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Energy Management in a Hybrid Vehicle Using Predicted Road Slope Information

Master of Science Thesis

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Abstract

Energy management in a hybrid vehicle is about optimizing a problem with several uncertainties. By decreasing the number of uncertainties new methods can help to provide better strategies. In a non-predictive energy management, there is no information available about the future driving conditions whereas in a predictive method future information together with past and present data is used within the strategy. If all future information is available, the optimal solution for the drive cycle can be found, but in reality, due to uncertainties in the driving conditions, some estimations must be made. Therefore it is interesting to see how limited information can affect the fuel consumption.

In this thesis, a method is developed based on having limited information about the upcoming driving condition consisting of an altitude profile provided by GPS, but there is no information about future speed profile. The results show up to roughly 2.5% less fuel consumption in comparison with a non-predictive energy management strategy, depending on the drive cycle. While fuel consumption is a decisive factor to conclude in an energy management strategy, battery wearing and drivability are inevitably needed to be considered as well.

The effectiveness of this new method depends on the level of variations in altitude profile and capacity of the battery. In more hilly drive cycles there is more opportunity to employ the information provided by altitude prediction of the road. Furthermore, it is showed that increasing the battery size can help the vehicle to have better performance in very hilly roads. As a result in one of the hilly drive cycles 100% increase in the battery capacity yield 2.7% less fuel consumption whereas in case of halving the battery size the increase in the fuel consumption is 6.5%.

Acknowledgement

We would like to thank our supervisor Astrid Lundgren in Volvo Technology who helped us a lot throughout this master thesis work and our examiner at Chalmers, Professor Torbjörn Thiringer, who guided us with his helpful contributions.

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Fredrik Johansson & Ali Rabiei
Göteborg, June 2010

Preface

Volvo concurs that Hybrid drivelines are an important step to reduce fuel consumption and, consequently, reduce the emissions of carbon dioxide [1]. The international “Highly Automated Vehicles for Intelligent Transport” project (HAVEit) aims at the realization of the long term vision of highly automated driving for intelligent transport. Within HAVEit, “Active Green Driving” (AGD) is a subproject which focuses on developing an advanced interface between the driver and the vehicle, in order to reduce the fuel consumption and emissions in heavy hybrid vehicles using a control strategy improved by forward looking sensors. With this predictive information the power split between the internal combustion engine and the electric machine can be adapted to use the energy storage in the most efficient way [2].

So far a non predictive energy management strategy has been created and simulated. Map data and Global Positioning System (GPS) enable construction of an electronic horizon on board in a vehicle. Based on this information the future drive cycle can be estimated and the energy consumption can be optimized with information about both the present situation and the predicted future. There can be times when the ICE can be turned off in the case when downhill driving is predicted. This is one of the advantages compared to the non predictive method which only optimizes the energy consumption based on present information.

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Abbreviation list

AGD	Active Green Driving
DP	Dynamic Programming
ECMS	Equivalent Consumption Minimization Strategy
EM	Electric Motor
EMS	Energy Management Strategy
GPS	Global Position System
HAVEit	Highly Automated Vehicles For Intelligent Transport
HEV	Hybrid Electric Vehicles
ICE	Internal Combustion Engine
pRSG	Predictive Reference Signal Generator
SOC	State of Charge

Symbol List

A	Area of vehicle front side
C_d	Rolling Resistance
C_{rr}	Rolling friction coefficient
$E_{auxiliary}$	Auxiliary demand between each prediction sample
$E_{battery}$	The total capacity of the battery
$E_{extreme}$	The additional energy needed beyond the maximum limit of the ICE
g	Gravitational acceleration
k	Index of predicted samples
k_{pMax}	Maximum gain of weight controller
k_{pMin}	Minimum gain of weight controller
m	Vehicle mass
m_f	Mass of fuel
$P_{electrical}$	Electrical power
P_{fuel}	Chemical power in the fuel
$ratio_{sample}$	Ratio of the travelled distance between two samples
$ratio_{horizon}$	Ratio between the consumption modes in the prediction
$SOC_{em\text{-}acc}$	Part of SOC_{ref} based on accelerations with EM

$SOC_{extreme}$	Part of SOC_{ref} based on calculations of extreme energy demand
$SOC_{kinetic}$	Part of SOC_{ref} based on changes in kinetic energy
SOC_{max}	Maximum allowed SOC level in the battery
SOC_{min}	Minimum allowed SOC level in the battery
SOC_{mode}	Part of SOC_{ref} based on mode calculations in the strategy
SOC_{ref}	Reference SOC level
SOC_{set}	Set value of preferred SOC level
SOC_{usable}	The amount of SOC that can be spent in current consumption mode
t_0	Start of prediction
t_1	End of prediction
T_{demand}	Torque demanded by the driver
T_{GB}	Torque of gear box
$T_{ICE,Max}$	Maximum torque of the internal combustion engine
$u(t)$	Torque split as a function of time
v	Actual vehicle speed
v_{mAvg}	Speed prediction based on moving average speed
v_{set}	The demanded set speed from the driver
W	Weight of electrical energy
W_{nom}	Nominal weight when SOC is equal to SOC_{ref}
$z(t)$	Discrete states as a function of requested torque, speed and time
$\Delta h(k)$	Height between each predicted sample
$\Delta SOC_{total\ reg}$	Total amount of energy predicted to be recuperated within the drive cycle
$\Delta SOC_{ch\ sus}$	Amount of SOC needed to ensure charge sustainability
$\Delta x(k)$	Distance between each predicted sample
$\Delta\theta(k)$	Road slope between each predicted sample
$\eta_{whl/bat}$	The efficiency of the conversion of energy from wheel to battery
ω	Angular engine speed

1 Introduction

One of the very first hybrid electric vehicles (HEVs) was Lohner-Porsche's Mixte, designed by Ferdinand Porsche in 1900 [3]. For the next few years different electric vehicles were competing with the cars powered by petroleum based fuels. By the 1920s, the demand for longer-range vehicles, driven by increasing sophistication of road building, plus lower price of the petroleum based fuels and the mass production of reasonably priced internal combustion engines (ICE) all led to reduced demand for electric powered vehicles. From the 1930s to the 1960s electric vehicles were barely developed beyond those of the very early years. However, the 1970's saw electric vehicle once again come to the attention of motor-manufacturers owing to a growing realization of the need to reduce the dependency on imported foreign crude oil and to limit exhaust emissions [4]. Since then, different HEVs have been developed in the automotive industry. The main breakthroughs in this field have been driven in recent decades by legislation to comply with tougher emission regulations and the increases in oil prices.

1.1 Problem background

So far, a non predictive energy management strategy (EMS) for a parallel hybrid bus has been developed and simulated. A map database together with a GPS system enables construction of an electronic horizon system on board in the vehicle. With this information the future drive cycle can be estimated and the energy consumption can be optimized based on the information about both present states and the predicted future. This is an advantage compared to the non predictive method which only optimizes the energy consumption based on present information.

For control and optimization of the energy flow from generation to consumption in the bus, an EMS is implemented. In this report, the aim of the EMS is to guide the vehicle to drive a route with the minimum possible fuel consumption while maintaining a charge sustaining operation of the electric storage device without decreasing the drivability of the bus. This is done by optimizing the overall system efficiency of the four basic components (ICE, electric machine (EM), battery and transmission). There are many different types of EMS and the level of complexity is depending on its aims and the prerequisites of the available information.

1.2 Purpose of the work

The aim of this work is to develop a strategy that will try to optimize the price of electric energy along a drive cycle, merely based on the information of the future road inclination which is derived from the e-horizon system. A goal is to use the price as an input to the EMS where the overall control of the energy flow in the whole system is processed. Finally the objective is to compare the developed strategy with different strategies used within the HAVEit-AGD project at Volvo Technology.

1.3 Limitations and prerequisites

The developed algorithm should be well adapted to the architecture of the previously designed energy management algorithms within the AGD-project, without requiring any major changes within the existing system.

The developed algorithm should be robust regarding sensitivity to uncertainties in input signals as well as performance in different types of traffic situations such as; urban, suburban, highway, etc. It should also be implemented in a way so that as few tuneable parameters as possible are used.

Since the processor- and memory capacity of the control unit in the bus is limited, the developed algorithm should not require more computational power than available when running the implemented control online in the test vehicle.

The predicted road inclination is used in the control algorithm, however further information of the future drive cycle e.g. predicted vehicle speed, road signs and traffic lights are not available.

The prerequisite in this master thesis is a predicted electronic horizon consisting of slope as a function of distance without any information of the speed trajectory during the future drive.

2 Background theory

2.1 Previous work

With regards to the information available for the EMS, they can be divided into two categories. It can either rely on information about previous and present condition or include prediction of the future circumstances. The EMS based on previous and present information, non-predictive EMS, aims for instantaneous optimization of the energy flow in the system. Since no information about the future driving condition is taken into account, the optimal solution for the entire drive cycle cannot be guaranteed. In contrast, the EMS based on future as well as present information, predictive EMS, can guarantee global optimal solution during the entire drive cycle. However, in reality this can seldom be achieved due to uncertainties in the prediction, such as other road users and the behaviour of other dynamic events influencing the traffic situation.

When all information about the future, such as requested torque and speed trajectory, is taken into account, dynamic programming (DP) can be used to find the theoretical and global optimal solution for an entire drive cycle. One of the biggest problems with DP is that it requires much computational power due to the number of operations that must be carried out and the amount of data that must be kept in the memory. Another drawback is that it requires all information about the future to be well formulated for all its task execution [5].

In [6] it is suggested to use approximate dynamic programming which, even though includes heuristics and much less grid points that divides the drive cycle into smaller segments, can give low fuel consumption with less than one percent higher compared to the DP. When the energy management is adapted into the environment in the hybrid bus, the computational power is restricted and the possibilities to use methods which are heavy to run in real time online are restricted. Other strategies which are more simplified and use less information about the future from sensors and other measurement equipment are therefore favourable if they can reach competitive fuel consumption values.

In several papers the equivalent consumption minimization strategy (ECMS) is used as a base in different vehicle configurations. ECMS, which is a simplified deterministic EMS, consists of evaluating the instantaneous cost function as a sum of the fuel consumption and equivalent fuel consumption related to the state of charge (SOC) level in the battery, since the electric- and fuel energy are not directly comparable. This equivalent factor is basically evaluated by considering average energy paths leading from the fuel to the storage of electrical energy [7]. There are several suggestions presented in other papers where different symbols or letters has been used for this equivalent factor. In this report the equivalent factor is called weight and is abbreviated as W. There are several concepts presented to adapt W online in a vehicle.

With information from the global position system (GPS) about the topographic profile and the average speed on each of the road segments of the planned trip, one paper [8] concludes that a predictive reference signal generator (pRSG) controlling the desired SOC together with the non-predictive ECMS, yields considerably better fuel consumption compared to only a non-predictive ECMS when driving on hilly roads. The problem of charge sustainability, which is the ability to ensure a predefined SOC level in the end of the prediction, is also considered. Since both strategies are causal they cannot exactly guarantee that the specified final SOC level is achieved.

2.2 Hybrid electric vehicle configurations

A hybrid vehicle combines two or more different power sources, allowing diversification of energy resources aiming for more fuel efficient and less polluting vehicles [9].

There are several drive train configurations such as series, parallel and series-parallel hybrid. In the series hybrids, the ICE drives an EM to produce electric energy that is stored in a battery and a separate EM powered by the battery and/or the EM is the only means of the propulsion of the vehicle. The parallel hybrid vehicles can use both the EM and the ICE to propel the vehicle simultaneously [10]. The battery can be charged through the EM either by the energy recuperated during the braking or by the energy produced by ICE.

In this report, the simulated bus is a parallel hybrid. In *Figure 1*, an overview of the energy flow in a parallel hybrid system is illustrated.

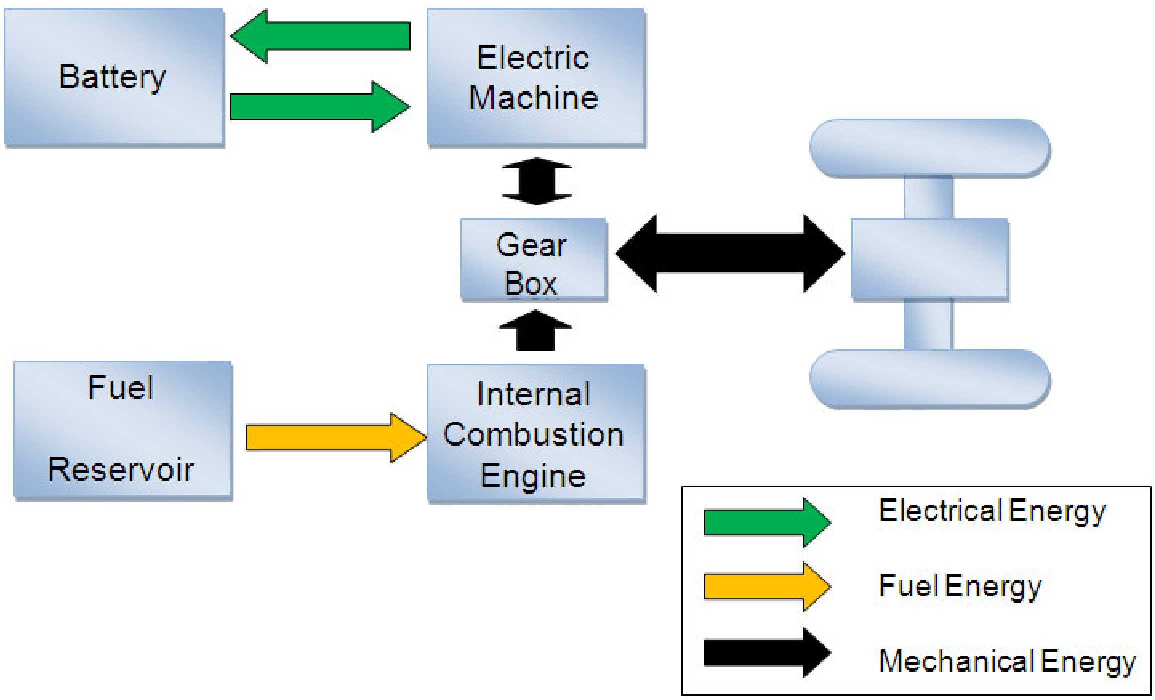

***Figure* 1**: An overview of the energy flow in a parallel hybrid vehicle.

2.3 Energy management strategies

There are several different types of HEV configurations and different control strategies which are needed to control the energy- and power flow to and from different components in the vehicle. All of these control strategies aim to satisfy a number of goals for HEVs. There are four key goals [9]:

- Maximize fuel economy
- Minimize emissions
- Minimize system costs
- Good driving performance

2.3.1 ECMS

Due to SOC charge sustainability requirement in a hybrid vehicle, the usage of the electric motor decided by the control strategy has to take not only the fuel consumption into account, but also the variations in the stored electrical energy. To deal with such aspects, various approaches have been proposed. It can be a PID controller with a tuning parameter which is adjusted according to the current SOC deviation or it can be a solution to an optimization problem. A more promising method is however to evaluate an instantaneous cost function as sum of fuel consumption and an equivalent fuel consumption related to the SOC variation. This method is called ECMS. In this EMS the power of the fuel is compared to the power of electric energy times the equivalent factor and the sum is minimized in a cost function according to equation (1). As a result, this equivalent factor is also called price of electricity since it compares the weighted electric energy to the energy in the fuel.

$$\min(P_{fuel} + W\ P_{electrical}) \tag{1}$$

The theoretical foundation of the ECMS can be derived by simplifying the following deterministic energy management problem [11]:

$$\min_{u(t),z(t)} \int_{t_0}^{t_1} \dot{m}_f\,(t,u(t),z(t))dt \tag{2}$$

with the following constraints

$$\frac{dSOC}{dt} = f\,(t,u(t),z(t)) \tag{3}$$

$$SOC(t_0) = SOC(t_1) \tag{4}$$

$$SOC_{\min} \le SOC(t) \le SOC_{\max} \tag{5}$$

In equation (2) and (3), u(t) represents the torque split between the internal combustion engine and electric motor and z(t) is the discrete states assumed to be a function of the requested torque and speed trajectories.

The battery limitations which are further explained in *3.1.1* are fulfilled in equations (3) and (5). The charge sustaining criteria is fulfilled by equation (4) where the SOC level in the end of the prediction, t_1 should be same as in the start of the prediction, t_0.

In *Figure 2*, the overall path of energy management based on ECMS is showed. The calculation of the equivalent factor, weight, is the main focus in this thesis work. This equivalent factor is later on used in the ECMS where the torque split between the ICE and EM is being performed.

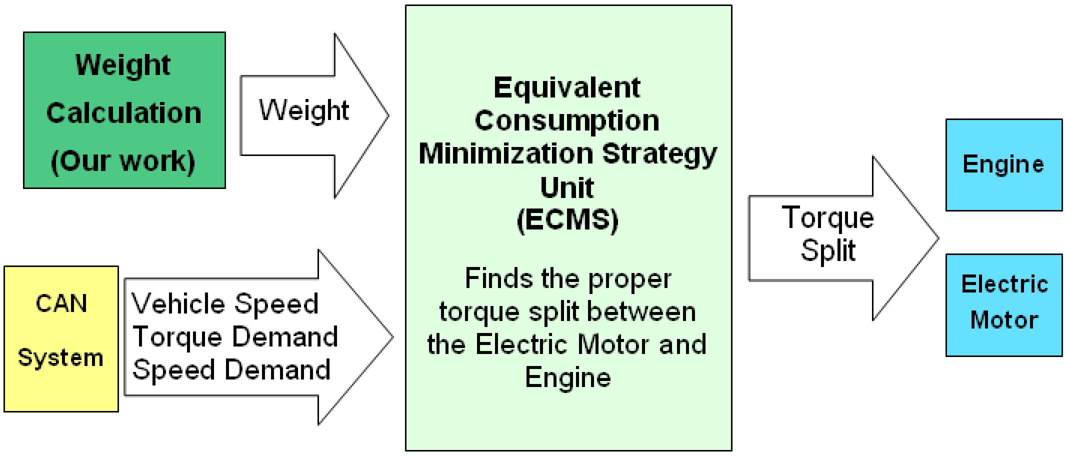

Figure 2: *The inputs and outputs of the ECMS.*

2.3.2 ECMS using weight function with pRSG

The inputs to the calculations of W, can rely on either predictive or non-predictive data. A non-predictive input can have a constant SOC_{ref} level and use it as a threshold when comparing it to the actual SOC. This will lead to a higher price of electric energy if the SOC is below the reference level or low price of electric energy when the SOC is above the reference level. The variation of the price can be set in a way to avoid violation of the SOC-window restriction, which is a prerequisite to extend the lifetime of the battery to a feasible level. A control strategy with a constant reference value provides good fuel economy as long as the battery is sufficiently large to absorb all the energy which is available during the recuperation events. If the amount of energy produced during the recuperations exceeds that limit, for instance in hilly driving profiles, the performance of the ECMS with a constant SOC reference value can decrease considerably.

If the weight function uses predicted data for estimation of the price, it can be called a predictive reference signal generator (pRSG). Within this thesis a signal generator is developed which is used to generate equivalent factor. The developed strategy will result in a SOC_{ref}-trajectory of the preferred level in the battery along the predicted drive cycle, based on the proposed strategy in [8]. Here the drive cycle is divided into fixed and free segments based on the information of the topographic profile and the average speed of the segments. The fixed segments are segments where the supervisory control cannot explicitly control the SOC level. This can be where the powertrain is either boosting, the torque from the gearbox is higher than what the ICE can produce ($T_{GB} > T_{ICE,max}$), or in recuperation mode when the electric machine is used as an generator ($T_{GB} < 0$). In these cases the electric path is determined by the driver or the drive cycle. The free segments are between the boosting and recuperation modes, where a SOC reference trajectory is generated based on the future predicted recuperative energies converted into SOC changes. These SOC changes are used together with the charge sustaining criteria to decide where the SOC level should increase, or decrease, to ensure that the use of the battery is optimized within the constrains.

3 System description

3.1 Vehicle components

In this section the components of the vehicle which are important for the energy management strategy are explained.

3.1.1 Energy storage system

Lithium-ion batteries are favourable to be used in hybrid vehicles because of their various advantages over other battery technologies. Lithium-ion batteries possess both a high specified energy and a high specified power. [12]. In spite of these advantages there are some improvements needed and there are further researches that needs to be done about batteries and their properties, in order to make the Lithium-ion technique more competitive, particularly in terms of costs and lifetime.

The aging of the battery, and consequently the batteries lifetime, are highly dependent on the change of the SOC level as well as the number of cycles it has been used. Also the rate of change in SOC level needs to be considered, together with the depth of the discharge and the temperature distribution within the battery, in order to extend the lifetime to a feasible level. In the simulations, the total energy throughput within the battery is used as an approximation of the battery lifetime.

There are some restrictions for the battery. The SOC-window for instance is limited between SOC_{min} and SOC_{max}, which is usually between 30~60%. These restrictions are considered within the EMS to avoid unnecessary wearing of the battery and premature aging. With regards to the maximum rate of change in the SOC, a higher rate is allowed when the battery is discharged compared to when it is charged. This means that a higher electric power can be transferred between the battery and the electric machine when it is working as a motor compared to when it is used as a generator.

The battery has a total energy of 4.3kWh. The maximum discharge power is 120kW and the maximum charge power is 90kW.

3.1.2 Internal combustion engine

A normal non hybrid city bus usually has a diesel engine of approximately 7 litres and 300hp.The diesel engine in the hybrid bus is a 5 litre engine with 215hp which corresponds to ca 150 kW.

3.1.3 Electric machine

The electric machine has a rated power of 120kW, same as the maximum rated discharge power of the battery. The maximum torque is limited to 800 Nm both when it is used as a motor and as a generator.

3.2 Simulation environment

The bus, its controllers and an anticipated driver are modelled in a MATLAB/Simulink environment as it is showed in *Figure 3*. The developed strategy in this thesis is part of the energy management system block.

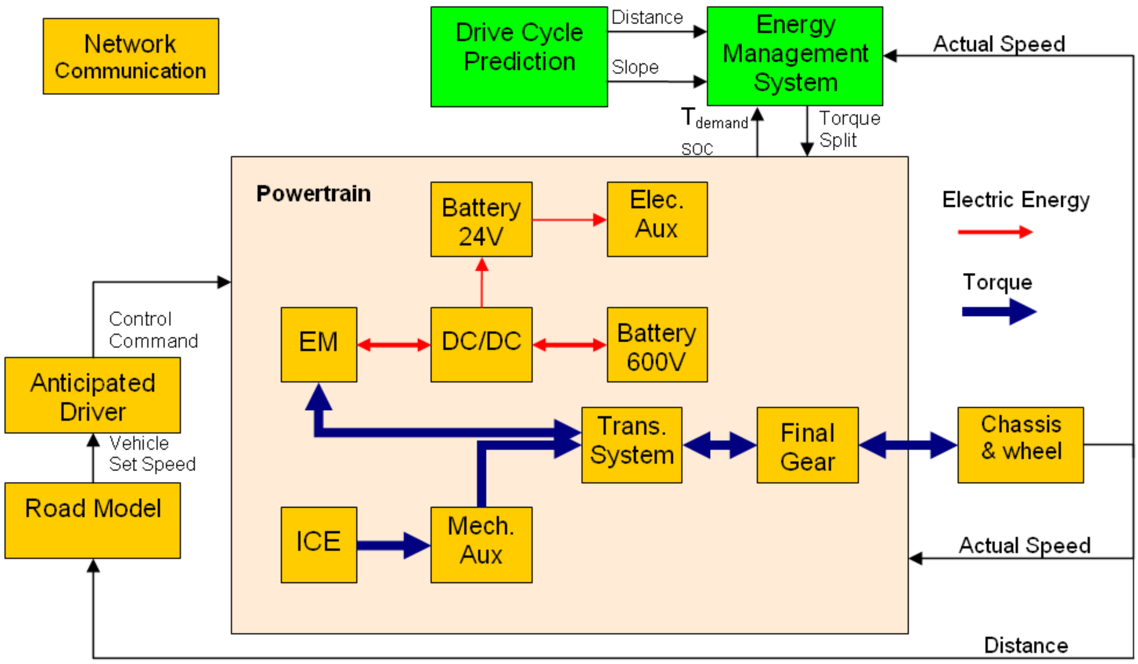

Figure 3: *The simulation environment.*

Anticipated driver

A model of an anticipated driver is developed. The model is a PI-regulator which reacts based on vehicles actual- and set points to decide acceleration, braking, changing gear, etc.

Road model

This part of the model contains the information regarding drive cycle, road profile and environmental condition along the road including temperature, pressure, etc. The anticipated driver makes decision based on road model values.

Powertrain

The model of the powertrain consists of a 120 kW/ 600 volts Li-Ion battery, a 24V battery for low voltage electric auxiliaries, an electric motor, a 5 litre combustion engine, a DC/DC converter, mechanical and electrical auxiliaries, transmission system and final gear.

Chassis

The chassis model includes the shafts, wheels and chassis.

Network communication

The network communication system is used as a platform to send and receive signals between different units in the entire system.

Drive cycle prediction

This part of the model includes the predicted future conditions of the drive cycle such as slope, distance and speed with information from the forward looking sensors and the e-horizon. This information will be used for energy management system.

Energy management system

This model contains ECMS and other related models which are needed for the energy management. The part of the energy management developed in this thesis is added here. Energy management system is further explained in section *4*.

4 Design of the energy management strategy

The overall configuration of the energy management system is illustrated in *Figure 4*. As can be seen, the equivalent factor between the electric power and the fuel power, W, is produced based on both predictive and non-predictive factors similar to the method explained in *2.3.2*. This weight value along with other data is then used in the ECMS unit to decide the torque split between the combustion engine and the electric motor.

The developed strategy can be divided into three major units; the energy calculation unit, the strategy unit and the weight calculation unit which are described more thoroughly in *4.1*, *4.2*, and *4.3*.

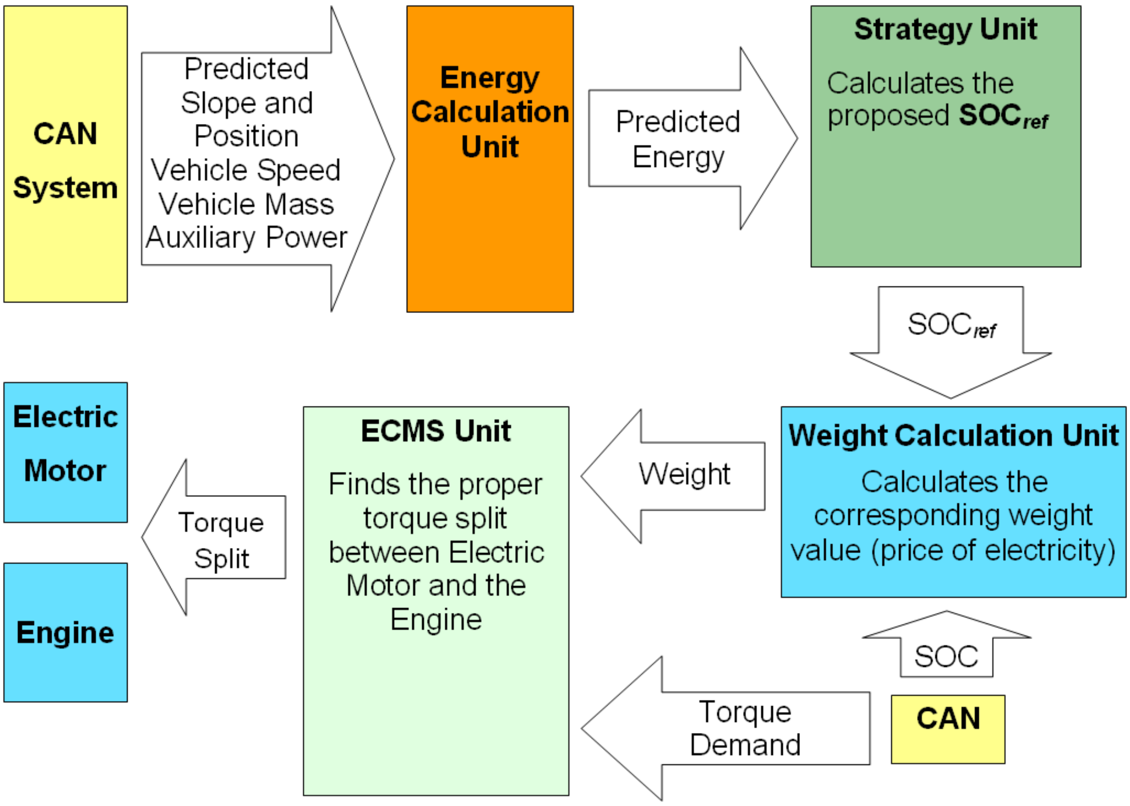

***Figure 4**: Flowchart of the entire energy management system.*

4.1 Energy calculation unit

This unit is used to calculate the energy exchange in the vehicle according to equation (6). ΔE is the amount of energy needed to propel the vehicle at the predicted speed for a given distance. A negative ΔE corresponds to where the vehicle is expected to regenerate energy.

This energy change is calculated for all prediction samples. The calculations include changes in potential energy, air drag, friction and auxiliaries.

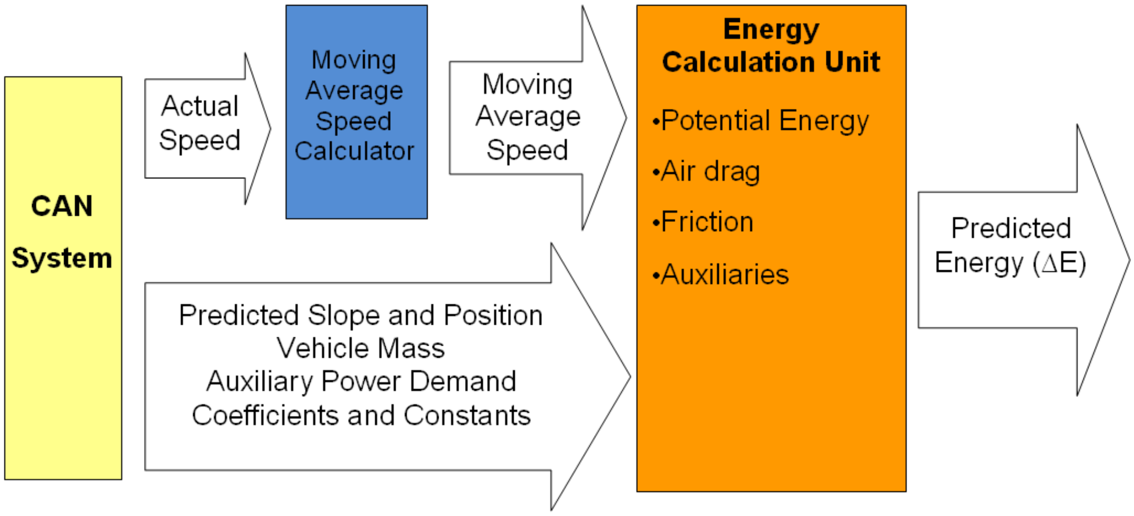

Figure 5: *Description of the energy calculation unit.*

$$\Delta E(k) = mg\Delta h(k)\cdot\sin(\theta(k)) - \frac{\rho\cdot v_{mAvg}{}^{2}C_d A}{2}\cdot\Delta x(k) - mgC_{rr}\cos(\theta(k))\cdot\Delta x(k) - E_{auxilaries}(k) \quad (6)$$

k : Index of predicted samples
m : Vehicle mass
g : Gravitational acceleration
C_d : Rolling resistance
A : Area of vehicle front side
v_{mAvg} : A rough speed prediction based on moving average speed as explained below
C_{rr} : Rolling friction coefficient
$\Delta h(k)$: Height between each predicted sample
$\Delta x(k)$: Distance between each predicted sample
$\theta(k)$: Road slope between each predicted sample
$E_{auxilaries}(k)$: Auxiliary energy demand in the vehicle between each prediction sample

4.1.1 Average moving speed calculator

One of the main constraints for the developed energy management strategy is the lack of a speed prediction. An estimation of the future speed is however needed for the calculation of air drag, among others. To fulfil this requirement, a suggestion is to use the values of the average speed during a number of previous samples. The number of samples should be high enough to represent a valid number but they should not be that high that they increase the needed computational power. For this application the average speed is calculated based on the instantaneous speed during the last 3 minutes. In order to avoid using the samples when the bus is standing still, the calculation is only enabled when the speed is above zero. As a result it is called moving average speed calculator. The initial value is set to 10m/s which is a typical speed in city environment.

4.2 Strategy unit

In the strategy unit, the predicted data amongst other data are used in order to generate the SOC_{ref} trajectory.

As can be seen in *Figure 6* the strategy unit consists of two separated units. In the first unit the predicted data are employed to generate the desired SOC_{ref} trajectory allowed by the physical limits of the battery. The battery prerequisites are described in *3.1.1*. The second unit, extreme torque compensator unit, is an optional unit which can be used for increasing the drivability of the vehicle. By trying to predict where the torque demand is extraordinary high, typically higher than the maximum torque output from the ICE, this unit compensates for those situations by increasing the SOC_{ref} in advance. This scenario is further described in *4.2.2*. The final output from the strategy unit will be used to generate the corresponding weight in the next unit.

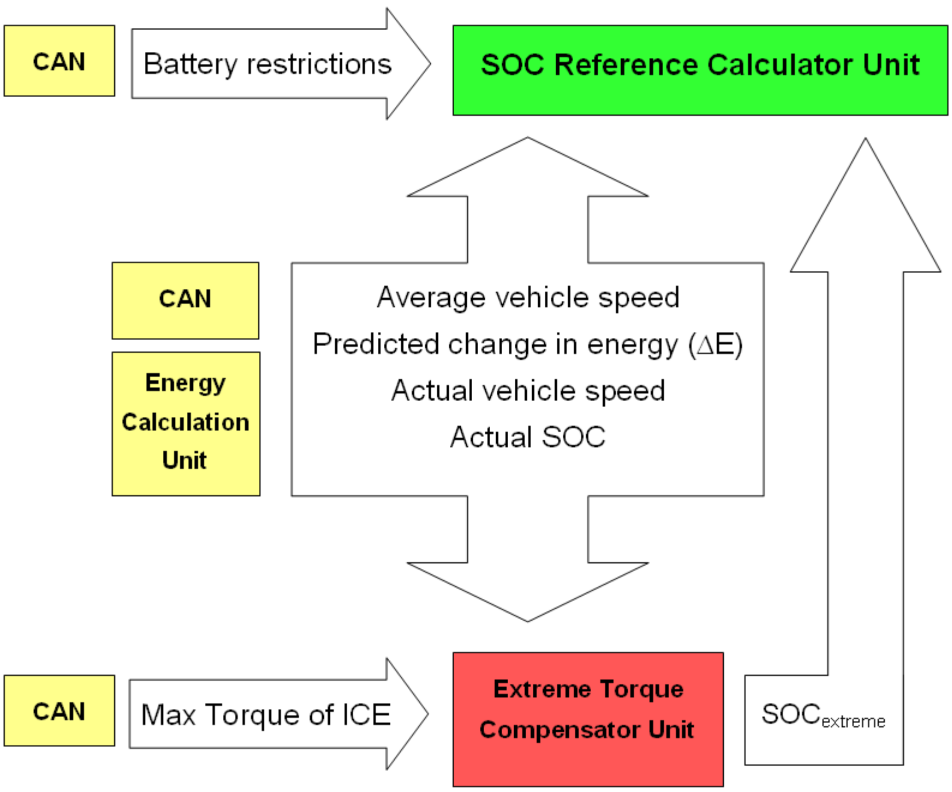

Figure 6: *The strategy unit.*

4.2.1 SOC reference calculator unit

The SOC reference calculator unit is the main part of the strategy unit in which the predicted data are employed. The inputs to this unit are the predicted change in energy (ΔE), the information about speed and the actual SOC level.

The main approach for the SOC reference calculation unit is based on an idea that the total amount of energy during the regenerative sections can be distributed among consumption sections along the upcoming e-horizon. This energy is transformed to its equivalent SOC_{ref} level by dividing it over the total energy capacity of the battery. Hence, the strategy decreases the SOC_{ref} level during the consumption sections as much as SOC is predicted to be increased during the regenerative sections, following the constraint of charge sustainability.

Equation (7) shows how the SOC_{ref} is calculated. SOC_{mode} can either be calculated by equation (8) or by equation (13) depending on which mode the strategy has. The short term variations of SOC due to kinetic energy, $SOC_{kinetic}$, and pure electric accelerations SOC_{acc} which are explained in section *4.2.1.3* are subtracted from the trajectory. Finally it is optional to include the effect of extreme torque demand, $SOC_{extreme}$, which is explained more in detail in section *4.2.2*.

$$SOC_{ref} = SOC_{\mathrm{mod}e} - SOC_{kinetic} - SOC_{em-acc} - SOC_{exterme} \qquad (7)$$

The SOC_{ref} obtained from equation (7) should meet two practical constraints that are forced by battery characteristics.

The SOC level should be within the SOC_{min} and SOC_{max} limits. Besides the rate of increase or decrease of SOC_{ref} should be less than the maximum allowed charge- and discharge rate of the battery. After this implementation the final SOC_{ref} is ready to be used for the final weight calculation.

The strategy starts with separation of two different modes called consumption mode and generation mode. To avoid unnecessary and frequent switches between modes the required number of samples before a mode change occurs is four consecutively samples. This is illustrated in *Figure 7*.

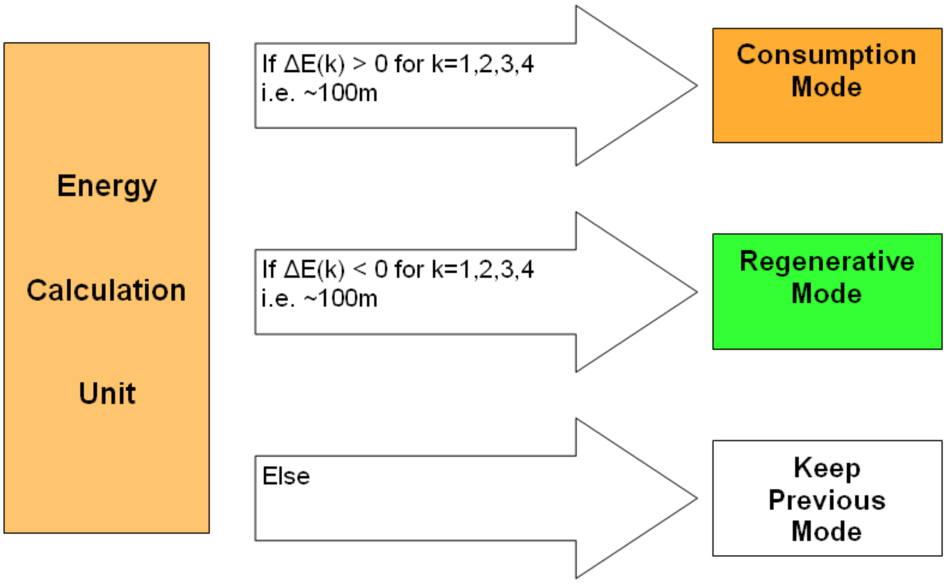

Figure 7: *Deciding the mode in the strategy; regenerative or consumption.*

4.2.1.1 Regenerative mode

When the strategy enters regenerative mode, the SOC_{ref} is increased according to the amount of energy which is expected from the vehicle to recuperate for a given distance. Consequently, SOC_{mode} is increased smoothly for each sample using the ratio of the travelled distance from the previous sample,

$$SOC_{\mathrm{mode}}(k) = SOC_{\mathrm{mode}}(k-1) + \frac{\Delta E(k)}{E_{battery}} \cdot \eta_{whl/bat} \cdot ratio_{sample} \quad (8)$$

k : Index of samples

$\eta_{whl/bat}$: Efficiency of the conversion of energy from wheel to battery

ΔE : Energy change between two prediction samples

$E_{battery}$: Total capacity of the battery

$ratio_{sample}$: Ratio of how far the vehicle has passed between two samples.

$SOC_{\mathrm{mode}}(k)$: SOC_{mode} at every predicted sample (k), in regenerative mode.

4.2.1.2 Consumption mode

The steps to find the SOC_{mode} in a consumption mode are explained below:

Calculation of total available recuperated energy

The sum of all negative energy samples calculated in the energy calculation unit based on equation (6) multiplied by the efficiency of the energy conversion from wheel to the battery can be considered as total available energy for recuperation within the e-horizon:

$$\Delta SOC_{total\ reg} = \eta_{whl/bat} \frac{\sum_{k=1,\Delta E(k)<0}^{k=end} \Delta E(k)}{E_{battery}} \tag{9}$$

k : Index of samples

$\eta_{whl/bat}$: The efficiency of the conversion of energy from wheel to battery

ΔE : The energy change between two prediction samples

$E_{battery}$: The total capacity of the battery

$\Delta SOC_{total\ reg}$: The predicted energy that can be stored in the battery during the drive cycle.

Ensuring the requirement of charge sustaining SOC

The very non linear nature of the vehicle, uncertainties in the prediction, unpredicted energy consumptions etc, can lead to situations where it is not realistic to think that it is feasible to use all predicted recuperation energy during the consumption modes. The vehicle could also start from a low SOC level. In order to compensate for these unpredictable situations, where there is a risk that the battery will not end up with the preferred SOC_{set} value in the end of the e-horizon, an additional limitation is added into the strategy. This is called SOC charge sustaining and it improves the assurance of that the SOC_{set} value can be reached, according to

$$\Delta SOC_{ch\ sus} = SOC_{set} - SOC \tag{10}$$

SOC_{set} is further analysed in *5.1.2.*

Distribution of available energy among all Consumption modes

The total amount of energy available for recuperation which is calculated in *4.1* should be distributed among the predicted consumption modes. By using the relation between each consumption mode and the sum of all consumption modes, a ratio describing how much of the predicted energy that can be spent in each consumption mode is derived. The proposed method to calculate the consumption ratio is simple and it is based on the idea that every consumption mode that needs more energy (i.e. greater ΔE) can spend more electric power and it seems reasonable to consume a higher portion of total available recuperated energy there. As a result consumption ratio for a given consumption section can be obtained by

$$ratio_{horizon}(m) = \frac{\Delta E(m)}{\sum_{m(1)}^{m(end)} \Delta E(m)} \tag{11}$$

$\Delta E(m)$: Predicted energy demand within the consumption mode with index m, where m goes from one to the number of consumption modes.

$ratio_{horizon}(m)$: Ratio between the consumption modes in the prediction.

In *Figure 8* a simple drive cycle consisting of two consumption modes demonstrates how a drive cycles is divided into two different consumption modes m(1) and m(2).

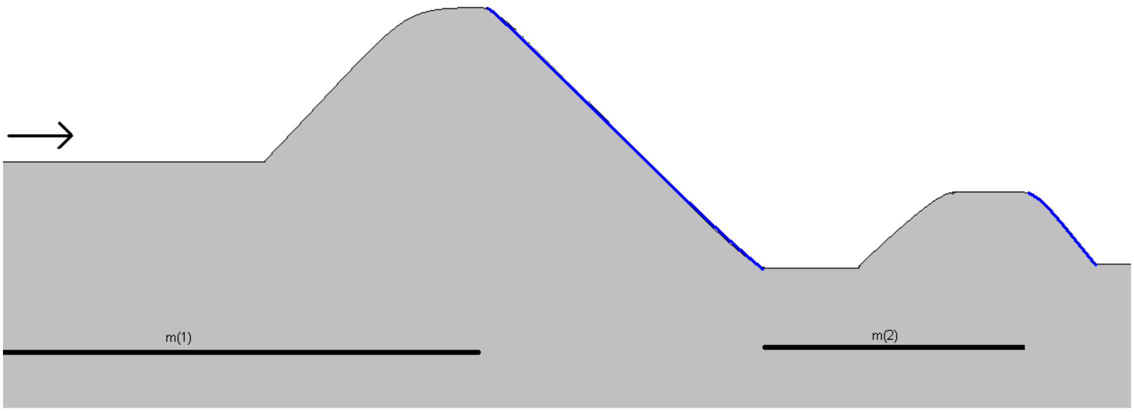

Figure 8: *Simple drive cycle demonstrating two different consumption modes.*

The amount that can be spent in each consumption mode is now defined by inserting the equations (9), (10) and (11) in equation (12).

$$\Delta SOC_{usable} = (\Delta SOC_{total\ reg} - \Delta SOC_{ch\ sus}) \cdot ratio_{horizon} \quad (12)$$

$\Delta SOC_{usable}(m)$: The amount of SOC that can be spent in current consumption mode

ΔSOC_{usable} can even be negative value depending on the drive cycle. For example in a flat drive cycle where there is no opportunity for recuperation, $\Delta SOC_{total\ reg}$ is zero. As a result any deviation of the SOC and SOC_{set} will lead to a positive value of $\Delta SOC_{ch\ sus}$ .Then ΔSOC_{usable} ends up with a negative value.

Finally the SOC_{mode} is calculated by equation (13) which adds the ΔSOC_{usable} in the current consumption mode to the previous SOC_{ref}.

$$SOC_{mode}(m) = SOC_{mode}(m-1) + \Delta SOC_{usable}(m) \quad (13)$$

4.2.1.3 Variations due to changes in kinetic energy

The variations of SOC due to changes in kinetic energy vary depending on the powertrain mode in vehicle. The variation is more significant if the vehicle is pure electric mode compared to hybrid mode. In the hybrid mode the weight is affecting the amount of electric energy used for acceleration but when the ICE is turned off, pure electric mode, only the EM can produce torque to propel the vehicle.

Hybrid accelerations

The effect of speed variations should be cancelled in the long term strategy since no information about speed is predicted. In order to do this, the corresponding SOC for accelerations and deceleration are subtracted instantaneously from the final SOC_{ref}. This implies that if the vehicle has a certain speed, it has a kinetic energy that can be finally transformed to electric energy hence the SOC_{ref} can be lowered during the accelerations as much as it is predicted to be recuperated during the decelerations.

$$SOC_{kinetic} = \frac{\frac{1}{2} m \cdot v^2}{E_{battery}} \cdot \eta_{whl/bat} \tag{14}$$

m : The vehicle mass
v : The actual vehicle speed
$\eta_{bat/whl}$: Efficiency of the conversion of energy from the battery to the wheels.
$SOC_{kinetic}$: Variation in SOC due to changes in kinetic energy in hybrid mode.

Pure electric accelerations

When the vehicle is in pure electric mode, the current SOC value varies directly based on the changes in kinetic energy, since the ICE is turned off. In order to compensate for this, the final SOC_{ref} is reduced as much as the kinetic energy needed for accelerations.

$$SOC_{em-acc} = \frac{\frac{1}{2} m \cdot v^2}{E_{battery}} \cdot \frac{1}{\eta_{bat/whl}} \tag{15}$$

m : Vehicle mass
v : Actual vehicle speed
$\eta_{bat/whl}$: Efficiency of the conversion of energy from the battery to wheel.
SOC_{em-acc} : Variation in SOC due to changes in kinetic energy in pure electric mode.

4.2.2 Extreme torque compensator unit

If the demanded torque is higher than what the ICE can produce the weight is no longer considered for deciding the torque split between the ICE and EM. In these situation the extra torque, needed to propel the vehicle, $T_{demand} > T_{ICE,Max}$ must come from where the torque is available regardless of the weight value.

When the prediction contains extreme torque demand, the SOC_{ref} is increased in advance to ensure that the required energy, in addition to what the ICE can produce, can be fulfilled by the electric motor. The corresponding SOC change is added to the SOC_{ref} until this extreme torque demand occurs.

If $T_{demand} > T_{ICE,Max}$ the required energy is calculated as

$$E_{exterme} = (T_{demand} - T_{ICE,Max})\omega t \tag{16}$$

T_{demand} : Torque demanded by the driver
ω : Angular engine speed

The energy needed can be converted to its equivalent SOC according to:

$$SOC_{exterme} = \frac{E_{extreme}}{E_{battery}} \tag{17}$$

This $SOC_{extreme}$ is distributed in the strategy unit to fit into the horizon by adding more SOC where the torque demand is low. Implementation of this unit is optional and it contributes more to the drivability rather than reduction of fuel consumption.

4.3 Weight calculation unit

The weight calculation unit can be described as a P-controller with a gain that varies with the shape of a tangent function between -π/2 and π/2. This type of controller is favourable if there is no or little information of the predicted future driving condition. The input to the controller is the SOC_{ref} from strategy unit and the actual SOC and the output is weight or W. The tangent controller works based on the following formula:

$$W = k\tan(aSOC + b) + m \tag{18}$$

Equation (18) should fulfil the following requirements:

1) $W(SOC_{\min}) = \infty$: The price of electricity is infinity when the SOC reaches SOC_{min}

2) $W(SOC_m) = -\infty$: The price of electricity is minus infinity when the SOC reaches SOC_{max}

3) $W(SOC_{Ref}) = W_{nom}$: The value of W when SOC is equal to SOC_{ref} is W_{nom}

Equation (18) with the requirements ends up with the following equations:

$$a = -\pi / (SOC_{\max} - SOC_{\min}) \tag{19}$$

$$b = \frac{-\pi}{2} - aSOC_{\min} \tag{20}$$

$$k_p = \frac{(k_{pMax} - k_{pMin})}{15} abs(SOC_{ref} - SOC_{set}) + k_{pMin} \tag{21}$$

$$k = \frac{k_p}{a} \cos(aSOC_{ref} + b)^2 \tag{22}$$

$$m = W_{nom} - k \tan(aSOC_{ref} + b) \tag{23}$$

K_p is the gain of the controller which changes between k_{pMin} and k_{pMax} where SOC_{ref} is varying according to *4.2.1*. The effect of controller's gain is investigated more in detail in 5.1.1.

In this controller a constant SOC_{ref} in the middle of the SOC-window gives a W very close to, W_{nom}, when the SOC is close to the SOC_{ref}. On the other hand W becomes very large or very small when actual SOC gets close to the SOC boundaries. In *Figure 9*, this behaviour is illustrated for three different SOC_{ref}. The maximum- and minimum values of SOCref are set to vary with a margin from SOC_{min} and SOC_{max} to avoid violating the SOC-window limit.

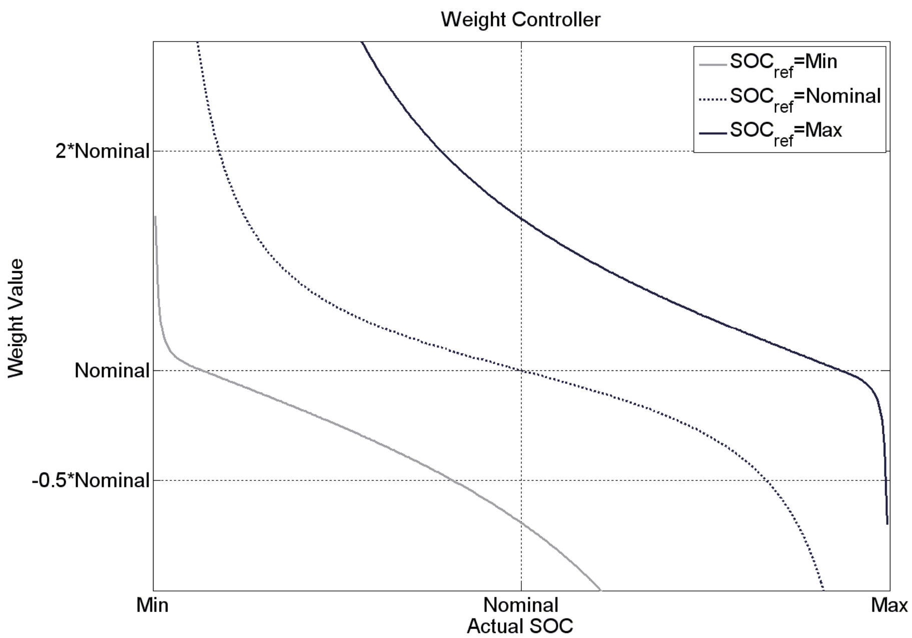

Figure 9: *Weight as a function of SOC at different SOC_{ref} values.*

5 Analysis

5.1 Tuneable parameters of the strategy

There are a number of correlated parameters which can be tuned in the model. Their relation is in many cases hard to distinguish due to the complexity of the model. Different parameters are studied and evaluated separately, holding the rest of the model as constant as possible.

5.1.1 Gain of tangent function controller

The controller in the weight calculation unit has a varying gain throughout the SOC-window which is confined to a minimum gain (K_{pmin}) and a maximum gain (K_{pmax}). The minimum gain is used when the SOC_{ref} is close to its nominal value when the maximum gain is used when the SOC_{ref} is close to the boundaries of SOC-window. The motivation behind having different gains for different SOC_{ref} is that the controller is harder when the SOC is close to its limits while it can be more relaxed in the middle of SOC-window.

In general, the selection of the controller's sensitivity depends on how accurate the SOC_{ref} is calculated in the strategy. If the SOC_{ref} trajectory is a good approximation close to the optimal solution, it is better to have a more sensitive controller but on the other hand if the SOC_{ref} is not a good estimation of the optimal solution it is not a good solution to have a controller which force the SOC_{ref} to the system harshly.

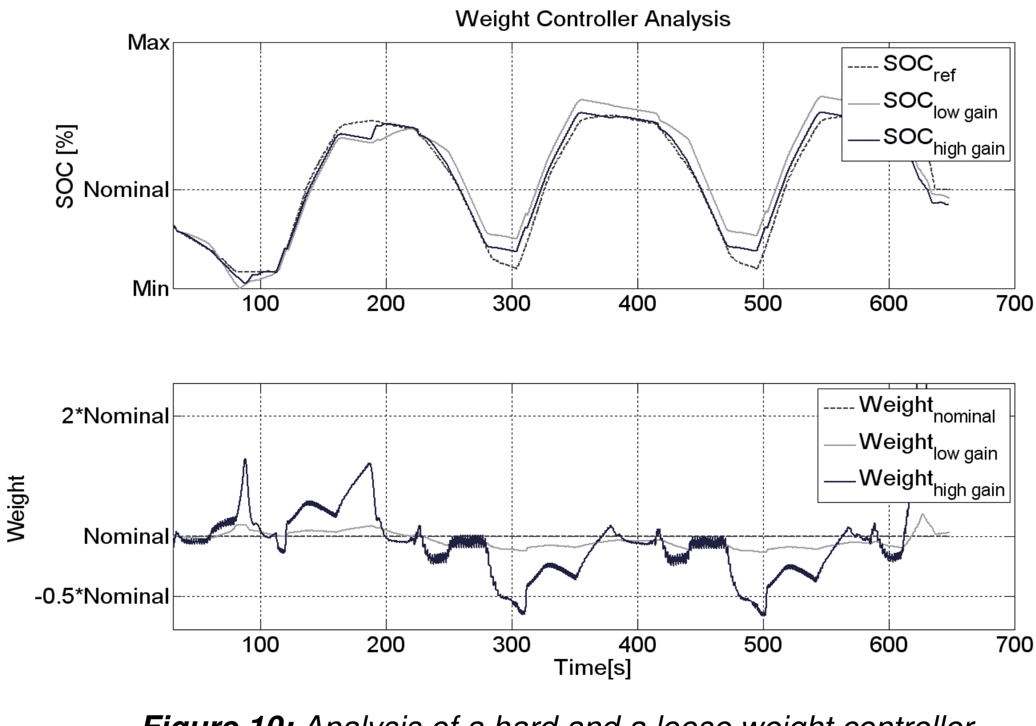

Figure 10: *Analysis of a hard and a loose weight controller.*

In *Figure 10*, the effect of having low gain (light gray) and high gain (black) is studied when the reference is constant. It can be seen that SOC follows the references more closely when the gain is high.

5.1.2 SOC set value

The SOC_{set} value is the SOC level that the strategy aims for in a long term during the entire drive cycle. By adjusting the desired SOC_{set} the general trend of the trajectory becomes higher or lower. As can be seen in the *Figure 11*, the upper graph shows the situation when the strategy aims for a low SOC_{ref} and the lower graph shows the situation when the strategy aims for a higher SOC_{ref}.

A low SOC_{set} gives room in the battery for recuperation of more the energy within the drive cycle, but there is a risk that the set value is not achieved due to uncertainties. Then there can then be a risk of violating the SOC_{min} restriction if the trend of SOC is too low.

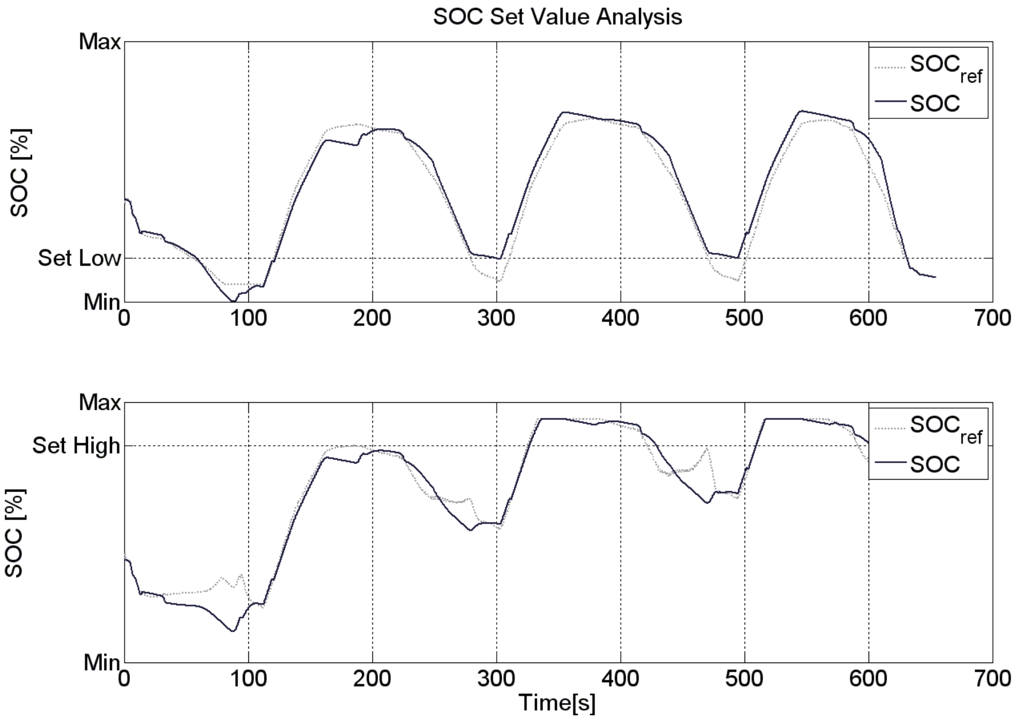

Figure 11: *SOC set value analysis.*

If the SOC_{set} value instead is too high, the possibility to regenerate energy can be limited. This is shown in *Figure 11* where the SOC value is not increased between 300s and 350s as much as it does between 100s and 150s in the lower graph, compared to the more similar behaviour in the upper graph, where the SOC_{set} value is low.

5.1.3 Parameters highly affected by the drive cycle

Some things are mainly affected by the actual drive cycle rather than the developed strategy. This influence can be adjusted to fit the drive cycle.

5.1.3.1 Influence of extreme torque compensator unit

When the average speed is a good description of the future driving profile the $SOC_{extreme}$ can be estimated accurately. In city environment however, frequent start and stops in the speed profile are common and obstruct an accurate prediction. By adjusting the amount of energy that is considered to be extreme the influence of $SOC_{extreme}$ can be controlled.

In *Figure 12*, the same drive cycle is simulated twice. In the upper part the original drive cycle is shown. In the lower part of *Figure 12* where $SOC_{extreme}$ is introduced, the SOC_{ref} is gradually increased from the beginning to compensate for the electrical energy required for very high torque demand conditions that happen in the drive cycle. In current drive cycle this behaviour is occurs between 800-850 seconds. Here, the SOC decreases more than the rest of the discharges, earlier in the drive cycle. This symbolises the usage of $SOC_{extreme}$.

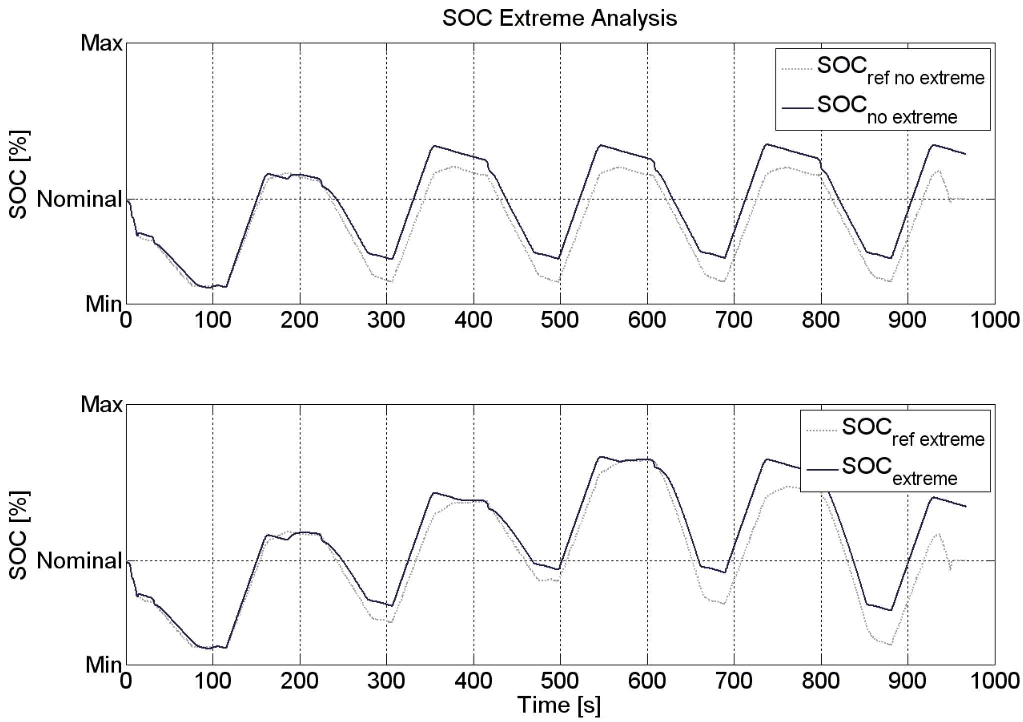

Figure 12: *Extreme torque analysis in a simple drive cycle.*

5.1.3.2 Influence of changes due to kinetic and potential energy

If there are many start and stops in the predicted regenerative modes, this can decrease the possibilities to recuperate energy compared to the drive cycles with more constant speed and therefore two factors for limiting the predicted potential energy and variations due to kinetic energy are introduced.

The EMS has slightly different settings for these limiting factors in drive cycles in city environment, *5.2.1* and *5.2.2*, and the highway drive cycle in chapter *5.2.3*. Since the strategy is developed for implementation in a city bus with the requirement of performing well in different kinds of traffic situations, including highway, these settings somehow needs to be modified. An automatic change is not implemented in the strategy.

5.2 Drivability

A prerequisite for the developed strategy is that is should not decrease the drivability of the vehicle. A precise definition of drivability is not available. However, a good drivability implies that the vehicle can meet the expectations of the driver including, but not limited to, torque and speed demands.

The investigation of the drivability is in this report based on the integrated difference between the demanded set speed, v_{set}, from the driver and the actual vehicle speed according to

$$\int_{t_0}^{t_1} (v_{set} - v)dt \qquad (24)$$

v_{set} : Demanded set speed from the driver

v : Actual vehicle speed

This calculation only considers when the vehicle accelerates and can therefore show rather high values without implying that the total performance of the vehicle has decreased severely. When the SOC level gets very close to SOC_{min} there are some emergency constrains affecting the drivability. These times are not included within the integration since they need to be further investigated.

5.3 Comparison between predictive and non-predictive EMS

There are many parameters influencing the results from the simulations, especially in drive cycles with varying speed. This makes the evaluation of the different parts, such as parameters affected by the drive cycle and the tuning parameters of the strategy, harder to differentiate and in most cases the model needs to be evaluated as a complete system. By adjusting the parameters, the correlation between the different parts in the system can be located but one single parameter is seldom affecting exclusively and therefore can plausible trends be hard to prove.

In this section the developed predictive EMS is compared with the non-predictive strategy in the following drive cycles:

AGD R01 has been chosen as a typical short intercity drive cycle which is a bus route in Mölndal, outside Gothenburg.

- Distance: 8 km
- Altitude change: 60 m
- Duration: 20 minutes

CBR85 has been chosen as a typical hilly intercity drive cycle which is bus route in Gothenburg.

- Distance: 23 km
- Altitude change: 70 m
- Duration: 70 minutes

Borås-Landvetter has been chosen as a typical highway drive cycle. The drive cycle is back and forth between Borås and Landvetter, outside Gothenburg.

- Distance: 87 km
- Altitude change: 150 m
- Duration: 60 minutes

5.3.1 Short intercity drive cycle

The altitude profile of the drive cycle can be seen in middle of the *Figure 13* , which shows a big hill in the beginning and then a more flat profile. The speed profile, presented in the lower part of the *Figure 13* shows frequent starts and stops which corresponds to a typical intercity bus route.

The actual SOC and SOC_{ref} provided by the non predictive method together with its weight value are also presented in *Figure 13 .* Since there is no prediction of the future driving condition, the only option for the non-predictive method is to have a constant SOC_{ref} equal to the nominal value throughout the drive cycle

In the non predictive strategy, the constant SOC_{ref} treats all deviations of SOC with the corresponding weight. A decrease in SOC during the uphill therefore is an undesirable incident and it leads to that the strategy either limits the usage of the electric motor or sometimes forcing the ICE to produce electricity.

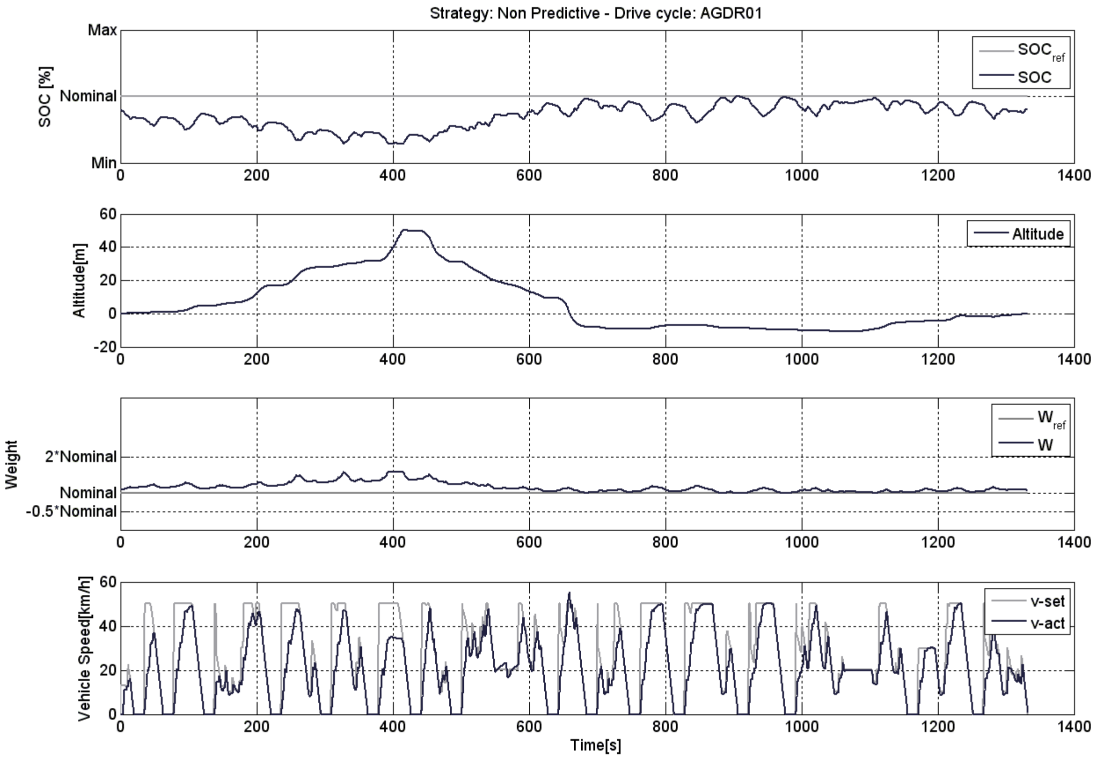

Figure 13: *Short intercity drive cycle with the non predictive EMS.*

In *Figure 14*, the predictive strategy is used so that the SOC_{ref} is no longer constant and it can be changed according to the information available about the future. The results obtained at the end of the route, is showed in *Table 1*. Using the predictive strategy has led to less fuel consumption, less energy throughput of the battery, less use of ICE to generate electricity but slightly higher deviation from the nominal SOC_{ref}.

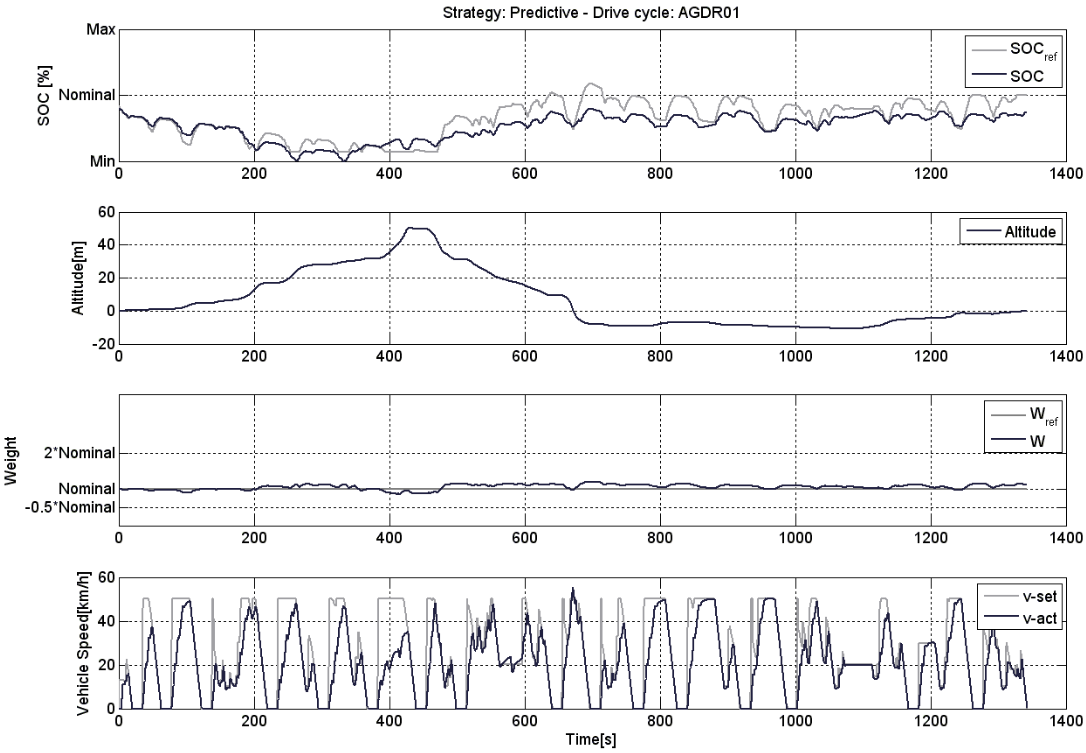

Figure 14: *Short intercity drive cycle with the predictive EMS.*

Table 1: *The results between predictive and non predictive EMS from the AGD R01 drive cycle.*

Strategy	Equivalent Fuel Consumption [%]	Energy Throughput of Battery[%]	Charging by ICE [%]	Deviation from SOC (nominal)	Drivability [%]
Predictive / Non-Predictive	-2,64	-9,21	9 / 16	-0.79 / 0.23	-0.5

5.3.2 Hilly intercity drive cycle

The altitude profile can be seen in *Figure 15*, which shows frequent hills dominated by one big hill in the middle of the route. The speed profile shows frequent starts and stops which represents a typical intercity bus route.

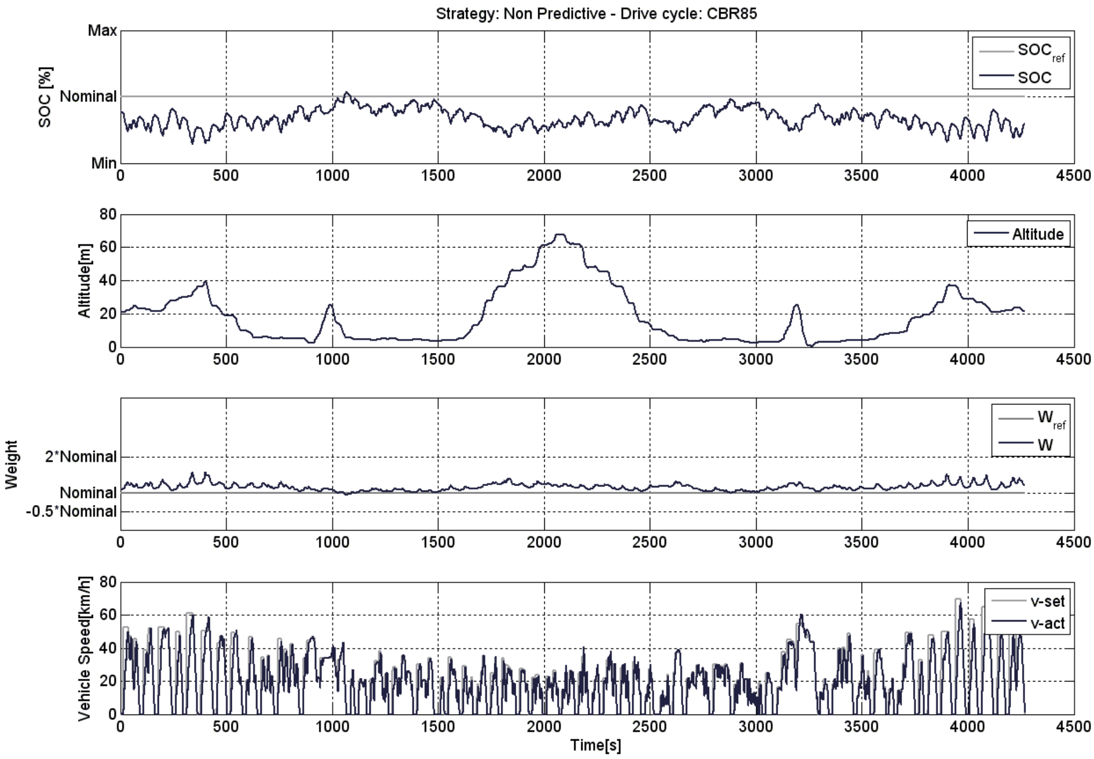

Figure 15: *Intercity drive cycle with the non predictive EMS.*

The predictive EMS in *Figure 16* allows lower SOC level in general during the entire drive cycle due to the predicted amount of recuperation energy within the drive cycle. The drivability however is probably affected negatively since the SOC level hits the SOC_{min} for a number of occasions but the calculation according to equation (24) shows very little difference. These violations of the SOC-window restrictions do not happen for the non predictive strategy in this drive cycle.

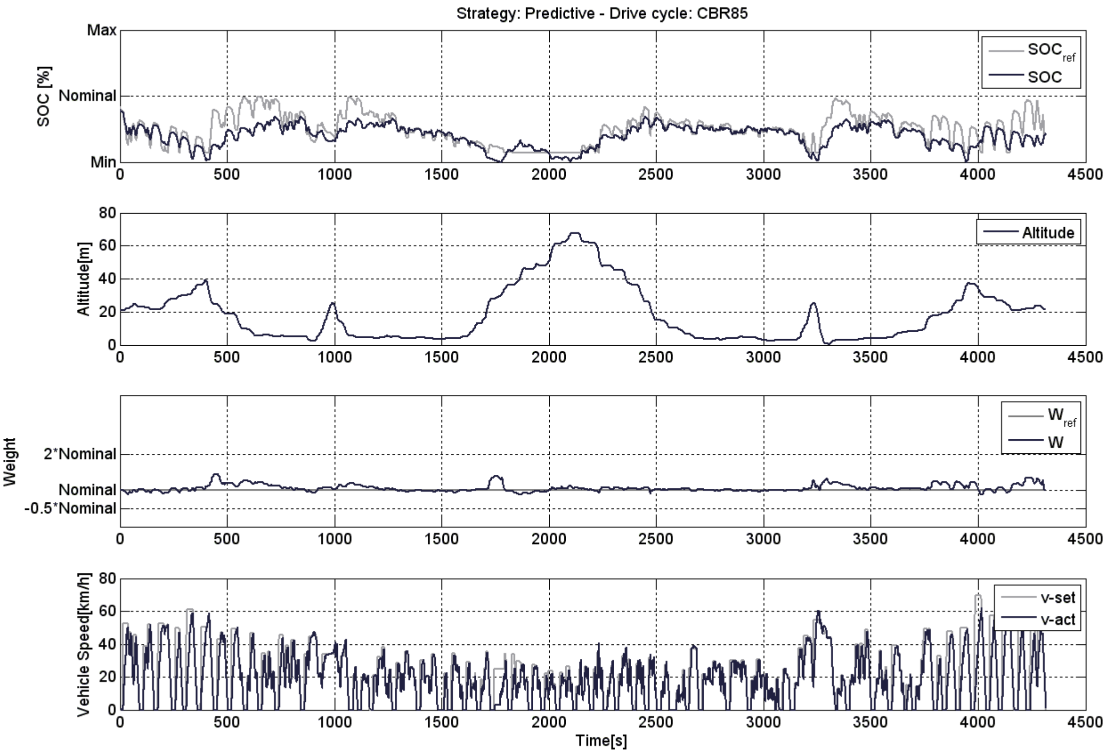

Figure 16: *Intercity drive cycle with the predictive EMS.*

Table 2: *The results between predictive and non predictive EMS from the CBR85 drive cycle.*

Strategy	Equivalent Fuel Consumption [%]	Energy Throughput of Battery[%]	Charging by ICE [%]	Deviation from SOC (nominal)	Drivability [%]
Predictive / Non-Predictive	-2,30	-20,04	7 / 20	-4.83 / 3.04	-0.4

5.3.3 Highway drive cycle

In the highway drive cycle, between Landvetter and Borås, the altitude change is greater than in the previous city drive cycles. The speed is also higher and more constant compared to the typical intercity drive cycles. Despite this the predictive strategy shows lower fuel consumption compared to the non predictive strategy, even though the results are not as good as in city drive cycles. The results from the simulations are shown in *Figure 17* and *Figure 18*.

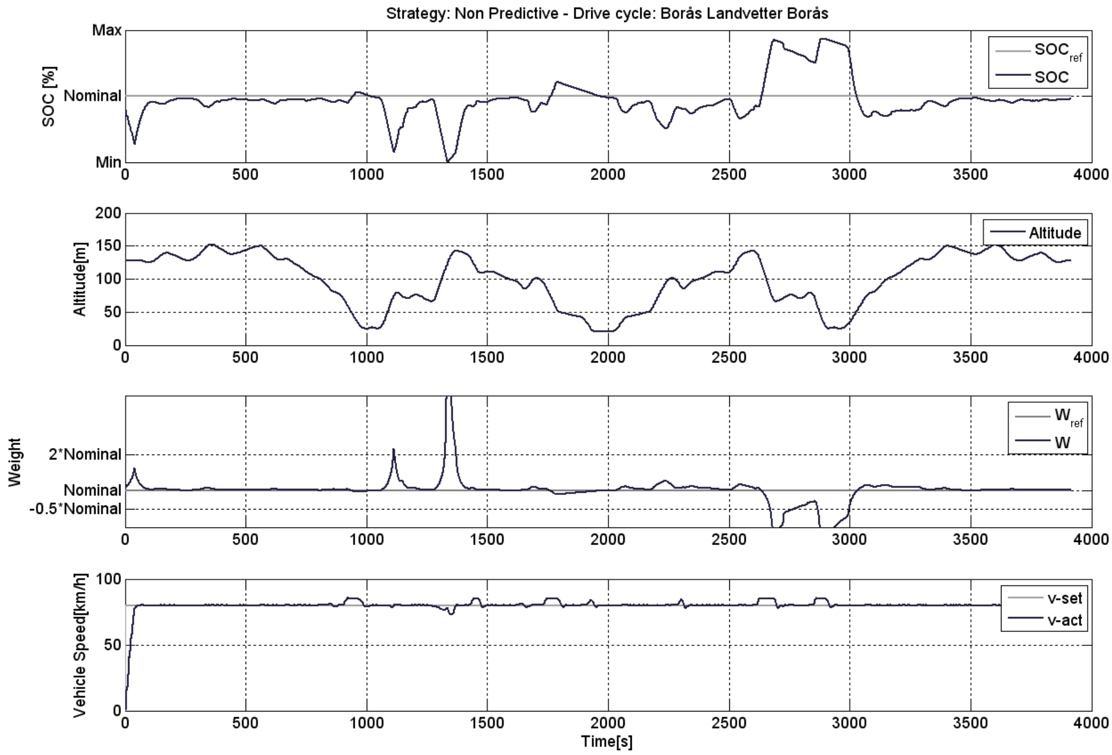

Figure 17: *Highway drive cycle with the non predictive EMS.*

In contrast, the predictive strategy decrease the SOC_{ref} with the amount of energy that can be later recuperated during the braking. With the high speed profile that this drive cycle posses the influence of kinetic energy is dominant thus it decreases the SOC_{ref} in the beginning of the drive cycle the as can be seen in *Figure 18*.

The integration for evaluation of the drivability is only calculated during the acceleration from standstill in the beginning. With the predictive strategy there is a decrease in speed at 1400s, but implementation of a correctly tuned extreme torque compensator unit this can probably be counter acted if the battery size is sufficiently big to store the needed energy.

Since the average moving speed calculator, described in *4.1.1*, is a good estimation of the speed profile there is potential for further development of the strategy to work better in this kind of drive cycles.

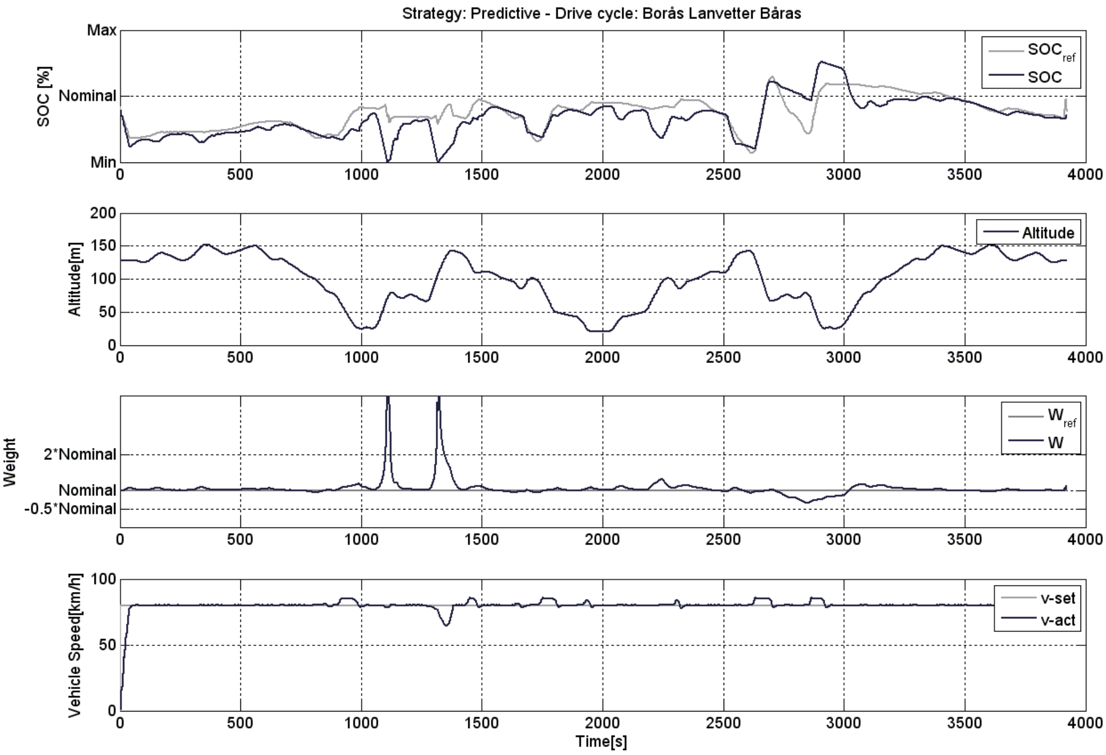

Figure 18: *Highway drive cycle with the predictive EMS.*

Table 3: *The results between predictive and non predictive EMS from the Borås-Landvetter highway drive cycle.*

Strategy	Equivalent Fuel Consumption [%]	Energy Throughput of Battery[%]	Charging by ICE [%]	Deviation from SOC (nominal)	Drivability [%]
Predictive / Non-Predictive	-0,56	-8,56	10 / 11	-1.32 / 2.46	-0.6

5.4 Battery size effect

In order to analyse the size of the battery the model has been simulated with double and half size of the battery. The same drive cycle and the same predictive energy management strategy as in *5.3.2* have been used for evaluation.

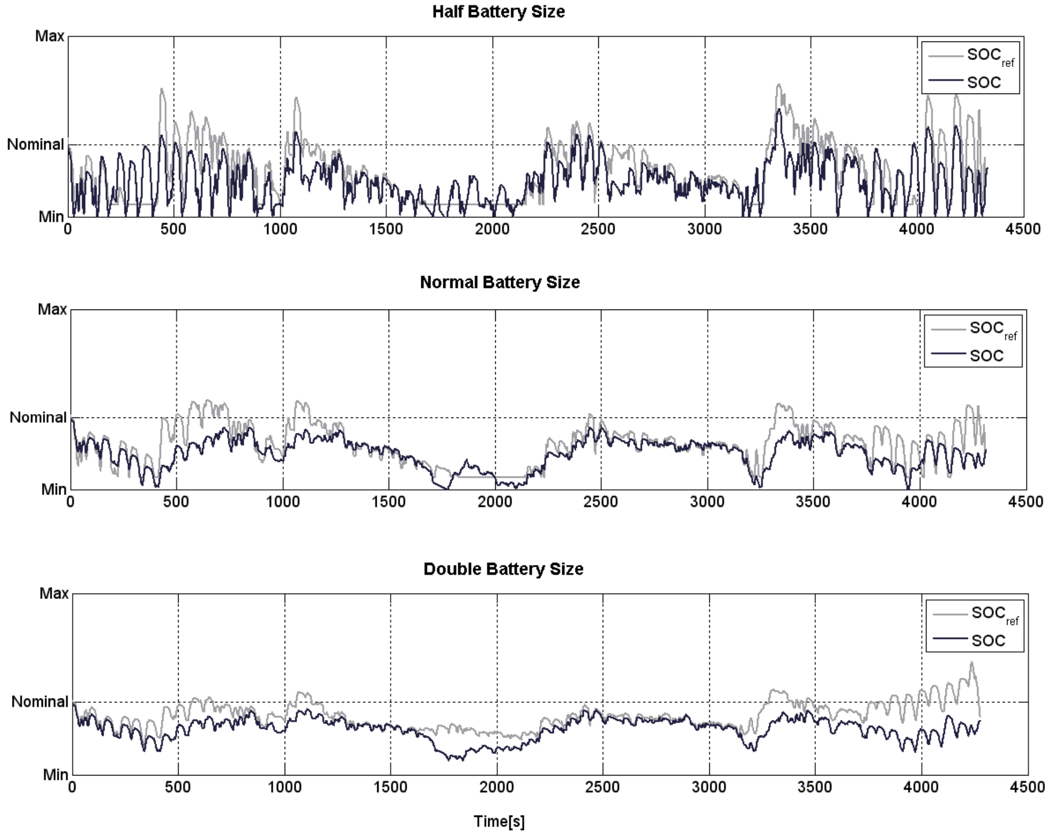

Figure 19: *Changed battery size in a city bus route with the non predictive EMS.*

As can be seen the *Figure 19*, by increasing the battery size less variation of SOC and SOC_{ref} is observed for the same drive cycle. This means that the strategy has more opportunity to use the electric power in the battery more without hitting the limits. In contrast, by decreasing the size of the battery the SOC level frequently hits the SOC_{min}. Every time the SOC reaches the SOC_{min}, EM cannot be used to propel the as a result it becomes harder to fulfil the torque demands from the driver.

Table 4: *The results between the predictive and the non predictive EMS from the CBR85 drive cycle with changed size of the battery.*

Battery size	Equivalent Fuel Consumption [%]	Normalised Energy Throughput of Battery [%]
50% vs 100%	6,29	104
100%	0	0
200% vs 100%	-2,76	-52

The results show that bigger battery can lead to decreased fuel consumption and the relative energy throughput at each battery cell is also following the expected pattern where a smaller battery will wear out faster according to the simplified lifetime estimation of the battery.

5.5 Charging by the internal combustion engine

The final fuel consumption and the amount of the power produced by the ICE that has been used for charging the battery, is often closely related. In general, a sufficient SOC-value should be enough to avoid this phenomena but if the SOC_{ref} is higher in relation to the current SOC, the weight calculations will result in an increased price for the electric energy and finally in this type of unwanted charging. Since the harshness of the weight function is varying within the SOC-window, the affect of charging differs along the drive cycle and a trade-off between a controller which is loose enough to avoid unwanted charging and strict enough to keep the SOC following the reference trajectory satisfying, is however affected by a combination of many parameters in the system and is therefore hard to tune.

The final strategy has been evaluated in the hilly intercity drive cycle CBR85 where the recuperation with the predictive and non predictive EMS is compared.

In *Figure 20* the efficiency for the working points where the ICE has been used for regeneration with the non predictive EMS is presented as a histogram. The darker parts represent when there has been a lot of recuperation close to that working point.

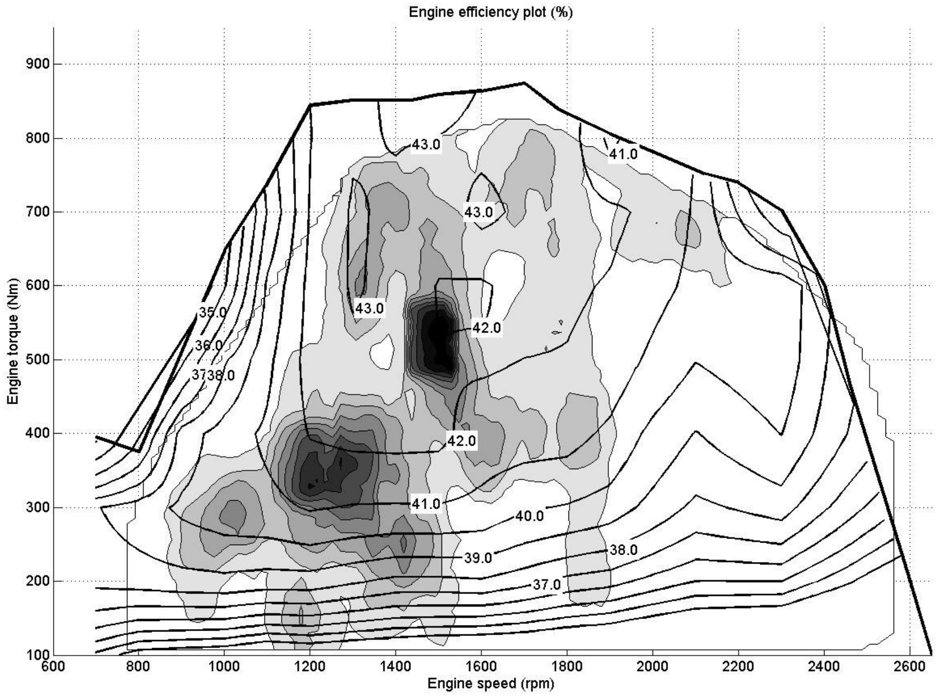

Figure 20: *Efficiency for the working points where the ICE has been used for charging the batteries with the non predictive EMS.*

In *Figure 21* is the efficiency histogram for the predictive EMS. The darker areas which are representing more frequent recuperation show that the speeds where the recuperation has taken place are similar with both the predictive and non predictive strategy. The torque is however lower in general. As a result, the efficiency is then lower for most of the working points. However, a lower torque means less fuel consumption at a constant speed and the total losses can therefore still be less.

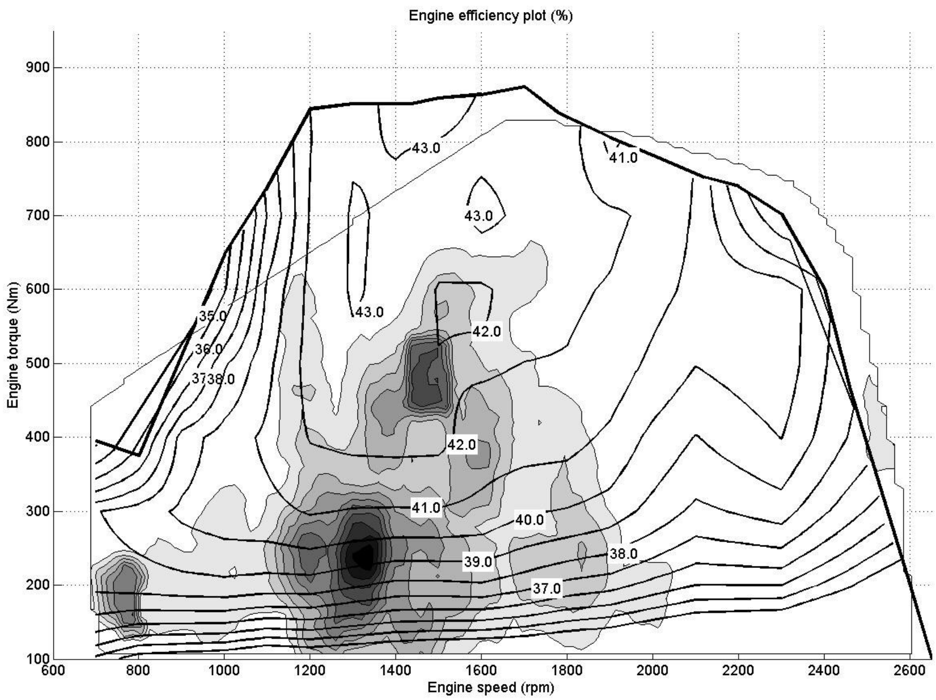

Figure 21: *Efficiency for the working points where the ICE has been used for charging the batteries with the predictive EMS.*

5.6 Physical limitations of the system

There are several things implemented in the strategy, enabling the strategy to follow the physical limitations of the system. One of them is when only the EM is used for acceleration from standstill. Then, the ICE is then turned off and this leads to a consumption of electric energy regardless of the weight.

The characteristic of $SOC_{extreme}$ is similar regarding its existence. When the energy demand is higher than what the ICE can produce, the torque demand is fulfilled with the EM, and an increased price of electricity cannot reduce the energy throughput from the battery. In order to avoid those disregards of changes in the weight, the surplus of energy is stored in the battery in advance.

By implementing these options in the strategy, the weight change radically even more seldom due to these situations. Instead the long term strategy is counteracting the situation, making the reference weight more stable.

6 Conclusions

In this chapter the conclusive result of the analysis chapter is provided.

6.1 Predictive vs. non-predictive EMS

The results from the analysis of the simulated drive cycles show less fuel consumption with the predictive method in comparison with the non-predictive one. However the results vary in different drive cycles. Considering the different drive cycles simulated in this thesis the best results are achieved in the city drive cycles.

6.2 Fuel consumption vs. drivability

While obtaining lower fuel consumption, which is a desirable result for an EMS, drivability needs to be taken into account as well. In general, faster accelerations lead to higher fuel consumption. The developed strategy shows no significant decrease of drivability except in highway drive cycles where extremely high torque demands can decrease the vehicle speed. However, this is probably solved with an implementation of a correctly tuned extreme torque compensator unit.

In the developed energy management strategy, the extreme torque demand compensator unit enhances the drivability at the expense of producing more electric energy with the ICE. This functionality is however difficult to be used due to uncertainties in the predicted speed.

6.3 Battery size

The energy management strategy decides the flow of electrical energy going to and coming from the battery. A small size of the battery put tougher restrictions on the energy management strategy, with regards to the use of electric energy. In contrast the fuel consumption is decreased slightly with the increased size of the battery.

The suitable battery size is closely related to the speed and altitude profile. More demanding drive cycles require bigger battery.

6.4 Future work

Further simulations should be done to fully estimate the potential of this energy management strategy and its possibility to reduce the fuel consumption.

The developed strategy works well in city environment and quite good in highway drive cycles. However, if it is going to be used mainly in highway drive cycles it should be further developed for this purpose.

It is desirable to have different settings when the bus drives in city environment or on the highway. By implementing an automatic or manual change between city- and highway drive cycles, better performance can probably be achieved.

Further investigation of battery size, including life cycle assessment, can conclude if it is beneficial to change the size.

The energy management strategy, developed for heavy hybrids, can be further used for implementation in other types of hybrid vehicles.

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