuming a gasoline engine as ICE, the fuel consumption of the best HEV is half of the conventional gasoline car. The difference in capital cost is almost neglectable. The reason is that a smaller, and thereby cheaper, ICE compensates for the extra capital cost of electrical propulsion components. As stated in Section 5.1.2, future electrical propulsion components are assumed to be substantially cheaper than in the present time scenario.

5.5 Sensitivity Analysis of Taxi Car

In this section a sensitivity analysis is performed. The objective is to investigate how some parameters influence the operating cost of a vehicle. The car powertrain candidates presented in Table 5.5 are in focus. The analysis is based on the assumptions in the present time scenario. Following cases are investigated:

- Case A: The interest rate i is changed from 5 to 0 %, i.e. i is changed with -5 percentage points.
- Case B: The distance that the vehicle travels during its lifetime D_{lifetime} is changed from 400 000 to 200 000 km, i.e. is D_{lifetime} changed with -50 %.
- Case C: The hours per day the vehicle is in duty T_{day} is changed from 8 to 2 hours, i.e. is T_{day} changed with -75 %.

Table 5.6: *Result of case study with taxi car in future scenario. It is remarkable that the conventional cars are less cost effective, compared to the hybrid cars, in this scenario.*

Cost ($\frac{€}{\text{km}}$)	**Type of powertrain**	**PPU size** (kW)	**Buffer size** (kW), (MJ)	**Price** (€)	**Energy** ($\frac{\text{MJ}}{\text{km}}$)	**Fuel** ($\frac{\text{l}}{\text{km}}$)
0.138	Par. HEV: Otto eng., NiMH battery	39	20, 3	18 400	1.88	0.0502
0.139	Par. HEV: Diesel eng., NiMH battery	77	47, 7.1	22 900	2.18	0.0557
0.142	Split HEV: Diesel eng., NiMH battery	77	20, 3	21 600	2.36	0.0602
0.146	Series HEV: Fuel cell, NiMH battery	50	42, 6.3	40 400	1.35	0.688
0.147	Series HEV: Diesel eng., NiMH battery	77	43, 6.5	22 800	2.43	0.0622
0.149	Split HEV: Otto eng., NiMH battery	39	47, 7.1	19 800	2.02	0.0539
0.150	Series HEV: Otto eng., NiMH battery	39	64, 9.7	20 500	2.02	0.0539
0.151	Series HEV: Fuel cell, Super cap.	50	170, 0.68	42 100	1.42	0.723
0.151	Par. HEV: Diesel eng., Super cap.	77	170, 0.68	24 400	2.46	0.0629
0.151	Fuel cell.	50	-	38 700	1.79	0.913
0.151	Conventional: Diesel eng.	77	-	20 300	2.77	0.071
:						
:						
0.25	Conventional: Otto eng.	71	-	18 600	4.39	0.117

- Case D: Case B and case C combined. This means that D_{lifetime} is changed with -50 % and T_{day} changed with -75 %. This case resembles how a car often is used in a family.
- Case E: The driving cycle is changed to a city cycle, plotted in Figure 5.5. Running on this driving cycle, the depreciation time, i.e. lifetime, is 11.5 years. For the initial "European Driving Cycle" the depreciation time is 4.2 years. An unchanged total traveled distance during the lifetime of the car is assumed.
- Case F: The driving cycle is changed to a highway cycle, plotted in Figure 5.5. The depreciation time is 1.6 years for this driving cycle.

All parameters not mentioned in a case are assumed to be unchanged. For example, the interest rate, prescribed in Appendix D, is defined as 5% for case B-F. Table 5.7 shows how the parameter changes affect the average cost change σ^{χ} defined by

$$\sigma^{\chi} = \frac{\sum_{1}^{N} \Delta c_i^{\chi}}{\sum_{1}^{N} c_i} \tag{5.1}$$

where N is number of powertrains and c_i is the initial cost for powertrain i. The initial costs are presented in Table 5.5. The cost change in case χ for powertrain i is denoted Δc_i^{χ}. Following conclusions can be made from Table 5.7:

- Case A indicates that the interest rate has a high influence on the operating cost. The operating cost decreases with interest rate.
- The total distance a vehicle travels during its lifetime, i.e. how many kilometers the capital cost is spread over, has a high influence on the operating cost. This is reflected in σ^{B}, i.e. an increased cost for case B.
- The more hours a vehicle is used per day, the lower is its capital cost. The reason is that the depreciation time is shortened if the vehicle is used many hours per day. This is reflected in σ^{C}, i.e. an increased cost for case C. According to Table 5.7 T_{day} has a moderate influence on operating cost.

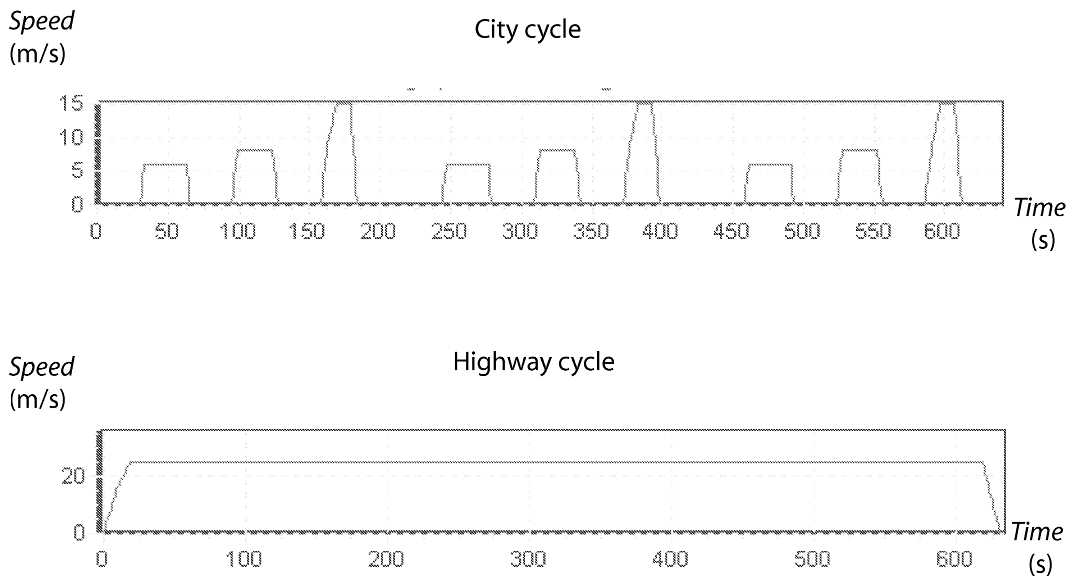

Figure 5.5: *Speed profiles of city cycle (upper panel) and highway cycle (lower panel). The maximum speed of the highway cycle 25 m/s, i.e. 90 km/h.*

Table 5.7: *Sensitivity analysis of the taxi car. The table presents how a parameter change influences the average change of operating cost. The parameters: interest rate i (case A), traveled distance during lifetime D_{lifetime} (case B) and hours per day in duty T_{day} (case C) are changed. In case D both traveled distance during lifetime and hours per day in duty are changed.*

Case A	Case B
$\Delta i = -5$ *percentage points* $\rightarrow \sigma^{\mathrm{A}} = -7.0\%$	$\frac{\Delta D_{\text{lifetime}}}{D_{\text{lifetime}}} = -50\% \rightarrow \sigma^{\mathrm{B}} = 51\%$
Case C	Case D
$\frac{\Delta T_{\text{day}}}{T_{\text{day}}} = -75\% \rightarrow \sigma^{\mathrm{C}} = 19.6\%$	$\frac{\Delta D_{\text{lifetime}}}{D_{\text{lifetime}}} = -50\%, \frac{\Delta T_{\text{day}}}{T_{\text{day}}} = -75\% \rightarrow \sigma^{\mathrm{D}} = 68.6\%$
Case E	Case F
Driving cycle = city cycle $\rightarrow \sigma^{\mathrm{E}} = 59\%$	Driving cycle = highway cycle $\rightarrow \sigma^{\mathrm{F}} = -22.6\%$

- From case D it can be concluded that the operating cost of a family car, that is rarely operated and has a relatively short lifetime, is much higher, in the order of twice the cost of an actively used taxi car.

- In case E the operating cost is heavily increased. The major reason is that more fuel is consumed if acceleration and braking is frequent.

- Case F shows that the operating cost of a highway cycle is lower compared to the combined cycle. The reason is that both fuel consumption and depreciation time is shorter in this cycle compared to the combined "European Driving Cycle".

Case A-F give results that are fairly self evident and intuitive. The fact that the result agree well with common sense strengthen the trustworthiness of THEPS.

Table 5.8 shows how case A-F affects the cost change

$$\sigma_i^{\chi} = \frac{\Delta c_i^{\chi}}{c_i} \tag{5.2}$$

Table 5.8: *Sensitivity analysis of taxi car. The table presents how a parameter change influence the operating cost of the powertrain candidates presented in Section 5.4.1. The parameters: interest rate (case A), traveled distance during lifetime (case B) and hours per day in duty (case C) are changed. In case D both traveled distance during lifetime and hours per day in duty are changed.*

i	c_i	Type of powertrain	σ_i^A (%)	σ_i^B (%)	σ_i^C (%)	σ_i^D (%)	σ_i^E (%)	σ_i^F (%)
1	0.122	Conventional: Diesel eng.	-5.7	42.6	16.4	57.4	68.8	-29.2
2	0.125	Par. HEV: Diesel eng., NiMH battery	-6.4	46.4	18.4	62.4	68.0	-25.0
3	0.129	Par. HEV: Otto eng., NiMH battery	-6.2	49	19.1	66.6	41.8	-16.3
4	0.138	Split HEV: Diesel eng., NiMH battery	-7.25	45.6	18.8	62.3	78.2	-26.1
5	0.141	Series HEV: Diesel eng., NiMH battery	-7.09	47.5	18.4	63.8	64.5	-24.1
6	0.145	Split HEV: Otto eng., NiMH battery	-6.21	39.3	16.5	53.8	42.8	-18.6
7	0.154	Par. HEV: Diesel eng., Super cap.	-7.14	52.6	20.1	70.8	57.1	-24.0
8	0.164	Split HEV: Diesel eng., Super cap.	-7.32	53.0	20.1	71.3	57.3	-23.2
9	0.165	Series HEV: Diesel eng., Super cap.	-7.3	52.1	20	70.3	60.0	-22.4
10	0.188	Conventional: Otto eng.	-3.22	25.5	10.1	34.0	105	-43.6
:								
:								
15	0.397	Series HEV: Fuel cell, NiMH battery	-9.82	75.3	27.7	101	37	-10.8

where Δc_i^χ is the cost change for powertrain i at case χ and c_i is the initial cost of powertrain i. From Table 5.8 following conclusions can be made:

- It is not wise to choose an expensive powertrain if the interest rate is high. σ_{13}^A is approximately three times higher than σ_9^A. σ_{13}^A is the cost change of the most expensive car and σ_9^A is the cost change of the cheapest car. In this case, the hybrid vehicles benefit from a descrease in interest rate. The reason is that they have a higher capital cost.

- From a cost perspecitve a car with a high component cost should not be occasionally driven. For example, in case D, is the operating cost of the most expensive car doubled with respect to the initial operating cost. This car is denoted σ_{13}^D.

- Hybrid cars of today (2004) have to be frequently operated, i.e. run a long distance per day to be cost effective. The reason is that the depreciation time normally is shortened if the cars are operated frequently.

- Strong[5] hybrid cars benefit from city driving. When driving in the city cycle the operating costs of the cars with a large buffer, i.e. powertrain 3 and 6 in Table 5.5, are increased less compared to the other cars. The reason is that the fuel consumption of these cars benefit from the city cycle. It is not self evident that the more expensive hybrid cars are cost effective in the city cycle because the depreciation time is longer for the city cycle compared to the initial "European Driving Cycle". A long depreciation time is, as stated earlier, not positive for the cost effectiveness of cars with a high component cost. Obviously, in the prescribed scenario, is the change in fuel consumption more significant than the increase in capital cost for the hybrid cars with a large buffer. It is, from Table 5.8, difficult to make a statement when it comes to the rest of the hybrid cars, i.e. those with a small buffer.

- Conventional cars benefit from highway driving. According to Table 5.8 the decrease in operating cost is especially large for the conventional cars in case F. The reason is that components for energy regeneration, e.g. the buffer, do not significantly decrease the fuel consumption for the highway driving cycle.

[5] Strong HEVs incorporates a large buffer. Section 2.3 gives more information about the difference between mild and strong HEVs.

5.6 Comparison to Existing Vehicles

The purpose with this section is to compare the result from THEPS with real vehicles. Especially fuel consumption is verified. Following vehicles are compared: a conventional bus, a hybrid fuel cell bus, a conventional car and a split hybrid car.

In [47] a conventional Volvo city bus is measured. The bus drives the same transport task as in the first case study, i.e. "Route 85". According to measurements in [47] the fuel consumption is 0.5 (l/km). This agrees well with the fuel consumption estimated by THEPS that is 0.51 (l/km). The chassis and coach data in the study are from [47] while the engine data is from [19].

In [25] a hybrid bus, equipped with a PEM fuel cell and NiMH battery, is tested and evaluated. When driving the bus on a cycle named "FTP 75" the energy consumption became 12.6 (MJ/km). The similar bus in THEPS has an energy consumption of 13 (MJ/km). This comparison should be carefully considered because the transport task and configuration not are the same.

The driving cycle presented in Figure 5.4 is a standard cycle named "European Driving Cycle" (EDC). Results of test drives of German cars are assembled at [50]. According to [50] the fuel consumption of some midsized gasoline cars is approximately 0.075 (l/km). If diesel is used, the fuel consumption is approximately 0.055 (l/km). Examples of such cars include: VW Golf, Ford Focus and Audi A3. Cars of model year 2002 are in focus. The fuel consumption for a conventional gasoline according to THEPS is 0.11 (l/km). For a conventional diesel car THEPS estimated the fuel consumption as 0.07 (l/km).

According to [45] the fuel consumption of Toyota Prius II is 0.05 (l/km) for a combined driving cycle. THEPS estimated the fuel consumption as 0.063 (l/km). The Prius is named 'Split HEV: Otto eng., NiMH battery' in Table 5.5 and has an engine model imitating the engine in Prius version I. Engine development and optimistic data from Toyota may explain the difference in fuel consumption. Another interesting aspect is that THEPS sized the battery very similar to the real Prius, 32 kW maximum buffer power according to THEPS and 39 kW maximum buffer power in the real Prius.

5.7 Summary

This section summarizes the results of this chapter. It is important to bear in mind that the results must be taken with caution because only a limited number of cases are studied. The case studies tend to favor HEVs due to the assumptions of high fuel costs[6] and urban transport tasks. Why HEVs are more cost effective in urban driving, than in for example highway driving, is explained in Section 2.3. Figure 5.6 shows that hybrid and fuel cell vehicles, for the studied applications, are more cost effective than conventional vehicles in the future scenario. For another application, for example a long distance truck, this might not be true. Some reflections from the case studies are:

- The probably most important reflection is that operating cost has a low dependency on fossil fuel costs. As exemplified in this chapter, more energy efficient technologies will reduce fuel consumption. In the case studies presented, future operating cost is similar or even lower than today, despite the assumption of more expensive fossil fuels in future. Present and future advancements in the field of electrical propulsion enable cost effective candidates such as FCVs, FCHEVs and HEVs.

- It is a challenge to develop cost effective HEVs and FCVs with the technology of today. According to the case studies, assuming present time circumstances, it is most feasible from a cost perspective to introduce hybrid powertrains in heavy vehicles that run on transport tasks which have many starts and stops. Much braking energy needs to be regenerated to motivate the extra component cost.

- According to Section 5.6, simulations with THEPS compared to measurements of existing vehicles agree well. Only the comparison with conventional cars is disappointing. THEPS estimated the fuel consumption as considerably higher, approximately 35%, compared to a real car. The major reason is probably that no suitable engine and/or engine size is present in THEPS[7]. The fuel consumption of a conventional car depends highly on the size and performance of the engine.

[6] Swedish fossil fuel costs are high compared to, for example, US fossil fuel costs.

[7] In the database of THEPS version 2.0 only ten sizes of each PPU type are presented.

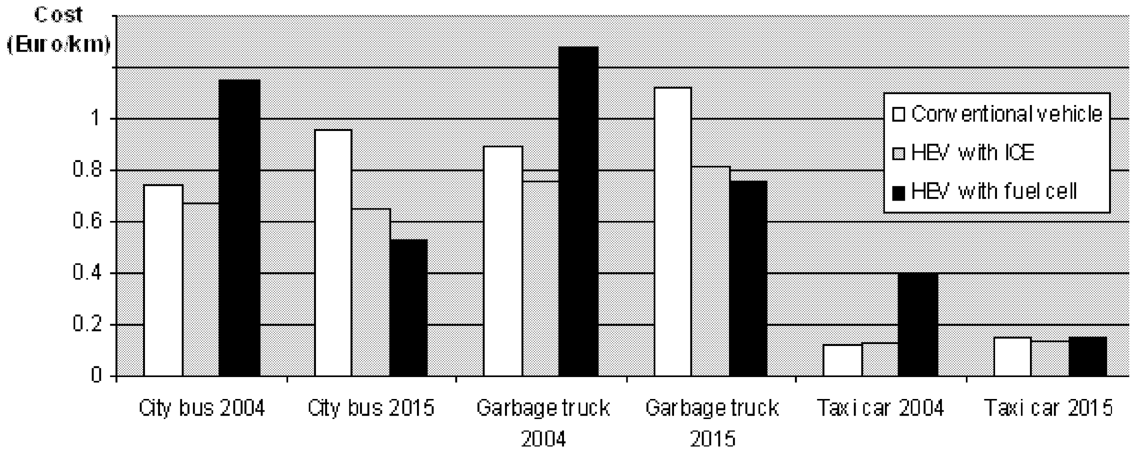

Figure 5.6: *Summary of case studies. White bars represent the most cost effective conventional vehicle, grey bars the most cost effective HEV and black bars the most cost effective FCHEV. The figure shows that hybrid and fuel cell vehicles are more cost effective, than conventional vehicles, in the future scenario.*

- THEPS gives a powertrain proposal that resembles a commercial car. Accoring to Table 5.5 'Split HEV: Otto eng., NiMH battery', a split HEV with a fairly small ICE and large buffer, seems to be a cost effective candidate. This is interesting because this powertrain is similar to the powertrain in Toyota Prius. Section 2.3 gives more information about Toyota Prius.
- It is difficult to precisely determine the best choice of hybrid powertrain configuration. However, powertrains with a parallel configuration have a general tendency to be cost effective in the case studies. The explanation is probably that they include relatively few components. A high efficiency between the ICE and the wheels also speaks in favor for the parallel HEV. Series HEVs tend to be more cost effective if much power can be regenerated. In the case studies incorparating a city bus or a garbage truck, the ranking[8] of a series hybrid bus is better than the case of a taxi car. This is logic because much energy can be regenerated in a series HEV because of its large electric machine. Component choice seems to have a higher impact than the type of configuration. Powertrains with a specific propulsion component often form a group in a table. For example is a super capacitor used as buffer in the most cost effective powertrains presented in Table 5.1. If type of configuration would have been the important choice, the same configuration but with different components would have formed distinct groups in the tables. This is not the case in any of the tables.
- Performance requirements are very important when it comes to sizing of vital powertrain components. An example of a performance requirement is the continuous top speed the vehicle must exceed. The PPU size is directly related to the maximum speed of the vehicle.
- In the Taxi car case study, Section 5.4, the design variables in the EMAs is optimized for the "European Driving Cycle". According to the sensitivity analysis, Section 5.5, the design variable setting of the EMAs also work for other driving cycles, a city and a high way cycle. This strengthen that the EMA proposed in Chapter 3 is robust, i.e. that it works for transport tasks it not is adapted for.

[8] A good ranking corresponds to a high position in a table.

Chapter 6

Summary of Appended Papers

This chapter summarizes the papers included in this thesis.

This chapter summarizes the papers included in the thesis. Figure 6.1 gives an overview of the papers presented in the thesis. Paper A and Paper B deal with conceptual powertrain design. Paper C compares two *Energy Management Algorithms* (EMAs). Paper D describes virtual prototypes of HEVs developed in the modeling language Modelica. In Paper E an algorithm for coordinated control of auxiliary systems is presented. The development of a scaled *Hybrid Electric Vehicle* (HEV) is described in Paper F.

6.1 Paper A

The major purpose of this paper is to describe the principles of a method with the aim to transform requirements and conditions into cost effective powertrains. An example of a requirement is the transport task. Some conditions are fuel cost and interest rate. In the literature-survey of this paper it is found that virtually nothing is done in the area of automating the conceptual design of powertrains. Most research is related to analysis of a prescribed powertrain. Major concepts introduced in the paper are:

- An optimization process is used to find the most cost effective powertrain. The size of the *Primary Power Unit* (PPU), the buffer size and parameters for the energy management strategy are used as design variables in the optimization. An *Evolutionary Algorithm* (EA), further described in B, is used for the optimization.

- A cost function is formulated, which minimum defines the best powertrain. The cost is defined as the operating cost. Vehicle operating costs are the costs due to vehicle value depreciation, fuel use, maintenance, wear on components, insurance and parking fees. Vehicle depreciation cost depends primary on the vehicle price and the interest rate. For simplicity, the only costs included in the operating cost are those that are easy to foresee. These are vehicle value depreciation, often named capital cost, fuel cost and emissions. It is very debatable if emissions should be regarded because they are difficult both to calculate and to price.

- A performance value is introduced. The purpose of the performance value is to verify that requirements are fulfilled. An example of a requirement is that the vehicle must be able to drive at a specific speed. If the PPU is too weakly sized the maximum continuous speed of the vehicle will be too low.

- Simplified vehicle models are used to estimate fuel consumption. Two powertrain models are presented. One model is used to simulate a conventional powertrain. The other model is used for series hybrid powertrains. Both models are of feed-backward type.

The result presented in the paper, an automated process for the proposal of powertrain layouts, is very promising and interesting. But some drawbacks and shortcomings can be identified:

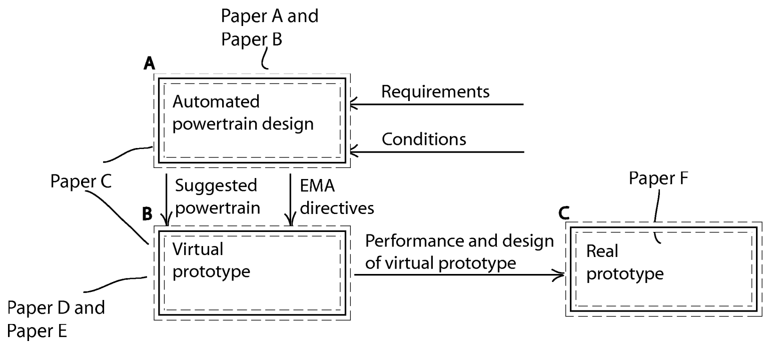

Figure 6.1: *Overview of papers presented in the thesis. The EMA specifies the energy management of the vehicle. The design of the powertrain and EMA is performed simultaneously. This corresponds to box A. In box B, the suggested powertrain is more accurately evaluated. The energy management in the virtual prototype is performed according to the EMA directives generated in box A. Box C, design of a real prototype, is in the thesis performed via a scale model car.*

- The energy management strategy cannot directly be implemented in a real vehicle, or another more accurate computer model. This is a major drawback because it is important to show that the design proposal can be used in practice.
- Only a few types of powertrains are modeled. The powertrains in focus are a conventional powertrain and a series hybrid powertrain. The conventional powertrain is equipped with a diesel engine and an automatic transmission. The hybrid powertrain uses a diesel engine or a fuel cell as PPU and a super capacitor or a NiMH battery as buffer.

All modeling and simulation are performed in Matlab. The advantage with Matlab is that it is widespread and easy to get familiar with. The major disadvantage is the computational speed. As indicated earlier, the paper introduces new questions and challenges. The alternative to use finite state machines to implement the control strategy is further investigated in Paper G. It is unfortunately concluded that a high computational effort is needed to create the finite state machine. Another disadvantage is that they only perform well on driving cycles they are trained on.

6.2 Paper B

This paper can be seen as an extension and improvement of Paper A. The objective, i.e. transform requirements and conditions into cost effective powertrains, is the same as in Paper A. The fundamental concept of using optimization in combination with simplified vehicle models is still utilized. The vehicle model is of feed-backward type. The idea of using a cost function, that reflects the operating cost, is also kept. Following improvements of the work presented in Paper A are done:

- An implementable control strategy is developed. By using FL, the control strategy is converted to a control algorithm. This is an important improvement because the control strategy could be interpreted by intuition and used in a virtual or real prototype. FL is further described in Appendix C.
- A generic powertrain model is implemented. Generic means that it can be used for different types of powertrains.
- A software tool named THEPS[1], developed in Delphi[2], realizes the proposed design method. THEPS is described more in detail in Appendix E. A database separated from THEPS defines several types of vehicle types, powertrains, components and driving cycles. The database enables a user to change data. An important aspect of THEPS is its flexibility. For example can the type of vehicle, that is going to be evaluated, be everything from a scale model car up to a heavy truck. Numerous types of

[1]THEPS is an abbreviation of Tool for Hybrid Electric Powertrain Synthesis
[2]Delphi is a software package for developing PC-software.

powertrain components can be redefined or even added by a user. This flexibility can be explained by the fact that there is a clear cut between algorithms and data structures, i.e. the software code is separated from the database. The code generated in Delphi is in the order of 1000 times faster than the code generated in Matlab. Another advantage of using Delphi is that a stand alone application is generated, i.e. the program can be used on almost any PC computer.

6.3 Paper C

The over all aim with this paper is to compare two different control algorithms used for energy management of HEVs. This paper presents and compares two possible EMAs where one algorithm uses FL and the other algorithm is based on an analytic formula. The algorithm based on FL is the same as in Paper B. This paper can also be seen as en extended description of the EMA presented in Paper B. The algorithm based on an analytic formula is from [10].

The algorithms are compared from three different aspects: complexity, degree of interpreation and differences in operation. Simulations, with the two algorithms, are also made in the paper. The conclusion made is that the algorithm based on FL is more complex, because it uses more parameters. Thereby it is more difficult to adapt the parameters to a specific powertrain and transport task. The advantage with the FL algorithm, compared to the algorithm based on an analytic formula, is that it is more flexible, i.e. it makes few assumptions about the powertrain characteristics.

6.4 Paper D

This paper describes a library for designing and evaluating HEVs. The vehicle models in the library are of feed-forward type and more detailed than the models used in Paper A and Paper B. It is important that a proposed powertrain and control algorithm can be used in practice. To demonstrate this, a prototype is necessary. It is very expensive and time consuming to build real prototypes. Virtual prototyping or computer simulation is therefore an almost necessary complement. The models presented in this paper are more detailed than the generic powertrain model presented in Section 4.7.2 because they have in the order of ten times more variables and parameters. A concrete example is modeling of electric machines. In the generic powertrain model, the efficiency of electric machines is modeled as a function of power. In the library described in this paper, the efficiency of electric machines is not constant but a function of speed and torque.

The language used for the development of the toolbox is Modelica [21], a language for modeling physical systems. It has been proposed as a standard by an international association. More about the association can be found in [21]. Modelica can handle problems in different areas, e.g. mechanics, electricity, chemistry, fluid dynamics and control theory. Another advantage is that the causality does not need to be prescribed. In most other simulation tools one needs to know the causality when designing a model.

Besides the model description, an example of a simulation of a series HEV is also made. The vehicle, a heavy city bus, has a fuel cell as the primary power unit and a super capacitor as buffer. The paper indicates that Modelica is very useful for modeling and simulation of HEVs.

6.5 Paper E

Auxiliary systems can be defined as systems not directly necessary for propulsion, e.g. the air conditioning system. These systems consume a significant part, approximately 5-30%, of the energy produced in a vehicle. The purpose of this paper is to propose a control algorithm that coordinates the power consumption of auxiliary power units with the total power demand of the vehicle. An example of a trivial strategy is to reduce power used in auxiliary systems when the vehicle accelerates. One benefit from this strategy is added traction force.

A control algorithm, based on FL, described in the paper is implemented in a virtual prototype. The parameters in the algorithm, represented by ξ in Table 6.1 and Figure 6.2, are tuned by optimization. The output from the FL algorithm P_{auxreq} is one of three linguistic values {small, medium, big}. P_{auxreq} influences the instaneous power demand from auxiliary power systems.

Table 6.1: *Rules in FL algorithm.*

Rule	Description
If p_{dem} *is small then* $P_{\mathrm{auxreq}} = \xi_1$	Low power demand, e.g. braking.
If p_{dem} *is medium then* $P_{\mathrm{auxreq}} = \xi_2$	Moderate power demand, e.g. cruising.
If p_{dem} *is big then* $P_{\mathrm{auxreq}} = \xi_3$	High power demand, e.g. acceleration.

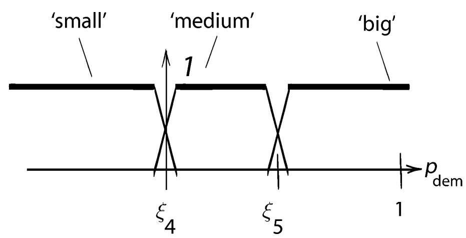

Figure 6.2: *Membership function used in the FL algorithm. Normalized power demand is defined as* $p_{\mathrm{dem}} = P_{\mathrm{dem}}/P_{\mathrm{demmax}}$.

A simulation of the virtual prototype, using the proposed control algorithm, indicates that coordinating the operation of auxiliary power units can decrease fuel consumption. Buffer wear is also decreased by this approach. It is also concluded that especially heavy vehicles benefit from coordinated control of auxiliary systems.

6.6 Paper F

The purpose of this paper is to describe the design approach and development of a hybrid electric scale model car. The paper exemplifies how computational methods, described in Chapter 3 and Chapter 4, can be used in real world product development. The complete process, from a requirement specification to a running car, is described in the paper. The model car enables to test the computational methods in practice.

Prototyping gives the possibility to increase the knowledge of the system to be analyzed and/or developed. It also verifies that no vital aspects are neglected in the design process. By running the scale model car, testing and data acquisition can be performed. For example, computer models can be verified by logging relevant signals. Another undertaking can be to examine that the EMA performs as expected in practice. Following aspects motivate the building of a model car prototype, instead of a prototype based on a full size car:

- Cost. A full size car is much more expensive both in component cost and time of component assembly.
- Safety. There is a much smaller risk of personal injury because the motion of the vehicle is externally controlled.
- Portability. The model car can easily be brought to alternative locations.
- Storage. A small model car is easy to store because it is small.

Beside powertrain design, real time programming and packaging are other important undertakings in the project. Figure 6.3 shows the packaging of the scale model car components. The packaging is not trivial, because the components barely fits in the scale model car.

One finding from the scale model car is that computer simulation is an almost necessary support when designing such a complex system such a hybrid vehicle. Another observation is that a scaled model car is a cost effective platform, suitable for prototyping.

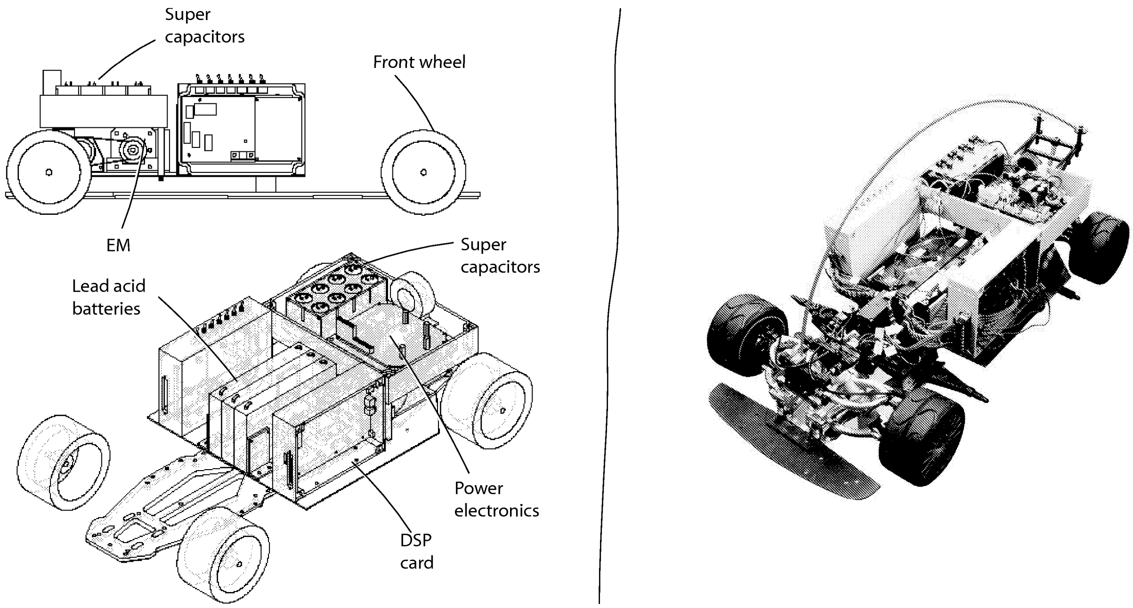

Figure 6.3: *Packaging of components in the scale model car. The car has a length of 0.9 m. It is propelled by a brushless electric machine with power electronics integrated. Two 12 V lead acid batteries are used as voltage source. The batteries are assisted by super capacitors. EM stands for electric machine and DSP for digital signal processor.*

Chapter 7

Discussion and Conclusions

Computer simulations are almost necessary in the design of *Hybrid Electric Vehicles* (HEVs). The reason is that developing HEVs is a complex problem with many design choices. The competitiveness of HEVs depends on both the hardware and software. The hardware corresponds to components in the powertrain and the software determines energy management of major propulsion components. One should also bear in mind that both technical and economic aspects are important when developing automobiles. It is important to know this when designing HEVs. Hardware design, software design, technical and economic aspects have been considered in the design methodology presented in the thesis. THEPS should be regarded as a method or tool that brings out cost effective concepts and disfavors poor concepts in an early phase of the design process. However, later in the design process, new design choices, probably of less significance, must be made. By an automated design process negative influence of human prejudice is avoided. An automated design process, realized by a computer, is advantageous in following cases:

- In product planning. Proposals from an automated design process can make it easier for a company to deside which products to bring in market.
- In product development. An engineer can be much more efficient because the computer performs the time-consuming work of comparing different solutions.
- When a customer buys a product. A customer can define requirements and the product that best matches the design proposal, from a computer, should be an adequate choice.
- When educating students and engineers. By using design software, principles and relations can be understood.

'Modelica HEV Library' shows that Modelica is a very promising alternative to, for example, Matlab[1], when it comes to modeling and simulation of HEVs. However, more can be done when it comes to the code syntax and the structure of the models. Another shortcoming, of the library presented in Paper D, is that relatively few components and configurations are used. In Paper F more mature Modelica models are presented. The major reason why the library not is further developed, in this thesis, is that similar or complementary activities are present within "Gröna bilen" [2]. One example of such an activity is a simulation center [52] with the purpose of assembling models from different projects been initiated. Another example is a work focusing on the control architecture of HEVs [36]. The strategy is to assemble experience from several activities in a future and a more competent library.

The following conclusions can be made from the results presented in this thesis:

[1] MATLAB is a widely-used program, performing numerical calculations. It has its own programming language, in which numerical algorithms can be implemented.

[2] "Gröna bilen" [51] consists of activities from several Swedish universities and companies related to hybrid and fuel cell vehicles

- The software tool THEPS gives reasonable design proposals. Many results, presented in the case studies in Chapter 5, agree well with common sense. The case studies shows, for example, that hybrid powertrains are especially cost effective if used in heavy vehicles running in urban areas. The reason is that more energy can be generated when the vehicle is heavy and starting and stopping is frequent. A heavy vehicle, normally, also run a longer distance during its lifetime compared to a car, i.e. its capital cost is spread over more miles. According to Section 5.6, the outcome from THEPS agrees well with measurements of existing vehicles. This does also strengthen the reliability of THEPS.

- In industrial projects it is important to regard the result of THEPS only as a first estimation. Further analysis needs to be made before trustful decisions can be made.

- In the case studies presented in Chapter 5, it is only for some applications cost effective to use hybrid and fuel cell powertrains in present time (2004). According to the case studies it is more cost effective to equip a bus or a garbage truck with a hybrid powertran than a car.

- Hybrid and fuel cell vehicles can be a more cost effective choice than conventional vehicles, for several applications, in a near future (2015). As exemplified in Chapter 5, more energy efficient technologies can reduce fuel consumption and emissions. In the case studies presented, future operating cost is similar or even lower than today, despite the assumption of more expensive fossil fuels in future.

- There will be no clear answer, for a customer, which type of powertrain to buy in future. The reason is that many cost effective powertrain candidates will be offered. The best choice will depend on the application.

- Performance requirements are very important when it comes to sizing of vital powertrain components. An example of a performance requirement is the continuous top speed the vehicle must exceed. The PPU size is directly related to maximum speed of the vehicle.

- Coordinated control of auxiliary systems can reduce both fuel consumption and component wear. This is especially relevant for heavy vehicles. The reason is that some auxiliary systems of heavy vehicles, e.g. the pneumatic system, can store fairly much energy. If an auxiliary system can store much energy, it can act as an additional buffer. In a pneumatic system the compressor tank has potential to be an additional buffer.

- A scaled model car, with hybrid powertrain, is a cost effective and safe alternative to a full sized prototype.

Chapter 8

Future Work

Some suggestions of future improvements and extensions are:

- Further development of THEPS. One interesting improvement of THEPS is to make it possible for the user to implement alternative *Energy Management Algorithms* (EMAs). This can for example be done by adding/changing rules in the FL rule base. Another improvement can be to reduce the computational speed with for example parallel computation. It can also be of interest to include more aspects in the cost model, e.g. emissions.
- Perfrom further validation of the generic powertrain model used in THEPS. By comparison with more detailed computer models or real vehicles the accuracy of THEPS can be determined. Such a comparison can also indicate how the model used in THEPS should be improved.
- Improve the EA used in THEPS. Many techniques are present, and will probably be developed in future, that improve the performance of EAs.
- Verification of the EMA. With complete knowledge of the transport task, optimal control techniques can be used to find the upper limit for how well the powertrain can be controlled [15][17][16]. Unfortunately the transport task is not exactly known in practice. Some situations are impossible to foresee, e.g. the driver needs to brake because of an unforseen situation. This means that optimal control techniques is more of academic or theoretic value. In a running vehicle an EMA is necessary. It is a challenge to design an EMA that is both possible to use in practice and is close to the theoretical optimum. An interesting idea is to use optimal control techniques to verify the EMA. By doing this it is possible to judge an EMA.
- More intelligent EMAs. In the EMA presented in Chapter 3 only speed is used for long-term decisions. However, one can think of using more sophisticated signals based on for example topology and traffic information. A similar idea influenced by [18] is to use traffic information to change the parameters in the short-term EMA during vehicle operation. It is for example conceivable to use one parameter setup for city driving and another for highway driving.
- Introduce an adaptive EMA. Adaptive means that there are parameters in the EMA which are slowly changed during the use of the vehicle. It is conceivable, for example, that the algorithm becomes more restrictive to use the buffer if the buffer starts to wear out.
- Optimize EMA parameters in the virtual prototype. THEPS proposes a preliminary parameter setting based on the simplified powertrain model presented in Section 4.7.2. An optimization of these parameters, based on a more detailed computer model, can be regarded as a refinement.
- Evaluate additional powertrains and components in THEPS. For example are high energy batteries an interesting PPU candidate, especially if the customer accepts a limited operating range of the vehicle.

- Further improvement of 'Modelica HEV Library'. It is of interest to increase the variety of powertrain types. More can also be done when it comes to the use of Modelica code features.
- Further improvement of the scale model car. Primary it is of interest to be able to use the scale model car to verify computer models and EMAs.

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Appendix A

Nomenclature

Acronyms, terms and symbols frequently used in the thesis are presented in this appendix.

Acronyms

ABS	Anti lock Braking Systems
CVT	Continuously Variable Transmission
EA	Evolutionary Algorithm
EM	Electric Machine
EMA	Energy Management Algorithm. An EMA is a set of mathematical instructions that proposes a reference buffer power $P_{\mathrm{b}}^{\mathrm{ref}}$ for a given situation should be distributed between the PPU and the buffer
FCV	Fuel Cell Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
FL	Fuzzy Logic
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
PPU	Primary Power Unit. The PPU is the power unit that, in a long time frame, provides the majority of the traction power in a hybrid vehicle. In a conventional vehicle it provides all power. The PPU can for example be a combustion engine or a fuel cell.
THEPS	Tool for Hybrid Electric Powertrain Synthesis

Terms

Algorithm	A set of mathematical instructions that must be followed in a fixed order, and that, especially if given to a computer, will help to calculate an answer to a mathematical problem.
Alternative powertrain	A non conventional powertrain, e.g. a fuel cell or a hybrid powertrain
Auxiliary power unit	A power unit not directly necessary for propulsion, can for example be the air conditioning system
Buffer	The buffer is the power unit in a hybrid vehicle that can provide traction power and store energy. The buffer can for example be a NiMH battery.
Chassis	The vehicle with powertrain excluded
Conceptual design	The phase, in the product development process, that generates broad concepts. The conceptual design phase is carried out in the beginning of a product development project.
Control algorithm	A set of instructions explicitely describing how something should be controlled
Control strategy	A set of instructions implicitely describing how something should be controlled
Data	Information organized for analysis or used as the basis for decision-making
Design variable	By optimization, a cost function is minimized by setting design variables.
Energy management	Primary controls the power distribution between the primary power unit and the buffer
Hybrid vehicle	A hybrid vehicle is a vehicle, that combines two or more sources of power for propulsion. A hybrid vehicle includes a buffer, that can store energy, in its powertrain.
Full hybrid vehicle	A vehicle with a buffer that can assist with a signifant part of the power demand for a long time
Genotype	The genetic material of a living being.
Long-term energy management	A strategy determining decisions relevant for a time frame of minutes
Mark-up	Reflects that the customer needs to pay more for a component than the manufacturer
Mild hybrid vehicle	A vehicle with a buffer that can assist with only a small part of the power or energy demand
Phenotype	When developed in a given environment the genotype becomes a phenotype, i.e. the physical and behavioral characteristics of an organism.
Powertrain	The system necessary for propulsion
Physical prototype	A running vehicle
Power converting components	Components in the powertrain that normally do not generate or store energy. These components typically transforms one type of power into a more suitable form. An electric machine is an example of such a component.
Short-term energy management	A strategy determining decisions relevant for a time frame of seconds
Virtual prototype	A computer model imitating a real vehicle

Symbols

a	Acceleration
$\boldsymbol{d}$	The set of time dependant parameters used in the powertrain model
€	Euro, currency of European union
ϵ_{SoC}	Deviation of SoC, a measure of how far SoC is from SoC^{ref}
$\eta_{\mathrm{x_1.x_2}}$	Parameter defining the efficiency between component x_1 and x_2.
$\boldsymbol{p}$	The set of constant parameters used in the powertrain model
p	Normalized power, i.e. $\frac{P}{P_{\mathrm{max}}}$
P_{b}	P_{b} is the physical buffer power, typically derived from measurements.
$P_{\mathrm{b}}^{\mathrm{ref}}$	The control signal that the EMA proposes. It does not necessary need to be equal to the physical buffer power P_{b}.
P_{bnom}	Nominal buffer power, i.e. a power that is adequate for long term use
P_{bmax}	Maximum buffer power
P_{dem}	Power demand from vehicle, brakes excluded
P_{demmax}	Maximum power demand from vehicle
P_{d}	Power demand from vehicle including braking power, i.e. $P_{\mathrm{b}} = P_{\mathrm{dem}} - P_{\mathrm{mbr}}$.
P_{mbr}	Power applied on mechanical brakes
P_{ppumax}	Maximum PPU power
P_{PPU}	Power produced in PPU
p_{r}	Priority of rule r
SoC	State of Charge, is a measure of the energy level in the buffer. In an emptied buffer SoC is zero percent while in a full buffer SoC is one hundred percent.
SoC^{ref}	Reference value of SoC
v	Speed
$\mathrm{v_{max}}$	Maximum continuous speed of vehicle
$\boldsymbol{x}$	States in the powertrain model
$\boldsymbol{\xi}$	Design variables, are defined from the genotype

Indexation

b	Buffer
ch	Charge
dc	Discharge
l	Lower
max	Maximum
mbr	Mechanical brake
nom	Nominal
opt	Optimal
ob	Only buffer
r	Rule
ref	Reference
u	Upper

Appendix B

Evolutionary Algorithms

This chapter describes terms frequently used in *Evolutionary Algorithms* (EAs) and the procedure of an EA. An introductory example and the problem of convergence is also presented. More about EAs can be found in [54][43][62].

EAs are often viewed as a global optimization method although convergence to a global optimum that is only guaranteed in a weak probabilistic sense. However, one of the strengths of EAs is that they perform well on noisy functions where there may be multiple local optima. In situations when gradient based methods tend not to get stuck on a local minimum, EAs can often find a globally optimal solution. EAs are well suited for a wide range of combinatorial and continuous problems. EAs have been successfully applied to a variety of optimization problems such as wire routing, scheduling, image processing, engineering design, parameter fitting and transportation problems.

The biological metaphor that constitutes the inspiring principles for EAs is taken from Darwinian evolution, which is based on the principle that only the fittest survive. The most successful individuals survive and have a relatively large number of offspring. Their genetic materials are then transmitted to following generations. The combination of such genes produces individuals whose suitability (fitness) to the environment sometimes transcends that of their parents. Species evolve in this way.

B.1 Genetic Algorithms

One method included in the family of EAs is genetic algorithms. Terms frequently used in genetic algorithms are:

- Individual. An individual can be considered as a solution candidate. Originally an individual is defined by its genotype.

- Genotype. The sum of genetic material included in a specific individual is named genotype.

- Phenotype. The phenotype corresponds to the characteristics of an individual, for example its size and shape.

- Fitness function. The fitness function constitutes another essential aspect of the genetic algorithm approach. It consists of some predefined criteria of quality that is used to evaluate the utility of a given individual. In an optimization problem of a function such as $f(x, y, z)$, the fitness function simply corresponds, presumably, to an absolute minimum or maximum of the function. The fitness can also, for example, measure a processing time or a real cost.

- Genetic operator. The objective with the genetic operators is to improve the genotype of individuals in the population. A crossover operator creates two new genotypes by mixing genotypes in two individuals in the present population. A mutation operator randomly changes a gene in a genotype.

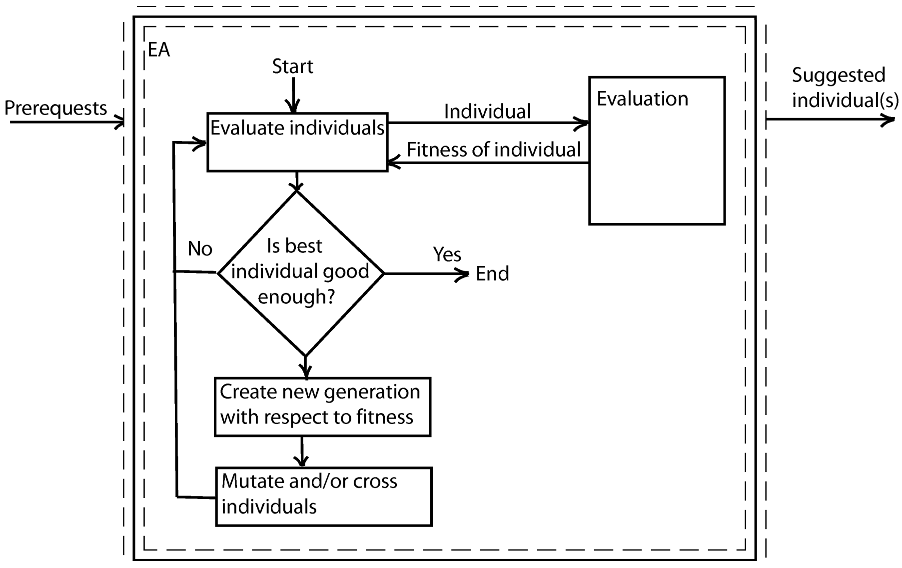

Figure B.1: *The procedure of genetic algorithms. The figure shows the main phases of a genetic algorithm: fitness calculation, creation of new generation and mutation/crossing of individuals. The fitness is defined as the inverse of the cost, i.e. the fitness should normally be maximized.*

B.2 The Procedure of a Genetic Algorithm

Figure B.1 shows the main phases of a genetic algorithm. At first an initial population is created. The genes of the individuals in the population are defined randomly at the initiation. The next phase is to evaluate the fitness of each individual. A value for fitness is assigned to each individual and depends on how well it solves the problem. The fitness is similar to the objective function in an optimization problem. Those individuals with a higher fitness value are more likely to reproduce offsprings. The offspring is a product of the father and mother, whose composition consists of a combination of genes from them. This process is known as "crossing over". It is a possibility that the offspring will mutate after reproduction. Typically a gene is randomly changed at mutation. When a new generation individuals are created, the procedure returns to the evaluation phase. This process normally continue until an individual that is good enough, i.e. has a fitness that is high enough exists.

B.2.1 An Introductory Example

In this section the procedure of an EA is exemplified on an one dimensional optimization problem. The problem is defined as

$$\begin{aligned} &\text{Max } f(x) \\ &f(x) = x - x^5 \end{aligned} \tag{B.1}$$

subject to the constraint

$$0 \leq x \leq 1 \tag{B.2}$$

The function f is plotted in Figure B.2. The mapping from the genotype $G_{\text{i,gene}}$ to phenotype x_i is defined by

$$x_i = G_{\text{i},1} \cdot 10^0 + G_{\text{i},0} \cdot 10^{-1} \tag{B.3}$$

The probability P_i for individual i to be chosen, for crossing or mutation, is defined as

$$P_i = \frac{f_i}{\sum f_i} \tag{B.4}$$

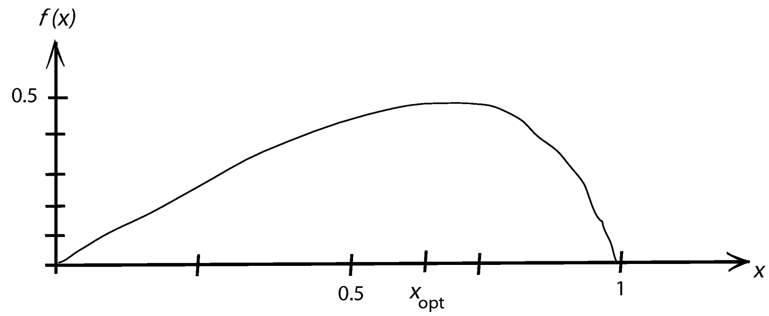

Figure B.2: *The objective function $f(x)$. The optimum is located at $x \approx 0.68$.*

Table B.1: *Possible evolution of individuals (solutions).*

Generation	i	Operations	G_i	x_i	f_i	P_i (%)
0	1	-	(2,6)	0.26	0.259	27.7
0	2	-	(1,1)	0.11	0.109	11.8
0	3	-	(7,9)	0.79	0.482	51.8
0	4	-	(0,8)	0.08	0.079	8.6
1	1	cross individuals	(2,9)	0.29	0.288	19
1	2	1 and 3	(7,6)	0.76	0.506	34.8
1	3	cross individuals	(1,9)	0.19	0.189	13
1	4	2 and 3	(7,1)	0.71	0.529	37.9
2	1	cross individuals	(2,1)	0.21	0.209	11.6
2	2	1 and 4	(7,9)	0.79	0.482	27.4
2	3	mutate individuals	(6,3)	0.63	0.531	29.5
2	4	1 and 2	(6,6)	0.66	0.535	29.7

Table B.1 presents an possible evolution. The genotypes of the individuals in the first generation are randomly set. All individuals, except individual 4, are selected as candidates to generation 1. These individuals are subject for the crossing operator. In generation 2 a solution, x_4, fairly close to the optimum is present. Figure B.3 shows how maximum and average fitness varies with generation. The crossing and mutation operators are described in Figure B.4.

B.3 Convergence

A specific problem with genetic algorithms is convergence. Convergence, illustrated in Figure B.5, means that mutliple individuals get stuck in a local minimum. One major reason is that the crossover operator results in a population with a low divergence in genotype. Following techniques can be used to decrease the risk of convergence [62]:

- Increase the probabilty for mutation. If this probablity is high the individuals will be more spread, but the risk is to end up in a random search method.
- Use rank selection. If individuals are selected upon their rank instead of their fitness directly, also indivduals with low fitness will have a significant change to be chosen to the next generation.
- Introduce subpopulations. The basic idea is to keep, in parallel, several subpopulations that are processed by genetic algorithms, with each one being virtually independent from the others. Typically,

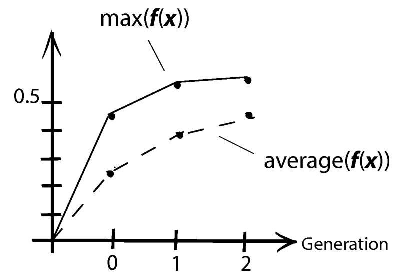

Figure B.3: *Maximum and average fitness as a function of generation. It is clear that the fitness increases during the evolution.*

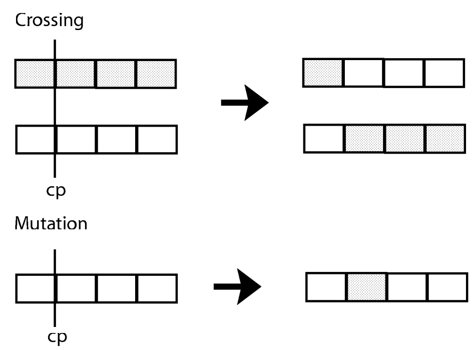

Figure B.4: *The crossing and mutation operators. The crossing operator swaps genes placed after the crossing point (cp). The mutation operator randomly changes the gene placed at the crossing point. The crossing point is randomly chosen for both operators.*

each subpopulation explore a limited part of the solution space.

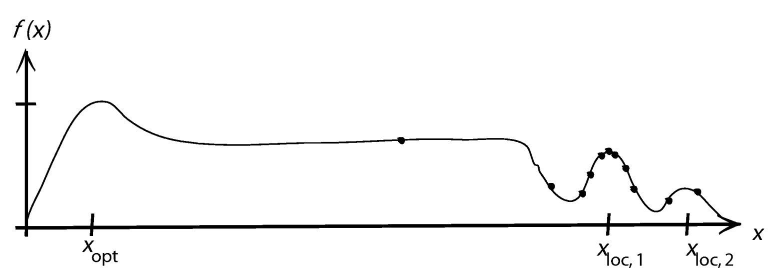

Figure B.5: *The problem of convergence in genetic algorithms. Several individuals get stuck close to the local minimum point* $x_{\mathrm{loc},1}$.

Appendix C

Fuzzy Logic

This chapter describes the history, exemplifies applications and gives characteristics of *Fuzzy Logic* (FL). An introductory example is given to clearify how FL works. More about FL can be found in [38][40].

FL can be seen as an extension of conventional boolean logic. FL can handle the concept of partial truth, i.e. truth-values between "completely true" and "completely false". Linguistic variables instead of numerical or Boolean values are used in FL. Such variables are combined to express rules, i.e. linguistic input/output associations.

Lotfi Zadeh, a professor at the University of California at Berkley, invented the concept of FL in the 1960's. It was presented not as a control methodology, but as a way of processing data by allowing partial set membership rather than crisp set membership or non-membership. This approach was not applied to control systems until the 70's due to the lack of computer capability in the 60's. Professor Zadeh reasoned that people do not require precise, numerical information input, and yet they are capable of highly adaptive control. Bearing this statement in mind it should be possible to design controllers using imprecise input. These controllers should be easier to implement. Today it is common to build real products around FL.

C.1 Applications and Characteristics of Fuzzy Logic

FL is suitable to solve many types of "real-world" problems, especially when a system is difficult to model, is controlled by a human operator or when vagueness is common. Some FL applications are:

- Automotive engineering. In automotive engineering FL has for example been used in anti-lock braking systems. The point of such a system is to monitor the braking system on the vehicle and release the brakes just before the wheels lock. A computer is involved in determining when the best time is to do this.

- Consumer electronics. Household appliances such as dishwashers and washing machines use FL to determine the optimal amount of soap and the correct water pressure for dishes and clothes.

- Decision support. For example meteorological systems can use FL.

Some benefits of FL are:

- Simplified and reduced development cycle. By FL it is possible to describe complex systems using knowledge and experience in simple English-like rules. It does not require any system modeling or complex math equations governing the relationship between in- and outputs.

- FL is fast and relatively easy to implement in a real time system. The memory required is substantially less than a lookup table, especially for multiple input systems. Real time implementation of FL is also normally simpler to debug and tune compared to a lookup table.

- FL is, in contrast to example Neural networks, easy to interpret.

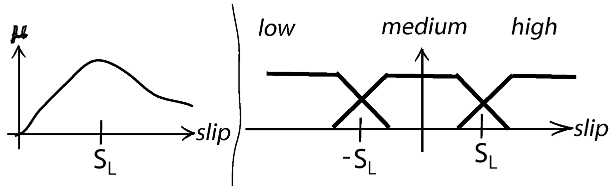

Figure C.1: *Friction versus slip and membership functions. The left plot shows that friction is decreased for high slip values, i.e. slip* $> S_{\mathrm{L}}$.

One disadvantage with FL is that powerful conventional analyze methods cannot be used. Such methods are for example stability analysis in linear and nonlinear control theory. Unfortunately FL has traditionally low respectability. That is maybe its biggest problem.

C.2 How Does Fuzzy Logic Work?

Three distinct phases can normally be identified in a FL calculation:

- 1) Fuzzification. Membership functions convert numeric values values to linguistic values. They can easily be graphically illustrated.
- 2) Rule evaluation. Fuzzy rules relate in- and output values in an intuitive way.
- 3) Defuzzification. The winning or active rule(s) determine the output value. Defuzzification is needed to transform the active rules into numeric values.

C.2.1 An Introductory Example

An example is performed in this section to make these phases more clear and explain how FL works. The position of the gas pedal in a car corresponds to a desired traction torque T_{des}. If the utilized friction is too high the wheel will start to skid. A skidding wheel corresponds to a high slip value, slip is defined as $slip = \frac{\omega \dot{R} - v}{\omega \dot{R}}$. Where R is the wheel radius, ω is the rotation speed of the wheel and v is the speed of the vehicle.

The left panel in Figure C.1 illustrates schematically how slip is related to utilized friction. This relation depends on type of tire and ground. The figure shows that the wheel should be prevented from skidding if high traction force is desirable. The reason is that friction is decreased for high slip values.

An interesting idea is to use FL to avoid skidding. The approach is here to define the torque affecting the wheel as the product of the torque desired by driver T_{des} and A. A is determined by a FL regulator and is a function of the slip. The purpose of the FL regulator is to map slip into A in such a way that skidding is avoided. In the first phase, fuzzification, membership functions according to the right panel in Figure C.1 is used. According to the figure, 'medium' slip is a non-skidding wheel.

To perform the second phase, rule evaluation, following rules are introduced:

- Rule 1. If *slip* is medium then A is one.
- Rule 2. If *slip* is low then A is zero.
- Rule 3. If *slip* is high then A is zero.

In the final step, defuzzification, a numeric value is obtained. A is defined as

$$A = \begin{cases} \frac{\sum_{r=1}^{R} y_r \cdot p_r \cdot \alpha_r}{\sum_{r=1}^{R} p_r \cdot \alpha_r} & (\sum_{r=1}^{R} p_r \cdot \alpha_r > 0) \\ 0 & (\sum_{r=1}^{R} p_r \cdot \alpha_r = 0) \end{cases} \tag{C.1}$$

Table C.1: *Evaluation of three slip values. The priorities of the rules are defined as* $p_r = (1, 1, 1)^{\mathrm{T}}$ *and the outputs as* $y_r = (1, 0, 0)^{\mathrm{T}}$*. The output* A *is calculated by (C.1).*

Input	Active rule(s)	Matching degree	Output
$slip = 0.5 \cdot S_L$	1	$\boldsymbol{\alpha} = (1, 0, 0)^{\mathrm{T}}$	$A = 1$
$slip = 1 \cdot S_L$	1 and 2	$\boldsymbol{\alpha} = (0.5, 0.5, 0)^{\mathrm{T}}$	$A = 0.5$
$slip = 2 \cdot S_L$	3	$\boldsymbol{\alpha} = (0, 0, 1)^{\mathrm{T}}$	$A = 0$

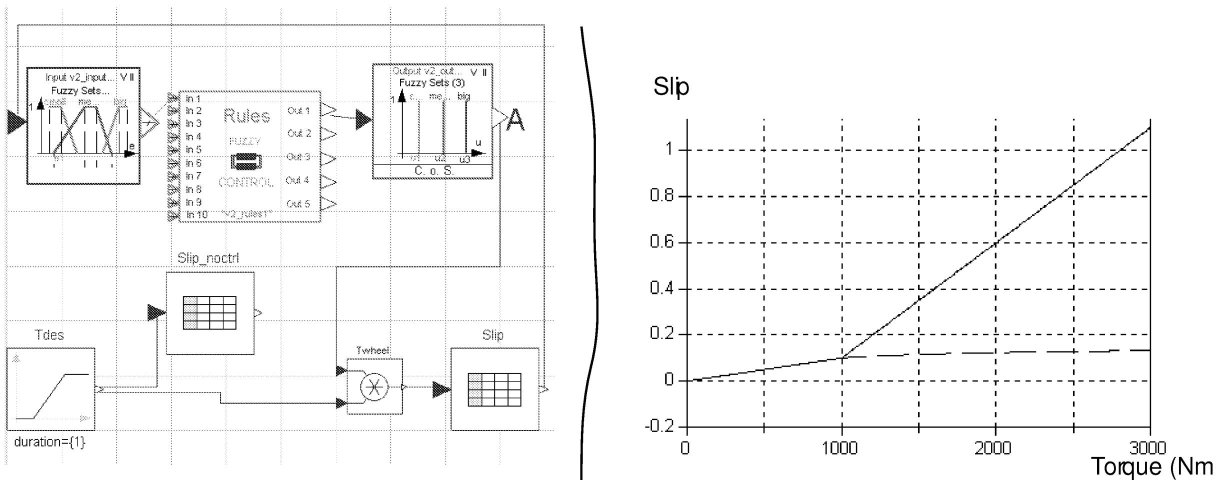

Figure C.2: *Implementation of traction control algorithm. Left panel: Modelica model. Right panel: simulation result. The dotted line represents slip when traction control is utilized. The solid line represents slip when no traction control is utilized.*

where R is number of rules, y_r is the output from rule r, p_r is priority for rule r, α_r is the matching degree for rule r. The matching degree reflects how true a rule is.

As an example, three different slip values are chosen: $slip_1 = 0.5 \cdot S_L$, $slip_2 = S_L$ and $slip_3 = 2 \cdot S_L$. The results are presented in Table C.1. The priorities of the rules are defined as $p_r = (1, 1, 1)^{\mathrm{T}}$ and the outputs as $y_r = (1, 0, 0)^{\mathrm{T}}$. Note that A does not directly change from one to zero when *slip* passes S_L. This change is characterized by the membership functions.

Figure C.2 shows an implementation in Modelica [21]. The three phases: fuzzification, rule evaluation and defuzzification can clearly be identified in the left panel of the picture. The dotted line, in the right panel, represents slip when traction control is utilized. It is clear that torque is limited when T_{des} is above 1000 Nm, i.e. the torque when the wheels start to skid.

Appendix D

Data Related to the Case Studies

Table D.1 includes chassis data for three vehicle types: a city bus[47], a garbage truck [48] and a taxi car [49]. The taxi car is of medium size, i.e. it has a size similar to cars like VW Golf or Ford Focus.

Table D.2 presents parameters settings of the EA. A large number of individuals are used because the search space is large. Rank selection and sub-population, further described in Section B, are techniques used to reduce the risk of convergence. Convergence is decribed Section B.

The mark-up factor, the interest rate, the minimum charge/discharge time[1] and the ratio of the planetary gear are presented in Table D.3. Also the maximum time to change between discharge and charge of the buffer is presented in the table. This time is exceeded if the PPU changes power to slow.

Table D.4 presents vital component data used in the database of THEPS. The fuel consumption data of PPUs are from Advisor [19]. The majority of PPUs, presented in Advisor [19], are from USA. The fuel cell data corresponds to targets set by FreedomCAR [46]. The efficiency curve of the fuel cell is presented in Section 2.5.1. FreedomCAR is an inititative of DOE (Department Of Energy in USA).

The data defines the parameters used in the powertrain component models presented in Paper B. For example efficiency versus power for PPUs. Parameters in polynomial functions[2] are set by curve fitting to experimental data present in Advisor [19]. For each PPU type, ten different sizes are defined in THEPS 2.0. As described in Section E.1.1 a PPU size corresponds to a specific row in a data base table. The efficiency-power relation, the specific power and price depends on the size. THEPS 2.0 handles hundred different buffer sizes. These sizes are determined from the design variable $\xi_{MassBuffer}$ by a linear scaling of buffer properties. For example is the maximum buffer power P_{bmax} calculated by the product of $\xi_{MassBuffer}$, the maximum allowed buffer mass[3] and the specific power of the buffer. The result is that the efficiency-power

[1] This is the mininum time the buffer must remain in charge/discharge mode when crusing, i.e. the driver drives at constant speed. The intention is to avoid frequent and disturbing switch of PPU power.

[2] Some powertrain component models, e.g. the PPU model, use polynomial functions.

[3] This mass is defined by the user of THEPS.

Table D.1: *Chassis data. The bus mass 'Mass of passengers' corresponds to a bus with half of the maximum number of passengers. In the mass 'Mass of passengers' of the garbage truck, garbage mass is included.*

Quantity	Bus	Garbage truck	Taxi car
Air resistance (m^2) $= C_d \cdot A$	0.7·7.5=5.25	0.5·7=3.5	0.26·2=0.52
Rolling resistance (-)	0.007	0.007	0.01
Total mass (powertrain excluded) (kg)	11 000	17 000	800
Mass of passengers (kg)	3 000	4160	160
Auxiliary power (kW)	5	15	2
Hours per day in duty (h)	20	8	8
Total life distance (km)	1000 000	500 000	400 000
Capital cost of chassis and body (€)	100 000	100 000	7 000

Table D.2: *Settings for the evolutionary algorithm.*

Number of individuals (-)	10 000
Number of sub-populations (-)	500
Probability for mutation (%)	5
Selection type	Rank
Number presentation	Digital float

Table D.3: *Other parameters.*

Quantity	Bus	Garbage truck	Taxi car
Mark up (-)	1.5	1.5	2
Interest rate (%)	5	5	5
Min charge/discharge time (%)	20	20	20
Ratio of the planetary gear (-)	2.6	2.6	2.6
Maximum time to change between discharge (s) and charge of the buffer	5	5	5

relation, the specific power and price not are size dependent for buffers in THEPS 2.0.

Table D.4: *Data on components and fuel. A * indicates that a property is assumed to change from present time to future time scenario.*

Component or fuel	Today (2004)	Reference	Tomorrow (2015)	Reference
Price (€/kW)				
* *Fuel cell*	1000	Fuel Cell Vehicles [30]	250	Estimation
Diesel engine	30	Fuel Cell Vehicles [30]	30	Fuel Cell Vehicles [30]
Gasoline Engine	20	Fuel Cell Vehicles [30]	20	Fuel Cell Vehicles [30]
* *Super capacitor*	50	Maxwell [35]	10	FreedomCAR [46]
* *NiMH battery*	30	Kanehira Maruo [56]	20	Estimation
Stepped transmission	10	Fuel Cell Vehicles [30]	10	Fuel Cell Vehicles [30]
* *CVT*	15	Estimation	10	Estimation
* *Electric machine*	30	Davis FutureTruck [57]	10	FreedomCAR [46]
* *Converter*	10	Davis FutureTruck [57]	5	FreedomCAR [46]
Specific power (kW/kg)				
* *Fuell cell*	0.15	FreedomCAR [46]	0.3	FreedomCAR [46]
ICE	0.3	Fuel Cell Vehicles [30]	0.3	Fuel Cell Vehicles [30]
* *Super capacitor*	5	Maxwell [35]	10	Estimation
* *NiMH battery*	1.3	Panasonic [34]	2	Estimation
Specific energy (kJ/kg)				
* *Super capacitor*	20	Maxwell [35]	40	Estimation
* *NiMH battery*	150	Panasonic [34]	300	Estimation
Life time (Nof cycles)				
* *Super capacitor*	500 000	Maxwell [35]	1000 000	Estimation
* *NiMH battery*	10 000	Panasonic [34]	20 000	Estimation
Efficiency (-)				
Super capacitor	0.90-0.99	Maxwell [35]	0.90-0.99	Estimation
NiMH battery	0.70-0.98	Panasonic [34]	0.70-0.98	Estimation
Stepped transmission	0.97	Bosch [33]	0.97	Estimation
* *CVT*	0.85	Power split CVT [58]	0.90	Estimation
Gear	0.98	Bosch [33]	0.98	Estimation
* *Generator*	0.85	PM motor drive [59]	0.90	Estimation
* *Converter*	0.93	PM motor drive [59]	0.95	Estimation
* *Electric machine drive*	0.85	PM motor drive [59]	0.90	Estimation
Fuel price (€/kg)				
* *Hydrogen*	5	Env. Systems [60]	3	Env. Systems [60]
* *Diesel*	1	Preem Petroleum AB [44]	1.5	Estimation
* *Gasoline*	1.5	Preem Petroleum AB [44]	2.2	Estimation
Fuel density (kg/liter)				
Hydrogen	0.014	Fuel Cell Vehicles [30]	0.014	Fuel Cell Vehicles [30]
Diesel	0.85	Bosch [33]	0.85	Bosch [33]
Gasoline	0.75	Bosch [33]	0.75	Bosch [33]

Appendix E

Developed Computer Tools

This appendix describes the computer tools made during the project: THEPS and 'Modelica HEV Library'.

THEPS is a tool for synthesis, i.e. the user defines requirements and conditions and the software gives design proposals. 'Modelica HEV Library' is a tool for analysis, i.e. the user "knows" the solution and wants to achieve more information. The idea is that the design proposal from THEPS should be possible to implement in 'Modelica HEV Library'. The intention is that the tools should have a close relation.

It is a complex task to model hybrid powertrains. The dynamics are varying from less than a μs to long-term effects like component wear. To achieve reasonable simulation time, it is necessary to limit the model complexity with regard to the purpose of the simulations. A simplified model, presented in Section 4.7.2, is used in THEPS, because short simulation time is needed. Computation time is less critical in 'Modelica HEV Library', resulting in the use of more detailed models in 'Modelica HEV Library' than the model used in THEPS. Computational time is crucial in THEPS because it evaluates numerous powertrains.

E.1 THEPS

Very few tools are availabe that automatically generate design proposals of powertrains. The author of this thesis has actually not found such a tool for alternative powertrains.

The major purpose of THEPS is to transform requirements and conditions into cost effective powertrains. The operating cost of a powertrain is minimized by optimization. The configurations and components presently included in THEPS are the same as the ones presented in Figure E.1. The tool or computer program is based on the principles described in Paper B. A nonlinear equation system describes the powertrain. To perform a simulation this equation system is solved in combination with an Euler solver. The timestep is set to 1 second. Figure 4.11 shows the simulation procedure of THEPS.

E.1.1 The Database of THEPS

A database separated from the executable file includes data on powertrain components, driving cycles and other vehicle data. Other vehicle data can for example be mass and coefficient of rolling resistance. Tables connected to each other contain the data in the database. Figure E.2 shows the layout of some tables in the database. The driving cycles are defined in such a way that slopes and emission free zones can be introduced.

One of the design variables specifies the type of powertrain. This design variable is named ξ_{TypePtCo} in Paper B. Assume that this design variable corresponds to a powertrain named 'SerFCA'. The PPU of this powertrain, i.e. 'FuelCellA' according to table 'Powertrains', is defined in table 'PPUs'. This table is found in the upper part of Figure E.2. In table 'PPUs' several PPUs are named 'FuelCellA'. The chosen one of these PPUs are determined by another design variable specifying the size of the PPU. This design variable is named ξ_{MassPPU} in Paper B. The data of the buffer for this powertrain, i.e. 'SuperCapA', can be found in table 'Buffers'. The data of the energy converting elements, for example electric machines, is found in table 'Energyconvs'. For the actual powertrain, energy converting elements are 'Wire', 'ElmA' and 'ConvA'.

It is very advantageous to use a separated database. A future user of THEPS can redefine powertrains and components. For example the price of fuel cells can be changed. New powertrains and components can

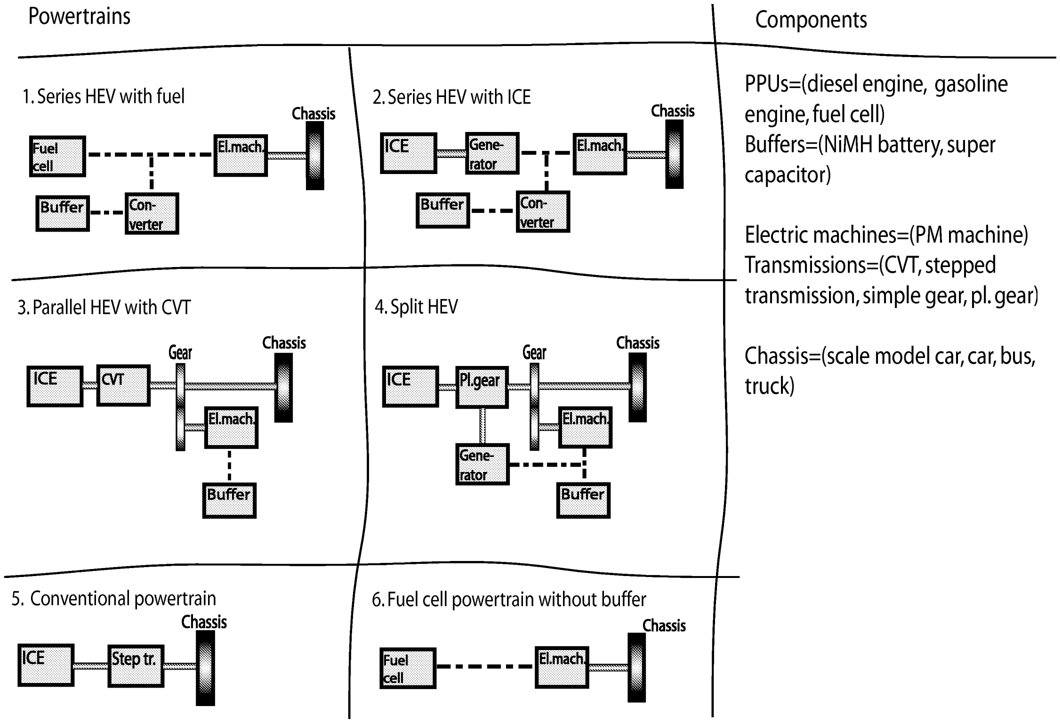

Figure E.1: *Powertrain configurations and components included in THEPS 2.0. For each PPU type, ten different sizes are defined in THEPS 2.0. The efficiency-power relation, the specific power and price depends on the size. THEPS 2.0 handles hundred different sizes. The efficiency-power relation, the specific power and price depends are not size dependent for buffers in THEPS 2.0.*

even be added by the user.

E.1.2 The User Friendliness of THEPS

Figure E.3 shows the graphical interface of THEPS, which drastically simplifies its use. Practically all options are set via the graphical interface. For example can the user define:

- If the optimization only should consider powertrains with a buffer, i.e. exclude powertrains not equipped with a buffer.
- The lower and upper limit of PPU and buffer mass respectively.
- The setting of interest rate and mark-up.

THEPS can simply be installed on almost any PC-computer. THEPS is standalone, i.e. it is not dependant on any other software. A small dictionary is also included in THEPS.

E.1.3 Limitations of THEPS

THEPS assumes that the ICE operates on its optimal line, i.e. at a specific combination of speed and torque. If a stepped transmission is used it is impossible for the ICE to operate exaclty on its optimal line. The more gears in the transmission, the closer to its optimal line the ICE can operate. The conlusion is that THEPS will generate a less accurate estimation of fuel consumption if a stepped transmission is used, especially a transmission with few gears. Powertrains that can use a stepped transmission are conventional and parallel powertrains.

It should also be pointed out that emissions are not included in THEPS Version 2. The reason is that calculation of emissions is a complex task that needs detailed models, i.e. long simulation times. However, it is, to some extent, possible to include the emissions cost in the fuel cost.

Powertrains:

Name	PPU	Buffer	Pnc	Pnb	Bnc	Bnb
ConvA	DieselA		StepGear			
FuelCellA	FuelCellA			Wire	ElmA	ConvA
SerFcA	FuelCellA	SuperCapA		Wire	ElmA	ConvA
⋮						

PPUs:

Name	Mass(kg)	Price(Euro)	MaxP(kW)	Popt	Wmax(rad/s)	....
DieselA	154	900	39.5	0.51	524	....
DieselA	226	1100	60.5	0.25	439	....
⋮						
FuelCellA	50	25 000	25	0.2	-	....
FuelCellA	100	50 000	50	0.2	-	....
⋮						

Buffers:

Name	SpecP(kW/kg)	SpecPnom(kW/kg)	SpecPrice(E/kg)	Etabcha ....
SuperCapA	3	2	200	0.42 ....
NiMHbattA	0.5	0.2	50	0.31 ....
⋮				

Energyconvs:

Name	Eta	SpecP(kW/kg)	SpecPrice(E/kg)	PenCr	PenAcc	....
StepGear	0.95	1	10	1.05	1.2	....
ElmA	0.85	1	10	1	1	....
⋮						

Figure E.2: *Examples of tables in the database of THEPS. The table in the top of the figure, 'Powertrains', can be seen as the main table. The items in the powertrain table point to a specific row in the other tables.*

E.2 'Modelica HEV Library'

There are several software environments suitable for analysing hybrid powertrain systems. In this thesis the Modelica environment has been used. It is at present a simulation program more widely used in academia than in industry. An important aspect in Modelica is its graphical user interface, which facilitates an easy overview of complex systems. Another aspect is the free causality, i.e. the user does not need to identify what is given in the problem. Examples of other accessible programs are Matlab/Simulink, Advisor [19] and V-Elph [53].

The toolbox can be regarded as a set of components that can be combined into different types of HEVs. The toolbox presently includes the same configurations as THEPS. All configurations include electric propulsion components, i.e. they are HEVs. To achieve trustworthy models, the models have primarily been compared with measurements from real components. More about developed Modelica HEV models can be found in Paper D.

The intention has not been to develop a commercial product or a widely used Modelica library. 'Modelica HEV Library' is supposed to be a virtual testbench for the design proposal suggested by THEPS. Using the library it can be shown that an EMA works in a feed-forward system. Fuel consumption has been in focus. Emissions can also be evaluated by using appropiate ICE models.

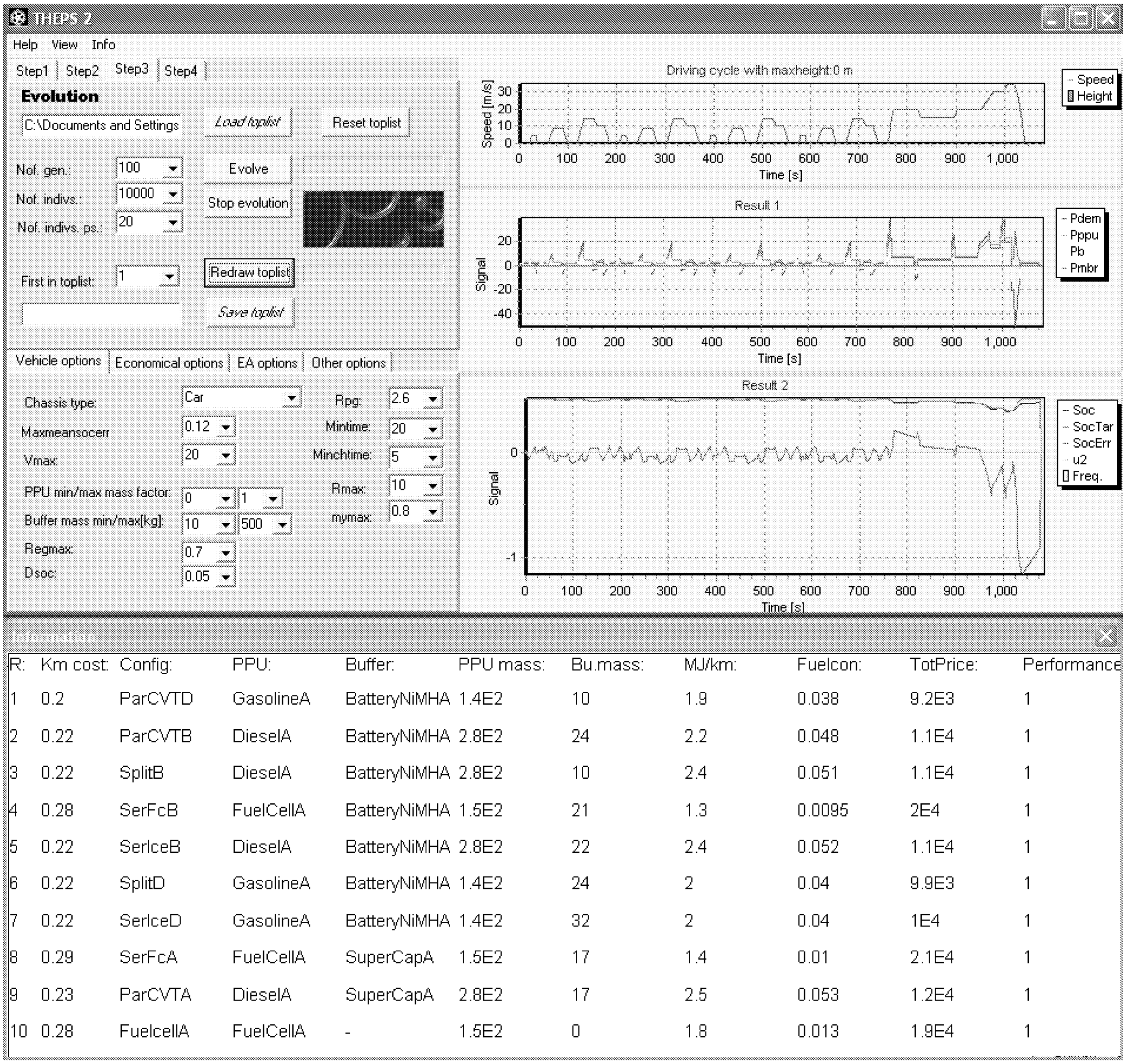

Figure E.3: *Screen-dump from THEPS. THEPS consists at present of approximately 3000 lines of code and can be installed on almost any PC-computer. The lower part shows the result window where the most cost effective powertrains are sorted and presented.*