CHALMERS

Analysis of Hybrid Management Strategies

Master of Science Thesis

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Abstract

In the automotive industry nowadays a lot of focus is set on environmental friendly vehicles, with the primary aim of reducing emissions and pollutants. The most efficient way of doing this is to increase the fuel economy, i.e. to make the vehicle drive longer on the same amount of fuel. Hybrid electric vehicles have been shown to be a popular way of achieving this, without compromising the performance and reliability present in the conventional vehicles. The idea behind this kind of vehicle is to combine two different power sources, typically a conventional fuel driven internal combustion engine and a battery driven electric machine, and use both of them to provide tractive forces to the vehicle. Adding this second power source results in a higher complexity of the powertrain, which requires a sophisticated control system to manage the power flow in the system, henceforth denoted the *hybrid management strategy*.

This master thesis is conducted at ZF Friedrichshafen AG, which currently investigate two different hybrid management strategies for hybrid electric vehicles in a simulation environment. An analysis of these two strategies is done for different vehicles setups, where fuel consumption will be regarded as the primary factor. Before the analysis is conducted, the simulation environment is extended with some different implementations, preventing errors to occur. More parts of the strategies and some gear shift strategies are implemented as well. When the performance of the hybrid management strategies are studied, it is seen that both strategies perform well, giving similar results. Though they differ in the behavior, they manage to get similar results. An important factor to consider is the parameterization of the strategies, as this influences the behavior and results significantly. The biggest difference between the two strategies has to do with how they manage the energy flowing in the battery.

As a last step, the two strategies are tested with a second gear shift logic, and it is seen that both of the strategies are able to perform well.

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Abbreviations

ECMS	Equivalent Consumption Minimization Strategy
EM	Electric Machine
HEV	Hybrid Electric Vehicle
HMS	Hybrid Management Strategy
ICE	Internal Combustion Engine
LUT	Look-Up Table
OEL	Optimal Efficiency Line
SML	Strategic Mode Logic
SoC	State of Charge
TD	Torque Distribution

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Chapter 1

Introduction

This chapter gives some background to the topic, and presents the idea behind the HEV (Hybrid Electric Vehicle). The problem description of this work is then discussed, as well as the main objectives. The chapter finishes with the outline of the report.

1.1 General Introduction

In 2007, 16.1 million new cars were sold in the U.S. [4]. In [3] it is stated that about 97% of these were so called conventional cars, meaning that they have one propulsion system, namely an ICE (Internal Combustion Engine). The most common types of fuel used for the ICE are gasoline and diesel, which both are refined versions of crude oil. When this fuel is used, exhaust emissions and pollutants are released into the air. The pollutant that attracts most of the attention is CO_2, which is one of the greenhouse gases. There is a constant pressure from organizations and governments on the automotive industry, as well as public concern, to reduce their impact on the environment. This has led to investments in more environmental friendly vehicles emitting less emissions and pollutants.

A better fuel economy, i.e. a low fuel consumption, is strongly correlated to a lower release of emissions and pollutants of the vehicles. Installing a catalyst in the vehicles is a step toward reducing pollutants, but to reduce the amount of needed fuel would be to get to the source of the problem. Another factor emphasizing the importance of a better fuel economy is the increase in oil prices during the recent years.

A better fuel economy can be achieved in many ways, e.g. by reducing vehicle weight, increasing efficiencies in the drive systems or even driving more environmental friendly. Another approach is to change to a power source that consumes less fuel, or even no fuel at all, such as compressed air or fuel cells. A battery is also one possible power source, and this alternative was quite popular as the electric vehicle was in series production in the 1990's. But mainly due to its high costs, long battery charging times and limited driving range, the electric vehicle's popularity quickly declined. An alternative to exchanging the ICE completely, is to combine it with a second power source. In this way the benefits of the ICE can still be exploited, in combination with the benefits of the other power source. This kind of vehicle, which uses two different power sources, is known as a hybrid vehicle. Examples of a hybrid vehicle could be an electric bicycle, which uses both an engine and muscle power, or a boat that has an engine and sails. The type of vehicle that is most interesting for more fuel effective purposes is called an HEV, which combines the long driving range of an ICE with good fuel economy and low exhaust emissions of a battery. To be able to get the energy from the battery, an EM (Electric Machine) is used, and the second power source is usually referred to as the EM. As stated in [16, 19], fuel consumption improvements of even up to 25% is achievable by the HEV compared to conventional vehicles, also resulting in reduced emissions and pollutants. The HEV, compared to the electric vehicle, does not depend on external charging of the battery and works well within the existing infrastructure for fueling at gas stations. One HEV that has gained much attention the last decade is the Toyota Prius, depicted in Figure 1.1. The Prius model is the first mass produced HEV and is currently market-leading in its segment [20]. It was introduced in the U.S. in the year 2000, and has steadily increased its sales every year with the releases of new models.

Figure 1.1: *Toyota Prius model NHW20 [5].*

The concept of the HEV is more complex compared to that of a conventional vehicle, much due to the multiple power sources. This will give more possibilities to operate the powertrain, but also results in a more complicated control system. Since two power sources are available, they have to interact with each other in an appropriate way. Hence, a crucial part of every HEV is the HMS (Hybrid Management Strategy), consisting of supervisory controls, managing the power in the system and the interaction of the ICE and the EM. A well designed HMS will surely increase the possibilities of improving the fuel economy, which is the most important task of the HEV.

1.2 Problem Description and Objectives

This thesis will investigate the functionality and performance of two existing HMSs, currently being developed at ZF Friedrichshafen AG. They are two separate strategies, and an analysis of them will be conducted. One of them is based on look-up tables which has been generated from optimization, where the fuel consumption is minimized using the ECMS (Equivalent Consumption Minimization Strategy). The other strategy has a more heuristic rule-based structure, and is less complex primarily for easier understanding, tuning and fault detection. ZF is interested in the differences between the two strategies, and wants to investigate what features are important to consider when designing an HMS. New ideas for the rule-based strategy are encouraged, and the results of these implementations will be studied. Another important part of the study is to see how the two HMSs are able to cope with various design layouts, such as different vehicle setups and gear shifting strategies. This will give an indication of their adaptability and robustness. To be able to conduct this study and to be confident in the results, the existing simulation environment for the HEV has to be improved, and extended with some implementations.

Considering this problem description, the main objective of the thesis can be summarized in the following formulation:

Improve and extend the current simulation environment, so that the system is working properly. This is done by implementations preventing errors to occur, and also implementations of new parts in the two HMSs. Then analyze and compare the HMSs, and study their effect on the fuel consumption, as well as evaluate the robustness when changing to various design layouts.

1.3 Outline of the Thesis

The remaining report is organized as follows. Chapter 2 explains more about HEV, its common setups and its most important components. In Chapter 3 the two HMSs that will be analyzed are described, and Chapter 4 gives an overview of how the simulation environment is set up, together with some new implementations. Chapter 5 gives the first simulation results, and the comparison between the two HMSs is discussed. Simulation results from various design layouts are presented in Chapter 6, followed by Chapter 7 which presents a new gear shift strategy. Finally the conclusions and recommendations are given in Chapter 8.

Chapter 2

Hybrid Electric Vehicles

This chapter introduces the concept of the HEV and presents its most typical configurations. A short description of the important parts of such a system is given, with focus on the two power sources, the ICE and EM. The chapter ends with a summary part.

2.1 Hybrid Electric Vehicles

As mentioned earlier, an HEV includes two power sources to propel the vehicle, an ICE and an EM. Hence there are two energy storage systems in the vehicle; a gasoline or diesel tank for fueling the ICE, and a battery for the EM. Often the HEV uses the ICE as a dominant power source and the EM as an assisting source, in order to provide a better fuel economy and lower emissions. Due to the low energy density of the battery compared to that of diesel or gasoline, the EM will give power for a shorter time than the ICE. This means, that in order to get a battery within the same "energy-range" as the fuel, the size and weight of it would have to be increased significantly, which is not an efficient solution for vehicles. When it comes to the storage systems, the fuel tank for the ICE is just like in a conventional vehicle, and is refueled at the gas stations when getting empty. On the other hand, the storage device for the EM, the battery, is recharged while driving the vehicle. This can be done in two ways; either by using extra power from the ICE, or by using free energy available when decelerating the vehicle.

Hybrid powertrains can be designed in many different ways, e.g. depending on how the vehicle will be utilized, configuration of the power sources, the number of clutches etc. In this work the two most common schemes of the HEV are emphasized, namely the *series hybrid* and the *parallel hybrid*.

2.2 Series Hybrid

In a series hybrid, the ICE is not mechanically coupled to the transmission's input shaft, but charges all its power to a battery. The battery then supplies power to a number of EMs, which are mechanically coupled to the transmission's input shaft providing it with power. A series configuration with two EMs is shown in Figure 2.1. The first EM is used to charge the battery with power from the ICE, and the second EM is coupled to the transmission's input shaft, providing power from the battery. An advantage of this configuration is that the ICE can be optimized to work in the vicinity of its best operating point, without considering the actual driving situation. For example when doing "stop and go" driving, which usually happens in urban areas, the ICE is exposed to fast transients leading to many working points. As the number of working points increase, optimizing the ICE usage becomes more difficult, eventually resulting in a low average efficiency of the ICE. In this situation the series configuration has the possibility of letting the ICE work at its optimal working point, since it is not dependent on the road conditions. One negative effect of the series setup is the need for two EMs, which are costly components. Another is the loss off energy, due to all the energy conversions which are present between the ICE and the transmission's input shaft.

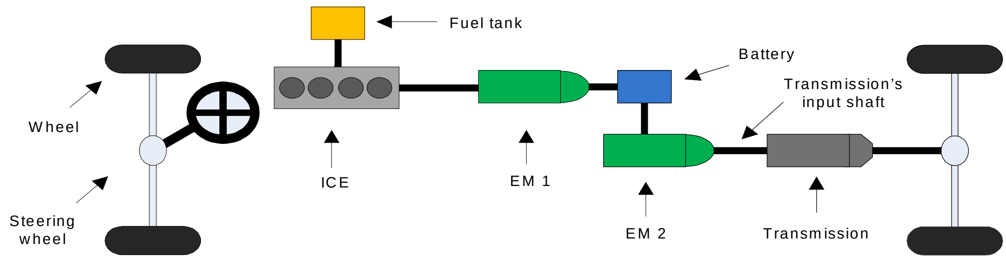


Figure 2.1: *A schematic of the series hybrid.*

2.3 Parallel hybrid

In the parallel hybrid depicted in Figure 2.2, both the ICE and the EM are mechanically coupled to the transmission's input shaft, on the contrary to the series hybrid. There is also the possibility to decouple the ICE with a clutch. When the ICE is coupled, the power from the sources are added in order to fulfill the demanded power. Since the power from the ICE acts directly on the transmission's input shaft, it does not need to go through all the power conversions as in the series setup, and a higher efficiency for the driveline is achieved. When the ICE and the EM are both coupled, they run at the same speed. The advantage of the parallel hybrid can be realized especially for long highway driving. In [9], it is stated that when driving at high velocities, the ICE is already working at points with high efficiencies, and the losses in the drivetrain between the ICE and the road are minimal. The parallel configuration is considered to be more efficient than the series one, when looking at a general driving pattern with both city and highway driving [6, 13]. Another benefit is that only one EM is needed, resulting in reduced costs, weight and space requirements.

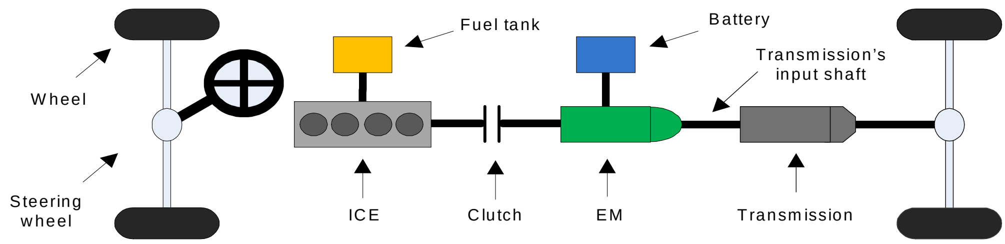


Figure 2.2: *A schematic of the parallel hybrid.*

In this thesis study the parallel hybrid is used, and the components which build up the parallel hybrid is explained in the following section.

2.4 Components in the Parallel Hybrid

2.4.1 Battery

The battery is the electrical energy storage, and usually the type Li-ion, NiMH or super capacitors. The battery is a so called *bi-directional storage device*, since it can charge and discharge itself when the vehicle is driving. An important part of the battery is its SoC (State of Charge), which tells how much energy [J] is available. The SoC should always be kept within a certain range of the battery capacity, e.g. 30% - 70%, in order to prolong its lifetime and increase its efficiency. When the battery level is starting to get either too low or too high, measures need to be taken to secure the limits from being reached. This, as will be seen later on, is done by the HMS, since it is responsible for controlling the SoC of the battery. If, for some reason, the SoC should reach very low or high levels, there are built-in safety features in the battery which disables it.

2.4.2 Clutch

The clutch is the component that connects and disconnects the ICE to the transmission's input shaft (not to be confused with the more commonly known clutch present in the transmission, which is used to shift gears). When the clutch is engaged (closed) the ICE is coupled to the transmission, providing torque. As the clutch is disengaged (opened), the ICE is disconnected from the driveline, and the demanded power of the driveline is provided only by the EM.

2.4.3 Fuel tank

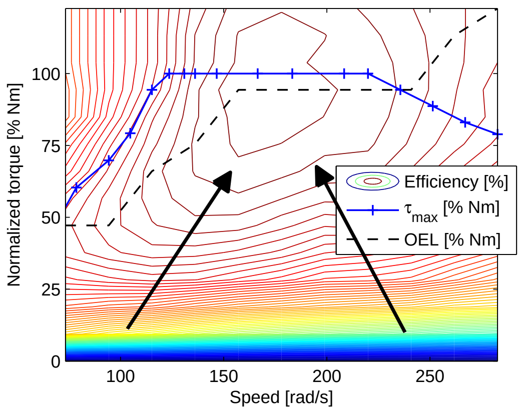
The fuel tank is the energy storage for the ICE, like diesel, gasoline, natural gas or hydrogen. This energy storage does not inherit the bi-directional functionality as the battery does, and is refueled when not driving.

2.4.4 Internal Combustion Engine

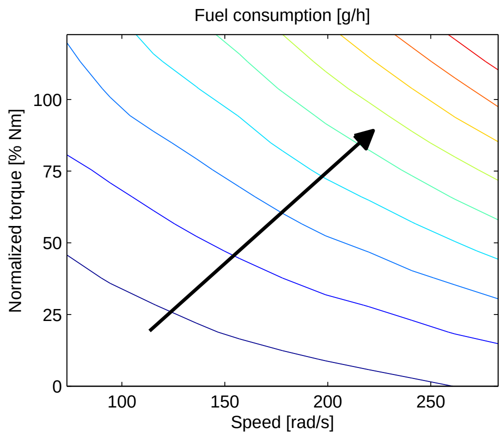
The ICE is the main power unit in the powertrain, converting chemical energy from a fuel/air mixture into mechanical energy on the driveline. Depending on the specific setup of the parallel hybrid, the ICE can be turned off during driving and/or during standstill of the vehicle, to e.g. save fuel and reduce noise. An essential part of any HMS is to understand the characteristics of the ICE, and especially its efficiency. This will be a frequently discussed element throughout the chapters when covering the HMS. The model of the diesel engine specifies the fuel consumption in [g/h] as a function of its operating point, which is defined by two values; the engine speed ω_{ICE} [rad/s] and the engine torque τ_{ICE} [Nm]. The fuel consumption is represented by a two dimensional matrix, which can be used to form fuel maps of the engine. A common representation of the fuel map is the engine efficiency, taken as the ratio of the mechanical output power and the chemical input power. The chemical input power is determined from the fuel's *lower heating value*, which tells how much heat is released during combustion, in other words the energy content of the fuel. The lower heating value for diesel is typically 44.5 [MJ/kg]. The engine efficiency, η_{ICE} [-], is computed as in (2.1)

$$\eta_{\text{ICE}} = \frac{P_{\text{m}}}{P_{\text{ch}}} = \frac{P_{\text{m}}}{lhv_{\text{f}} \cdot f_{\text{c}}} \quad [-] \tag{2.1}$$

where P_{m} [W] is the mechanical output power, P_{ch} [W] the chemical input power, lhv_{f} [J/kg] the lower heating value and f_{c} [kg/s] the fuel consumption. Another common representation of the fuel map is the *brake specific fuel consumption*, which in fact is inversely proportional to the efficiency of the ICE. Example of an efficiency map is presented as a contour plot in Figure 2.3(a). The torque is normalized to the maximum torque of the discussed power source, and this kind of normalization is used for all torque axes in the following plots.



(a) Efficiency map, optimal efficiency line and the maximum torque of a diesel engine. The arrows indicate increasing efficiency, where the highest efficiency point is about 40%.



(b) Fuel consumption of a diesel engine, where the arrow indicates increasing fuel consumption.

Figure 2.3: *Example of an efficiency map (left) and fuel consumption (right) of a diesel engine.*

Also shown is the OEL (Optimal Efficiency Line), which describes the best torque and speed combination for any given power. The power, P, is computed from these two variables, as in (2.2)

$$P = \tau \cdot \omega \quad [W] \tag{2.2}$$

where τ [Nm] is the ICE torque and ω [rad/s] is the angular speed of the ICE's crankshaft. Most relations expressed in this work will be torque-oriented, since the strategies are well explained using torques.

Given the actual output shaft speed and demanded torque from the driver, is it still possible to change the ICE working point. The ICE speed is controlled by the gear shifts in the gear box, whereas the ICE torque is controlled by the HMS. To get closer to the OEL, which clearly would be advantageous in an efficiency perspective, the operating point of the ICE can be moved. By combining an increase/decrease of the speed and torque, the working point can be moved over the torque-speed plane. To move the operating point by increasing/decreasing the torque is an important functionality of the HMS, which will be discussed more in Section 3.2.2.

The fuel consumption of an ICE can also be shown in a speed-torque plane, as in Figure 2.3(b). Here it is seen that the fuel consumption increases as the torque and the speed increases. It is understood that the idea of keeping a high efficiency of the ICE does not necessarily mean a low fuel consumption. Keeping low speeds and low torques will give a low fuel consumption, but on the other hand the efficiency of the ICE might be very low, which brings a contradictory effect.

2.4.5 Electric Machine

The EM is the second power unit in the powertrain, and functions both as a motor and a generator. The motor mode is used when the EM supplies tractive force to the vehicle by converting the electrical energy in the battery to mechanical energy at the driveline, leading to a discharge of the battery. The generator mode is enabled when the EM recuperates mechanical energy from the vehicle during braking, called *regenerative braking*, or during a recharge from the ICE. This energy is converted to electrical energy charging the battery. The efficiency of the EM is also described by an efficiency map, shown in Figure 2.4 for both positive and negative torques (used as a motor or generator).

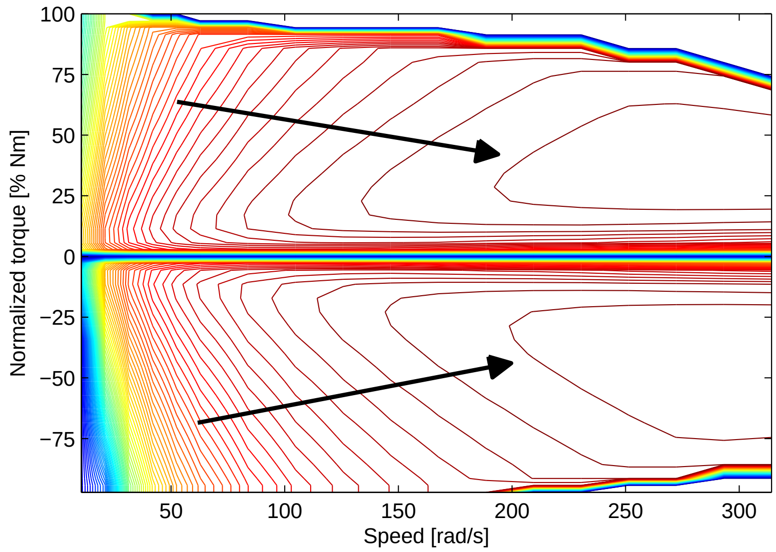


Figure 2.4: *Example of an efficiency map for an EM, for motor mode (positive torques) and generator mode (negative torques). The arrows indicate increasing efficiency, where the highest efficiency point is about 90%.*

2.4.6 Transmission

The transmission device (gear-box) is used for adjusting the speed of the driveline to a desired speed of the wheels. It consists of a set of gears with different conversion ratios, and yields a torque-speed conversion from a (usually) higher speed of the driveline to a lower speed at the wheels, but with a higher torque. Included in the transmission device is also the clutch enabling the gear shifts (not to be confused with the previously discussed clutch, which couples and decouples the ICE from the driveline).

2.5 Impact of Hybridization

Due to the flexibility and the additional components of the parallel hybrid powertrain compared to that of a conventional vehicle, some objectives and benefits can be listed, such as the following:

- The ICE can be sized for a lower torque, since the EM can be used for boosting [16, 19]. Though, the maximum vehicle velocity should not be increased when adding the EM, since this velocity always has to be achievable, even without the EM (due to manufacturer specifications).

- Less wear on the brakes and reduction of waste energy due to regenerative braking.
- Longer lifetime of the ICE, since unfavorable situations are avoided due to the power assisting EM.
- Smaller and lighter fuel tank.
- Electric driving, where the fuel consumption is at idle consumption or zero.
- Less noisy operation since the ICE can be turned off during standstills.

To use the EM for regenerative braking is a very important functionality of the HEV, and will be explained further in the next chapter.

2.6 Summary

This chapter gives an introduction to the HEV and the most important components of the parallel configuration. The efficiency maps of the ICE and the EM are discussed, and their importance for the coming chapters is emphasized. It is realized that a HEV has a more complex structure compared to a conventional vehicle, but that it also gives more flexibility in how to design and control the system as a whole. The benefits of this will be shown later in Chapter 5, 6 and 7, when the HEV is simulated.

Chapter 3

Hybrid Management Strategies

In this chapter the idea behind the HMS is discussed together with its layout, followed by a description of the existing HMSs that will be studied in this work. Finally a summary part is given.

3.1 Hybrid Management Strategies

Regarding the previous sections, it is obvious that there is the need of a supervisory control system for the hybrid powertrain, to let it operate in an efficient way. It is mainly the two power sources, the ICE and the EM, and their interaction that need to be controlled. This control system is called the HMS, and is a crucial part of every HEV. To put it in a compact formulation, the objective of the HMS in this work is the following:

- To control the mode of the vehicle, i.e. mainly to set the status of the ICE (on/off).
- To control the cooperation of the ICE and the EM, i.e. to decide the torque split between them.

The goal of the HMS may be to e.g. minimize the fuel consumption or the emissions, or a combination of both. In this thesis the HMSs are optimized against minimizing the fuel consumption.

The HMS is divided into four separate segments; *SML (Strategic Mode Logic)*, *TD (Torque Distribution)*, *SoC Controller* and *Brake Management*. The main structure of this division is seen in Figure 3.1, together with one important output from the SML and two from the TD. The four parts, even though they are separated, strongly interact and affect each other. Their functionalities are described below.

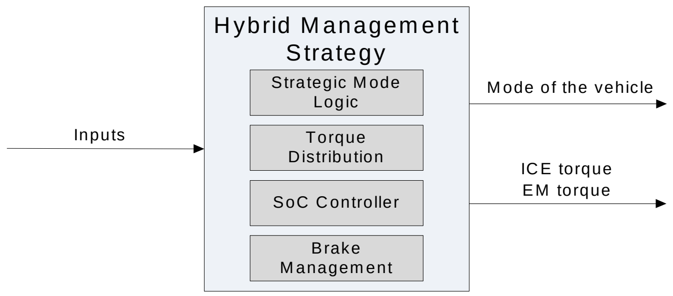


Figure 3.1: *The structure of the HMS as implemented in the simulation environment.*

3.1.1 Strategic Mode Logic

In this part the decision about the mode of the vehicle is taken, where the most used modes are; *Electric Drive with ICE off*, *Electric Drive with ICE on* and *Hybrid Drive*. All of these modes describe different driving situations, and should be appropriately selected. The strategic mode of the vehicle is directly correlated to the status of the ICE, which can either be on or off. To control the status of the ICE is an important factor and doing so has a great potential to save fuel. Below the three modes are described more in detail, with their respective torque calculations.

Electric Drive with ICE off
In this mode the vehicle is propelled only by the EM, and the clutch in Figure 2.2 is disengaged. It does not require any torque from the ICE, and therefore it is turned off. All the demanded torque by the driver is taken from the EM, and the equations describing this mode are shown in (3.1)

$$\begin{array}{rcll} \tau_{\mathrm{ICE}} & = & 0 & [Nm] \\ \tau_{\mathrm{EM}} & = & \tau_{\mathrm{driver}} & [Nm] \end{array} \tag{3.1}$$

where τ_{ICE} [Nm] is the torque from the ICE, τ_{EM} [Nm] is the torque from the EM and τ_{driver} [Nm] is the demanded torque by the driver. To be in this mode will definitely have benefits regarding the fuel consumption and the emissions, since no fuel is consumed. A typical condition for switching the ICE off is when the vehicle comes to a standstill, and no torque is demanded by the driver.

Electric Drive with ICE on
This mode is similar to the one previously discussed, since the vehicle is propelled by using only the EM and the clutch in Figure 2.2 is disengaged. The difference is that the ICE is kept running at the idle speed. The two equations describing this mode are stated in (3.2)

$$\begin{array}{rcll} \tau_{\mathrm{ICE}} & = & \tau_{\mathrm{ICE,\ idle}} + \tau_{\mathrm{load}} & [Nm] \\ \tau_{\mathrm{EM}} & = & \tau_{\mathrm{driver}} & [Nm] \end{array} \tag{3.2}$$

where $\tau_{\mathrm{ICE,\ idle}}$ [Nm] is the required idle torque, and τ_{load} [Nm] is the extra torque required for some applications such as the steering. Keeping the ICE on obviously leads to higher fuel consumption and more emissions compared to turning it off, but this mode might be necessary, since many vehicles need the ICE to power e.g. the air condition and the steering. There is also an energy loss when turning the ICE on, and turning it off should be avoided if it needs to be turned on again shortly after, which e.g. can happen if the battery is very low.

Hybrid Drive
In this mode the ICE and the EM are both used to propel the vehicle, and the clutch in Figure 2.2 is engaged. The sum of their torque contribution results in the demanded torque by the driver, as in (3.3)

$$\tau_{\mathrm{driver}} = \tau_{\mathrm{ICE}} + \tau_{\mathrm{EM}} \quad [Nm] \tag{3.3}$$

This is the most elaborate mode, as the torque needs to be split between the two power sources. There are infinitely many ways of combining the two power sources, and somehow the split has to be computed. This is where the importance of the TD is understood, as it is responsible of computing this split.

3.1.2 Torque Distribution

The task for this part of the HMS is to decide the torque distribution for the system, when the mode Hybrid Drive is active. It is determined how to operate the two torque paths in the most favorable way, to satisfy the torque demand by the driver. In some situations it might be advantageous to take all the torque from the ICE, and nothing from the EM, typically when the SoC of the battery is very low. This would mean that the HEV is operated as a conventional vehicle, as the EM is not used. On the other hand, when the battery is fully charged, the best might be to supply most of the torque to the driveline from the EM, and only a small amount from the ICE. These kind of decisions are made in the TD part. The strategy can be designed in numerous ways, and is an important part of the HMS, in order to get a good performance.

3.1.3 State of Charge Controller

This part is responsible for controlling the SoC of the battery, in such a way that it is kept within the allowed limits. The two analyzed HMSs have different ways of doing this, as will be seen later.

3.1.4 Brake Management

The brake management system is needed for the HEV, in comparison to the conventional vehicle. It should make sure that the driver gets what he demands when braking, at the same time letting the components in the HEV operate in an efficient way. The two HMSs have the same brake management, and therefore there is no focus on this part when doing the comparison. In Section 4.6 the brake management is discussed further.

3.2 Rule-Based Hybrid Management Strategy

One of the two HMSs is the rule-based strategy, as mentioned in Section 1.2. The structure of this follows the one illustrated in Figure 3.1, and here the three parts SML, TD and SoC controller are explained.

3.2.1 Strategic Mode Logic

The SML is represented by a discrete-event system[1], and implemented as a stateflow chart in the Simulink environment. A simplified version is presented in Figure 3.2. Each mode of the vehicle is represented by a specific state, in which an action can be performed when activated. In order to switch mode (state), the transition, illustrated by a line, needs to be fired. The transitions can be e.g. time functions and/or value functions, and represent conditions for changing the mode, such as demanded power or standstill detection. When the transition is fired, a new state is entered, and the vehicle switches mode. Every state can have many transitions connecting to different states, and are fired in a prioritized order if they should occur at the same time.

[1]For more information about discrete-event systems, see [2] and [7].

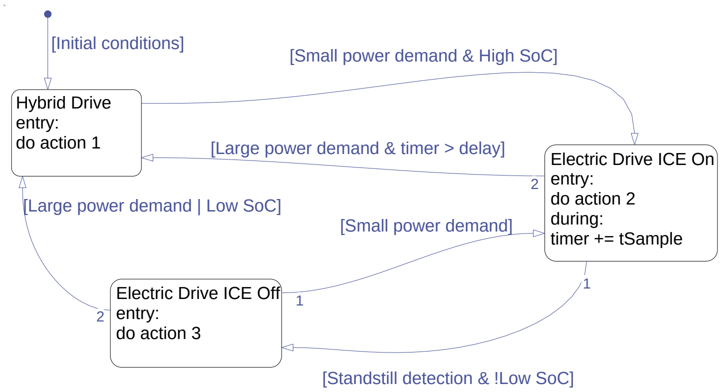


Figure 3.2: *Simplified version of the stateflow diagram, representing the SML for the rule-based strategy.*

Depending on the current driving conditions, the SML will choose one of the modes Electric Drive with ICE off, Electric Drive with ICE on or Hybrid Drive for the vehicle. To make the switch between the different modes is a crucial point of the HMS, and surely much fuel can be saved if the mode changes are done correctly. One of the main variables deciding the switch is the torque demanded by the driver, in a relation to the current energy state of the battery. The power demand is computed from the driver as in equation (2.2). Then a time is computed, which tells how long the battery will be able to provide this power for the vehicle, if all the demanded power is given by the EM. Since this variable tells how long the vehicle can be driven electrically (either Electric Drive with ICE on or Electric Drive with ICE off), it can be compared to thresholds deciding the switching of the modes. The logic can be explained as in the following:

- If the vehicle is able to drive electrically for more than 20 seconds, considering the current torque demand and SoC, switch to the mode Electric Drive with ICE on.
- If the vehicle is able to drive electrically for less than 10 seconds, considering the current torque demand and SoC, switch to the mode Hybrid Drive.

Typically the torque demand from the driver is high for accelerations, and therefore the time the vehicle will be able to drive electrically is short. Hence the SML will choose the mode Hybrid Drive, where the ICE can provide the high torque demand. If the vehicle is driven in a downhill, the demanded torque by the driver is very low (even negative), and electric driving should be chosen. Many variables are used in the logic deciding the mode of the vehicle, though the torque demand from the driver in relation to the SoC is the most important. Examples of other variables deciding the switching between modes are *standstill detection*, *parking brake*, *ICE temperature*, *vehicle velocity*, *gear shift*, etc. It can also happen that when going downhill, the battery becomes fully charged, and no more energy can be stored. In that case it might be better to switch from electric driving to hybrid driving, and use the engine braking functionality of the ICE.

It should be remembered that the TD in the HMS is only active in the mode Hybrid Drive, as the other modes only use the EM for traction. Therefore, the TD is much dependent on the behavior of the SML, and the SML can be seen as a deciding function over the TD.

3.2.2 Torque Distribution

The idea behind the TD in the rule-based strategy is to have the possibility to always operate the ICE at a high efficiency. This can be done by moving the actual operating point closer to the optimal working point as in Figure 3.3, to increase the efficiency, and the methodology is known as *load leveling*.

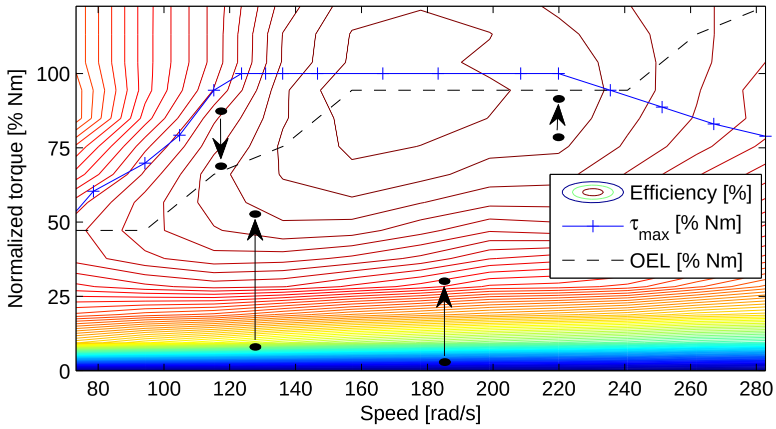


Figure 3.3: *Four arbitrary working points of the ICE are selected, to show that they can be moved to an area with a higher efficiency.*

In [1], it is thoroughly described that for a vehicle which is ICE dominated, like this one, the overall system efficiency is expected to be higher if the ICE is considered more than the EM, when designing the control system. Hence the focus will be set on improving the conditions under which the ICE is working.

The TD for the rule-based strategy is computed in two steps as in (3.4)

$$\begin{aligned} \tau_{\text{EM}} &= \tau_{\text{EM, EM Boost}} + \tau_{\text{EM, ICE Torque Increase}} + \tau_{\text{EM, ICE Torque Decrease}} + \tau_{\text{EM, Regenerative Braking}} & [Nm] \\ \tau_{\text{ICE}} &= \tau_{\text{driver}} - \tau_{\text{EM}} & [Nm] \end{aligned} \tag{3.4}$$

The torque from the EM is calculated from four different parts, namely *EM Boost*, *ICE Torque Increase*, *ICE Torque Decrease* and *Regenerative Braking*. They are best explained with the help of Figure 3.4 in combination with the previously discussed ICE efficiency map, Figure 2.3, and is done in the following.

EM Boost

This part will assist the ICE when a high torque is demanded by the driver, especially when doing accelerations and e.g. hill-climbing. In Figure 3.4, the ICE is shown in the speed-torque plane, with the maximum torque line and the maximum driver torque line. The maximum torque is depending on the specifications of the ICE, and it will not be able to provide a torque over this line. In this work, the maximum driver torque line is set so that it coincides with the highest value of the maximum torque line of the ICE. The torque from the EM due to boost, $\tau_{\text{EM, EM Boost}}$ [Nm], is given in (3.5)

$$\tau_{\text{EM, EM Boost}} = \begin{cases} \tau_{\text{driver, max}} - \tau_{\text{ICE, max}} & [Nm] \quad \text{for} \quad \tau_{\text{driver}} > \tau_{\text{driver, max}} \\ \tau_{\text{driver}} - \tau_{\text{ICE, max}} & [Nm] \quad \text{for} \quad \tau_{\text{ICE, max}} < \tau_{\text{driver}} < \tau_{\text{driver, max}} \\ 0 & [Nm] \quad \text{for} \quad \tau_{\text{driver}} < \tau_{\text{ICE, max}} \end{cases} \tag{3.5}$$

where $\tau_{\text{ICE, max}}$ [Nm] is the maximum torque of the ICE. As soon as the driver demands a torque above the maximum torque line, the EM boost function will be enabled. If the driver demanded torque is below the maximum torque line, the EM boost function is disabled.

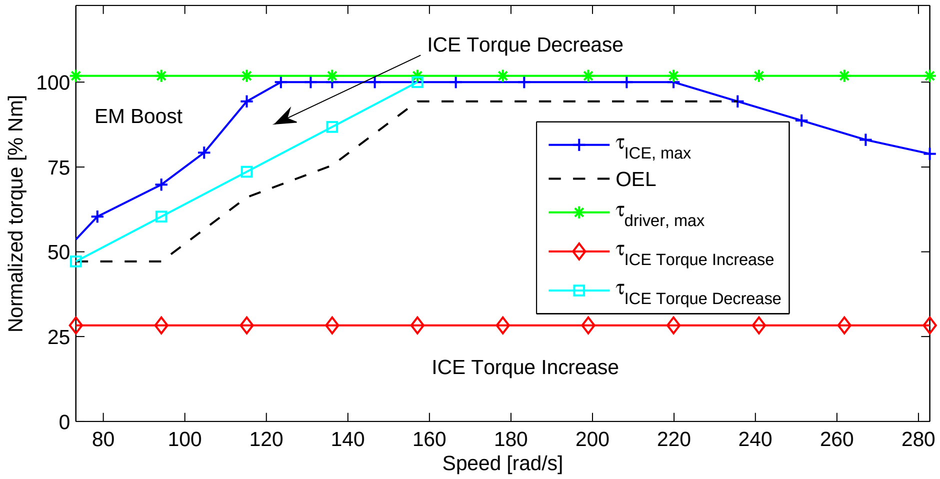


Figure 3.4: *The curves representing the features in the rule-based TD. The ICE torque increase and the ICE torque decrease curves are set to arbitrary values.*

ICE Torque Increase

This function, as its name implies, will increase the torque of the ICE. This is to take more torque than is demanded by the driver, and use it to charge the battery. The extra torque from the ICE can be seen as an equivalent negative torque from the EM, due to the computations of the ICE torque in equation (3.4); as the EM torque decreases, the ICE torque increases. The idea behind this feature has to do with the efficiency map of the ICE, as explained in Section 2.4.4. In Figure 3.4 the OEL and the ICE torque increase line are both shown. If the ICE is operated at a low efficiency below the ICE torque increase line, it could be advantageous to increase the torque to reach a higher efficiency, and store the extra energy in the battery. If the driver demands a torque below the ICE torque increase line, the torque of the ICE will be increased to the ICE torque increase line. Since this will result in a higher torque (and power) from the ICE than the driver demanded, the extra torque will be used to recharge the battery, which is formulated in (3.6)

$$\tau_{\text{EM, ICE Torque Increase}} =$$

$$\begin{cases} \tau_{\text{driver}} - \tau_{\text{ICE Torque Increase}} & [Nm] \quad \text{for} \quad 0 < \tau_{\text{driver}} < \tau_{\text{ICE Torque Increase}} \\ 0 & [Nm] \quad \text{for} \quad \tau_{\text{driver}} > \tau_{\text{ICE Torque Increase}} \end{cases} \tag{3.6}$$

where $\tau_{\text{ICE Torque Increase}}$ [Nm] is the value of the ICE torque increase line. If the driver demanded torque is above this line, it results in no torque increase. The value from equation (3.6) is saturated in a way that it always stays negative (negative EM torque gives positive ICE torque). To increase the torque of the ICE will lead to higher fuel consumption, but the hope is that more than this fuel can be saved at a later stage, by using the energy it managed to store in the battery during the ICE torque increase. It should be noted that increasing the torque of the ICE and save the extra energy in the battery will not necessarily be beneficial. This is due to the losses in the electrical system which occurs when converting the mechanical energy from the ICE to electrical energy for the battery. The extra energy taken from the ICE might be "lost" due to all the conversions, which would mean that the ICE torque increase was not useful. In this case the functionality of the torque increase should be disabled, and the EM should recharge the battery only by regenerative braking.

ICE Torque Decrease

This function can be seen as the opposite of the previous discussed one, as it decreases the torque of the ICE, i.e. takes less torque from the ICE than is demanded by the driver, and uses torque from the EM instead. If once again consulting equation (3.4), it is understood that a lower torque of the ICE is represented by a higher torque from the EM. This function also relates to the ICE efficiency map, but works in another region compared to the ICE torque increase. In Figure 3.4, the ICE torque decrease line is shown. If the driver demands a torque above this line, the torque of the ICE is lowered to the value of the line. In this way, the inefficient operating points present in the top left corner of the ICE efficiency map can be avoided (though this engine has quite high efficiency there also). The equations are given in (3.7)

$$\tau_{\text{EM, ICE Torque Decrease}} = \begin{cases} \tau_{\text{ICE, max}} - \tau_{\text{ICE Torque Decrease}} & [Nm] \quad \text{for} \quad \tau_{\text{driver}} > \tau_{\text{ICE, max}} \\ \tau_{\text{driver}} - \tau_{\text{ICE Torque Decrease}} & [Nm] \quad \text{for} \quad \tau_{\text{ICE Torque Decrease}} < \tau_{\text{driver}} < \tau_{\text{ICE, max}} \\ 0 & [Nm] \quad \text{for} \quad \tau_{\text{driver}} < \tau_{\text{ICE Torque Decrease}} \end{cases} \tag{3.7}$$

where $\tau_{\text{ICE Torque Decrease}}$ [Nm] is the value of the ICE torque decrease line. If the driver demanded torque is below this line, it results in no torque decrease. In equation (3.7), the value of the ICE torque decrease is saturated in a way that it always stays positive (positive EM torque gives negative ICE torque). In contrast to the ICE torque increase, this function will give a lower fuel consumption when activated. Since the ICE efficiency map is non-linear, different amounts of fuel can be saved depending on the different working points. It is therefore important to do the ICE torque decrease when much fuel can be saved, with a little amount of electrical energy.

Regenerative Braking

This is perhaps the most important part of the HEV and its fuel consumption savings. The regenerative braking is enabled when the vehicle is braking. e.g. at traffic lights and downhill slopes. For a conventional vehicle, in braking situations the kinetic energy of the vehicle is disposed in the mechanical brakes at the wheels, converting the energy into waste heat. Instead of using the mechanical brakes, the HMS will use the EM to take up the energy and recharge the battery. The braking of the vehicle is represented by a negative torque demanded by the driver, and the equation for the regenerative braking is given in (3.8)

$$\tau_{\text{EM, Regenerative Braking}} = \begin{cases} \tau_{\text{driver}} & [Nm] \quad \text{for} \quad \tau_{\text{driver}} < 0 \\ 0 & [Nm] \quad \text{for} \quad \tau_{\text{driver}} > 0 \end{cases} \tag{3.8}$$

where $\tau_{\text{EM, Regenerative Braking}}$ [Nm] equals the negative driver demanded torque. If the driver demanded torque is positive, it results in no regenerative braking. Since this part is not concerned about the ICE efficiency, no figure is shown in this case.

Final EM torque computation
Each of the parts are limited such that they do not interfere with the other parts, and they are active in their region defined by the lines. Some parts might be active simultaneously, but it is guaranteed that their individual contributions are limited to their operational region. The result of adding these four features together is the EM torque of the TD, previously formulated in equation (3.4).

The tuning parameters of the rule-based TD are the lines of the ICE torque increase and the ICE torque decrease, and should be set to values giving a good control of the ICE efficiency. The EM boost and the regenerative braking will be active as previously discussed.

3.2.3 State of Charge Controller

Up till now, the discussion of the ICE torque increase and the ICE torque decrease has only been seen as a way to reach a better efficiency of the ICE. But the two features have a second purpose as well, as they will be the SoC controller of the rule-based strategy. Not only will they care about the efficiency of the ICE, but also about the SoC level of the battery. Consider the following two examples:

- If the SoC level is getting too low, the charge of the battery needs to be increased. The best thing would be to do it by regenerative braking, but it is not known when a situation like that will occur. To be sure not to deplete the battery, the ICE needs to be used to charge the battery. This is done by taking more torque from the ICE than the driver demands, and charge it into the battery. Therefore the ICE torque increase function is enabled, as it does exactly this thing.

- If the SoC instead is getting too high, it would be preferable to use the battery as much as possible, and the ICE as little as possible. Therefore the ICE torque decrease is enabled, and less torque is taken from the ICE, with the purpose to use the battery more and save fuel.

As realized from the example above, the ICE torque increase and the ICE torque decrease have two missions; one of them is to increase the efficiency of the ICE, and the other one is to keep control of the SoC level. It can be argued that the effect of the ICE torque increase/decrease should be stronger when the SoC is getting to its low and high extremes. Hence, the increase and decrease lines are stronger and more effectful in these cases, and the focus is set on controlling the SoC. If the SoC would actually reach its extremes, the increase and decrease are very strong to force the SoC away from these points, to prevent battery damage. In this case the efficiency of the ICE is disregarded, as saving the battery is more important. When the SoC is in a normal range (zone), not close to the low or high extremes, no actual control of the SoC is required and it is allowed to move freely. In this case the focus is set on the efficiency of the ICE.

3.3 Table-Based Hybrid Management Strategy

The second HMS follows the same layout as the rule-based strategy, as it also consists of the parts SML, TD, SoC controller and brake management, though they are implemented in another way (except the brake management). Some parts of the table-based strategy are implemented from the Dymola software into the Simulink environment, as they not yet existed. The strategy is mainly based on look-up tables, containing data from the ICE, EM and other important components of the vehicle. These tables are optimized by using the ECMS method, explained further down in the section about the TD. First the SoC controller is explained, then the TD and last the SML.

3.3.1 State of Charge controller

This HMS has a dedicated SoC controller, which objective is to control the SoC level in a predictive way, by adjusting the SoC of the battery to a specified level. The prediction is based on future recuperation possibilities, which become available when the velocity of the vehicle increases. A feedback controller, Proportional-Integral (PI) controller type, is implemented to track a certain set value, which changes throughout the route. Its implementation is shown in Figure 3.5.

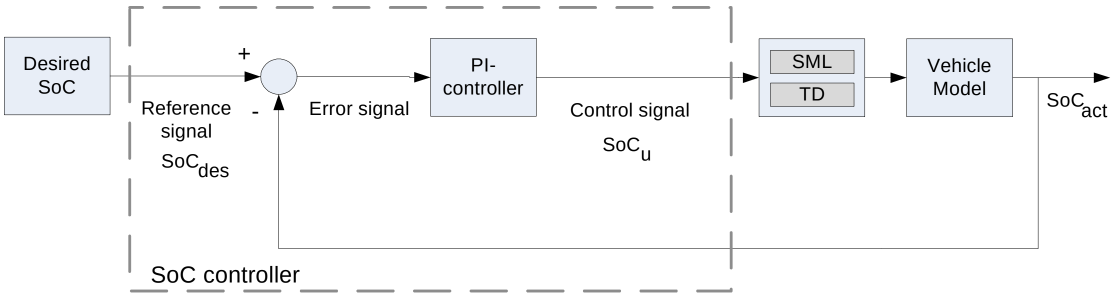


Figure 3.5: *SoC controller for the table-based strategy.*

The SoC_{des} should be followed without major oscillations, and should (eventually) be reached exactly, which implies that integral action is needed in the controller. The error signal is computed as $SoC_{\mathrm{des}} - SoC_{\mathrm{act}}$, and the control signal SoC_{u} is used as input to two tables in the SML and the TD. Since this control signal is used for both the SML and the TD, potential conflicts between them are avoided as the SoC is increased or decreased. A desired SoC level is set to a base value, e.g. 52%, which can be lowered as the velocity of the vehicle increases. The expression for the reference SoC, SoC_{des}, is given in (3.9)

$$SoC_{\mathrm{des}} = \beta - E_{\mathrm{k}} = \beta - \frac{m \cdot v^2}{2} \quad [\%] \tag{3.9}$$

where β is the base value expressed in [J], E_{k} [J] the kinetic energy, also fully expressed with the mass m [kg] and the velocity v [m/s]. The reason for the desired SoC to change, is that the kinetic energy of the vehicle increases with the velocity (squared), and this energy has a potential to be recuperated and converted to electric energy when braking, charging the battery. The desired SoC is lowered to increase the charging capacity of the battery for the regenerative braking, so that it does not overcharge. It is always better to use the energy in the battery than not be able to recuperate the available braking energy. Therefore, sometimes the EM will be used more at working points that will discharge the battery, even if it is not optimal from a TD point of view.

In [18], another kind of predictive strategy is used for simulations with an HEV. There the route of the vehicle is assumed to be known a priori, and a prediction is made of when to empty the battery, to assure sufficient absorbing capacity for the coming regenerative braking. This can be seen as a kind of extreme SoC controller, as it exactly knows when to lower the desired SoC to discharge the battery ahead of the decelerations. In real life, the route and the driving conditions are not known in advance, and therefore the predictive SoC controller based on kinetic energy used here is a good compromise, and has potential to lower the fuel consumption.

3.3.2 Torque Distribution

The torque distribution for the table-based strategy is based on the so called ECMS, which is a local optimization strategy considered to be relatively easy to realize. The variable subjected to the optimization is the fuel consumption, i.e. the fuel consumption is minimized. It is based on the fuel flow in the system, and is explained more below.

ECMS
The ECMS is an instantaneous minimization strategy, which means that it tries to optimize the fuel consumption at every time instance. The result is the optimal torque distribution between the ICE and the EM, which uses the minimum amount of fuel at each time instance. One could first think that only using the battery would lead to no consumption at all, and that it would be the best idea. However, the problem is that the battery will be depleted fast, and only the ICE can be used for further driving. Thus, in order not to deplete the battery at a fast rate, it has to be recharged during the drive, either by means of regenerative braking which does not consume any fuel, or by power supplied by the ICE, which does consume fuel. Since the charge sustaining behavior of the battery is a criteria, the EM will consume fuel in some sense, when it uses power from the ICE to recharge the battery. But, since the energy taken from the battery does not give an indication of how much fuel it is equivalent to, the fuel consumption from the two sources is not directly comparable. Therefore the energy taken from the battery will be converted to an equivalent amount of fuel, so that it can be compared to that of the ICE. The equation that will be used for the optimization describes the instantaneous total fuel flow in the system, $\dot{m}_{\mathrm{f}}^{\mathrm{tot}}(t)$, as in (3.10)

$$\dot{m}_{\mathrm{f}}^{\mathrm{tot}}(t) = \dot{m}_{\mathrm{f}}(\omega_{\mathrm{ICE}}(t), \tau_{\mathrm{ICE}}(t)) + \dot{m}_{\mathrm{f}}^{\mathrm{eq}}(\omega_{\mathrm{EM}}(t), \tau_{\mathrm{EM}}(t)) \quad [kg/s] \tag{3.10}$$

where $\dot{m}_{\mathrm{f}}$ is the ICE fuel flow and $\dot{m}_{\mathrm{f}}^{\mathrm{eq}}$ is the equivalent fuel flow, representing the energy taken from the battery. When doing the calculations for the EM's equivalent fuel consumption, the efficiencies of the components have to be taken into account. This is because some power will be lost, for example when using the ICE to charge the battery (converting from ICE to EM, EM to battery, battery to EM and finally EM to transmission's input shaft), instead of taking it directly to the transmission's input shaft. Since these efficiencies depend on future working points, which are unknown, they will be represented by mean values.

The ECMS is concluded in the following statement:

- Depending on the required speed and torque at a point in time, an optimal control signal is available which distributes the torque between the ICE and the EM in such a way that the total instantaneous fuel consumption is minimized.

The ECMS is computed off-line, and the values of the optimal control signal is stored in a table used in the on-line implementation.

Implementation of the ECMS

The values from the ECMS is used in a four dimensional table, to compute the torque split between the ICE and the EM, illustrated in the left of Figure 3.6. The inputs are the demanded torque by the driver, the speed of the transmission's input shaft, the actual SoC and the desired change of SoC coming from the SoC controller. The desired SoC change, SoC_{u}, gives an indication of the ICE torque increment that is necessary to reach the desired SoC. The output will be the desired torque of the ICE, τ_{ICE} [Nm], which is subtracted from the driver demand to make out the EM torque, τ_{EM} [Nm]. Both equations are shown in (3.11)

$$\begin{aligned} \tau_{\mathrm{ICE}} &= LUT_{\mathrm{output}}(\tau_{\mathrm{driver}}, \omega_{\mathrm{input}}, SOC_{\mathrm{act}}, SOC_{\mathrm{u}}) \quad [Nm] \\ \tau_{\mathrm{EM}} &= \tau_{\mathrm{driver}} - \tau_{\mathrm{ICE}} \quad [Nm] \end{aligned} \tag{3.11}$$

where LUT_{output} [Nm] is the output from the four dimensional table.

A surface plot describing the TD is shown in Figure 3.7, where the SoC inputs are fixed to a certain value. For every combination of speed and driver demanded torque τ_{driver}, there is a defined torque taken from the ICE, τ_{ICE}.

Though this strategy is computed in an optimal way, it does not necessarily mean that it will perform optimal under conditions other than those used for the optimization itself. The optimization is dependent on e.g. vehicle setup and estimated mean efficiency values, and if these conditions are changed, it will affect the strategy. The ECMS tables used for this work are computed in another software and its special optimization conditions will not be the same when it is simulated. This will of course affect the results, and should be kept in mind when doing the comparison.

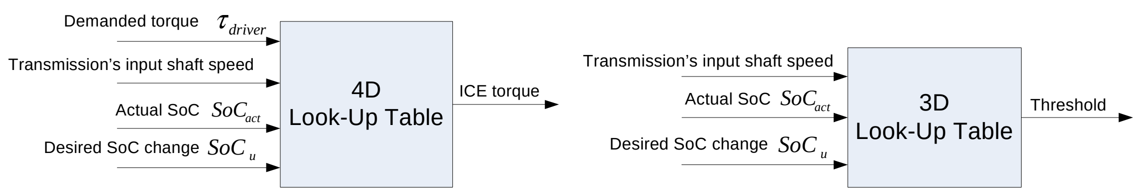


Figure 3.6: *The two tables used in the TD (left) and the SML (right) for the table-based strategy.*

3.3.3 Strategic Mode Logic

The principal part of the SML is a table, shown in the right of Figure 3.6. Its output is a threshold which will be compared to the driver demanded torque, and make a decision about the status of the ICE. The expression is shown in (3.12)

$$ICE\ Status = \begin{cases} on & \text{for} \quad \tau_{\mathrm{driver}} > \text{threshold} + \text{hysteresis} \\ off & \text{for} \quad \tau_{\mathrm{driver}} < \text{threshold - hysteresis} \end{cases} \tag{3.12}$$

where both time and amplitude hysteresis is added to avoid frequent toggling. The inputs to the table are the speed of the transmission's input shaft, the actual SoC and the desired change of SoC coming from the SoC controller. The three inputs will influence the decision in the following way:

- Input shaft speed: The characteristics of the components in the system are dependent on different input shaft speeds. At low ICE torques the fuel efficiency is low and Electric Drive will be desired instead of Hybrid Drive. This means that the fuel will be used in a more efficient way.
- Actual SoC: For a low actual SoC, the decision will be biased towards keeping the ICE turned on, and vice versa for a high actual SoC.
- Desired SoC change: If a positive change is desired from the SoC controller, the decision will be biased towards keeping the ICE turned on (recharging power is taken from the ICE to increase the SoC). On the other hand, if there is a negative change desired from the SoC controller, the decision will be biased towards turning off the ICE.

The surface plot in Figure 3.7 can be used to describe the SML as well. Here the highlighted red curve shows the threshold value when the ICE is turned on/off.

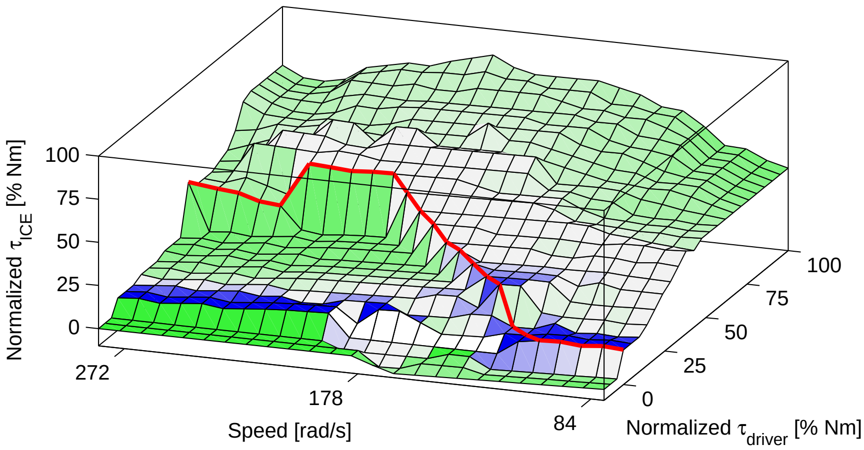


Figure 3.7: *Surface plot for the SML and the TD of the table-based strategy.*

3.4 A Global Optimal Control Strategy: Dynamic Programming

A commonly used approach in literature to find the global optimal HMS is dynamic programming, which is based on Richard Bellman's principle of optimality [12, 11, 8]. The control problem is stated as minimizing a cost function, such as fuel consumption, and dynamic programming is used to find the optimal way to use the ICE and the EM. The optimal strategy is obtained through recursive computation, where the equations are solved backwards in time. The final state of the system is used as a starting point for the algorithm, and the best way (out of all possible ways) to get to this state from the starting state is chosen as the optimal control law. For every instance in time many different control signals are plausible, but only one is optimal. Due to all these possible control signals which have to be calculated and evaluated, lots of computation effort is required. This long computation time is a great disadvantage of the global optimization approach and hence not applicable for real-time implementation in the vehicle. The other reason for its lack of implementation possibilities is that the route which the vehicle will drive needs to be known beforehand, to be able to make use of the recursive feature of the algorithm. This is not the case for normal driving, though research is being made that is using traffic and road information from GPSs.

Since this work is focused on the comparison between two realizable control strategies, the dynamic programming approach is not implemented.

3.5 Summary

In this chapter the concept of the HMS is explained, and the essential parts are described. An HMS's purpose is to use the power sources, ICE and EM, in a way that fulfills the demanded performance, and the HMSs are optimized against fuel consumption in this work. The parts in the HMS are the TD, SML, SoC controller and brake management. The TD is the part which decides the split of the torque between the ICE and the EM, and will be active when the vehicle is in the mode Hybrid Drive. The SML handles the switching of the modes in the vehicle, which can be any of the three *Electric Drive with ICE off*, *Electric Drive with ICE on* and *Hybrid Drive*. The SoC controller handles the charge level in the battery, to protect it from damage and optimize the performance.

The two HMSs which will be analyzed in this work are extensively discussed, and their implementations are given. The rule-based strategy has a more transparent configuration, which is based mainly on optimizing the operation of the ICE. The table-based strategy is on the other hand obtained through optimization, where the ECMS gives the tables which are used. In this strategy also an explicit SoC controller is implemented.

To get an overview of the two HMSs, a table of their features is shown in Table 3.1.

Table 3.1: *Overview of the HMSs.*

HMS	*Strategic Mode Logic*	*Torque Distribution*	*SoC controller*
Rule-based	Changes mode depending on the current torque demand in relation to e.g. the battery charge and allowed EM torque. The main part is a stateflow, which switches mode depending on the inputs.	Based on engineering intuition and component efficiencies. The TD is divided into different functions; ICE Torque Increase and Decrease, EM Boost and Regenerative Braking. The outputs are then summarized.	Included in the TD and the SML.
Table-based	Changes mode depending on the relation between the output from the look-up table and the driver demanded torque.	Look-up table based on ECMS optimization.	Explicit PI - controller which sends signals to the TD and the SML.

Chapter 4

The Simulation Environment

This chapter presents the simulation environment used in the work, like driver, driving cycles, etc. Some specific implementations and fixes in the simulation environment are discussed. In the end of the chapter is a summary part.

4.1 Simulation Environment

The software used for the simulations and the data analysis is MATLAB and its simulation tool Simulink. Some parts, for example the model of the vehicle, is build up in the Modelica language, and is only available in Dymola. These Dymola parts will be called on by Simulink, and are integrated in the Simulink environment.

The simulation environment at ZF is a big and complex system, with a large number of parameters and variables. This system has been developed in a way so that the step from simulations to real vehicle should go as smooth as possible. Therefore, many functions and features which are used in the simulation environment are very complex for simulation purposes, but are still implemented for an easier transition to the real vehicle. This sometimes caused difficulties when analyzing and extending the simulation environment, as the structure of the system was not completely known.

The system is constructed in the way shown in Figure 4.1, which can also be seen as a hierarchy of the decision making process. The part *Hybrid Management Strategy* has been discussed in the previous chapters, and consists of the two HMSs that will be analyzed. It is the highest level, where all requests should be allowed and there is no consideration of how it later will be realized. This is the part which will be implemented in the real vehicle. The outputs are sent to another part, considered as a "black-box" in this work since the functions in here are unknown, due to confidentiality reasons. Here, the requests from the HMS will be realized through operational signals, if it is allowed by the hardware. As this part was concealed, it sometimes created problems during the debugging, since it was unclear how the output from the black-box was computed. Finally the outputs are forwarded to the third part, containing the modeled vehicle.

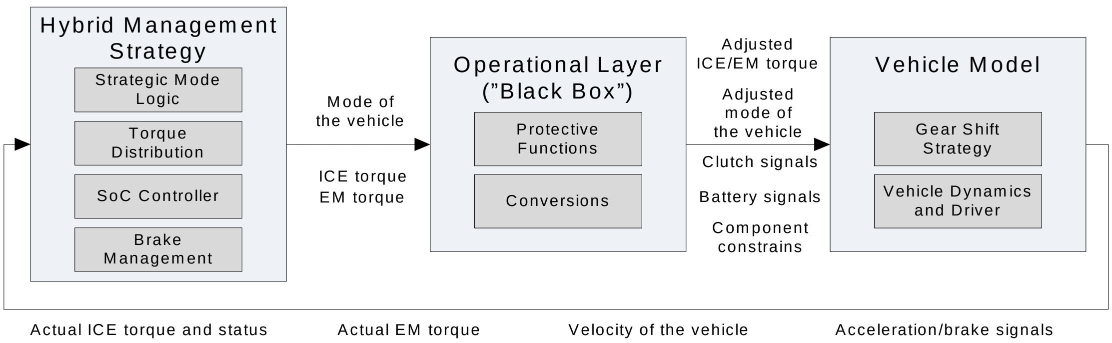


Figure 4.1: *The structure of the simulation environment at ZF, together with some important inputs and outputs.*

4.1.1 Implementations and Improvements

The simulation environment is extended, e.g. two gear shift strategies are implemented (more in Chapter 7). Improvements of the simulation environment are also implemented and two examples are discussed further down, the other ones are left out.

Avoiding Dead-Lock

During the simulations of the system, it is realized that the vehicle can easily get stuck in different states, like a kind of "dead-lock". This often results in that the vehicle is unable to provide power to the wheels, or shift gears, and the simulation crashes. The cause of this is that too many different state changes are requested by the system simultaneously, and it can not treat them all in a proper way. This has mainly to do with problems in the implementation of the operational layer and the interaction with the vehicle model. An example of a typical dead-lock is shown in Figure 4.2, where the vehicle mode and the gear shifts are shown.

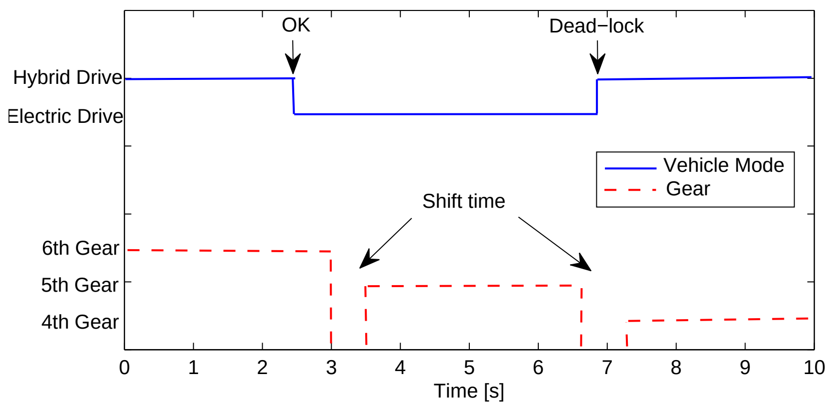


Figure 4.2: *A dead-lock situation which could occur in the system, if the mode of the vehicle was changed during a gear shift phase.*

For every gear shift, there is a certain shifting time which is necessary to engage the new gear. If a mode change would occur during this shifting time, it could result in a complete dead-lock of the system. Since the main focus is set on the Hybrid Management Strategy part, the solution is to make sure that the requested mode change is put on hold until the shift is completed. It can be thought of as a queuing system, where the requested state transitions are organized and only allowed when certain conditions are met. This might lead to a disadvantage for the HMS, if a requested mode is not allowed for some seconds.

Derating of the EM
The initial HMS had a part for limiting the negative torque requested by the EM, which purpose was to prevent negative torque on the transmission's input shaft at standstill. If that was not done, it could cause undesired negative acceleration for the vehicle, which should be avoided both for comfort and safety reasons. Also, another very important reason for limiting the negative EM torque is that it inflicts mathematical errors in the Dymola model, and as a result the simulation crashes.

The limitations of the EM torque is necessary, but should be used as seldom as possible, only close before and at standstill situations. One of the implemented improvements is that the EM torque is not limited if the acceleration is over a specified positive threshold, to make sure that the EM only is limited when the vehicle is going to a standstill. Previously, only the speed of the input shaft was considered, which did not take care of the positive acceleration. Another problem was that the TD calculated the different torques without any knowledge of when the EM was limited. This could lead to the following problem:

- The ICE torque is increased and the EM torque decreased, leading to a battery recharge. After this, the negative EM torque is derated, which results in an unnecessary increase of the ICE torque, since it would be equalized by the mechanical brakes, and not used for recharging the battery which was the intention.

After the fixes, this problem could no longer occur.

4.2 Vehicle

The simulated vehicle is a small delivery truck, similar to the one seen in Figure 4.3. Its components include, among others, an ICE, an EM, clutches, a battery, vehicle driveline and mechanical brakes. The dynamics of the vehicle and tires are also present, and parameters such as drag coefficient, mass and rolling resistance. The vehicle is not a fully electrical vehicle, meaning that it is not able to drive electrically when the ICE is turned off. Therefore the mode Electric Drive with ICE off can only be selected when the vehicle is at standstill, meaning that the electric driving is done in the mode Electric Drive with ICE on.

Figure 4.3: *Small delivery truck used for the simulations [15].*

4.3 Driving Cycles

In order to run the simulations for the vehicle, a predefined driving cycle is used. The cycle is specified by a desired velocity of the vehicle, for different points in time of the simulation. The cycle can be designed in a countless of ways, but should preferably represent a real driving pattern which is typical for the specific vehicle. A somewhat more synthetic cycle, with constant acceleration and deceleration parts, will also be used. This cycle is especially good to study the behavior of the vehicle, to easier find unwanted effects and faulty behavior, since it is easy to know the wanted behavior. The three driving cycles which the vehicle is tested on are shown in Figure 4.4.

In this work, one important aspect is to test the behavior of the HMSs on different cycles, since it is very easy to sub-optimize the HMS to perform well on one certain cycle. The more cycles that are tested, the more confident one can be about the performance of the HMS. Though, simulating many and long cycles is a tedious task, and the selection ultimately has to be limited to a few.

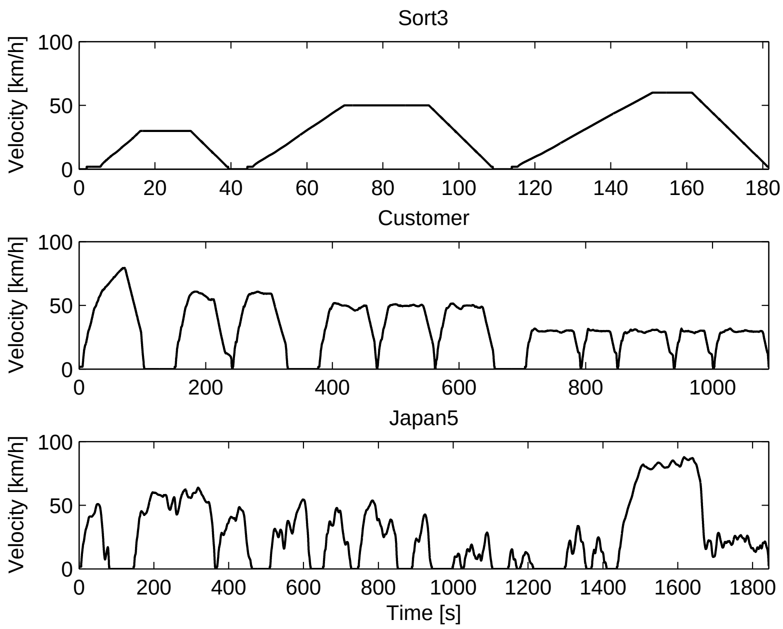


Figure 4.4: *Three cycles that are used in the simulations with the small delivery truck.*

4.4 Level of the State of Charge

An important remark considering the simulations is the charge of the battery, the SoC. In order to get comparable results from two different simulations, the SoC level for each of the simulations has to be well balanced. This means that the simulation should end with an SoC value that is close to the start value, i.e. it should have a small ΔSoC. This is formulated in (4.1).

$$|\Delta SoC| < \epsilon \tag{4.1}$$

where |ΔSoC| [% units] is the absolute value of the ΔSoC, and ϵ [-] is a threshold. The threshold should preferably be as small as possible. If the |ΔSoC| would be too large, the results of the fuel consumption could not be accurately studied. Consider the following example:

- Simulation 1 starts with SoC of 50%, and finishes with SoC of 60%. It has increased the SoC of 10%, which has increased the total fuel consumption, due to higher power from the ICE.
- Simulation 2 starts with SoC of 50%, and finishes with SoC of 40%. It has decreased the SoC of 10%, which has decreased the total fuel consumption, due to lower power from the ICE.

If the fuel consumption of the simulations were to be compared, it would give misleading results. The first simulation would have a disadvantage of its increased SoC level, and the second simulation would have an advantage of its decreased SoC level. If there was a linear relation between the fuel consumption and the ΔSoC, a balanced SoC would not have been as crucial. In that case, a factor x could be used to "scale" the actual fuel consumption, taking the ΔSoC into account. But, since there is no linear dependency of the two variables, i.e. the factor x does not exist, a balanced SoC is very important for the analysis.

In order to minimize the ΔSoC, an algorithm has been developed to compute an optimal start SoC, which tries to minimize the $|\Delta\text{SoC}|$ in (4.1). Since the main part of the analysis will be to compare the fuel consumption from different simulations, the fuel consumption itself will be used as an important variable in the algorithm. Some criteria for the algorithm are shown below, and the algorithm is schematically presented as a flowchart in Figure 4.5.

- A maximum of 15 simulations will be run (though for the simulations done in this work, a balanced SoC was found before 15 simulations).
- Two simulations, one with a positive ΔSoC and one with a negative ΔSoC, should occur.
- If the fuel consumption for the last iteration is only differing slightly compared to the best value up until "now" (which is given from the best ΔSoC), a good start SoC was found.

In the algorithm, several simulations are iterated. For every simulation, it is checked if the criteria for a balanced SoC level is reached, otherwise it continues to iterate (maximum 15 times). A new start SoC is computed after every iteration and used as a start SoC for the next iteration, with the aim of giving a more balanced SoC level. The result of the algorithm will be the best start SoC, and the most accurate value of the fuel consumption (interpolated between the two best iterations) used for the comparison. The algorithm is explained further in Appendix A.

4.5 Driver Model

One important aspect which has to be considered is how the vehicle will respond to the demand from the driver. The additional components in the HEV powertrain will give the vehicle further possibilities to react on the driver's demand, though, since the driver is used to a conventional vehicle, the response should be similar for the HEV. This is important for safety reason, but also for comfort. The features that the driver expects

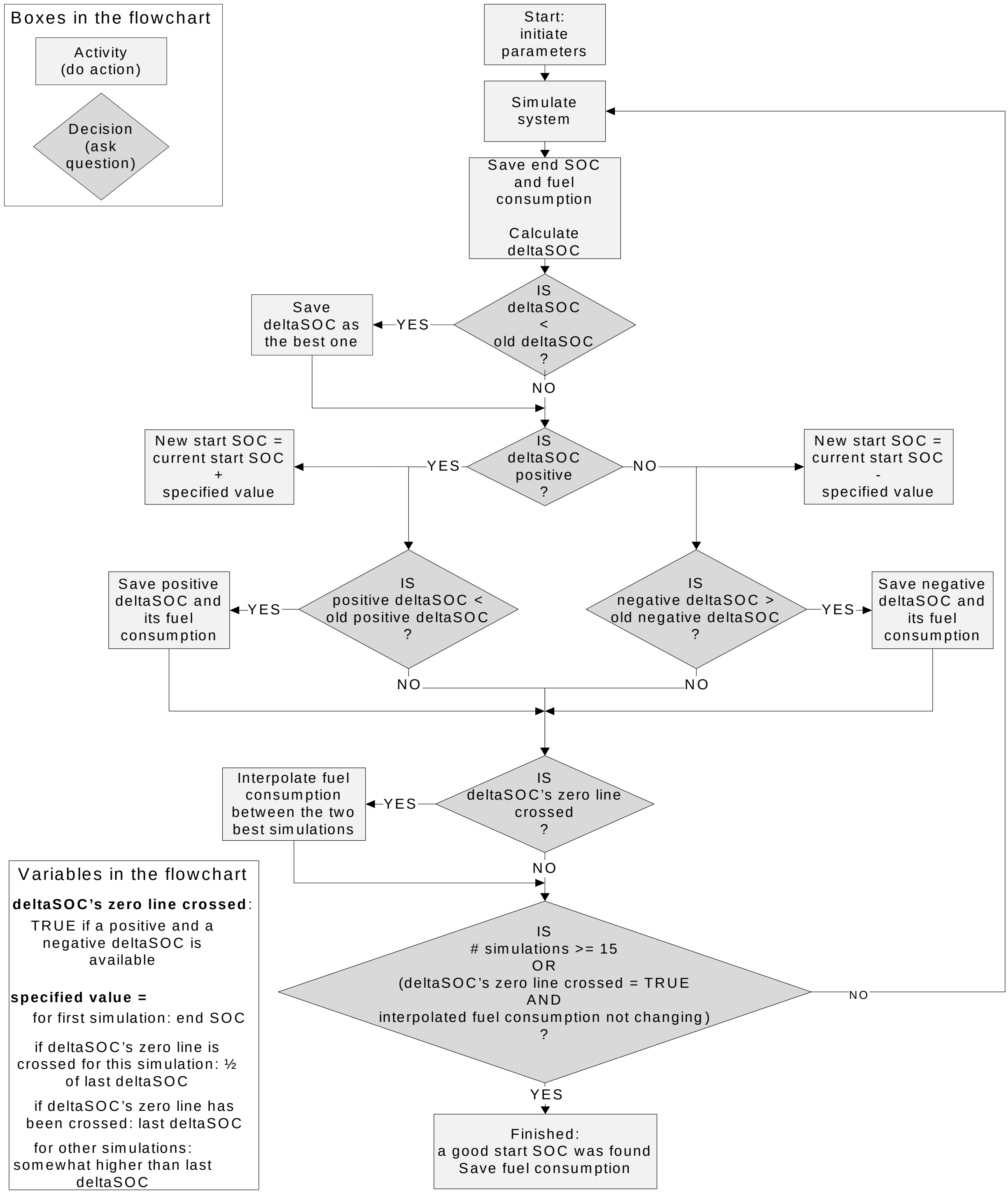


Figure 4.5: *Algorithm to balance the SoC level, presented as a flowchart.*

are primarily the vehicle response from the acceleration and brake pedals.

When pressing the accelerator pedal, a positive torque should accelerate the vehicle, and if the accelerator pedal is released, a low negative torque should be the result. The torque should be specified for a certain angle of the accelerator pedal, when pressed, and an ICE angular speed. It is similar when releasing the accelerator pedal; the negative torque should be the same for a certain pedal angle and an ICE angular speed.

The response from the vehicle, when the brake pedal is pressed down, should be fast and predictable for the driver. To make the HEV work in a predictable way, an angle on the brake pedal should affect the vehicle with a particular negative force, which is similar to a negative torque on the transmission's output shaft.

In the real vehicle, used for testing, the EM torque is only connected to the accelerator pedal, because of the actual configuration. The simulation model is therefore implemented in the same manner. When the accelerator pedal is pressed, a positive EM torque can be used by itself, or in combination with the ICE, to fulfill the demanded torque. A negative torque from the EM, which occurs when releasing the accelerator pedal, will be interpreted as engine brake by the driver. The difference between the engine brake for the HEV in the simulations, and a real conventional vehicle, is the force of the engine brake.

A conventional vehicle can only brake with the ICE, but the HEV can also use the maximum negative torque of the EM. The brake pedal in the HEV model has no major differences to that in a conventional vehicle; all negative force from the brake pedal is performed by the mechanical brakes.

The driver implemented in the model will only use the mechanical brakes if the engine brake, with the ICE and the EM, can not fulfill all the braking force. In this way the maximum energy is recuperated. Situations which need the mechanical brakes occur, in electric driving, when the negative demanded torque is below the minimum allowed EM torque, or when the battery is fully charged. In hybrid driving it occurs when the negative demanded torque is below the minimum allowed EM + ICE torque. The reason for this implementation is that the real vehicle has a mechanical connection between the brake pedal and mechanical brakes, just like in a conventional vehicle.

As mentioned above, it is important that the HEV behaves in a predictable way. Therefore, changes in the SoC should not influence how the vehicle responds to the driver's demand. A typical example is the EM boosting functionality. It requires energy from the battery, but when the SoC is too low, the EM boosting is not available anymore. This might be dangerous if the driver does not get the expected power, e.g. in an overtaking situation. A similar problem occurs when braking with negative EM torque; if the SoC is too high, indicating a full battery, the EM braking is not available. To solve the problem with the EM boost complication, it can be chosen to only allow torques up to the maximum ICE torque, to make sure that it is always possible to fulfill the driver demand regardless of the SoC. If it is chosen to allow higher torques than the maximum ICE torque, which is the case for the simulated vehicle, it can be advantageous to keep the SoC at a high level, so that the EM boost functionality always can be used. Also, the highest torque possible should not be too high, so that the EM boost will discharge the battery fast.

To solve the problem with an unexpected behavior, when the driver requests a negative torque, a brake management system should be implemented. When the driver wants to brake and presses down the brake pedal, a brake management should analyze if this can be accomplished with the EM, or if also the mechanical brakes are needed. The brake management should make sure that the driver gets the negative torque he expects and at the same time minimize the use of the mechanical brakes.

4.6 Driver Implementation

A part of the simulation environment is the artificial driver, which is intended to resemble the driving style of a real driver. The purpose of the driver is to track the desired velocity of the vehicle for every time instance, as predefined in the cycle previously discussed. This is done by adjusting the accelerator and brake pedal. The modeled driver is implemented with a PI-controller, seen in Figure 4.6.

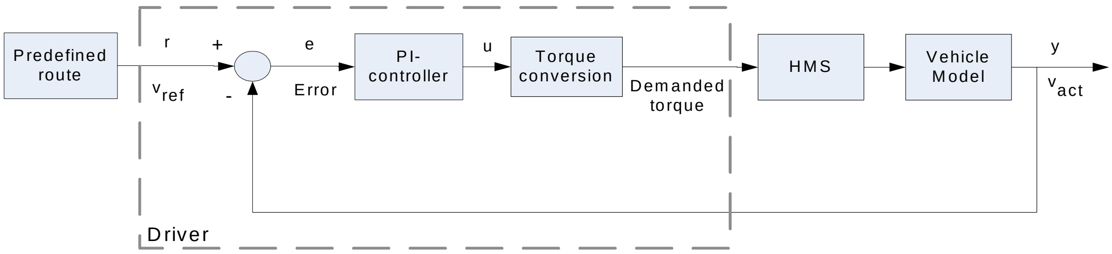


Figure 4.6: *Basic parts of the artificial driver used in the simulations.*

The controller takes the desired velocity from the predefined driving pattern as a reference signal, and subtracts the actual velocity from the vehicle model. This results in the error signal, e, also given in (4.2)

$$e = desired\ velocity - actual\ velocity \tag{4.2}$$

The error signal is sent to the PI-controller and then converted to a torque, which makes out the requested torque by the driver, at the transmission's input shaft. This torque is used as an input signal to the HMS and the vehicle model, which finally sends out the actual velocity of the vehicle. The proportional and the integral gain in the driver had to be tuned, making it follow the desired trajectory in a good way.

There is mainly one difference observed in behavior compared to that of a real driver. It has to do with the gear shifting, especially for accelerations. When shifting a gear, the driver shows a large increase in requested torque, which probably would not occur for a real driver. The reason for this is because the clutch is disengaged during a gear shift, and there is no torque on the driveline propelling the vehicle at that moment. The driver reacts on this loss of velocity, and increases its demanded torque. This would not be the case for a real driver, since it is accepted to loose some speed when shifting the gear, and the real driver would not react on this.

Since the driver will not be able to follow the cycle perfectly and its behavior is dependent on the behavior of the system, it will affect the simulations differently. Therefore, it is important to make the driver follow the cycle well, so that it does not influence the analysis to a great extent.

4.7 Benchmark Model

In order to understand the benefits of the HEV more clearly, and relate it to somewhat "common facts", a conventional vehicle will be used as a benchmark model. It is created by changing the settings in the model of the HEV. The conventional vehicle will not use the EM, and the ICE is the only power source. Since the ICE always needs to be on give the torque demanded by the driver, the SML and the TD are not necessary, and will therefore be disabled. Thus, it will be possible to do an absolute comparison of the two HMSs, where the conventional vehicle works as a base. The analysis will be more clear, if a comparison is made to a more "familiar" type of vehicle.

4.8 Summary

In this chapter the structure of the simulation environment is given. It is implemented in Simulink, except for parts of the vehicle model which uses Dymola. Some implementations are given which have to be done to be able to simulate the vehicle. Also two important improvements are discussed, where the first one avoids dead-lock situations. The second one is the limiting of the negative EM torque when coming close to standstills, in order to avoid discomfort for the driver and simulations to crash.

The type of vehicle which is simulated is a delivery truck, and can only turn off the ICE at standstill. Therefore, the potential fuel savings of driving electrically are not as high compared to if the ICE could be turned off during driving. The driving cycles which the vehicle will be simulated on are given. To compare the fuel consumption between different configurations, an algorithm is implemented. The algorithm tries to balance the start and the end SoC for every simulation, to not let the difference in SoC influence the fuel consumption results.

The vehicle should behave in a predictable way for the driver, which is important both for safety and comfort reasons. The vehicle response on the acceleration and brake pedal should not be dependent on factors outside the driver's knowledge. The HEV should respond similarly to the driver demand, as in a conventional vehicle, since the driver is used to a conventional vehicle. The implementation of the driver is mainly a PI-controller, which tracks the velocity profile available in the cycle information data.

A conventional vehicle has been implemented, which only uses the ICE as a power source. This is done to make the comparison easier between the two HMSs, because the conventional can be used as a benchmark.

Chapter 5

Simulation with Rectified Layout

In this chapter the delivery truck is simulated with the two HMSs on different cycles, and the results are studied. Firstly the original rule-based strategy is analyzed, in order to see how it is performing, and possible improvements are implemented. Both the SML and the TD are tuned to give the rule-based strategy a good performance. Secondly the improved rule-based strategy is compared to the table-based strategy, and the result is discussed. The chapter ends with a summary part.

5.1 Improving the Original Rule-Based Strategy

The specifications for the vehicle used in the first simulations are given in Table 5.1. It represents a rather large battery and a fully loaded truck.

Table 5.1: *Vehicle specifications for the first simulations.*

Li-Ion Battery	Capacity: 27 Ah
Vehicle	Total mass: 7100 kg
Hybridization	Electric Drive with ICE on and Hybrid Drive
Gear shift logic	Speed-based

When the original set up of the rule-based strategy is simulated, some unwanted effects are observed, which need to be treated. The two most important are listed below, together with their respective solutions.

5.1.1 Calculation Error when ICE Torque Decrease and EM Boost Occurred Simultaneously

Problem
As explained in Section 3.2.2, the TD has four functions that computes a part of the EM torque, which are then added together resulting in the total EM torque. Since the outputs from these four functions are added, it is important that they do not interfere with each other, as by doing so will ruin the purpose of the separate functions. It is discovered that the two functions *EM Boost* and *ICE Torque Decrease* interfere with each other, when the driver demands a torque over the maximum torque of the ICE. In the left part of Figure 5.1, a working point is specified above the maximum torque line. Since the ICE can not provide this torque, the EM Boost function will decrease the working point to the τ_{max} line. If the ICE Torque Decrease function is enabled simultaneously, it lowers the working point to the specified ICE Torque Decrease line. The sum of these

two results in a working point which is too low, and not the one intended by the ICE Torque Decrease.

Solution

This is solved by limiting the effective region of the ICE Torque Decrease, to torques lower than τ_{max} only, hence making sure that they do not occur at the same time. The result is shown in the right part of Figure 5.1.

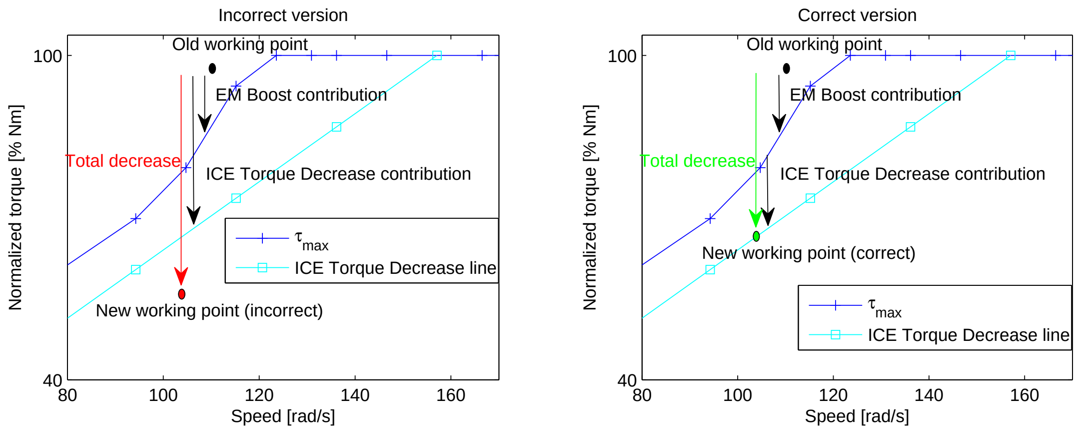


Figure 5.1: *The incorrect version of the EM Boost and the ICE Torque Decrease interaction (left), and the correct version (right).*

5.1.2 State of Charge Controllers Synchronization Issues

Problem

The TD has one system for controlling the SoC, and the SML another one. This means that these two parts can have different opinions of how the SoC should be affected. The SML calculates how many seconds the EM can provide the demanded torque, if kept constant, until the battery would reach its lower allowed limit. This time is then compared with different thresholds, responsible for the transitions between the different vehicle modes. On the other hand, the TD operates differently depending on the actual SoC level. It can be seen as the SML uses a more adapting calculation method, depending on the demanded torque, while the TD uses fixed values. The problem with this different SoC interpretation is that the SML can request electric driving at very low SoC values. Then, when a transition to hybrid driving occurs, the TD observes that the SoC is too low and forces a recharge to protect the battery. This kind of rapid recharge will influence the fuel consumption negatively.

Solution

Several approaches were tested, where some gave worse results and others were too complex for the implementation. The final solution implemented is to let the SML calculate the time until the SoC would go below a higher threshold than the lower allowed SoC-level. This higher threshold is then synchronized with what the TD recognizes as an “undesired region”, i.e. too close to the not allowed working range of the battery. In this way the unnecessary fast recharge behavior, which can occur when switching from electrical driving to hybrid driving, is avoided.

Synchronization for the high SoC level is also implemented, since it seems reasonable to avoid fast discharges, at low ICE efficiencies.

Following these initial changes, is the tuning of the SML and the TD.

5.1.3 Tuning the Strategic Mode Logic

After the synchronization between the thresholds for the SoC levels in the SML and the TD, the time-thresholds in the SML are modified. These times are changed in different directions, shorter and longer, but no pattern in the fuel consumption is seen. As a result, the best values from all the tests are taken. Preferably, all regions with low efficiency for the ICE should be driven electrically. This is not something unreasonable, since these regions are at low torques, meaning that the EM should be able to fulfill these torque demands. Though, due to different transitions, hysteresis and low SoC levels, the ICE still needs to work in these regions.

5.1.4 Tuning the Torque Distribution

This task consists of deciding the degree of the ICE torque increase and decrease, which means setting the ICE torque increase and decrease lines in Figure 3.4 at good positions. In this section a trial and error approach is done, and in Section 6.4.2, a more mathematical approach is carried out to decide the lines.

"Engineering intuition" as well as analysis of component efficiencies are used to decide test levels for the increase and decrease lines, similar to [11]. To isolate the effects of the two features, this analysis is divided into two separate parts, one for the ICE torque increase and one for the ICE torque decrease.

Tuning the ICE Torque Increase
Six different combinations of ICE torque increase lines are set up in a way that represents their degree of ICE torque increase. It ranges from low, no ICE torque increase, to high, ICE torque increase to the OEL. The values are selected by studying the ICE efficiency map in combination with the ICE fuel consumption, Figure 2.3, trying to find a good compromise between efficiency and fuel consumption. If the efficiency of the ICE can be increased much, with only little increase in fuel consumption, it might be advantageous to do the ICE torque increase. But if an increase in the ICE efficiency means that much more fuel will be used, probably it is not worth doing it. Hence the lowest efficiencies, present at low torques, can be avoided by using the ICE torque increase. A high increase in efficiency with a low increase in fuel consumption can be achieved. Clearly a trade off has to be made between increasing the efficiency of the ICE, and momentarily decreasing the fuel consumption.

What should not be forgotten when tuning the ICE torque increase is the efficiency of the other parts of the vehicle, e.g. the battery, the transmission and the EM. The EM will affect the possibility to recharge the battery, and how efficiently the stored electric energy is used. In Figure 2.4 it is seen that the efficiency of the EM is quite low for low torques. This means that small torques supplied to the EM results in a recharge at a low efficiency, which is not preferable, as much of the recharge energy is lost. A contradiction between the ICE torque increase and the EM's efficiency is therefore present; a small increase of the ICE torque, at low torques, is desired, but the EM efficiency would be higher with a larger increase.

The different ICE torque increase lines are simulated on two cycles, Customer and Japan5, and the results showing the fuel consumption as a function of the degree of ICE torque increase are given in Table 5.2.

Table 5.2: *Fuel consumption results as a function of the degree of ICE torque increase for two cycles, expressed relative to the base value of 100% set for zero ICE torque increase.*

Degree of torque increase	*Customer*	*Japan5*
Low (no increase)	100 %	100 %
.	100.1 %	99.9 %
.	100.1 %	99.9 %
.	100.2 %	99.9 %
.	100.1 %	99.9 %
.	100.5 %	100.1 %
High (OEL)	103.4 %	102.2 %
A second approach		
Close to OEL	100.5 %	101.4 %

It is seen that, for both cycles, the fuel consumption fluctuates marginally as the degree of ICE torque increase is set higher. When interpreting the simulation results, mainly three reasons for this are found.

1. **Because of the SML:** The SML often switches from hybrid driving to electrical driving when the demanded torque from the driver is low. This means that the TD becomes disabled in the low efficiency regions, as the electrical driving is active. Hence, many of the low efficiency operating points, present at low torques for the ICE, are removed by the SML rather than the TD. This can effectively be shown from a simulation result on the Japan5 cycle. In Figure 5.2, the operating points of the EM in electrical driving are plotted on the efficiency map of the ICE. This is to show what operating points are avoided for the ICE, and performed by the EM in electrical driving. As seen, the operating points of the EM are mainly in the low efficiency area of the ICE. For this simulation, about 44% of the torques below 28 [% Nm] are supplied by the EM in electric driving, thus helping the ICE to avoid these working points.

2. **Efficiencies in the electric system:** The result can also be due to a low efficiency of the electric system. Since an ICE torque increase will charge the battery, there are many power losses from all the conversions (ICE to EM, EM to battery, battery to EM and finally EM to transmission's input shaft). It can result in that not enough energy is saved in the battery, making the ICE torque increase useless.

3. **Characteristics of the ICE:** The similarity in result between different increase lines can be connected to the efficiency characteristics of the ICE, Figure 2.3(a). The potential improvement of this ICE, when using it in an HEV compared to a conventional vehicle, is not that large. This is due to the slow change and small difference in the efficiency for this engine. Small changes in torque do not give big changes in efficiency, and the ICE does not have many bad operating points, but rather many good operating points. As a result, in most operating points of the ICE, similar efficiency is achieved, meaning that recharging the battery, with all its power losses, is not beneficial.

Thus, in a fuel consumption perspective, small benefits are seen from having an ICE torque increase, which increases the efficiency of the ICE and charges the battery. Due to these effects, it is not motivated to have any ICE torque increase, and this feature is disabled for now. The ICE torque increase line in Figure 3.4 can therefore be removed, which reduces the complexity of the TD, and makes it more transparent. Recharge by increasing the ICE torque will only occur when the SoC reaches a very low value, and is done only to increase the SoC, not for efficiency reasons. In [11] similar results are obtained when using dynamic programming for a similar type of vehicle, as using the ICE torque increase functionality only marginally improves the overall efficiency of the system.

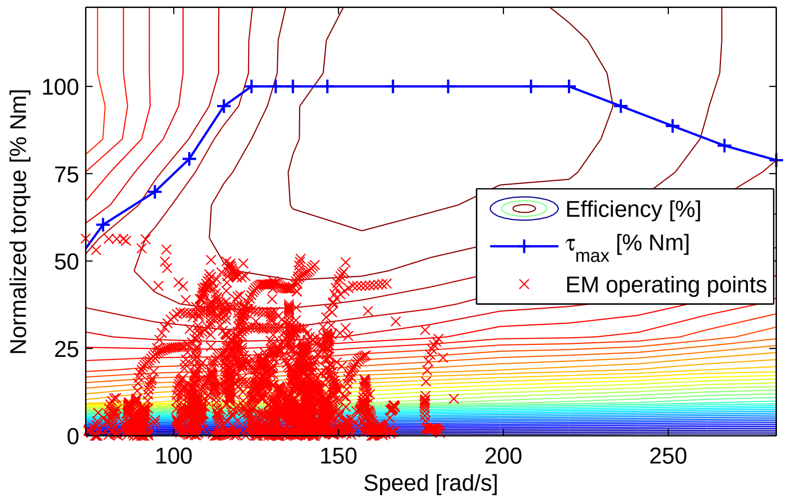


Figure 5.2: *Operating points of the EM, shown on the ICE efficiency map for the Japan5 cycle.*

A Second ICE Torque Increase Approach

Another idea of using the TD is to focus on when it is best to charge the battery, i.e. to increase the SoC by doing an ICE torque increase. It would be best when the ICE efficiency is as high as possible, to overcome most of the conversion losses in the electric system [17]. Therefore, an approach of increasing the ICE torque to the OEL line is tested, since this is where the efficiency is the highest. When doing this, the EM efficiency map must also be considered, so that the EM is working in an efficient region. A region of the transmission's input shaft speed, 135 - 235 rad/s, is selected for the tests, since this is considered sufficient as the vehicle mostly is driven at these speeds. Then some different degrees of ICE torque increase are specified to be used. Shown in the last row of Table 5.2, is one selected degree and its fuel consumption. Similarly to the other results, it only changes (increased) the fuel consumption marginally, and therefore it is decided not to use this functionality for now.

Tuning the ICE Torque Decrease

A similar approach is taken when the ICE torque decrease line is found. Simulations with different degrees of ICE torque decrease are run and studied, ranging from no ICE torque decrease to an ICE torque decrease down to 28 [% Nm]. It is seen that the effect of the ICE torque decrease is depending on the SoC. When the SoC is within a "normal" range, e.g. 44% to 56%, the best results are obtained when the ICE torque decrease is disabled. But as the SoC increases, the results improve when the line is set to that of the OEL, i.e. the line describing the optimal ICE operating points (Figure 3.4). All torques between the maximum torque line and the OEL line are decreased to the OEL line. When no ICE torque decrease is used, the SoC gets very high and reaches its extreme limit, which affects the result negatively. If the ICE torque decrease is set lower than the OEL, no improvements are seen. And since decreasing below the OEL line would mean decreasing the ICE efficiency, the result seemes reasonable.

A very important reason to have an ICE torque decrease, which lowers the SoC, has to do with the regenerative braking functionality. If the SoC reaches its high limit, regenerative braking is not possible anymore, and this energy would be lost in the mechanical brakes. Therefore it is always better to use the battery so that regenerative braking is possible, even if the energy is not used optimally, compared to having a too high SoC such that regenerative braking is no longer possible. It is decided to enable the ICE torque decrease only when the SoC level is high, and the ICE torque decrease line is set to that of the OEL.

5.2 Comparison of the Rule-Based Strategy and the Table-Based Strategy

After these modifications, the rule-based strategy is considered to be working well, and a first comparison of the HMSs can be made. In Figure 5.3 some different data for a (balanced SoC) simulation with the two HMSs are shown, and explained shortly further down. The data is expressed as a function of position [m] instead of time [s], for comparison reason. Depending on how the HMS choses to perform the cycle, the simulation time varies slightly, and therefore the simulated vehicles are not at the same position at the same time. It is preferable to use the position of the vehicle, since it will make the simulations comparable on a cycle, even if they drive at different velocities. In the fifth subplot, the desired cycle is shown. It should be noted that the actual cycle for both strategies follow the desired cycle with only small deviations, but to keep the figure distinguishable, these are not plotted.

In the first subplot, the SoC of the table-based strategy is kept close to its desired value, which is set to 52%. This is due to its SoC controller, which tracks the set value when the vehicle is driving. The desired SoC is never changed, and stays at 52% throughout the whole cycle due to the large battery. The kinetic energy of the vehicle has the potential to lower the desired SoC for high velocities, to make room for recuperation energy. Though, this energy is much smaller than the energy in the large battery, hence it will not affect the desired level. For the rule-based strategy, there is no strict control over the SoC, and it varies around 43% for this cycle. The extreme limits are not reached at any point for either one of the strategies.

For the braking sequences (e.g. at 1400 m and 2400 m), the negative EM torque in the third subplot indicates that regenerative braking is active and manages to charge the battery, increasing the SoC. For the accelerations (e.g. at 1500 m and 2500 m) the ICE torque in the second subplot is higher for the rule-based strategy, since it only uses the EM for boosting, compared to the table-based strategy which takes much more torque from the EM. This extra EM torque is mainly due to the SoC controller, which will result in a discharge of the battery in an efficient way. The discharge during accelerations can be explained by the following:

- After a regenerative braking situation, the SoC will often become higher than the desired value of 52%, and an EM torque increment is signaled by the SoC controller for the coming acceleration. This may not be completely optimal regarding the fuel consumption, to discharge during the acceleration, but is the “price” one has to pay for having a good control of the SoC at all points.

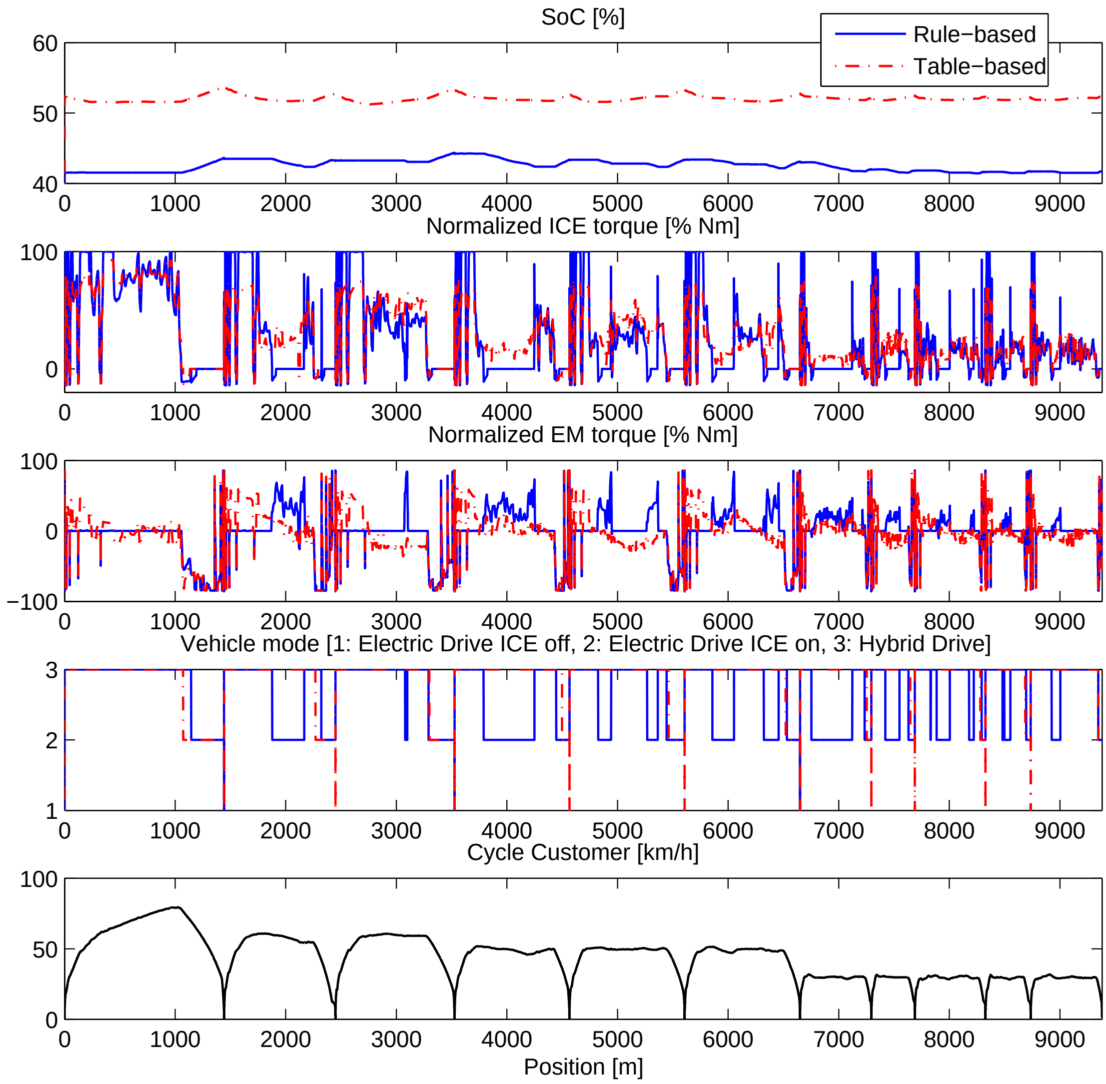


Figure 5.3: *Simulation results for the rule-based strategy (solid blue) and the table-based strategy (dash-dot red), showing the SoC, ICE torque, EM torque, vehicle mode and cycle.*

At e.g. 3000 m the table-based strategy increases the torque from the ICE and charges the battery, which is understood by the negative EM torque. The reason for this is also the combination of the SoC controller (actual SoC lower than desired SoC) and the efficiencies of the components. The alternating ICE torque increase and decrease is the typical behavior of the table-based strategy, which rarely happens for the rule-based strategy. This leads to much more usage of the battery, constantly charging and discharging, and the energy flow in the battery is about two times that of the rule-based strategy. This can also be seen when studying the energy flow in the battery for the two strategies, as shown for the Japan5 cycle in Figure 5.4.

For the plateaus with close to constant velocities (e.g. at 4000 m and 7000 m) the SML in the rule-based strategy choses the mode Electric Drive with ICE on due to the low power demand from the driver. The ICE will be decoupled, providing no torque, and instead the EM will propel the vehicle and the SoC will decrease. Both strategies are able to turn off the engine at the longer standstills (1500 m, 3500 m and 6600 m), and the rule-based strategy also turns it off for a short duration at the shorter standstills (e.g. at 8250 m 8750 m). Since these standstills are very short, around 2 seconds, it will not affect the fuel consumption comparison to a great extent.

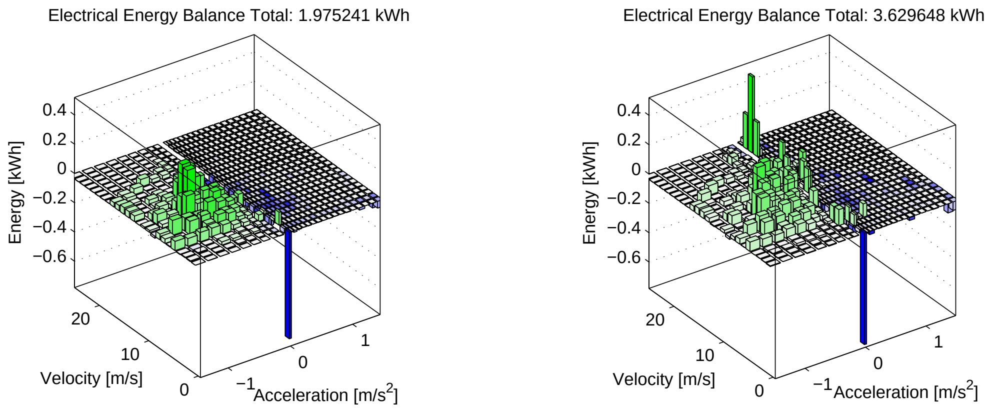


Figure 5.4: *The energy flow in the battery for the rule-based strategy (left) and the table-based strategy (right). Green boxes indicate recharging and blue boxes discharging.*

The fuel consumption for the three cycles are listed in Table 5.3. Both strategies manage to outperform the conventional vehicle on all cycles, by 11% on the average. Moreover, their individual fuel consumption does not differ significantly, but there is small advantage of the rule-based strategy on all three cycles. Even though the strategies show a quite different behavior regarding their SML and TD, the effect on the fuel consumption is small.

Table 5.3: *Fuel consumption results for the two HMSs for three different cycles, expressed relative to the base value of 100% set for the conventional vehicle.*

HMS	*Sort3*	*Customer*	*Japan5*
Conventional Vehicle	100 %	100 %	100 %
Rule-based	86.0 %	88.1 %	89.4 %
Table-based	86.7 %	88.9 %	90.0 %

The potential for improving the fuel consumption in a conventional vehicle, by making it into a HEV, depends on several factors, like the ICE, the EM, vehicle mass, cycles etc. With this heavy vehicle the driver will frequently demand the maximum torque from the ICE, which will then work on its maximum allowed torque, where the efficiency is high, see Figure 2.3(a). Because of this, the potential for increasing the efficiency is low, which means that moving the working point to the OEL will not increase the efficiency significantly.

Another factor that influences the fuel saving possibility for an HEV is the simulated cycle. Both HMSs turn off the engine at standstill situations, while a conventional vehicle lets the engine run on idle speed. Therefore cycles with many standstills will be beneficial for an HEV.

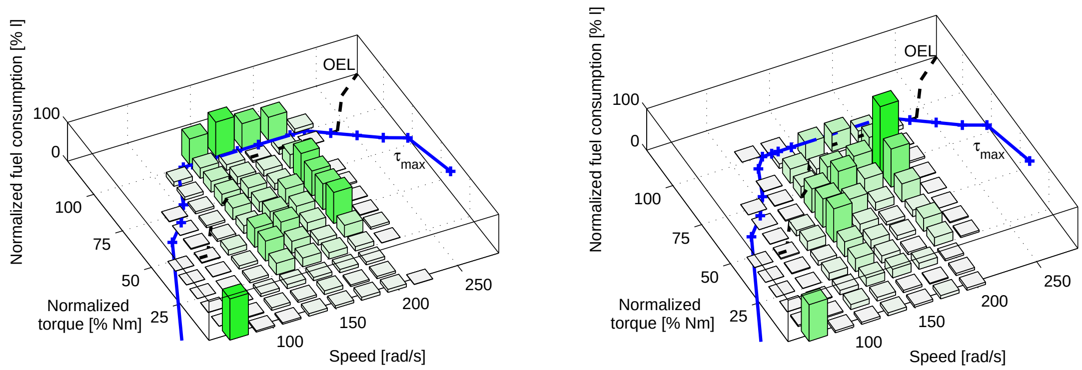


Figure 5.5: *Operating points of the ICE, where the height of the boxes represents fuel consumption. The rule-based strategy (left) and the table-based strategy (right).*

To get a better idea about the operation of the ICE, which is an important component, the operating points are plotted on its efficiency map. This is shown in Figure 5.5 for the rule-based strategy and the table-based strategy, both on the Japan5 cycle. The operating points are represented by histogram boxes, and their height is the fuel consumption. In this way it can be determined where most of the fuel is consumed, i.e. what working points consume most fuel. The fuel consumption is normalized to a fixed fuel consumption value, and this kind of normalization is used for all fuel consumption axes in the following plots. Also shown is the OEL line of the ICE. When looking at the figures, it is seen that the rule-based strategy has four high boxes at the maximum torque line, which happens during the accelerations. These are not present for the table-based strategy, since it choses to decrease the ICE torque and assist with the EM instead. There are also more operating points at the lower torques for the rule-based strategy, around the speeds 150 - 200 rad/s. One can say that there is a tendency of the table-based strategy, to move the highest torques down, and the lower torques up, to focus them around the OEL line. Though, this does not necessarily mean that it is always good to concentrate the operating points around the OEL, which is explained by the following:

- **Move the highest torques down:** The operating points at the highest torque, which are present for the rule-based strategy, are performed at a high efficiency, close to the optimal. To move these further down, below the OEL line, like the table-based strategy does sometimes, will result in a lower efficiency which is not preferred.

- **Move lower torques up:** To move the lower torques closer to the OEL will increase the efficiency of the ICE, but the question is how much improvement it will give, compared to the extra fuel it costs. Many of the moved points were already at high efficiencies, thus only giving a small improvement in efficiency of the ICE. Also, increasing the torque will give a larger power flow over the battery, and the absolute losses will increase.

These effects can explain why the rule-based strategy, with less energy flow through the battery, actually gets a somewhat lower fuel consumption on the simulated cycles.

Also the fact that the rule-based strategy drives more electrically can reduce the fuel consumption.

5.3 Summary

This chapter first focuses on improving the original rule-based strategy, where two problems are addressed. The first one is a calculation error between the ICE torque decrease and the EM Boost, which occurred when they both were enabled at the same time. This is managed by limiting the area in which the ICE torque decrease is working. The second one is some problematic concerning the synchronization of the SML and the TD, as their interpretation of the SoC level differed. This could lead to unnecessary fast recharge behavior when going from electrical driving to hybrid driving.

The rule-based strategy is then tuned, by adjusting the parameters in the SML and the TD. It is concluded that for the SML, it is important to let the EM propel the vehicle when the driver demanded torque is at low ICE efficiencies. For the TD, different combinations of ICE torque increase and decrease are tested, so that the operating points of the ICE are moved to more efficient areas. It is seen that the fuel consumption only changes marginally when the lines are changed. The reasons for the small changes in fuel consumption were e.g. that the SML choses electrical driving at low ICE efficiencies, losses in the electrical system and the smooth characteristics of the ICE efficiency map. It is decided to only use the ICE torque increase and decrease functionalities if the SoC would get close to its limits. This will control the SoC, and can be considered as the SoC controller of the rule-based strategy.

Then the rule-based strategy is compared to the table-based. It is seen that the strategies have different ways of controlling the SoC; the table-based strategy always wants to control the SoC to keep it around a set value, the rule based only steers the SoC if it gets close to the battery limits. Therefore, the SoC in rule-based strategy is closer to the battery limits than the table-based. The table-based strategy shows a tendency to discharge during accelerations in Hybrid Drive, while the rule-based drives more in Electric Drive. The table-based strategy uses the EM around twice as much as the rule-based, which might affect the lifetime of the components.

The comparison of the fuel consumption shows similar results for the rule-based and the table-based strategy, which can be e.g. because of the heavy vehicle. With this heavy weight, the ICE is working at high efficiencies, which there is little (or no) expected gain of moving the operating points. The table-based strategy changes the working points closer to the OEL of the ICE, but does not improve the fuel consumption.

Chapter 6

Simulation for Various Design Layouts

In this chapter the HMSs will be tested for various design layouts, like smaller battery size, smaller vehicle weight and no possibility to drive electrically. This variety of design layouts are applied to test the robustness of the strategies, to see how well they are able to perform with new prerequisites. It can affect the behavior of the strategies differently, and the result will be analyzed and discussed. A summary part is presented in the end of the chapter.

6.1 Battery Size Reduction

The first vehicle configuration, which was used in the previous chapter, had a very big battery (27 Ah). There are mainly three disadvantages of a big battery; because of its high cost, its large space requirements and its heavy weight. It is also understood, when looking at the SoC in Figure 5.3, that it does not vary much, and the range of the battery is unnecessary large. Therefore, it seems reasonable to analyze the result of reducing the battery size, in which its capacity is better utilized. The battery size is set to 1/20 of the original size, and this size is chosen so that the limits of the battery will be reached. In this way the simulations will show how the strategies perform when the SoC goes to its extreme values. The vehicle specifications with the new battery size are shown in Table 6.1. Note that a change in battery size does not affect the weight of the vehicle, for simulation and comparison purposes.

Table 6.1: *Vechicle specification for the second simulations, with reduced battery size.*

Li-Ion Battery	Capacity: 1.35 Ah
Vehicle	Total mass: 7100 kg
Hybridization	Electric Drive with ICE on and Hybrid Drive
Gear shift logic	Speed-based

6.1.1 Comparison of the Rule-Based Strategy and the Table-Based Strategy

The simulation results are presented in Table 6.2. Both strategies still outperform the conventional vehicle, but there are smaller improvements compared to when the larger battery was used (Table 5.3). This is an effect of the battery change, and can be understood when looking at Figure 6.1, where simulation results are presented for the Customer cycle. As expected, the SoC varies much more now, and even reaches its maximum limit at some points during the decelerations. Hence, some available kinetic energy is wasted in the mechanical brakes, and less recuperation is possible compared to the bigger battery. This will lead to an increase of the fuel consumption, which is seen in Table 6.2.

Table 6.2: *Fuel consumption results for the two HMSs for three different routes, expressed relative to the base value of 100% set for the conventional vehicle.*

HMS	*Sort3*	*Customer*	*Japan5*
Conventional	100 %	100 %	100 %
Rule-based	89.4 %	90.3 %	90.3 %
Table-based	87.9 %	91.3 %	90.0 %

There is one notable difference in the behavior of the rule-based strategy and the table-based, at the point when the battery gets saturated during the deceleration. The rule-based strategy will leave the electric driving mode, and switch to hybrid driving instead, which is indicated by the three arrows in the figure. This can be motivated since no more recuperation is possible, and it might be better to couple the ICE and use it for braking. To couple the ICE for negative torques can decrease the fuel consumption, compared to letting it run on idle speed. The table-based strategy on the contrary, stays in the electric driving with the ICE decoupled, and can therefore not use it for braking, thus all the braking is done by the mechanical brakes. This could be one reason why the fuel consumption is lower for the rule-based strategy on the Customer cycle.

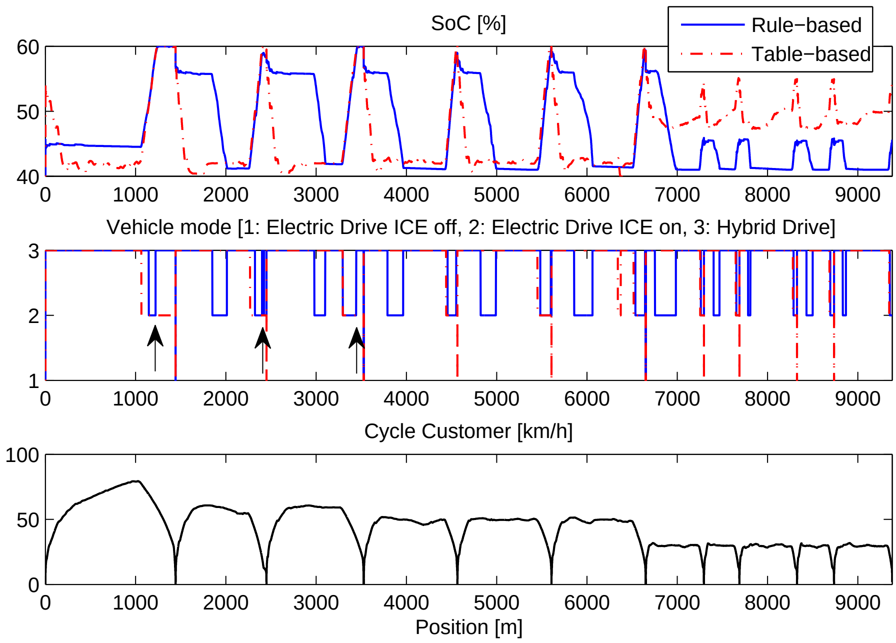


Figure 6.1: *Simulation results for the rule-based strategy (solid blue) and the table-based strategy (dashed red), showing the SoC, vehicle mode and cycle.*

For the Japan5 cycle, the battery never gets fully charged, therefore this reasoning is not applicable there. The potential of the engine braking will be investigated further in Section 6.4.1.

When looking at the results from the Sort3 cycle in Table 6.2, the table-based strategy has a lower fuel consumption compared to the rule-based strategy. This is due to the SoC controller, and will be analyzed here.

Influence of the SoC Controller
For a smaller battery, the SoC controller of the table-based strategy will become more influential on the simulation results, since the kinetic energy of the vehicle is in a range comparable to the energy of the battery. Data from the Sort3 simulation is presented in Figure 6.2. When the vehicle velocity increases over a certain threshold, the kinetic energy starts to influence the desired SoC, which is lowered, and the battery is discharged more. The battery discharge is done to allow enough space for the regenerative braking energy, which will be available when the vehicle starts to brake. For the rule-based strategy there is no desired SoC, hence no efforts are made to lower the SoC of the battery. For the first two deceleration parts of the cycle, both HMSs are able to recuperate all the available braking energy, and no energy is lost because of an overcharged battery. Though, for the third deceleration, the upper bound of the SoC is reached for the rule-based strategy before the vehicle stops (marked with an arrow in the figure). This limits the regeneration possibility during the braking, and some potential recharging energy is lost in the mechanical brakes. Whereas for the table-based strategy, since it discharged the battery before the deceleration, the absorbing capacity in the battery is sufficient to recuperate all the braking energy. In this case the advantage of the SoC controller is evident, and the table-based strategy saved energy by using this functionality, which is reflected in the lower fuel consumption.

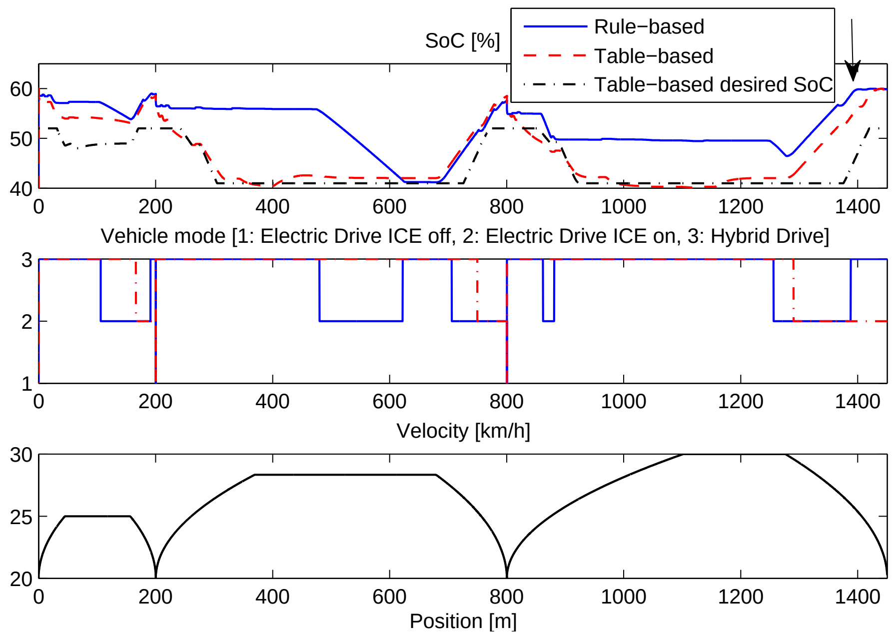


Figure 6.2: *The SoC for the two HMSs plotted together with the desired SoC for the table-based strategy, the vehicle modes and the cycle.*

Another effect of the SoC controller can be realized when looking at the modes of the vehicle. For the first two plateaus with constant velocity, the table-based strategy does not drive electrically, contrary to what the rule-based strategy does. This is much due to the SoC controller, which discharged the battery during the acceleration phase. If there would have been no discharge, the table-based strategy probably had been able to drive electrically at the plateau, since the battery would have had more charge. At first, it is not clear if driving electrically for a longer time is better than discharging during the acceleration phase and drive electrically for a shorter time. Though, it will have an impact on how the modes are chosen. (For the simulations in Section 6.2, it seems that driving electrically is beneficial.)

Due to these results, it is not certain that the SoC controller always will give a lower fuel consumption. Though, a well tuned SoC controller definitely has advantages, with the reasoning that it is better to use the electric energy even in non-optimal points, compared to not to be able to recuperate.

6.2 Battery Size and Vehicle Weight Reduction

From the previous simulations it was seen, that with a heavy vehicle, the driver often demanded a high torque from the ICE. To operate at a high torque results in high efficiencies for the ICE, due to the structure of its efficiency map, Figure 2.3(a). This means that there is little potential for the strategies to increase the efficiency of the ICE, by moving the operating points. Therefore, it seems interesting to analyze the HMSs with a lighter vehicle and the same ICE, for which the driver will demand lower torques, and it is done in this section.

The vehicle specifications with the new weight are shown in Table 6.3, where also the smaller battery size is used.

Table 6.3: *Vehicle specification for the third simulations, with reduced battery size and vehicle weight.*

Li-Ion Battery	Capacity: 1.35 Ah
Vehicle	Total mass: 2500 kg
Hybridization	Electric Drive with ICE on and Hybrid Drive
Gear shift logic	Speed-based

6.2.1 Comparison of the Rule-Based Strategy and the Table-Based Strategy

The results from the simulations are listed in Table 6.4. As can be seen, the rule-based strategy performs better on all three cycles compared to the table-based strategy. With the lighter vehicle, it becomes more difficult to use the electric energy in an efficient way. The reason for this is described with the ICE characteristics and (6.1)

$$m \downarrow \cdot a \cdot v = \tau \downarrow \cdot \omega \tag{6.1}$$

Now it is studied what happens with the torques, when the vehicle becomes lighter. The desired acceleration a and velocity v are the same as before, independently of the mass m of the vehicle, since it is the same driver and the same cycle. The rotational speed ω

only depends on the velocity of the vehicle, and therefore it is the torque that decreases, when the vehicle gets lighter. This has the effect, that the torques are often below the OEL line, and additional use of positive EM torque will move the ICE working points down to worse efficiencies, away from the OEL line. Moreover, if a negative EM torque is used, the ICE efficiency will be increased. Hence, with this lower vehicle weight, there are many good working points for recharging the battery with the ICE increase functionality, but difficult to find good working points for discharging with the ICE decrease functionality.

Table 6.4: *Fuel consumption results for the two HMSs for three different routes, expressed relative to the base value of 100% set for the conventional vehicle.*

HMS	*Sort3*	*Customer*	*Japan5*
Conventional	100 %	100 %	100 %
Rule-based	83.1 %	87.0 %	86.4 %
Table-based	88.0 %	90.1 %	86.7 %

The operating points of the ICE for both vehicle weights are shown in Figure 6.3 for the Japan5 cycle, where the lighter vehicle clearly has lower ICE torques.

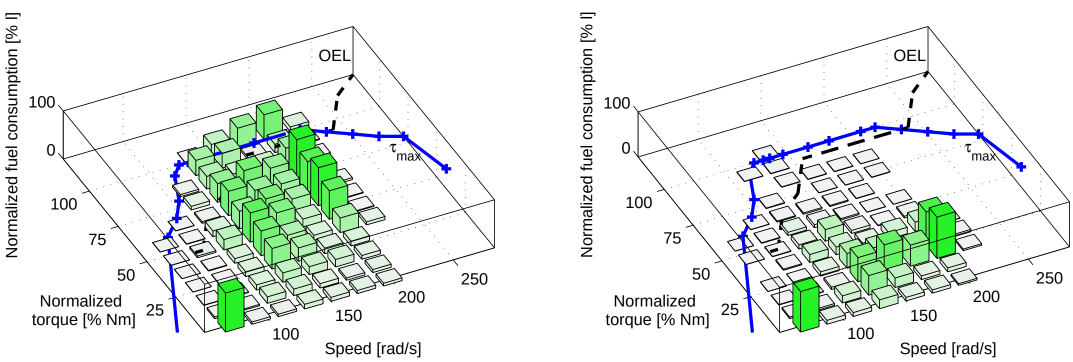


Figure 6.3: *Operating points of the ICE, where the height of the boxes represents fuel consumption. The table-based strategy with vehicle weight 7100 kg (left) and vehicle weight 2500 kg (right).*

The table-based strategy increases and decreases the ICE working points more than the rule-based strategy, much because the SoC controller wants to reach its desired SoC level. The changes in desired SoC, due to the kinetic energy of the vehicle, will also lead to more use of the EM, both for positive and negative torques; positive torques when the SoC should be lowered (decreasing the ICE working point), and negative torques when the SoC should be raised (increasing the ICE working point). The table-based strategy operates in many working points where it seems reasonable to recharge the battery, but when the strategy requests a decrease of the SoC, it is difficult to find good points to discharge the battery. E.g., if the desired SoC goes down, the table-based strategy might decrease to worse ICE efficiencies than was used for recharging the battery. This would mean that the recharged energy "cost" more fuel compared to what was saved when it was used.

When looking at the Sort3 cycle, there is a much lower fuel consumption for the rule-based strategy compared to the table-based strategy. Some data from this simulation is illustrated in Figure 6.4. The reason for the lower fuel consumption has to do with how the strategies chose the vehicle modes. The rule-based strategy drives more electrically, which seems to be beneficial, as no other clear reasons for the lower fuel consumption are found. If more tuning is done for the table-based strategy, a similar behavior can be obtained.

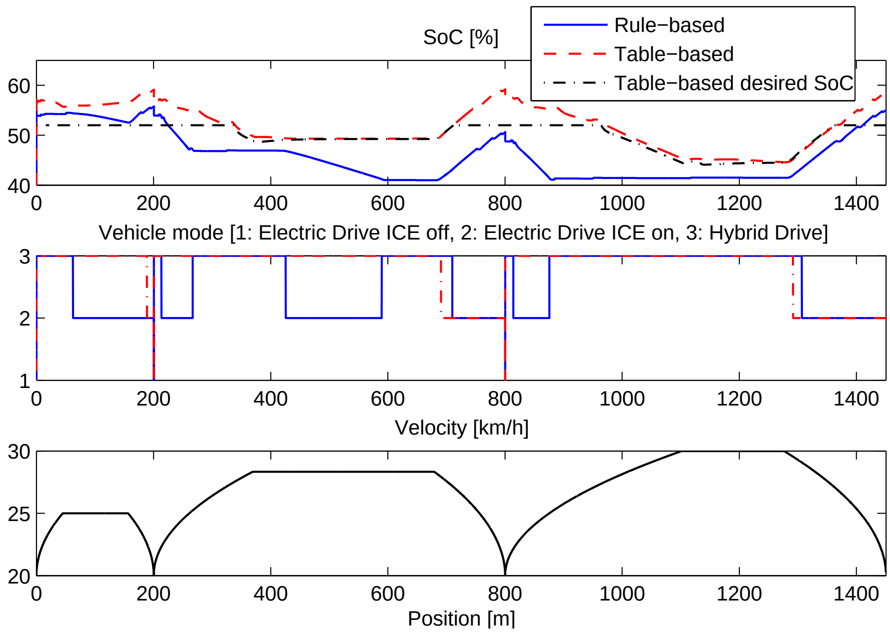


Figure 6.4: *The SoC for the two HMSs plotted together with the desired SoC for the table-based strategy, the vehicle modes and the cycle.*

6.3 No Electrical Driving

The last design layout which the HMSs will be tested with, is to change the possibility to switch mode. The mode Electric Drive with ICE on is disabled, and the vehicle is only able to drive in hybrid mode, with the ICE always coupled. For standstill situations it is still possible to decouple and turn off the ICE. Since the energy no longer can be used in the electric driving mode, it will put more pressure on the strategy to use it in the hybrid driving mode.

The vehicle specifications are shown in Table 6.5, where the small battery size and light vehicle are used.

Table 6.5: *Vehicle specification for the fourth simulations, where no electric driving is possible.*

Li-Ion Battery	Capacity: 1.35 Ah
Vehicle	Total mass: 2500 kg
Hybridization	Only Hybrid Drive (ICE off at standstill)
Gear shift logic	Speed-based

6.3.1 Comparison of the Rule-Based Strategy and the Table-Based Strategy

The fuel consumption results are presented in Table 6.6. The first noticeable thing is that both strategies have a higher fuel consumption, when compared to the vehicle setup which could drive electrically, Table 6.3. Four points can be listed which contribute to this increase in fuel consumption:

- **Overcharged battery:** It is more difficult to discharge the battery for the rule-based strategy, since it needs to do it in hybrid driving.
- **ICE efficiency:** The ICE will operate more on lower efficiencies in the lower torque region, since it always needs to be coupled.
- **Less recuperation:** The regenerative braking will occur in hybrid drive, which will charge the battery less compared to doing it in electric driving (more about this in Section 6.4.1).
- **Idle speed:** The fact that the ICE is coupled to the wheels will increase the ICE speed, since it is always higher than the idle speed. For the case when the ICE does not provide any torque, the fuel consumption will be higher when the ICE is coupled. This is because higher ICE speeds give higher fuel consumption, and it would in this case be beneficial to decouple the ICE and let it run at idle speed.

When looking in Table 6.6, it is also seen that on the Sort3 and Customer cycles, the table-based strategy consumes less fuel, which is due to its SoC controller. This is similar to what happened in Section 6.1.1, the upper limit of the battery is reached for the rule-based strategy, which leads to wasted energy in the regenerative braking situation. The table-based strategy manages to discharge the battery before the braking situations, and can store the kinetic energy in the battery, resulting in a lower fuel consumption.

Table 6.6: *Fuel consumption results for the two HMSs for three different routes, expressed relative to the base value of 100% set for the conventional vehicle.*

HMS	*Sort3*	*Customer*	*Japan5*
Conventional Vehicle	100 %	100 %	100 %
Rule-based	96.9 %	92.9 %	89.2 %
Table-based	93.1 %	92.1 %	89.8 %

There is a minor advantage for the rule-based strategy on the Japan5 cycle, and this is examined further. A plot of the SoC and the fuel consumption is given in Figure 6.5 for the two HMSs. During the first half of the cycle, the SoC hits the maximum limit many times for the rule-based strategy, and regenerative braking energy is lost. This is reflected in the higher fuel consumption compared to the table-based strategy. Around 7500 m, there are many short standstill situations, where the ICE is turned on and off. This will consume energy from the battery, and the SoC of the rule-based strategy is lowered, away from its maximum limit. Therefore, during this last half of the cycle, it can recuperate all the available braking energy. The fuel consumption of the two strategies approaches each other, and at the end of the cycle the table-based strategy actually has a higher fuel consumption. This means that on the last half, the table-based strategy lost all its advantage it had from the fist half. This has much to do with what happens around 8000 m, where the battery is recharged a lot, and the fuel consumption increases significantly. If the cycle would have ended at e.g. 7500, before this fast recharge, the table-based strategy would have had a lower fuel consumption.

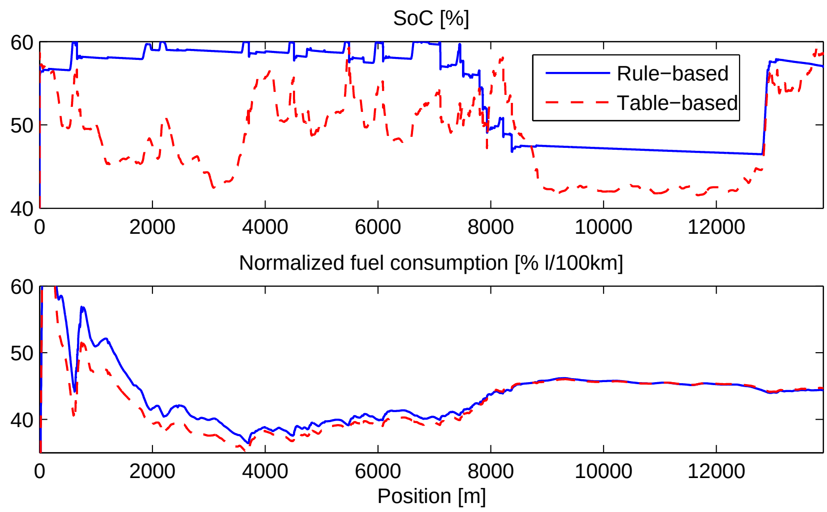


Figure 6.5: *The SoC and the fuel consumption from the Japan5 route. The base value for the SoC controller in the table-based strategy is at 52%.*

Tuning the two HMSs

Like in the previous simulations, the desired SoC of the table-based strategy is set to 52%, which in some cases leads to fast recharges when the actual SoC is below 52%. To reduce the strong recharging behavior and see if it improves the fuel consumption, the SoC controller is tuned, by setting its desired value to 45% instead. The same setup, with only hybrid drive is simulated, and the results are given in Figure 6.6. The average level of the SoC for the table-based strategy is clearly lower, and moves around the set value of 45%. Some fast recharges are succesfully removed, e.g. at 3500 m and 8000 m. When looking at the fuel consumption, it is marginally lower for the first half of the cycle, but the same for the second half, totalling at 89.7%. This is still higher compared to the rule-based strategy, which ended up at 89.2%.

In Figure 6.6, the tuned rule-based strategy is also shown, and it is seen that the SoC is kept away from the maximum limit. The tuning is done with a gradient based method for setting the ICE torque increase and ICE torque decrease lines, and will be explained further in Section 6.4.2. The resulting fuel consumption for the tuned rule-based strategy is 87.9%, and is a rather large improvement from the previous value of 89.2%.

It is concluded that both the strategies show a better result when some tuning is carried out.

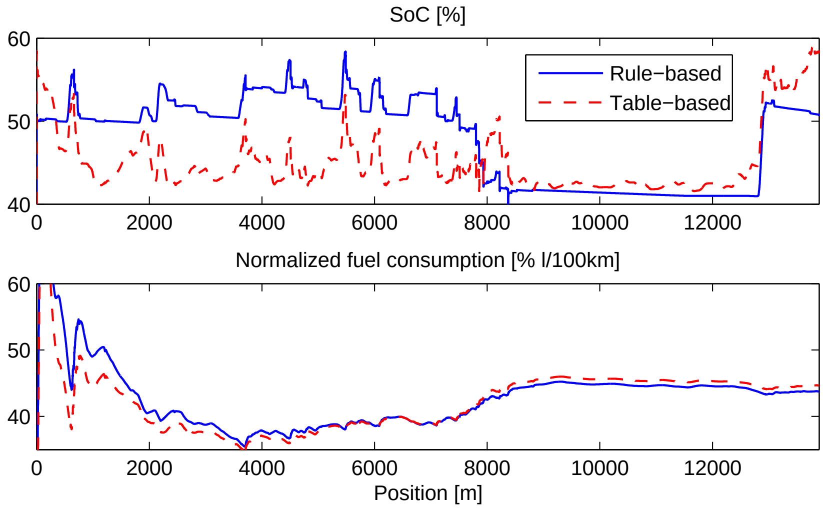


Figure 6.6: *The SoC and the fuel consumption from the Japan5 route. The rule-based strategy uses the gradient based method for its TD, and the base value for the SoC controller in the table-based strategy is tuned to 45%.*

6.4 Other Ideas

6.4.1 Hybrid Drive When Braking

When the vehicle is driving electrically with the ICE decoupled running at idle speed, it consumes some fuel, since torque is needed to keep the ICE on. It is noticed in the simulations, that when the vehicle enters a braking situation, the mode Electric Drive with ICE on is chosen. If instead the Hybrid Drive would be requested, the ICE would stay coupled. There is an advantage of keeping the ICE coupled in braking situations, as the negative torque from the driveline can be used to power the ICE, reducing the fuel consumption. This is called *engine braking*, and is also sometimes preferred for conventional vehicles, instead of disengaging the clutch and brake with the mechanical brakes. Therefore a new question is posted:

Is it better to couple the ICE, rather than decoupling it, when the driver is demanding a negative torque (decelerating the vehicle)?

If this idea, to keep the ICE coupled, would improve the results, it could be implemented in the two HMSs. Simulations are run for the two HMSs, with the small battery (1.35 Ah) and the light vehicle (2500 kg), as in Section 6.3. A typical braking sequence is selected from the rule-based strategy, showing the main results in an efficient way. In Figure 6.7, the fuel consumption together with the SoC and the cycle are shown for two simulations; one braking in electric mode and one braking in hybrid mode.

When braking occurs in electric mode, the EM is the only power source coupled to the driveline and can use all the available negative torque for recuperation. When braking in hybrid mode, where the ICE is coupled, there is a minimum torque required to keep the ICE running, which can not be used by the EM for recuperation. Hence some possible recuperation energy is lost as it is needed for the ICE. This results in the higher SoC for the electric braking vehicle, which is able to recuperate about 41% more energy. Moreover, as expected when braking in hybrid mode, the fuel consumption is lower compared to braking in electric mode (about 26% lower), since the ICE does not need to provide any torque for itself.

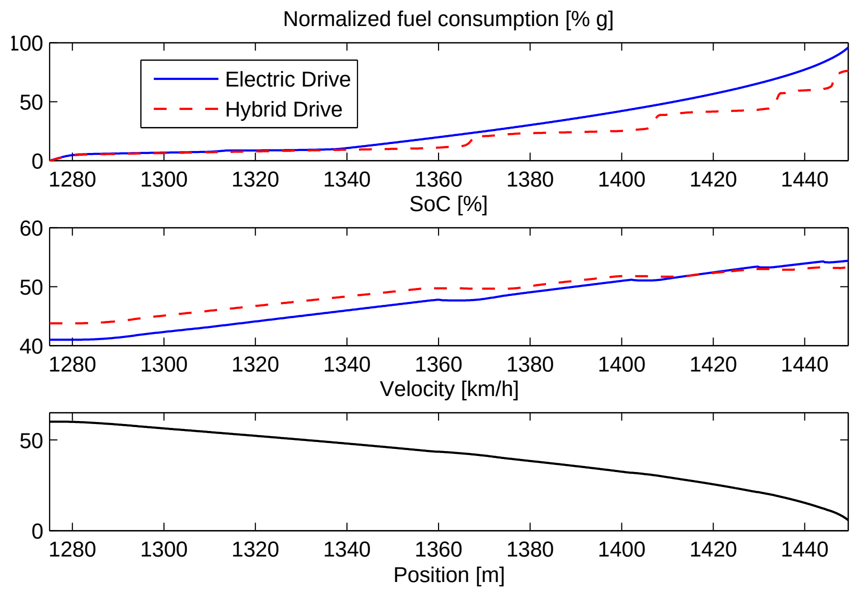


Figure 6.7: *Simulation data from a braking sequence, for Electric Drive (solid blue) and Hybrid Drive (dashed red).*

The overall results show that braking in electric mode is better than braking in hybrid mode. This can be explained by the lost regenerative braking energy, but also by two other effects related to gear shifts, listed below.

- **ICE synchronization:** When a down shift occurs in hybrid mode, the speed of the ICE has to be synchronized (accelerated) to the transmission speed of the new gear. This requires additional torque from the ICE during the clutch disengage/engage phase, which will increase the fuel consumption. If the vehicle would have been in electric driving, the ICE is decoupled during the gear shifts, and the synchronization is not necessary for the ICE.

- **Shifting time:** It is seen that the downshifts in hybrid mode required more time compared to those in electric mode, which makes the recuperating time for the EM shorter. If another shifting strategy would be used, preferably one that shifts less, the outcome might be different. Also an active engine control, which can reduce the gear shift time, might improve the result [14].

6.4.2 Gradient Based Method for Deciding the Torque Distribution Parameters

When the lines for the ICE torque increase and decrease were chosen in Section 5.1.4, it was based on a series of test results. Also a more mathematical way of finding these lines has been developed, and is described here. First a way of setting the ICE torque increase lines is discussed in this part, followed by a way of setting the ICE torque decrease lines.

ICE Torque Increase

Increasing the ICE torque and using the EM as a generator will increase the fuel demand of the ICE. Therefore, this change of ICE working point has to consider how much fuel will be saved with the recharged electric energy.

One approach, for recharging the battery, is to try avoiding the low efficiency regions of the ICE, rather than trying to work as much as possible at the high efficiencies. The low efficiencies are usually at low torques, where the efficiencies are increasing fast. This means that with a little cost of more fuel, much more power can be delivered by the ICE.

Another approach to recharge the battery is to try to optimize the efficiency of the recharged electric energy. This would mean that the ICE working points would be increased to get close to the OEL line. To also consider the efficiency of the EM will lead to small increases of the ICE torque, due to its high efficiency in this region.

In Section 5.1.3, the approach to increase to the OEL line was tested, but no improvement in fuel consumption was seen, when compared to the other ICE torque increase lines. One reason for this result might have been that in the region around the OEL line, the efficiency is not changing much. This means that the needed fuel for a higher efficiency is high, or that extra fuel will not increase the output power from the ICE significantly.

In order to get a structured way to decide the lines for the ICE torque increase in the rule-based strategy, a script is developed. The script analyzes the torques, for a constant input shaft speed, and indicates when it is beneficial to increase the ICE working point, from the driver demanded torque. This is done for a number of different input shaft speeds. Two different inequalities for increasing the ICE working points are formulated and tested. Both calculations are based on the first approach, trying to avoid low efficiencies. To make it more comprehensible, the ICE angular speed is constant in each inequality and therefore not considered.

The first inequality is given in (6.2)

$$\frac{\frac{d\eta(\tau_{\mathrm{driver}},\tau_{\mathrm{wp}})}{d\tau_{\mathrm{wp}}} \cdot P(\tau_{\mathrm{wp}}) + \eta(\tau_{\mathrm{driver}},\tau_{\mathrm{wp}}) \cdot \frac{dP(\tau_{\mathrm{wp}})}{d\tau_{\mathrm{wp}}}}{\frac{dP(\tau_{\mathrm{wp}})}{d\tau_{\mathrm{wp}}}} > \upsilon \tag{6.2}$$

where P [J/s] is the fuel flow, which depends primarily on the torque in the new ICE working point. η [-] is the total efficiency of the system, and is the relationship between the fuel flow and the mechanical power output. It is trivial to calculate the efficiency of the power going from the ICE directly to the wheels, since this data is in the look-up tables presented in Section 3.3.2. The efficiency of the power recharged into the battery is estimated since this power (energy) will be used in the future. By analyzing some simulations, a factor between the increase in fuel and the stored electric energy is found. This factor is used so that the benefits of recharging the battery with the ICE can be analyzed. υ [-] is a tunable threshold which the left-hand side of the inequality will be compared to, to investigate the benefit of a certain ICE torque increase.

The inequality is based on two ideas about how to increase the total efficiency of the system. The first idea is that it is good to increase the ICE torque if the recharged energy has higher efficiency than the average efficiency of the system. This is represented by the efficiency term, $\eta(\tau_{\mathrm{driver}},\tau_{\mathrm{wp}})$ in the numerator. The second idea is that it is good to increase the efficiency, represented by the efficiency derivative term $\frac{d\eta(\tau_{\mathrm{driver}},\tau_{\mathrm{wp}})}{d\tau_{\mathrm{wp}}}$, in the numerator. To punish the increase in fuel flow, when the efficiency is increased, the efficiency derivative term $\frac{d\eta(\tau_{\mathrm{driver}},\tau_{\mathrm{wp}})}{d\tau_{\mathrm{wp}}}$ is divided by the derivative of fuel flow, $\frac{dP(\tau_{\mathrm{wp}})}{d\tau_{\mathrm{wp}}}$.

The derivative of the efficiency, $\frac{d\eta(\tau_{\text{driver}},\tau_{\text{wp}})}{d\tau_{\text{wp}}}$, is much smaller than the derivative of the fuel flow, $\frac{dP(\tau_{\text{wp}})}{d\tau_{\text{wp}}}$, and therefore the numerator is multiplied by the fuel flow, $P(\tau_{\text{wp}})$. This is done to relate the numerator to the denominator in a good way.

A second inequality is also constructed for different reasons, mainly because of its fewer approximations and easier structure. It is given in (6.3)

$$\frac{P_{\text{fuel}}(\tau_{\text{wp}}) - P_{\text{fuel}}(\tau_{\text{driver}})}{(P_{\text{m}}(\tau_{\text{wp}}) - P_{\text{m}}(\tau_{\text{driver}})) \cdot \eta_{\text{EM}}} < \psi \tag{6.3}$$

where P_{fuel} [J/s] is the fuel consumption in the specific working point of the ICE, P_{m} [J/s] is the mechanical power at the input shaft, and η_{EM} [-] is the efficiency of the EM. ψ [-] is a tunable threshold which the left-hand side of the inequality will be compared to, to investigate the benefit of a certain ICE torque increase.

The idea behind (6.3) is that the numerator represents the cost for the ICE torque increase, while the denominator represents the gain. The cost is how much the fuel consumption will increase and the gain is how much energy that can be used to charge the battery. This means that a low value of the left-hand side will argue for an increase of ICE torque.

Some new ICE torque increase lines are selected with help from the script, and applied in the rule-based TD. These new lines were first tested for the vehicle setup as in Section 5.1, with the weight 7100 kg and battery size 27 Ah. This did not give any considerable change in the fuel consumption. The reason is that this heavy vehicle already works at high efficiencies, where the ICE torque increase functionality is not active.

After these tests, the vehicle weight is changed to 2500 kg and the battery size to 1.35 Ah, so that the vehicle specifications are the same as in Section 6.2. With this lighter vehicle, a better fuel consumption is obtained as shown in Table 6.7, where also the results with the old lines from Table 6.4 are shown at the bottom.

Table 6.7: *Fuel consumption results for the rule-based strategy based on the script, expressed relative to the base value of 100% set for the conventional vehicle.*

HMS	*Sort3*	*Customer*	*Japan5*
Conventional Vehicle	100 %	100 %	100 %
Rule-based with gradient based method			
Inequality (6.2)	81.9 %	86.1 %	83.3 %
Inequality (6.3)	82.2 %	86.3 %	83.9 %
Rule-based without gradient based method			
Old lines from tests	83.1 %	87.0 %	86.4 %
Table-based	88.0 %	90.1 %	86.7 %

The results from the script based on the two different inequalities differs slightly, and it is difficult to say if it is because of the chosen thresholds, υ and ψ, or the inequalities themselves.

ICE Torque Decrease
One of the comparisons between the two different HMSs was made when the vehicle only could drive in Hybrid Drive, Section 6.3. This meant that the electric driving was not used, and that the TD was the primary way of saving fuel through decreasing the ICE torque. This test was made for the light vehicle, 2500 kg, leading to that the ICE worked on low torques. In those simulations, the lines to which the rule-based strategy decreased the ICE torque, were too high to be used for this light vehicle. The rule-based strategy could not use its electric energy, resulting in a too high SoC, causing recuperation energy to be lost. Therefore, a script is made which computes more suitable ICE torque decrease lines, using the electric energy more, making space for the recuperation energy. The script makes sure that the electric energy is used in an efficient way and the efficiency of the ICE is not considered. It is deactivated when the SoC reached low values, to lower the risk of depleting the battery. The inequality used for the script is given in (6.4)

$$\frac{P_{\mathrm{fuel}}(\tau_{\mathrm{wp}}) - P_{\mathrm{fuel}}(\tau_{\mathrm{driver}})}{(P_{\mathrm{m}}(\tau_{\mathrm{wp}}) - P_{\mathrm{m}}(\tau_{\mathrm{driver}})) \cdot \frac{1}{\eta_{\mathrm{EM}}}} > \zeta \tag{6.4}$$

where ζ [-] is a tunable threshold which the left-hand side of the inequality will be compared to, to investigate the benefit of a certain ICE torque decrease.

This inequality analyzes where most fuel can be saved with the least amount of electric energy. In the numerator the amount of saved fuel for decreasing the ICE torque is given. The denominator gives the consumption of electric energy for the demanded EM torque.

The result from using this script was given in Section 6.3, and showed a lower fuel consumption.

6.5 Summary

In this chapter the HMSs are subjected to some various design layouts, to see how robust they are to changes. The first change is to decrease the battery size, to 1.35 Ah from 27 Ah. By doing so, a larger range of the battery size is used. Compared to the bigger battery, a higher fuel consumption is seen, since less electric energy can be stored in the battery.

It is seen that the SoC controller of the table-based strategy changed the desired SoC level, since the kinetic energy of the vehicle is not negligible, compared to the battery size. The SoC controller shows some benefits, as it manages to discharge the battery before the regenerative braking, making space for the available braking energy. The rule-based strategy, due to its less strict control of the SoC, fails to do so. Moreover, the SoC controller in the table-based strategy also affects the possibility to drive electrically, since it often uses the battery energy for the accelerations.

A configuration with smaller battery and lighter vehicle is also analyzed, and in this case the HMSs work at lower ICE efficiencies, because of the lighter weight. The results show that the rule-based strategy drives more electrically, and in this way probably gets a lower fuel consumption. By tuning the table-based strategy, a similar behavior could be obtained.

The HMSs are also tested when the vehicle only can drive in Hybrid Drive, except at standstill, where it is able to chose Electric Drive with ICE off. This setup has a higher fuel consumption due to several reasons, e.g. the ICE works at lower efficiencies and less energy can be recuperated. Both HMSs are then tuned to improve the fuel consumption results.

It is analyzed if the fuel consumption decreases, when more engine brake is used. No improvement could be seen, due to that gear shifts in hybrid drive take longer time, and the ICE needs to be synchronized.

A script is developed to find the parameters in the rule-based TD, with a gradient based method. These parameters are implemented and results in a decrease of the fuel consumption. The main benefits of setting the parameters in this way are: more systematic, easier to use, fewer and more understandable tuning parameters.

Chapter 7

Implementation of a Second Gear Shift Strategy

Up till now, the HMSs have been studied for some various design layouts, such as different battery size and vehicle weight. Another important part of the HEV that has not yet been discussed is the shifting of gears, i.e. the gear shift strategy. From the simulations it is understood that the gear shifts of the vehicle influence the overall behavior significantly, and it is expected that a well tuned gear shift strategy can improve the fuel economy considerably [10]. In this chapter the HMSs are tested with a second, more advanced, gear shift strategy which is created and implemented. It is studied how the HMSs are able to cope with the second shift strategy, and also its general effect on the HEV, compared to the first gear shift strategy. A summary of the chapter is given in the end.

7.1 Gear Shift Strategies

There are two gear shift strategies implemented for the HEV, one based on the speeds of the transmission's output shaft, and one more advanced which tries to follow the OEL line of the ICE and the EM, similar to what is done in [17]. So far the speed-based strategy has been used for the simulations, and now the system will be tested with the OEL-based strategy. They are both described in the following two sections.

7.1.1 Speed-Based Gear Shift Strategy

The idea behind the speed-based gear shift strategy is a bit simpler than the one in the OEL-based, but also more stable. For every available gear the transmission's output shaft speed should be kept within a certain range, to use the ICE in an efficient way. When the transmission's output shaft speed goes lower or higher than these thresholds, it would be better to do a downshift and an upshift respectively. The thresholds are functions of the throttle position (driver demanded torque), to keep a lower gear if the driver demands a high torque, e.g. at steep hills or when overtaking. The strategy is implemented from Dymola with look-up tables, one for downshifts and one for upshifts, in which the thresholds are specified for the available gears. The tables are two dimensional, where the inputs are the actual gear and the throttle position. The outputs from the tables are the desired threshold for the transmission's output shaft speed. The following applies for the downshift table and the upshift table:

- Downshift: *if the calculated threshold is higher than the actual output speed, a lower gear is requested.*

- Upshift: *if the calculated threshold is lower than the actual output speed, a higher gear is requested.*

In this way the gears are selected in a systematic pattern, and follows the velocity of the vehicle closely. The gear-shifting map for the speed-based shift strategy is shown in Figure 7.1, which is a graphical way of describing the gear shifts. The range between the downshift and the upshift for each gear is the hysteresis present, which is necessary to avoid frequent toggling between gears.

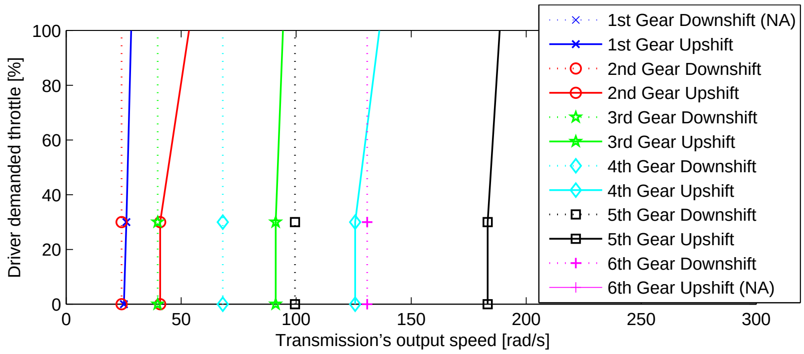


Figure 7.1: *Gear-shifting map of the speed based strategy, where dotted lines represents a down-shift and solid lines represents an upshift.*

7.1.2 Optimal Efficiency Line-Based Gear Shift Strategy

The OEL-based strategy originates from the concept to let the active power source operate at its peak efficiency, to overcome unnecessary losses in the system. Since there are two power sources present, it has to be decided how to optimize the gears regarding the ICE and the EM. When driving in hybrid mode, the ICE is the dominating power source and the ICE efficiency will decide the gear shifting policy. When switching to electric mode, the ICE is decoupled and the gears will instead be switched to achieve a high efficiency of the EM. As remembered from the efficiency maps of the ICE and the EM (Section 2.4), the optimal working point for any given power is described by the OEL line. The objective is to select the best gear to get as close as possible to the peak efficiency, still fulfilling the demand from the driver. Here the power from the driver is considered rather than the torque, since the specific torque is irrelevant for the shift strategy. The gear shifting problem can be seen as reversed to the TD problem, since the speed of the transmission's input shaft is computed, and not considered as given. For every power demand, an appropriate speed of the transmission's input shaft is computed, and used as an input to the shifting logic. The scheme with a table and a stateflow chart is presented in Figure 7.2, where the final output is the optimal gear. Since this shifting policy only considers the requested power, extra features have to be implemented to make it more stable and robust. An example is the speed of the input shaft, which is considered when shifting, to avoid too high and too low speeds, which might damage the hardware.

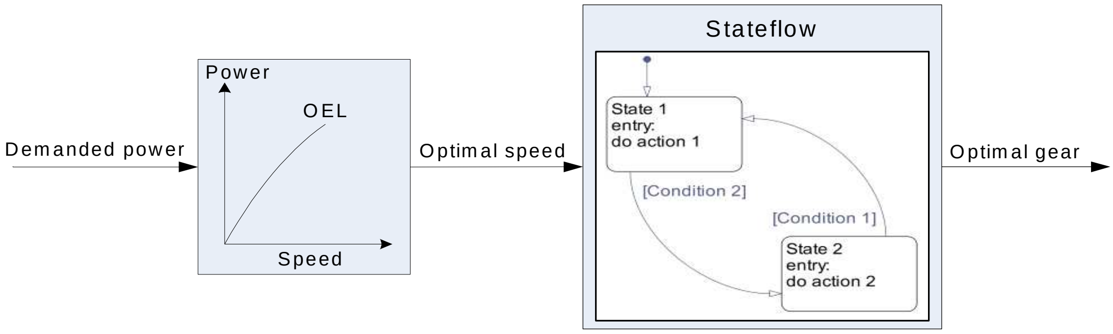


Figure 7.2: *The implementation of the OEL-based shift strategy.*

7.1.3 Tuning of the Gear Shift Strategies

One important part of the work is to make the gear shift strategies perform as well and stable as possible, which requires tuning. It is a complicated task, since they influence the behavior of the HMS and the system itself significantly. Many functions needs to be implemented, and below a short list of the gear shift strategies most important common features is presented, as well with a list of some special features of the OEL-based strategy.

Common:

- It is not allowed to request a gear shift when the system is coupling or decoupling the ICE, or when a gear shift already is in progress. It was discovered that if a gear shift request occurred at the same time as one of these events, the simulation crashed.
- It is not allowed to shift gear when the requested mode of the vehicle differs from the actual mode. For example when driving in hybrid mode, a request to go to electric driving is signaled, and the system starts to prepare for the change. If a gear shift would occur at this point, the change of mode is interrupted and the simulation fails (similar to the problem described in Section 4.1.1).
- It is only allowed to shift down to 1st gear if the vehicle is close to a standstill or the acceleration is positive. This is to avoid selecting gear one too early when braking, since it is uncomfortable for the driver.

OEL-based strategy:

- There is a predictive behavior of the strategy which tries to avoid unnecessary gear shifts, by looking forward in time, in this case 0.1 s. The forward looking is done by checking the gradient of the optimal speed output from the table, and compute its future value. This is then taken into account when computing the optimal gear. E.g. if the actual input speed is increasing and it is seen that in 0.1 s it will be best to choose the current gear, it is desired to keep the current gear. If instead a gear shift would occur at this point, the optimal speed would not be followed as well. This implementation might also lead to that wrong gear will be selected, if the prediction turns out to be false. Though, these errors in prediction are not shown in the results. The look ahead feature proves to prevent some unwanted gear shifts, resulting in a better tracking of the optimal speed.
- There is some hysteresis between the gear shifts for the OEL-based strategy, which is used as a tuning variable. With a small hysteresis, the gears are shifted more

frequently. This makes it possible to often hit the optimal gear, but also to interrupt other changes in the system, e.g. the change of mode. Many gear shifts will also lead to less recuperation and discomfort for the driver. When the hysteresis is increased, less gear shifts occur, interrupting less in the system, though making it more difficult to hit the optimal gear. A hysteresis which does not cause too much shifting and mostly hits the correct gear is chosen.

- If the ICE speed drops below its idle speed, a downshift is stressed on the system, as a safety feature not to damage the ICE.
- There is a safety mechanism in the control unit for the ICE, which limits its speed. To avoid requesting speeds over this limit, an upshift is stressed in the strategy to lower the speed of the ICE, if the requested speed would be higher than the limit.

Many of the safety features for the OEL-based strategy are not implemented in the rule-based one, since it is not necessary. This is due to its simple structure, which does more stable and predictive gear shifts.

7.2 Comparison of the Rule-Based Strategy and the Table-Based Strategy

The vehicle specifications for the simulations are shown in Table 7.1. It is chosen to continue with the smaller truck and the smaller battery, as it is more challenging for the strategies.

Table 7.1: *Vehicle specifications for the simulations with the second gear shift strategy.*

Li-Ion Battery	Capacity: 1.35 Ah
Vehicle	Total mass: 2500 kg
Hybridization	Electric Drive with ICE on and Hybrid Drive
Gear shift logic	OEL-based

The conventional vehicle, the rule-based strategy and the table-based strategy are all simulated on the three cycles, and the fuel consumption is listed in Table 7.2. Both the strategies are able to handle the second shifting strategy in a good way. There is an advantage for the table-based strategy on the Sort3 cycle, and a small advantage on the Japan5 cycle. There are two points in the Sort3 simulation where the rule-based strategy requested both a change in vehicle mode and gear simultaneously, which causes some problems in the system. This leads to a decrease in the vehicle velocity, and the driver reacts strongly on this, causing the fuel consumption to increase. Since this is just a coincidence which can occur in the simulations for both HMSs, no conclusions can be drawn from this, other than that both HMSs performs well with the second gear shift strategy.

7.3 General Analysis of the Second Gear Shift Strategy

One interesting question that arises, is how well the second gear shift strategy performs compared to the first one, and if it is able to shift the gears in a more efficient way. This can be studied when the data from the first shift strategy is combined with the data from the second shift strategy, which is done in Table 7.3. Here only one cycle is presented,

Table 7.2: *Fuel consumption results for the two HMSs for three different routes, expressed relative to the base value of 100% set for the conventional vehicle.*

HMS	*Sort3*	*Customer*	*Japan5*
Conventional	100 %	100 %	100 %
Rule-based	92.9 %	88.2 %	88.5 %
Table-based	89.7 %	88.8 %	87.7 %

not to have too much data. By looking at the results for the conventional vehicle, it is seen that the second shift strategy is able to save about 5.9% fuel. This indicates that the second shifting strategy performs well, regardless of the HMS. Also the two HMS are able to save more fuel with the second shift strategy.

Table 7.3: *Fuel consumption results for the two HMSs for three different routes, expressed relative to the base value of 100% set for the conventional vehicle with the OEL-based gear shift strategy.*

HMS	*Customer*
OEL-based shift strategy	
Conventional	100 %
Rule-based	88.2 %
Table-based	88.8 %
Speed-based shift strategy	
Conventional	105.9 %
Rule-based	92.2 %
Table-based	95.4 %

To see how the two shift strategies operate and select the gears, two data sets are chosen for examination; the speed-based and the OEL-based shift strategy, with the rule-based HMS on the Customer cycle. First the data is checked for positive powers when the vehicle is driving with the ICE, since this is the main traction situation, and second the negative powers in electric driving are selected.

In Figure 7.3, the gear operating points are presented in a plot with the ICE power demand vs. transmission's output shaft speed. The different gears are clearly distinguishable in some ranges of the output speed. The 1st, 2nd and 3rd gear are similarly chosen for the two strategies, but the higher gears are selected differently. The OEL-based shift strategy tends to choose a *higher gear* for lower output speeds, and two main clusters are discovered, at 90 rad/s and 150 rad/s, where it selects a higher gear. Two important equations regarding the gear shifts are given in (7.1).

$$\begin{aligned} P &= \tau \cdot \omega_{\text{in}} && [W] \\ \omega_{\text{in}} &= GR \cdot \omega_{\text{out}} && [rad/s] \end{aligned} \tag{7.1}$$

where the first one is the same power equation as in equation (2.2), but now with the index for the speed written out. For the second equation, ω_{in} [rad/s] and ω_{out} [rad/s] is the transmission's input and output shaft speed respectively, and GR [-] is the gear ratio. The power P and the output speed ω_{out} are considered as given, and the input speed ω_{in}

can be changed by switching the gears. A higher gear results in a lower GR, and the input speed will decrease. To still fulfill the power demand, a higher torque is needed. Hence, the two strategies give the same power and output speed, but with different gears, where the OEL-based shift strategy tends to chose a higher gear, resulting in a lower input speed and a higher torque. The reason, why a combination of lower input speed and higher torque gives a better fuel consumption, can be explained with Figure 7.4. The fuel consumption of the ICE is plotted, with three power lines which represent often used powers. Due to the small negative gradient of the power lines (especially for the 10 kW line), it is beneficial from a fuel consumption perspective to lower the speed, since only a small torque increase is required to fulfill the power demand. This will result in a lowering of the fuel consumption for the OEL-based shift strategy.

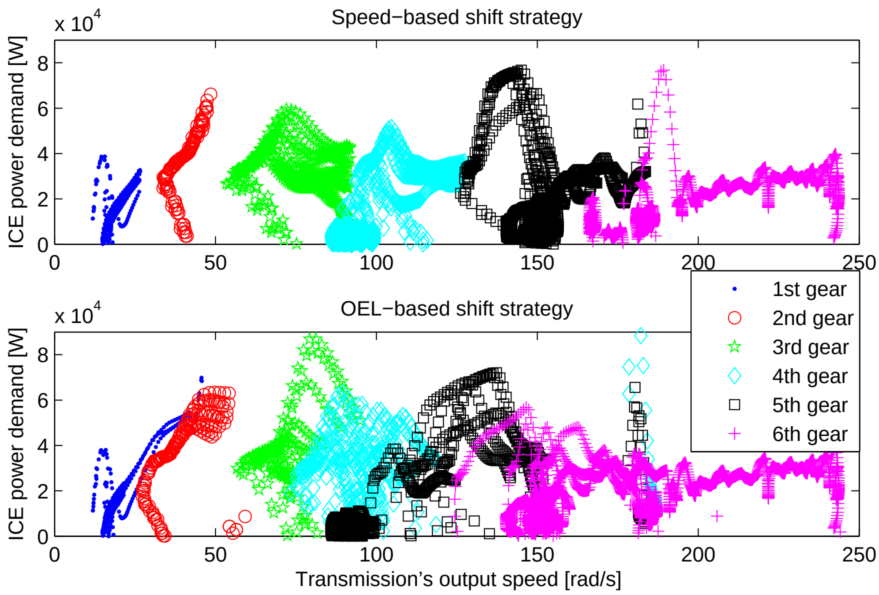


Figure 7.3: *Gear operating points of the rule-based shift strategy (top) and the OEL-based shift strategy (bottom), for positive powers in hybrid driving.*

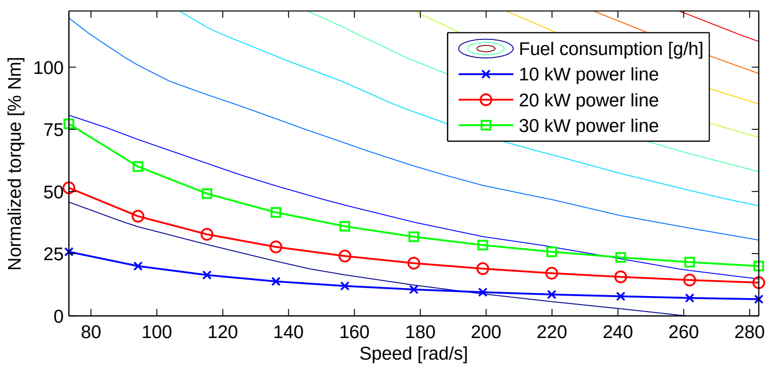


Figure 7.4: *The fuel consumption of the ICE together with three typical power lines.*

The gear operating points for the negative powers are shown in Figure 7.5 for the two shift strategies. Now the gear shifts are done toward optimizing the efficiency of the EM. The result is reversed compared to the one for positive powers, as the OEL-based strategy tends to chose a *lower gear* compared to the speed-based strategy. The equations in (7.1) still hold for this situation. Since a lower gear results in a higher gear ratio, the input speed is higher. To still fulfill the demanded power, the torque needs to be lowered. Hence, a combination of higher speed and lower torque seems to be favored. This can be explained with Figure 7.6, where three negative power lines are plotted on the efficiency map of the EM, together with the OEL line. The reasoning is not as evident as it was for the ICE, therefore an example is chosen to illustrate. Take e.g. the output speed of 120 rad/s in Figure 7.5, where the speed-based shift strategy choses the 5th gear, and the OEL-based shift strategy mainly choses the 4th gear. This results in an input speed of:

$$\begin{array}{rcll} \text{Speed-based:} \quad \omega_{\text{in}} & = & GR_{5\text{th}} \cdot \omega_{\text{out}} = 1.0 \cdot 120 = 120 & [rad/s] \\ \text{OEL-based:} \quad \omega_{\text{in}} & = & GR_{4\text{th}} \cdot \omega_{\text{out}} = 1.4 \cdot 120 = 168 & [rad/s] \end{array} \tag{7.2}$$

At the chosen output speed of 120 rad/s the power is about -15 kW, and therefore this line should be followed. In Figure 7.6 the two resulting input speeds are indicated with arrows, and it is seen that the OEL-based shift strategy managed to get closer to the OEL line.

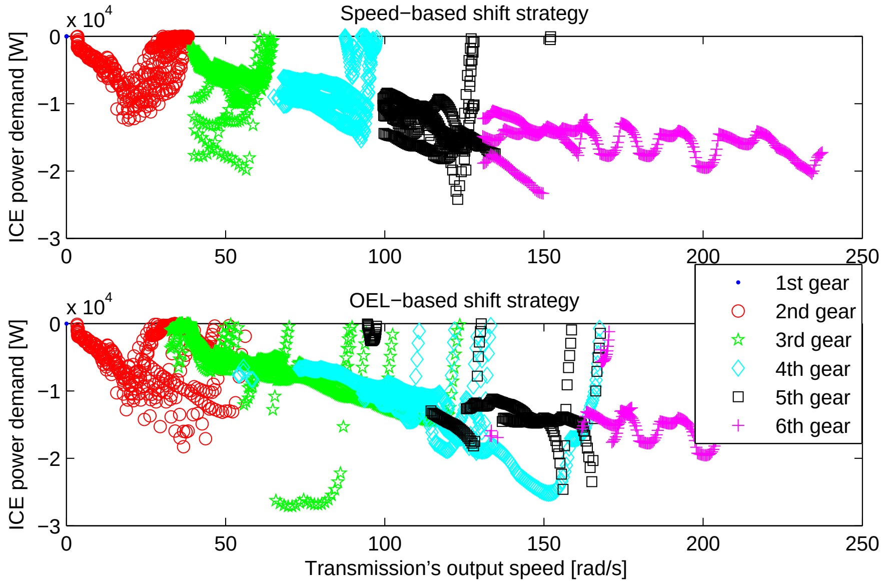


Figure 7.5: *Gear operating points of the rule-based shift strategy (top) and the OEL-based shift strategy (bottom), for negative powers in electric driving.*

Another thing that is discovered when changing the gear shift strategy, is the importance of *when* and *how often* the gear shifts occur. If there are many gear shifts at the beginning of the regenerative braking situation, much of the kinetic energy of the vehicle is lost (velocity squared), since during disengagement of the gear no recuperation is possible. Therefore, one should strive to have as few gear shifts as possible during the regenerative braking, especially at high velocities. Though if there are few gear shifts, it will limit the possibility to get close to the OEL line. A trade off has to be made of how the gears should be selected.

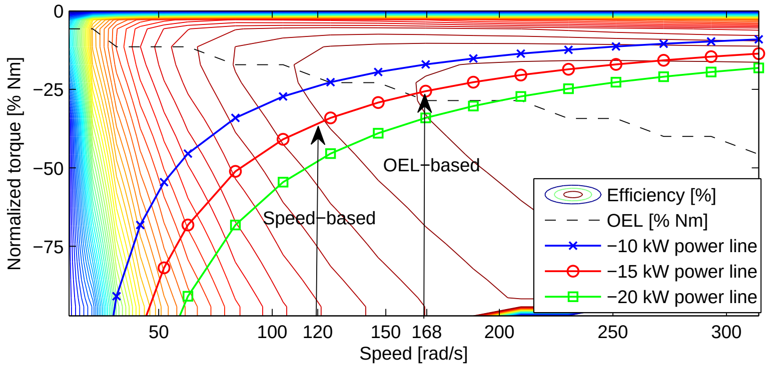


Figure 7.6: *The EM efficiency map together with three typical power lines and two arrows used in an example.*

7.4 Table-Based Strategy With Adapted Gear Shift Strategy

When the table-based strategy was developed in the Dymola software, an adapted gear shift strategy was developed as well. This adapted shift strategy is based on the table-based HMS, and they can be considered as one system since they are actively communicating with each other. To show the effect of having an adapted gear shift strategy to the HMS, the table-based strategy is simulated with its adapted shift strategy. The result is presented at the bottom of Table 7.4, together with the previous data from Table 7.3. It should be noted that the simulation is done in Dymola rather than in Simulink, but when simulating the other setups in Dymola, it showed similar results as in Simulink, and therefore the results can be compared. The result shows that the fuel consumption can be lowered even further, with about 3 % points, if an adapted shift strategy is used with the HMS. Hence, the importance of the shift strategy is clearly realised.

Table 7.4: *Fuel consumption results for the two HMSs for three different routes, expressed relative to the base value of 100% set for the conventional vehicle with the OEL-based gear shift strategy.*

HMS	*Customer*
OEL-based shift strategy	
Conventional	100 %
Rule-based	88.2 %
Table-based	88.8 %
Speed-based shift strategy	
Conventional	105.9 %
Rule-based	92.2 %
Table-based	95.4 %
Adapted shift strategy (Dymola)	
Table-based	85.6 %

7.5 Summary

This chapter shows how the two HMSs are able to handle a second gear shift strategy, as well as the gear shift strategy's impact on the HEV itself. The first gear shift strategy, denoted speed-based shift strategy, which has been used in the previous chapters, is based on the speed of the output shaft and the throttle position. These two variables are inputs to two different look-up tables; one for upshift and one for downshift. The outputs are compared to the speed of the input shaft to decide when to do a gear shift.

The second gear shift strategy, denoted OEL-based shift strategy, instead tries to make the active power source decide the preferred gear, so that it is operating at a high efficiency. It gets the demanded power from the driver and a look-up table's output is the optimal ICE or EM speed. An output is computed to find the best gear. The OEL-based shift strategy needs features to prevent the input shaft speed to get too high or too low, and the hysteresis between different gears need tuning. A large hysteresis means bad following of the desired gear, but better regenerative braking and less synchronization of the ICE. The speed-based shift strategy does not need many extra functions to work, because of its simpler structure. Though, some features are necessary for both shift strategies, e.g. to avoid dead-lock, and these are implemented.

The two HMSs are both able to perform well with the OEL-based shift strategy, but none of the HMSs gets any direct advantage compared to the other. The importance of the gear shift strategy itself is realized, as the shift strategies are compared. The OEL-based shift strategy saves more fuel when driving with the ICE, since it often selects a higher gear, resulting in a lower speed and higher torque. When the vehicle is driven electrically, the OEL-based shift strategy selects a lower gear, which gives a higher speed and lower torque. It seems that the best way to shift the gears is to consider the active power source, i.e. the ICE or the EM.

The table-based HMS also has its own gear shift strategy, developed in Dymola. The combination of the table-based HMS and its adapted shift strategy gives better results than the other setups.

Chapter 8

Conclusions and Recommendations

This chapter first provides the main conclusions from the preceding chapters, and then the recommendations for future work. Results that were expected will not be thoroughly explained, e.g. the benefit of HEV compared to conventional vehicle.

8.1 Conclusions

The main objective with this thesis is to evaluate two different HMSs, a rule-based and a table-based. This is a complicated task for several reasons. One aspect is the influence of different external factors outside of the HMS, e.g. driver behavior, chosen cycle or influence of the vehicle model, like different gear shift strategies. As can be seen in the tables giving the fuel consumption results, these factors affect the rule-based strategy and table-based strategy differently. It is therefore difficult to give a clear answer which one of the two HMSs that is performing best, since the answer depends much on the circumstances.

Another factor which complicates the analysis of the HMSs is the influence of the parameterization. Obviously the HMS does require reasonable parameterization, but it is difficult for the observer to derive the benefits to either a good structure of the HMS, or a good choice of parameters.

The two HMSs show quite different behavior, as is seen in the choices of vehicle mode from the SML, and the torque split between the ICE and the EM in the TD. The SML for the table-based strategy shows a strong tendency, for the current parameterization, to drive in Hybrid Drive. The rule-based strategy drives on the contrary much more in Electric Drive. The TD for the table-based strategy is much more active than the TD for the rule-based, both for increasing and decreasing the ICE working point. This will lead to more use of the EM and might have an effect on the life cycle of the battery and the EM.

Even though there are differences between the two HMSs, the fuel consumption results are similar. The primary reason for this is the current vehicle setup. Since it is not possible to turn off the ICE while driving, the potential fuel savings of decoupling the ICE are not that high. The ICE efficiency map has smooth characteristics which limits the benefits of moving the working point. The subject about small changes in fuel consumption is discussed in Section 5.1.4, concerning parameterization of the rule-based strategy.

One clear difference between the HMSs is how the SoC is controlled. The table-based strategy always tries to control the SoC in the desired direction. The rule-based strategy only tries to affect the SoC when it is too close to the allowed battery limits. With the current parameterization, the SoC controller in the table-based strategy is very active, which means there is a strict control of the SoC. This leads to, in some cases, that much energy can be recuperated while braking, but also that the electrical energy is discharged in ways that are not optimal. An example of this is when the SoC is high after recuperation during a downhill, and the vehicle starts to increase its velocity. The table-based strategy discharges with the TD during the acceleration phase. On the contrary, the rule-based strategy uses the electric energy after the acceleration phase, and drives electrically. From a fuel consumption perspective, it seems to be better to use the energy in Electric Drive rather than in Hybrid Drive, and therefore the rule-based strategy is better in this case. If the cycle is different, with no possibility to drive electrically before braking, the table-based strategy is better. In this case the SoC will become too high for the rule-based strategy, and the battery can not recuperate all the electrical energy available during the braking.

There are other types of vehicles where a strict control of the SoC is very important, e.g. to always keep a high SoC when coming to a standstill, to be able to power certain applications. If such a vehicle would be simulated, the benefit of a more controlled SoC, and the importance of the SoC controller, would become more evident. Another factor which also favors a more controlled SoC has to do with the EM boost functionality. If the driver is used be able to e.g. overtake with extra power from the EM, this should always be possible. But when the SoC runs low, this feature is not available any longer. With an SoC controller, which can have a high set value, it would be easier to guarantee this EM boost functionality.

The study of HMSs is an important topic to make the hybrid vehicles established in the automotive industry, and still much work can be done related to this area.

8.2 Recommendations for Future Work

ZF has done extensive work with the HEV and this thesis is a part of that work. There is more work to be done within the HEV simulations, and here some recommendations are given for the future work. The recommendations are primarily given within the areas dealt with in this thesis.

One part of this thesis is to correct and improve the behavior of the system. Examples of these changes are to avoid mathematical errors and to avoid letting the vehicle perform in an undesired way. The changes are made in the HMSs and in the vehicle model, but not in the operational layer, since it is a black box in this thesis. This means that changes which in fact should be in the operational layer, are in other parts. Therefore, all the implemented changes should be verified so that they function as planned, independent of e.g. the cycle, gear shift strategy or design layout.

To improve both HMSs the benefits of them has to be found and analyzed, and the ideas from them should be combined to see if the fuel consumption results improve. An example is the functionality in the rule-based strategy, to go to Hybrid Drive when the SoC gets close to its limits. This might also improve the results for the table-based strategy, if it would be implemented in that one.

Some work has been done to find parameters for the rule-based strategy in a structured way, with the mathematical method for the TD. Further work needs to be done within this area, e.g. by dynamic programming or with a script that does many trials and extracts the best parameters. Both these approaches will require much computer resources. Another way could be to improve the scripts used in the thesis, so that they use data from the hardware to suggest suitable parameters.

Further work should be done on the "human machine interface" between the driver model and the vehicle model. If it is implemented well, the vehicle behaves in a way that the driver expects. This means e.g. that the response from the acceleration and brake pedal in the vehicle should be independent of the SoC level.

The actual vehicle has a direct connection between the brake pedal and the mechanical brakes, and therefore there is a special implementation for the brake management. In the future, there should be an explicit part for the brake management, which can handle different vehicle setups. An example is for configurations which can split the braking force, requested from the brake pedal, between the EM and the mechanical brakes. For this setup the desired braking force should be fulfilled and the recuperated energy maximized.

It would be a good idea to analyze if the vehicle weight should have a bigger influence in the design of the HMSs. This is especially interesting for trucks, which have big differences in weight depending on the load they are carrying. As can be seen in the thesis, the working point of the ICE is dependent on the vehicle weight. This may influence how the EM should increase and decrease the ICE working point. The vehicle weight also affects the recuperated energy, since a higher weight means more kinetic energy, which can be stored in the battery.

When doing the analysis of the two HMSs, focus has been on minimizing the fuel consumption. It has not been evaluated how the hardware handles the different strategies. Maybe a lower fuel consumption can be achieved to a cost of higher wear and tear on the components. E.g., the table-based strategy, with the current parameterization, lets twice as much electric energy go through the battery compared to the rule-based strategy for some simulations. The influence of the HMSs on the comfort of the vehicle is important for the owner of the vehicle, and needs further analysis. Also the influence of the HMSs on the emissions needs to be investigated.

The simulation results show both positive and negative aspects with an explicit SoC controller (as in the table-based strategy), and therefore further work could be done on how to optimize it. The desired behavior of the SoC controller needs to be specified, and then the parameterization can be done. An SoC controller with knowledge about the route, from e.g. a GPS, is another topic that can be looked into.

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Appendix A

State of Charge Level

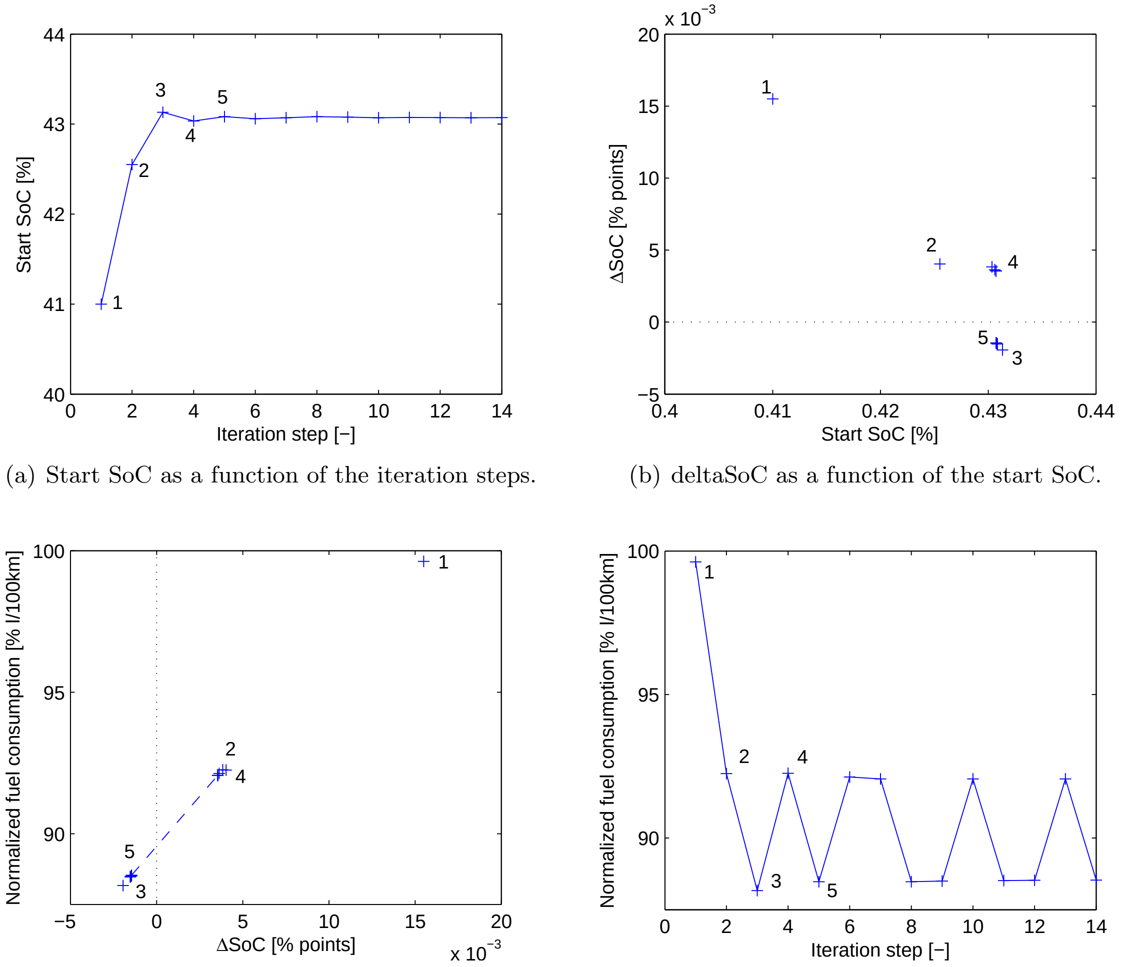
One result of the algorithm balancing the SoC is presented and discussed here, to give more understanding about how it works.

In Figure A.1, the result from one simulation is shown and the first five iterations are numbered. First focus on the two top plots. The first simulation starts with an SoC of 41% (arbitrary value) as in Figure A.1(a), and finishes at a higher SoC level (not shown in the figure), which gives a positive ΔSoC as in Figure A.1(b). Hence, the best guess for the new start SoC is a higher value, which will make the difference in start SoC and end SoC smaller. Therefore a positive value is added to the current start SoC, and used as the new start SoC for the next simulation as in iteration 2 in Figure A.1(a). This simulation also finishes at a higher SoC level compared to the start value, and a gives a positive ΔSoC as in iteration 2 in Figure A.1(b). Again a positive value is added to the current start SoC to become the new start SoC, as in iteration 3 in Figure A.1(a). For the third simulation the result is different. It finished with a lower SoC level compared to the start SoC, and the ΔSoC becomes negative, as in iteration 3 in Figure A.1(b). Therefore, a negative value is added to the current start SoC to make out the new start SoC. The algorithm continues in this way, and the start SoC converges around a value of 43.1%, as in Figure A.1(a). As seen in Figure A.1(b), the ΔSoC never manages to get completely to zero, but switches around the zero line for the last iterations.

Computation of the fuel consumption
The behavior of the ΔSoC is also seen in Figure A.1(c), which shows a plot of the fuel consumption as a function of the ΔSoC. The fuel consumption strongly changes even with a small change in ΔSoC. As seen for these simulation results, it is very difficult to get a ΔSoC of zero. For example if the start SoC for simulation 4 was chosen as the best start SoC, a fuel consumption of around 92 [% l/100km] would be the result. But if the start SoC for simulation 5 was chosen instead, a fuel consumption of around 88 [% l/100km] would be the result. This becomes even more evident when looking at Figure A.1(d), where the fuel consumption is plotted for every iteration. For iteration six and seven, the fuel consumption is not changing much, compared to for example between iteration seven and eight. Hence it is difficult to "estimate" a certain behavior of the complex system, which is an effect from its high non-linearity due to e.g. hysteresis. Therefore, since a ΔSoC of zero is difficult to obtain, and the fuel consumption is very sensitive to the start SoC, an interpolated value will be used as the final fuel consumption for the different simulations. It is computed as the interpolation between the two best fuel consumption values, obtained from the best positive ΔSoC and the best negative ΔSoC. This is represented in Figure A.1(c), where the dashed blue line

hits the zero line of the ΔSoC.

It can be noted that the behavior of a strategy might change due to different start SoC values. For example if one setup would have a balanced SoC at 50%, it has a (large) span of 20% in which it can vary its SoC (maximum limit 60% - minimum limit 40%). If a second setup has a balanced SoC at 59% and a third one at 41%, they would be limited by the upper limit and the lower limit respecticely. Though, he fact that a balanced SoC for every simulation is necessary for the comparison, makes the effect accaptable. Also for a small battery size, this effect will become less stressing, since the battery limits will be reached easier throughout the smilumation.



(a) Start SoC as a function of the iteration steps.

(b) deltaSoC as a function of the start SoC.

(c) Fuel consumption as a function of the deltaSoC.

(d) Fuel consumption as a function of the iteration step.

Figure A.1: *Four plots of the algorithm which gives the best balanced SoC and the fuel consumption.*