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Simulation of a Series Hybrid Vehicle

Anders Joelson

Department of Automatic Control
Lund Institute of Technology
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Department of Automatic Control
Lund Institute of Technology
P.O. Box 118
S-221 00 Lund Sweden

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Author(s)
Anders Joelson

Supervisor
Anders Romare, Volvo and Karl Johan Åström, LTH

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Abstract

This report treats the development and use of a model for simulation of series hybrid vehicles. The report is subdivided into two parts. The first part describes the simulation model. This description focuses on ideas rather than implementation details. The models are as far as possible based on measurements on existing components. In the second part the work is focused on finding an operating strategy that minimises the fuel consumption and the emissions while maximising the battery lifetime. The fuel consumption of a hybrid vehicle and a conventional vehicle are compared when both vehicles are driven on gasoline. The main result is that the hybrid vehicle consumes about 10 % less fuel in spite of the fact that the hybrid vehicle is 50 % heavier than the conventional vehicle. Moreover an energy flow study is done for the hybrid vehicle. In this study it is noticed that the efficiency of the hybrid vehicle is surprisingly poor.

Key words
Series hybrid vehicles, Static models, Operating strategies, Optimised set point, Energy flows.

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Preface

Today's battery technology constitutes a severe bottleneck for the development of electric vehicles. The batteries' poor energy storing capacity and large mass heavily reduces performance and driving range of an electric vehicle. There are however several ways to circumvent the battery problem. One possibility is to combine the battery with an internal combustion engine into a hybrid system. Such a system can, if it is operated in a wise way, give both small emissions and reasonable performance. However, to run a hybrid system in a clever way is a quite hard problem. For example it is not easy to decide when, at which speed and for how long to operate the internal combustion engine.

The purpose of this thesis is to evaluate what possibilities a series hybrid configuration can give. This work is subdivided into two parts. In the first part a simulation model of a Volvo 850 GLE in series hybrid configuration is built. The model is as far as possible based on data from real physical components. In the second part the model is used for studying how different operating strategies influence emissions and performance. The aim of the second part is to find an operating strategy that accomplishes the following goals:

- Minimise the emissions
- Minimise the energy consumption
- Maximise the battery lifetime
- Optimise the vehicle performance

Unfortunately those goals cannot be fulfilled all at the same time. Therefore the work will be focused on finding an operating strategy that in a reasonable way compromises between the different goals.

The work has been performed at Volvo Technological Development in Gothenburg in co-operation with the Department of Automatic Control at Lund Institute of Technology in the summer of 1994.

The contents of the report can be summarised as follows: Section 1 gives a brief orientation about hybrid vehicles and batteries. Section 2 describes the simulation model that is used to evaluate different operating strategies for series hybrid vehicles. This description focuses on ideas rather than implementation details. Section 3 contains issues concerning the evaluation of different control strategies for series hybrid vehicles. Finally Section 4 summarises the results in the report. The report also contains two appendices. Appendix A lists some of the key features of the test vehicle and Appendix B summarises the new tough emission laws that are introduced in the state of California beginning in 1995.

Acknowledgement

First I want to thank my supervisor at Volvo Technological Development in Gothenburg Mr. Anders Romare for letting me do my master thesis at his department. It was Mr. Romare that presented the project idea and he has been very helpful during my work at Volvo. Further I want to thank my supervisor at the Department of Automatic Control at Lund Institute of Technology Prof. Karl Johan Åström for his support during all stages of this project and for giving many valuable points when examining this report.

I am also grateful to Dr. Per Ekdunge at Volvo Technological Development for letting me use his battery model and for spending a lot of time discussing battery issues with me. Further I am very grateful to Lic. Eng. Anders Lasson at Volvo Technological Development. He is the department's expert on electric drive systems and his help has been invaluable during the implementation of the electric drive system in my simulation model. Lic. Eng. Lasson also has have many good ideas how to improve the original Ricardo simulation model.

Finally I want to give a special thank to Dr. Per Persson, who also is working at Volvo Technological Development. During this project he has pointed out many important view points that I certainly not would have discovered on my own. For example it was Dr. Persson that came up with the idea to study energy flows in the way that is done in this thesis. Without the help from Dr. Persson I do not know where this project would have ended.

Contents

1 Introduction

1.1 Hybrid vehicles

A standard way to classify hybrid vehicles are to distinguish between series hybrid vehicles and parallel hybrid vehicles. In this section the differences between the concepts are pointed out. Moreover advantages and drawbacks are discussed.

1.1.1 Series hybrid vehicles

The characteristic feature of a series hybrid vehicle is that only the electric motor delivers power to the wheels. The internal combustion engine delivers power to a generator that in its turn supply either the battery or the electric motor with power. A sketch of this type of hybrid vehicle is shown in Figure 1.

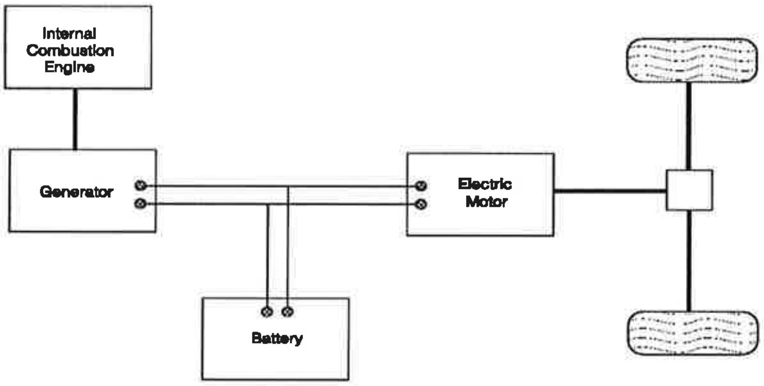

Figure 1: Outline diagram of a series hybrid vehicle.

Since all power to the wheels is supplied by the electric motor, it is the electric motor that limits the total output power from the vehicle. This implies that a fairly powerful electric motor has to be chosen if the vehicle performance shall be reasonably good. The internal combustion engine strength is however not critical since it is assisted by the battery in supplying power.

Some of the advantages and drawbacks with the series configuration can be summarised as follows. The main drawback with series hybrid vehicles is that the electric motor has to supply all power to the wheels. A powerful electric motor calls for big currents and in order to supply big currents the vehicle has to be equipped with a strong battery or a powerful internal combustion engine and this result in a negative influence on the vehicle mass and by that also a negative influence on the vehicle performance. One great advantage with the series configuration is that the internal combustion engine is driven only as a secondary energy source. Hence it is possible to run the engine in a smooth way and by that obtain small emissions. Finally it should not be impossible to find clever control strategies for minimising the emissions from a series hybrid vehicle since there are no restrictions when and how to run the internal combustion engine.

1.1.2 Parallel hybrid vehicles

A sketch of a parallel hybrid vehicle is shown in Figure 2. As seen in the figure, the main feature of the parallel configuration is that both the electric motor and the internal combustion engine can deliver power to the wheels. This implies that a considerable amount of work has to be spent in designing a transmission system that split the wheel power demand between the motor and the engine. Thus it is not unlikely that the transmission system in the parallel case tends to be more complicated and by this less reliable than in the series case.

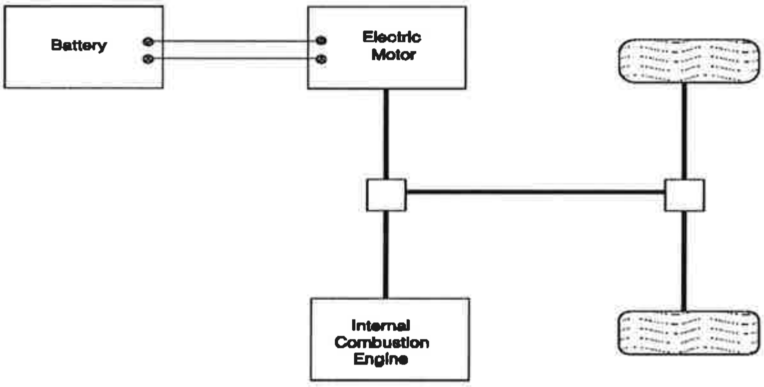

Figure 2: Outline diagram of a parallel hybrid vehicle.

Since the electric motor in the parallel case is assisted by the engine in delivering power to the wheels the electric motor can be made smaller in the parallel case than in the series case. A result of this is that the battery can be made smaller and thus the vehicle mass decreases compared with the series case.

In the parallel case it is likely that the internal combustion engine runs in a more irregular way than in the series case in order to help the electric motor to deliver peak power to the wheels. This makes it very hard to derive a control strategy that minimises the emissions.

1.1.3 Test procedures for hybrid vehicles

A standard way to evaluate how much emissions an ordinary vehicle exhaust is to use some type of pre defined drive cycle. A typical drive cycle defines at what speed the driver runs the vehicle at a certain time. Such drive cycles are derived for various cases for example for urban driving, highway driving, etc. Using pre defined drive cycles is a straight forward way to compare the emissions from different vehicles.

Evaluating the emission results of a hybrid vehicle is not quite that simple since the emission depends on whether the internal combustion engine is running or not. It is obvious that more parameters have to be considered than just the speed when defining a drive cycle for a hybrid vehicle. In [4] it is proposed that one way to go when evaluating how much emissions a series hybrid vehicle exhaust is to consider both the vehicle speed and the state of charge of the battery (cf. Section 1.2) when defining a drive cycle. If the condition is introduced that the battery has to be charged and discharged a certain number of times in every drive cycle the case when only the battery is used as power supply to the electric motor is avoided.

1.2 Batteries

The limiting component in an electric vehicle is the battery. It is due to limitations of today's battery technology that the decision is made to use the hybrid vehicle concept in the first place. This section summarises some of the battery parameters that has to be considered when designing a control system for hybrid vehicles. A more extensive discussion of battery issues can be found in [2].

A fundamental battery parameter is the *state of charge* (SoC). This parameter is defined as the currently available charge divided by the charge available when the battery is totally charged. It is important to keep the SoC within certain limits if the battery shall be operated in an ideal way. For example it is wise to set the upper SoC limit somewhat less than the full value since a certain margin must be kept for charging through regenerative braking. The lower SoC limit must not be set too low because if the SoC is driven to a far too low level there is a risk that the battery reverses, i.e. the battery starts to consume power instead of delivering it. Finally it is worth mentioning that the SoC parameter is not direct measurable. It is thus necessary to design some kind of observer if the SoC is to be used as an input signal to the vehicle control system.

Another important issue to consider is the battery temperature. The battery temperature affects both battery losses and lifetime. For example a too low temperature causes the internal resistance to increase and by that also the battery losses. A too high temperature however affects the battery lifetime in a negative way.

The battery temperature is connected to the current drawn from the battery. The temperature increases when the battery is discharged and decreases when the battery is charged. Hence the battery temperature can be controlled through variation of the current drawn from the battery.

2 Modelling a series hybrid vehicle

2.1 Introduction

A vehicle is a quite complicated system to model since it is composed of several more or less nonlinear subsystems with time constants that span over a wide range. Due to the great complexity of the system it is important that in an early stage of the modelling decide which system features that the model shall catch and which properties that can be neglected.

In this project the model shall be used for studying how the whole system behaves rather than for studying details in the behaviour of a specific subsystem. Interesting time constants are around 10 seconds and since several subsystems are considerably faster than that, those systems can be represented by static models. Moreover simplicity will be prioritised since it is desirable to minimise the simulation time.

The car that is modelled is a Volvo 850 GLE in series hybrid configuration. The electric motor and the generator are 90 kW asynchronous machines from Siemens, the internal combustion engine is a Volvo N1 engine and the battery consists of NiCd cells from DAUG. The number of cells depends on which control strategy that is used to operate the internal combustion engine.

As a base for the Volvo 850 GLE simulation model has served a Matlab/Simulink hybrid vehicle simulation model developed by Ricardo Consulting Engineers Ltd. From this model the top layer and some software for presentation of the simulation results have been used. Details about the original model can be found in [1]. In the following sections the Volvo 850 GLE simulation model is described and some of the ideas behind the implementation of the different subsystems is presented.

2.2 Model structure

To give the possibility to exchange certain subsystems in an easy way, the simulation model is divided into a number of subsystems. The division is done so that every subsystem more or less corresponds to a physical component in a real Volvo 850 GLE. A block diagram that shows how the different subsystems are connected to each other is shown in Figure 3. Details about the different blocks are accounted for below.

2.3 Drive cycle

The drive cycle block contains a look-up table with the current drive cycle, i.e. a table that specifies a certain drive speed for each time step. From this look-up table a speed reference is delivered to the driver at each time step. Further the drive cycle block contains the system time.

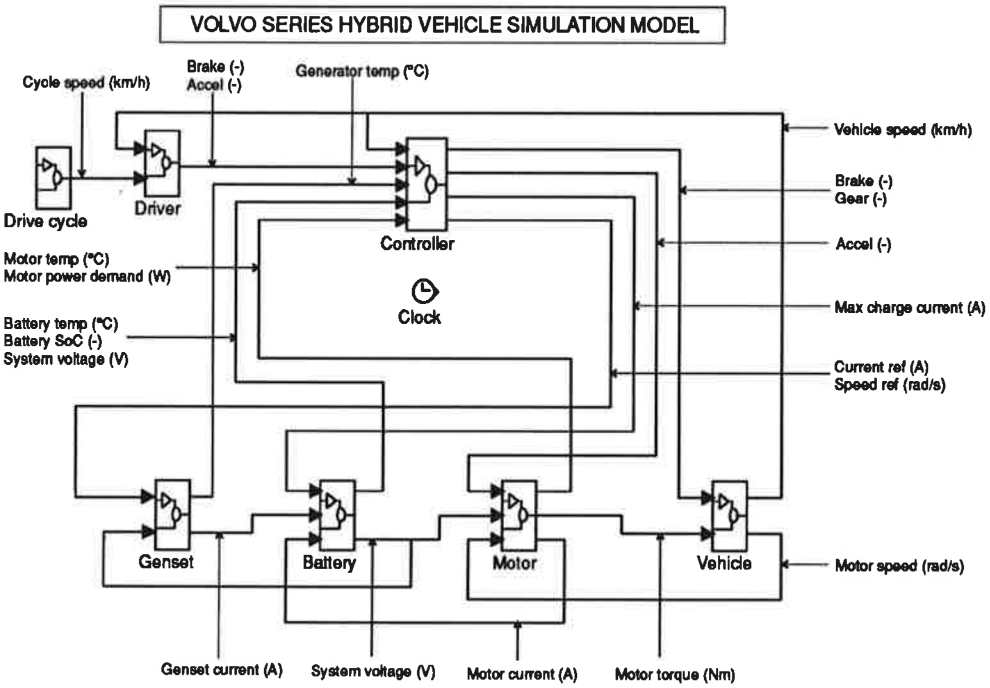

Figure 3: Top level view of the Volvo 850 GLE series hybrid vehicle simulation model.

2.4 Driver

The driver is modelled by a PI-controller. This controller compares the reference value from the drive cycle block with the actual speed of the car and then delivers a suitable throttle or brake level.

2.5 Controller

The vehicle control system is located in the controller block. The main task of the control system is to operate the internal combustion engine in such a way that the emissions and the fuel consumption are minimised. To accomplish this the controller block is provided with suitable measurement signals from the other blocks. Which measurement signals that are needed depend on which control strategy that is used to operate the engine.

2.6 Genset

The genset (generator engine set) block contains models of the internal combustion engine and the generator. Furthermore a DC to DC converter is included in this block in order to make it possible to control the power delivered by the generator. The following four sections describes how the genset components are implemented and how they are coupled together.

2.6.1 Engine

The internal combustion engine is modelled by a static model. The following discussion motivates why: The time constants of an internal combustion engine are fairly small. For example it takes parts of a second for the torque to reach a reference value and the corresponding time for the speed is perhaps some second. Compared to those times the changes in reference values that a driver causes when following a certain drive cycle are quite slow. Hence it is not unreasonable to model the engine by a static model since the objective with the model is to study the over all system behaviour rather than studying details in component behaviour.

The internal combustion engine model works as follows: It has two input signals, a reference speed and a reference torque. Through those signals the load (i.e. the generator) tells the engine which speed and which torque the engine has to deliver. The engine then uses the reference values to, through look-up tables, calculate which emissions and which fuel consumption the given speed and the given torque results in. The look-up tables gives the instantaneous emissions and the instantaneous fuel consumption in the unit milligrams per second. 3D plots of the look-up tables are shown in Figure 4.

The values in the look-up tables are based on measurements from a real Volvo N1 engine. This engine is a 90 kW four-stroke engine with four cylinders and speed torque characteristics as shown in Figure 5. The emission and fuel consumption measurements are done for constant speed and constant torque and are given in the unit milligrams per second. Between the measurement points linear interpolation has been used to obtain smooth look-up tables. Moreover the measurement data set has been linearly extrapolated in order to cover the cases when the torque is zero. Unfortunately the measurements do not cover cases when the torque is less than zero (i.e. motor brake) but it is not unreasonable to suppose that the emissions and the fuel consumption are approximately the same for negative torque as for zero torque and this approach has been used in this engine model. For zero speed the emissions and the fuel consumption are of course zero.

As a consequence of the emission and fuel consumption measurements are done for constant speed and constant torque, the model does not catch transient phenomena of the engine. It is therefore not unlikely that the emissions from the simulated N1 engine become a bit smaller than the emissions from a real engine. Finally the emission given in the look-up tables is raw emissions, i.e. emissions from an engine without catalyst. A reasonable estimation of the emissions from a N1 engine with catalyst is to take the emission values from the look-up tables and multiply by 0.01.

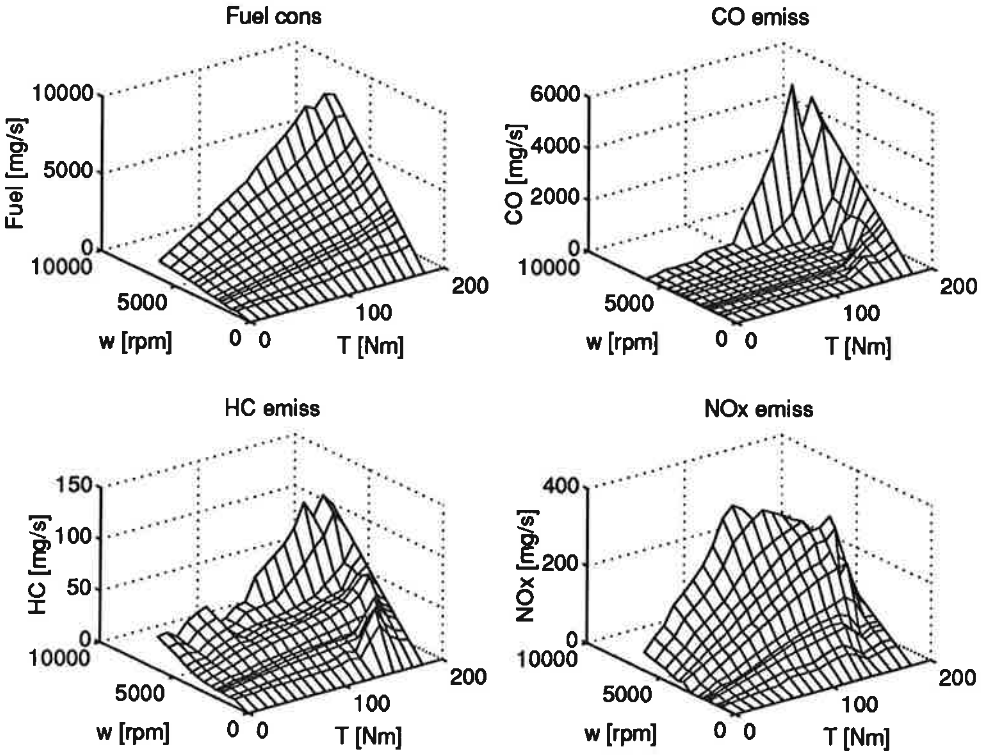

Figure 4: 3D plots of the emission and fuel consumption look-up tables.

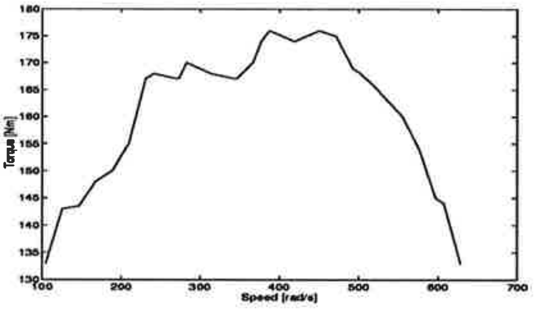

Figure 5: Measured torque-speed characteristics of the Volvo N1 engine.

2.6.2 Generator

For the conversion of the mechanical energy that is delivered by the internal combustion engine to electric energy that can be used by battery and motor, is used an 90 kW asynchronous generator with accompanying AC to DC converter. The time constant of such a generator lies typically in the milliseconds range why a static model can be reasonable also for this component. From the generator manufacturer it is possible to obtain data about the losses the generator and converter gives at a certain mechanical input power. By means of such data it is straight forward to build a static model of the generator-converter set. In this project the following approach has been used:

The generator-converter set receives a reference power and a reference speed as input signals. Via a look-up table it is checked whether the demanded power can be delivered by the generator at the speed in question. If so is the case the power is delivered as an output otherwise the maximal power at the current generator speed is delivered. Moreover another table look-up is done to decide which torque that is needed to deliver the output power at the current generator speed. This torque is delivered as an output signal.

2.6.3 Converter

The DC to DC converter is introduced in order to give full control of what electric power that is delivered from the genset. This converter is of step-down type and it is located between the generator and the battery/motor with the high voltage side faced towards the generator.

Also for the converter a static model is suitable since the time constants of this component are very small compared to the time constants of the other systems. The model in this project is based on power equilibrium and it is very simple. It is based on the assumption that the efficiency of the converter is relatively constant within a reasonable working range. With this assumption it is straight forward to implement a model of the converter. A more precise model can be obtained by means of some kind of look-up table for the efficiency.

The input signals to the converter model are a reference current, the input power and the output voltage. By means of those signals and the constant efficiency assumption from above the input power that is needed to produce the reference current is calculated. This input power is delivered as an output signal. By means of the output voltage and the input power, the output current is calculated and delivered as an output signal. Hopefully this output current is the same as the reference current.

2.6.4 Connection

A scheme that shows how the three different subsystems in the genset block are connected is accounted for in Figure 6 and the different subsystems co-operate in the following way. From the controller block the genset receives a reference current and a reference speed and from the battery the genset receives the system voltage. The reference speed is fed to the engine that instantaneously accelerates to the desired speed. The reference current and the system voltage are given to the converter which in its turn calculates the input power needed in order to deliver the reference current. This calculated input power is given as a reference power to the generator that, by means of this reference power and the reference speed, calculates which torque the generator need in order to deliver the reference power. The calculated torque is fed to the engine that uses the torque and its speed to calculate the emissions and the fuel consumption. If the generator manages to deliver the power it gives this power as an input to the converter which in its turn calculates the genset output current. In the case that the generator only can deliver a part of the demanded power the genset output current becomes a bit smaller than the reference current from the controller block.

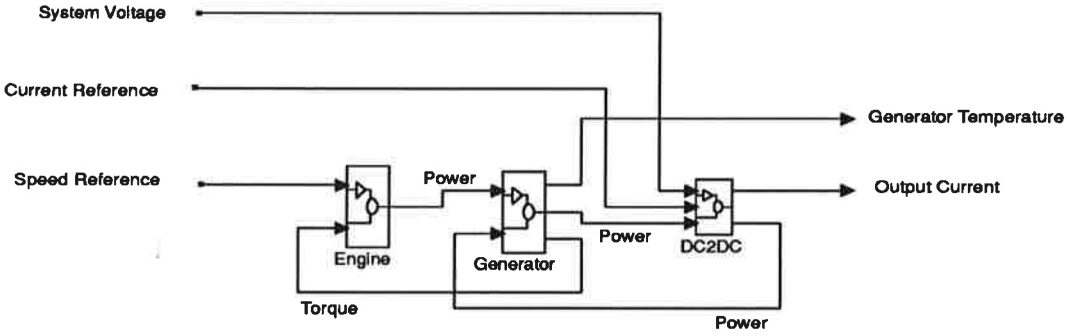

Figure 6: Connection of the three subsystems in the genset block.

2.7 Battery

The battery is in contrast to the generator and the internal combustion engine a very slow system. For example the time constant of SoC is rather in the range of minutes than seconds. Hence it is necessary to model the dynamics of the battery. The battery used in this model is a model of a Nickel-Cadmium battery from DAUG in Germany. The battery model is developed by Dr. Per Ekdunge and details about the model can be collected from [2].

2.8 Motor

As power supplier to the wheels in the Volvo 850 GLE series hybrid vehicle simulation model is used a model of a 90 kW converter provided asynchronous motor from Siemens. The time constants of speed and power are for this kind of motor in the size of some second. The driver of the vehicle is assumed to change the reference values quite slowly compared to those time constants so it is not unreasonable to assign the motor a static model. From the motor manufacturer it is possible to obtain data over losses in converter and motor for a given torque and a given speed. It is by means of such data set and some kind of power equilibrium relation fairly simple to implement a static motor model.

The motor in the Volvo 850 GLE simulation model works as follows: The motor receives a torque reference from the controller block, the speed of the wheels from the vehicle block and the system voltage from the battery block. By means of a power equilibrium relation and the loss data the current that the motor will pull out from the battery is calculated. This current becomes the motor output.

The torque-speed characteristics of the asynchronous motor are accounted for in Figure 7. This figure shows that the motor delivers a decent torque over the whole speed range. A result of this is that there is only need for a single gear that reduces the motor speed to reasonable wheel speed.

Finally regenerative braking is implemented in the model, i.e. when the driver wants to motor brake the motor is operated as a generator. The power that then is delivered can be restored to the battery. Hence it is advantageous to use motor braking compared with using the mechanical brakes.

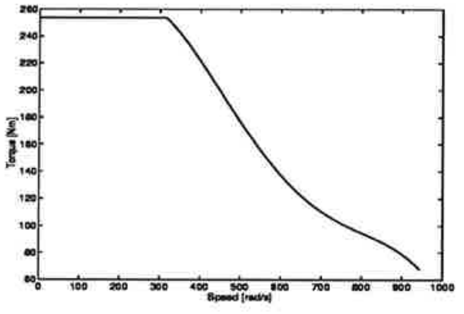

Figure 7: Torque-speed characteristics of the asynchronous motor.

2.9 Vehicle

The vehicle block contains models of vehicle dynamics, the retarding forces that act on the vehicle and the reduction gear that is mentioned in the motor section. The vehicle dynamics are modelled by means of a first order system, i.e. the forces that act on the vehicle divided by the mass of the vehicle are integrated one time in order to calculate the vehicle speed.

The retarding force that acts on the vehicle is drag resistance, rolling resistance, braking force and the influence of the road gradient. The drag resistance is supposed to be proportional to the vehicle speed squared and the rolling resistance and the influence of the road gradient is supposed to be proportional to the vehicle mass. The braking force is given by the driver's influence on the brake pedal.

3 Controlling a series hybrid vehicle

3.1 Introduction

The control system of a hybrid vehicle operates on two levels. On the lower level, things concerning the control of the individual components are taken care of. A typical task for the control system on this level is to give the components nice responses for changes in their reference values. On the higher level things concerning operating the whole system is accomplished. This part of the control system deals with questions like how to operate the system to obtain minimal emissions and minimal fuel consumption. To summarise, the lower level deals with control strategies and the higher level deals with operating strategies. This report will focus on the operating issues since the static character of the simulation model makes it most suitable for those kinds of studies

For the evaluation of the different operating strategies, two versions of the model described in the previous section will be used. In the first version the battery can deliver all power that the electric motor needs without any assistance of the internal combustion engine. Thereby it is possible to obtain zero emissions on parts of the distance that the vehicle cover. In the second version the battery can only deliver 50% of the electric motor peak power and that result in that the internal combustion engine must work all the time. The advantage with this kind of operating strategy is that the amount of battery cells can considerably be reduced and by that also the vehicle mass and price. It is out of the question to shut off the internal combustion engine when using this operating strategy since it takes far too long time to start the engine if the electric motor suddenly wants more power than the battery can deliver.

In order to make it possible to study whether a hybrid vehicle configuration gives any improvement in comparison with a conventional vehicle, the simulation result of the hybrid vehicle model is compared with simulation results of a conventional car. This conventional car uses the same internal combustion engine and the same car body as the hybrid vehicle while the battery, generator and electric motor are omitted.

The remaining of this section is organised in the following way: Section 3.2 gives some restrictions that the battery imposes on the system, Section 3.3 deals with the minimisation of emissions and fuel consumption, Section 3.4 contains a description of the test procedure that is used when the different operating strategies are evaluated and finally Section 3.5 contains the simulation results.

3.2 Restrictions

The battery undeniably is the most sensitive component in a hybrid vehicle so the operating strategy must, besides minimising the emissions and fuel consumption, satisfy some restrictions concerning the battery. The following points must be fulfilled by the NiCd battery used in this project:

- The battery temperature increase must stay around 10 K.
- Charging is forbidden when the battery temperature exceeds 313 K.
- The maximum voltage per battery cell is 1.55 V when charging the battery.
- The battery SoC should not sink below 20% due to the reversing risk.

The temperature dependence of the battery is a fairly complicated process. However it is possible realize that the battery temperature ought to be dependent of the internal resistance of the battery since an increased internal resistance should give an increased heat release. Measurements on a NiCd cell show [2] that the internal resistance of the cell increases when the SoC goes towards zero. It is by that possible that the first and second point from above should be fulfilled if the SoC of the battery is not allowed to sink to a far too low level.

Concerning the third point, simulations with the battery model have shown that the maximum charge current that gives the cell voltage of 1.55 V is an almost linear function of the SoC of the battery. It is by that quite simple to decide which the maximum allowed charge current is for a given SoC.

3.3 Optimisation

The key to obtain decent emission and fuel consumption results are to drive the internal combustion engine in an optimised way. Since the engine is modelled by maps it is fairly easy to find optimal set points of the engine. An optimal set point of the engine is conveniently defined as the engine speed that for a given output engine power gives the minimum emissions and fuel consumption per produced output energy.

If the emission and fuel consumption maps from Section 2 shall be used for the calculation of the optimal engine set point they have to be transformed from the quantity mass per second to the quantity mass per energy. A suitable unit for the quantity mass per energy is in this case g per kWh. When the transformation of the maps has been done the maps in Figure 8 are obtained. A close inspection of those maps gives that the fuel consumption has a minimum of approximately 230 g per kWh, the CO emission has a minimum of about 15 g per kWh, the HC emission has a minimum of roughly 2.34 g per kWh and NOx emission has a minimum in the neighbourhood of 6.84 g per kWh.

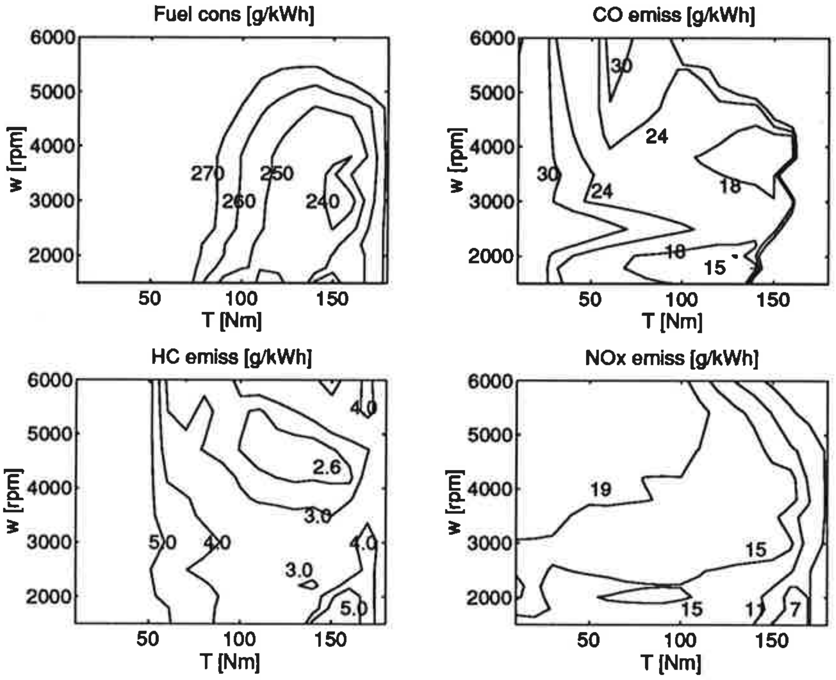

Figure 8: Level curve plot of the emission maps and the fuel consumption map.

Further Figure 8 shows that the minimal values of the emissions and the fuel consumption do not coincide in torque and speed.

The first step in an optimisation procedure is to construct some kind of loss function with those functions that shall be optimised. Since all maps are greater than zero, it is possible to use the sum of all four maps as a loss function. There is however a large difference in magnitude between the different maps why it is necessary to standardise the maps before summing them, otherwise the fuel map would probably kill the influence of the rest of the maps. A reasonable standardisation approach is to divide all values of a map by the minimum value of the map and by that obtain maps that have the same order of magnitude of its values, at least for points near the minimum of the map. Moreover the maps for fuel consumption, CO emission and HC emission are quite similar to each other while the NOx map is a little bit of an outsider. Therefore it is not unlikely that the sum of the fuel consumption, CO and HC maps will destroy the influence of the NOx map. A possible way to counteract this scenario is to multiply the standardised NOx map with a suitable factor, for example 3. The discussion from above can be summarised in the following loss function:

$$V = \frac{1}{230}fuel + \frac{1}{15}CO + \frac{1}{2.34}HC + \frac{3}{6.84}NO_X$$

A level curve plot of the loss function can be found in Figure 9.

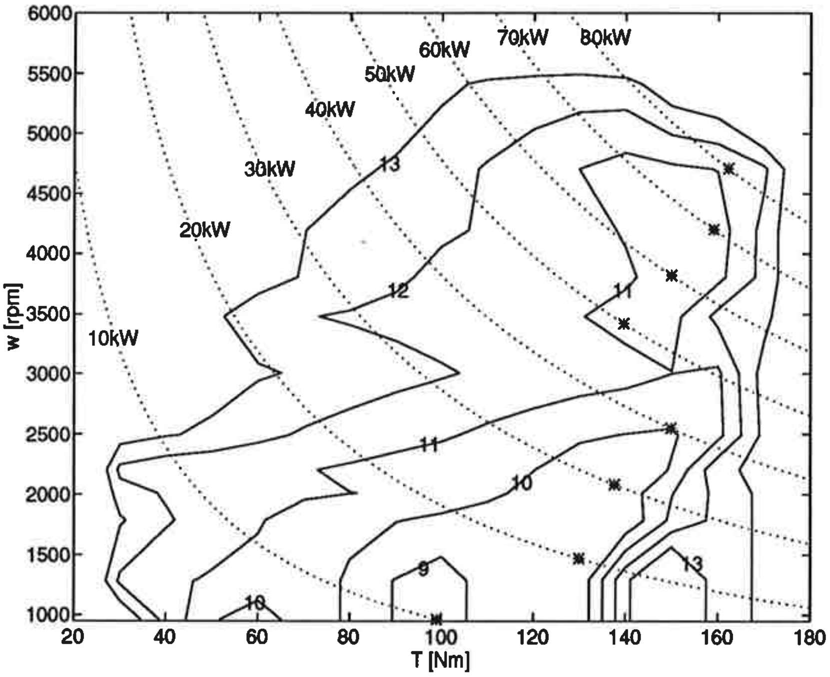

Figure 9: Level curve plot (solid lines) of the loss function that is used when looking for optimal set points of the internal combustion engine. The figure also contains constant power curves (dotted lines) in the range 10 to 80 kW. The minimum V at every power curve is marked with a '*'.

It is now straight forward to calculate the engine speed that minimises V for a given engine output power level. The method that has been used is explained by the following example. Consider for example the 50 kW curve in Figure 9. In order to find the speed that minimises V for the power level 50 kW the loss function V is evaluated for every point on the 50 kW curve. The engine speed that gives the minimum V after those evaluations is the optimum speed of the power level 50 kW. This procedure is then performed for suitable spaced power levels in the power range of the engine.

The result of the minimisation is accounted for in Figure 10. The upper plot shows the minimum V as a function of the motor output power P and the lower plot show which motor speed that gives the minimal V for a given output

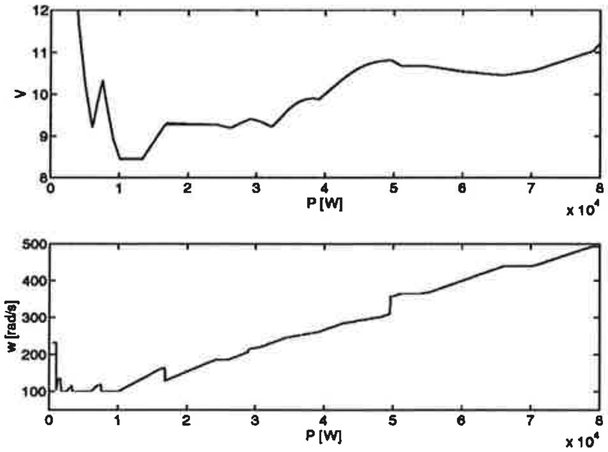

Figure 10: Plots that result from the optimisation of the loss function V.

motor power P. The conclusion that can be drawn from the plots are that the internal combustion engine used in the model shall be operated at a power of 10 to 14 kW and at a speed of 100 to 140 rad/s in order to minimise V. In Table 1 the emissions and the fuel consumption of the optimal powers and the optimal speeds are listed. Finally if the power level 14 kW appear to be too low for charging the battery, the alternative power level 32.3 kW can be suitable since the upper plot in Figure 10 shows a dip for this power level.

Table 1: Emissions and fuel consumption of some optimised set points.

P [kW]	ω [rad/s]	Fuel [g/kWh]	CO [g/kWh]	HC [g/kWh]	NOx [g/kWh]
10	101	231.06	19.81	3.57	10.59
12	120	230.35	19.78	3.55	10.52
14	140	232.77	19.27	3.56	10.92
32.3	231	240.89	16.87	2.86	13.31

3.4 Test procedure

The test procedure that will be used for the evaluation of the different operating strategies for the internal combustion engine follows the ideas from Section 1. As underlying speed cycle, a combination of the standard cycles FTP 72 (Federal Test Procedure) and US highway are used. Plots of those cycles can be found in Figure 11. A speed cycle begins with a FTP 72 cycle followed by a US highway cycle and is finished by a FTP 72 cycle. This cycle combination will in the following sections be referred to as the FHF cycle. The FHF cycle is then repeated so many times that the battery can be charged and discharged a suitable number of times. The cycle that the emission and fuel consumption calculation are based on starts at an arbitrary SoC level of the battery and are completed when the battery reaches the same SoC level after equal number of charges and discharges.

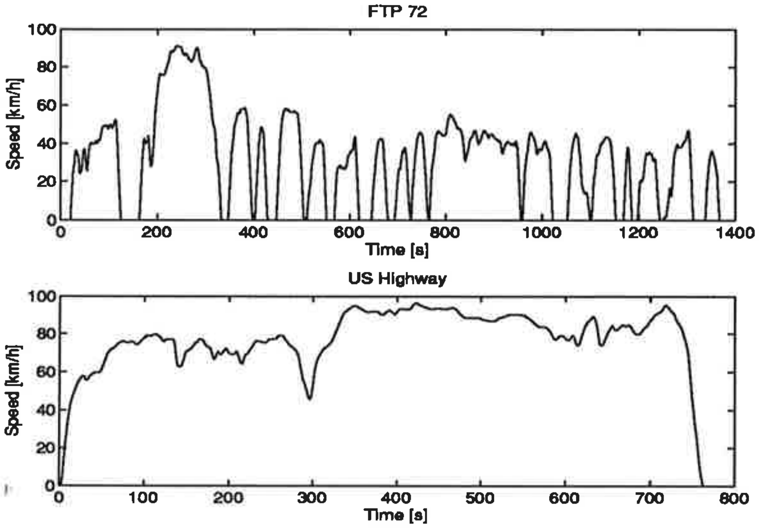

Figure 11: Plots of the FTP 72 and the US highway drive cycle.

3.5 Simulation results

3.5.1 Conventional vehicle

Model features

As mentioned in the introduction, a model of a conventional car has been developed in order to give the possibility to study whether the hybrid configuration gives any improvement in comparison with a conventional car. To obtain this model the drive cycle, driver, controller, engine and vehicle block from the hybrid vehicle simulation model have been coupled together as shown in Figure 12. However some modifications have been introduced the controller block to adjust the controller to the new motor configuration. Moreover the number of gears has been increased from one to three. The car model that is obtained through those modifications is very similar to an ordinary Volvo 850 with the only difference that a standard Volvo 850 is not equipped with a N1 engine.

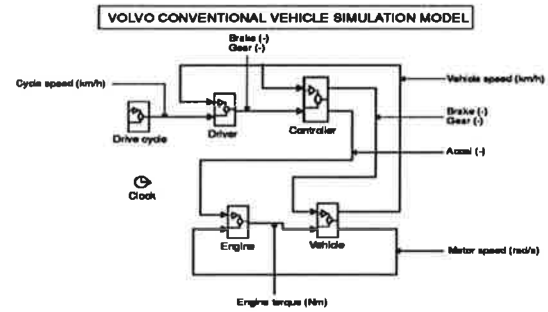

Figure 12: Top level view of the conventional vehicle simulation model.

Some features of the conventional car model are summarised in Table 2. Note that the mass of this model is only 1330 kg. The mass of a hybrid configuration will increase dramatically since a battery, a generator and an electric motor are introduced in the car. The drain power entry of Table 2 contains losses of air-condition, ABS, etc.

Table 2: Some key features of the conventional car model.

Tot vehicle mass [kg]	1330
Engine	90 kW N1
Number of gears	3
Drain power [kW]	2.5

Simulations

Emission and fuel consumption results of the conventional car model when using the FHF cycle are summarised in Table 3. The values in Table 3 serve as yard sticks when evaluating the different operating strategies for the series hybrid vehicle configuration.

It is also instructive to study the energy flow between the different components in the vehicle in order to obtain information about the efficiencies of

Table 3: Simulation results of the conventional car model.

Drive cycle	FHF
Total distance covered [km]	40.5
Drive time [s]	3530
Fuel consumption [g/km]	97.38
CO emissions [g/km]	5.851
HC emissions [g/km]	1.685
NOx emissions [g/km]	4.829

the components. Some different energy flows are defined in Figure 13 and the numerical values from a simulation are given in Table 4. The values in this table will be used when the different hybrid vehicle configurations are evaluated in the following sections.

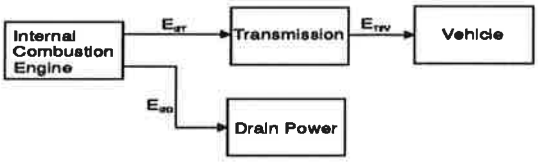

Figure 13: Energy flow diagram of the conventional vehicle simulation model.

Table 4: Energy flow values of the conventional vehicle model.

Drive cycle	FHF
Total distance covered [km]	40.5
Drive time [s]	3530
E_{I2T} [MJ]	19.05
E_{I2D} [MJ]	7.389
E_{T2V} [MJ]	17.92

3.5.2 Hybrid vehicle configuration 1

Model features

Some of the basic features of hybrid vehicle configuration 1 is collected in Figure 14. In this configuration the battery can deliver the whole power to the motor and the internal combustion engine is only used for loading the battery. Key data of hybrid vehicle configuration 1 is listed in Table 5.

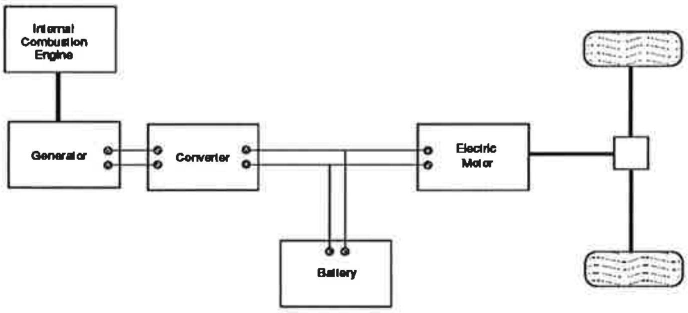

Figure 14: Some basic features of hybrid vehicle configuration 1.

Table 5: Key data of hybrid vehicle configuration 1.

Total vehicle mass [kg]	1980
Battery mass [kg]	360
Number of battery cells	270
Battery peak output power [kW]	80
Max battery charge power [kW]	35
Engine	90 kW N1
Generator	90 kW Siemens
Motor	90 kW Siemens
Number of gears	1
Drain power (AC, ABS, etc.) [kW]	2.5

Operating strategies

Since the internal combustion engine in this configuration not has to deliver any power to the electric motor, the operating strategy can be designed entirely from the demands of the battery. A quite simple strategy is to run the internal combustion engine in two modes, on or off. When the motor is on, an optimal power level from Section 3.3 is used and the mode shift can be governed by for example the battery SoC. The battery temperature can be controlled through variation of the SoC limits where mode shift is performed. In Table 6 are listed the different parameter values that will be evaluated in the next section. For all strategies the engine is turned on when the battery SoC sinks below the level "Min battery SoC" and the engine then remains on until the battery SoC exceeds the level "Max battery SoC". Strategy 1 to 4 uses speed and power levels adopted from the optimisation section. Strategy 1 uses a quite low optimised power level and the simulation in next section will show if this low power level manages to keep the SoC within the specified SoC levels. Strategy 2 to 4 uses a higher but still optimised power level. Further Strategy 2 to 4 uses some different choices of SoC levels in order to show how the battery temperature increase varies with different SoC levels. Strategy 5 uses non optimised engine set points in order to give a hint how good the loss function from the optimisation section really is. The motor speed used in Strategy 5 is the speed that gives the maximum torque of an engine output power of 32.3 kW.

Table 6: Parameter values that will be tested when simulating hybrid vehicle configuration 1.

	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
ICE P [kW]	14	32.3	32.3	32.3	32.3
ICE ω [rad/s]	140	231	231	231	208
Max battery SoC	0.85	0.85	0.85	0.55	0.85
Min battery SoC	0.5	0.5	0.3	0.3	0.5

Simulations

In this section the results of the evaluation of the different parameter choices from the previous section are accounted for. The section however begins with a test how long distance the vehicle can cover only using the battery. Those test results are listed in Table 7.

Table 7: Test of the possible driving range when only the battery is used as energy source.

Drive cycle	FHF
Total distance covered [km]	35.61
Drive time [s]	2893
Battery temp increase [K]	8.07
Start battery SoC	1.00
Stop battery SoC	0.20

The evaluations of the different operating strategies from the previous section begin with an account of the variation of the battery SoC and battery temperature when the different strategies from Table 6 are used to operate hybrid vehicle configuration 1. This account is done in Figure 15 to 19.

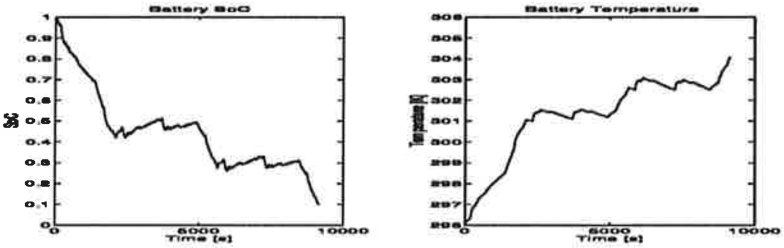

Figure 15: Battery SoC and battery temperature when Strategy 1 is used to operate Configuration 1.

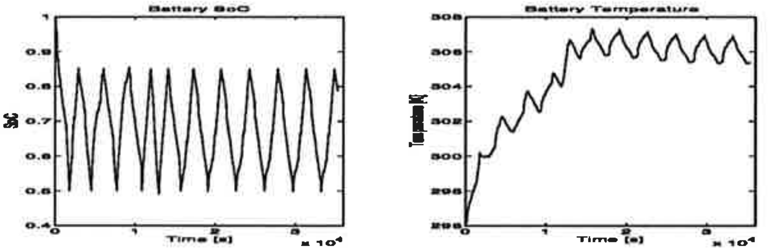

Figure 16: Battery SoC and battery temperature when Strategy 2 is used to operate Configuration 1.

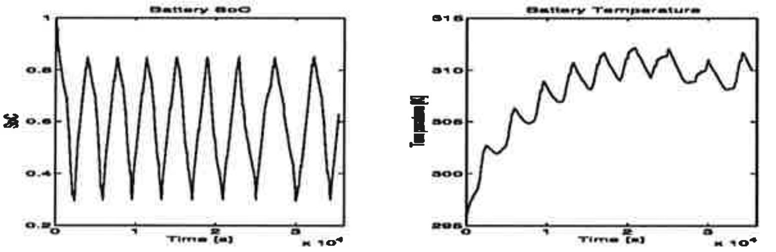

Figure 17: Battery SoC and battery temperature when Strategy 3 is used to operate Configuration 1.

Figure 15 shows that the power level 14 kW is too low to be able to keep the SoC between the specified limits. The power level 32.3 kW is on the other hand high enough to accomplish this task. In Figure 16 to 19 the statement is verified that it is possible to control the battery temperature through variation of the SoC limits. Finally it is seen from the figures that only Strategy 2 and Strategy 5 manages to keep the temperature increase around 10 K.

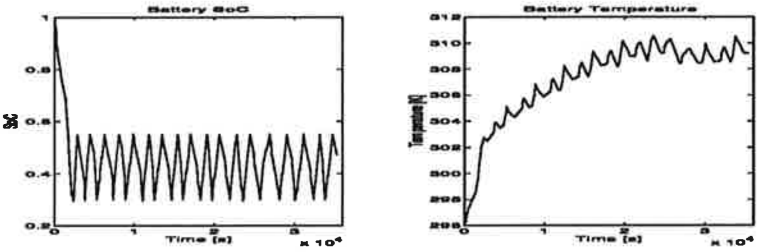

Figure 18: Battery SoC and battery temperature when Strategy 4 is used to operate Configuration 1.

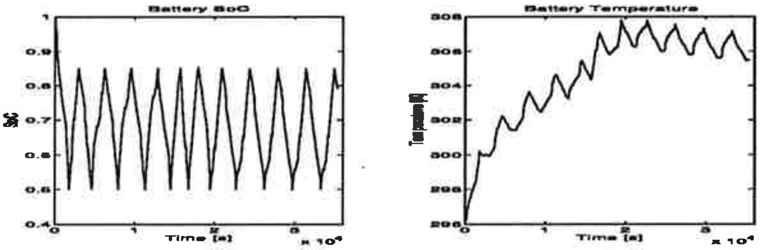

Figure 19: Battery SoC and battery temperature when Strategy 5 is used to operate Configuration 1.

Table 8: Simulation results of hybrid vehicle configuration 1.

	Strategy 2	Strategy 3	Strategy 4	Strategy 5
Drive cycle (repeated)	FHF	FHF	FHF	FHF
Total distance covered [km]	366.2	323.6	365.4	366.2
Drive time [s]	31925	28205	31870	31920
Fuel cons [g/km]	87.48	89.93	89.48	94.63
CO emiss [g/km]	6.131	6.302	6.271	28.08
HC emiss [g/km]	1.038	1.067	1.062	2.035
NOx emiss [g/km]	4.837	4.973	4.948	2.722

The results of the fuel consumption and emission calculations are accounted for in Table 8. Only Strategy 2 to Strategy 5 is listed in the table since Strategy 1 does not manage a complete test cycle. The emission calculation is based on the covered distance between the first and the last peak of the SoC plots from

Figure 16 to 19. This limit point choice accomplishes that the only input energy to the system comes from fuel. The distance covered between the limit points is accounted for in the row with label "Total distance covered".

The following conclusions can be drawn from Table 8. A first observation is that the fuel consumption, CO emissions and HC emissions are considerably lower for the optimised engine set points than for the non optimised engine set point. On the other hand the NOx emissions are quite higher for the optimised engine set point than for the non optimised set point. This clearly shows that the loss function from the optimisation section gives a compromise between the different kinds of emissions that the engine exhaust. Moreover a comparison between Table 8 and Table 3 gives that is it possible to drive the hybrid version of the vehicle with considerably lower fuel consumption than the conventional vehicle when the internal combustion engine stands for all the input energy to the system. This is a quite astonishing result since the hybrid version of the vehicle is 650 kg heavier than the conventional vehicle. Another observation is that the emissions from the hybrid configuration are not reduced significantly compared to the conventional vehicle. Further the emission results are quite high compared to the Californian emission laws given in Appendix B. This is due to the fact that the engine in the simulation model is not equipped with a catalyst.

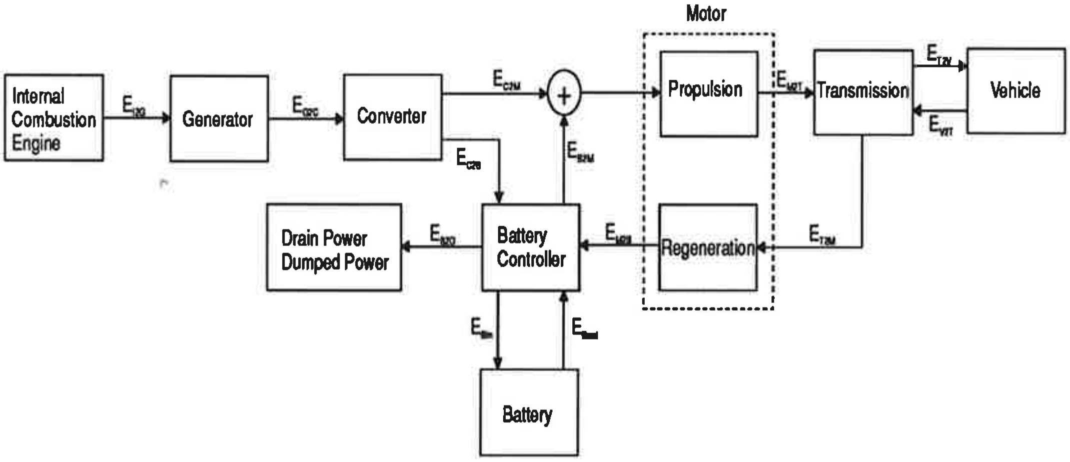

Figure 20: Energy flow diagram of hybrid vehicle configuration 1.

The simulation model can, besides delivering emission and fuel consumption results, provide a picture of the energy flow in the system. This flow is of particular interest for hybrid vehicles since there is a wealth of ways of controlling the energy flow between the different components in a hybrid vehicle. The energy flows in hybrid vehicle configuration 1 is defined in Figure 20 and some numerical values obtained from simulations are listed in Table 9. Notice however that

Figure 20 is *not* an energy balance diagram. This means that the input energy to some block may differ slightly from the output energy from the same block due to the fact that some losses are not explicitly indicated in the diagram. Finally, the energy flows in Table 9 do not say much in themselves but they can be used to calculate some quite interesting efficiencies. Some highlights among those efficiencies are collected in Table 10.

Table 9: Simulated energies of hybrid vehicle configuration 1.

	Strategy 2	Strategy 3	Strategy 4	Strategy 5
E_{I2G} [MJ]	478.76	435.01	488.61	490.40
E_{G2C} [MJ]	352.33	320.13	359.58	351.88
E_{C2M} [MJ]	138.08	96.66	118.33	136.41
E_{C2B} [MJ]	196.62	207.47	223.27	197.88
E_{B2D} [MJ]	82.39	71.91	81.94	82.19
E_{Bin} [MJ]	194.97	205.30	220.62	194.92
E_{Bout} [MJ]	176.21	180.47	195.33	177.07
E_{B2M} [MJ]	138.03	147.42	157.67	139.48
E_{M2B} [MJ]	37.48	33.17	37.52	37.52
E_{M2T} [MJ]	205.15	181.39	205.06	205.00
E_{T2M} [MJ]	51.23	45.33	51.28	51.30
E_{T2V} [MJ]	196.95	174.13	196.86	196.80
E_{V2T} [MJ]	53.37	47.21	53.42	53.44

Table 10: Some efficiency highlights of hybrid vehicle configuration 1.

	Strategy 2	Strategy 3	Strategy 4	Strategy 5
$(E_{C2M}+E_{C2B})/E_{I2G}$	0.6991	0.6991	0.6991	0.6817
$E_{M2T}/(E_{C2M}+E_{B2M})$	0.7430	0.7432	0.7430	0.7430
E_{M2B}/E_{T2M}	0.7316	0.7317	0.7317	0.7314
E_{Bout}/E_{Bin}	0.9084	0.8791	0.8854	0.9084
$E_{T2V}/(E_{I2G}-E_{V2T})$	0.4630	0.4490	0.4524	0.4504
$E_{M2B}/(E_{C2M}+E_{B2M})$	0.1357	0.1359	0.1359	0.1360

The efficiencies in Table 10 can be interpreted as

- the efficiency of the generator and converter,
- the efficiency of the electric motor in propulsion mode,
- the efficiency of the electric motor in regeneration mode,

- the ratio between the output energy from the battery and the input energy to the battery,
- the electric efficiency of the vehicle and
- the relative amount of energy that is regenerated.

Table 10 gives the remarkable result that the electric efficiency of the vehicle lies around 45% for all strategies. A comparison with Table 4 shows that the efficiency of hybrid configuration 1 is considerably lower than the corresponding efficiency of the conventional vehicle. This makes it even more astonishing that the hybrid configuration can drive with lower fuel consumption than the conventional vehicle. Consequently the optimised set point is that good that it manages to compensate for an increased vehicle mass as well as for poor system efficiency. Finally it is noteworthy that around 13.5% of the system input energy are regenerated to the system through regenerative braking.

3.5.3 Hybrid vehicle configuration 2

Model features

Hybrid vehicle configuration 2 is equipped with a battery that can deliver only half the peak power of the electric motor. A drawback with this kind of configuration is that the internal combustion engine must run all the time since it takes far too long time to start the engine if the electric motor suddenly wants more power than the battery can deliver. An advantage with Configuration 2 compared to Configuration 1 is that the battery mass and price reduce considerably. Another advantage with Configuration 2 is that the temperature of the engine and catalyst can be kept steady and that should influence the emissions in a positive way.

A sketch of Configuration 2 is shown in Figure 21. The converter between the battery and the rest of the system is included in order to keep the system voltage on a decent level. The battery alone would give a far too low system voltage. Finally some key data of Configuration 2 is summarised in Table 11.

Operating strategies

As mentioned in the previous section, the internal combustion engine must run all the time when series hybrid vehicle configuration 2 is used. This gives two main alternatives for the operation of the internal combustion engine. In the first alternative the internal combustion engine delivers the main part of the power to the electric motor while the battery delivers the power peaks. In the second alternative it is the battery that delivers the main part of the power to the electric motor while the engine delivers the power peaks. If the second alternative is used the engine is idling the most of the time that is advantageous if emissions per time unit are considered but devastating if emissions per produced

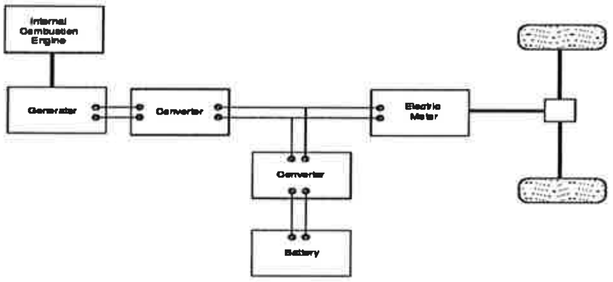

Figure 21: Sketch of hybrid vehicle configuration 2.

Table 11: Key data of hybrid vehicle configuration 2.

Total vehicle mass [kg]	1880
Battery mass [kg]	245
Number of battery cells	180
Battery peak output power [kW]	40
Max battery charge power [kW]	23
Engine	90 kW N1
Generator	90 kW Siemens
Motor	90 kW Siemens
Number of gears	1
Drain power (AC, ABS, etc.) [kW]	2.5

output energy are considered. It is thereby likely that the first alternative gives somewhat lower emissions than the second alternative.

Independently of which alternative that is used the battery sooner or later will be discharged. It is by that reasonable to introduce some kind of battery charge mode in the operating strategy that for example increase the power level of the internal combustion engine when the battery SoC sinks below a certain level.

On basis on the above discussion, the operating strategies in Table 12 have been designed. Strategy 7 to 9 works as follows: Mode 1 is used if the power demand of the electric motor is less than 40 kW. If the power demand of the electric motor is greater than 40 kW, Mode 2 is used. Moreover Mode 2 is used when the battery SoC sinks below "Min battery SoC". The engine output power then remains in Mode 2 until the battery SoC exceeds the level "Max battery SoC." Finally, the system peak power becomes the sum of the peak power of the battery and the power level in Mode 2 when Strategy 7 to 10 is used.

In Strategy 6 the power level in Mode 2 is that low that an additional mode, Mode 3, has been introduced. Mode 3 is only used when the power demand

Table 12: Parameter values that will be tested when simulating hybrid vehicle configuration 2.

	Strategy 6	Strategy 7	Strategy 8	Strategy 9	Strategy 10
Mode 1 ICE P [kW]	0	0	14	14	0
Mode 1 ICE ω [rad/s]	105	105	140	140	105
Mode 2 ICE P [kW]	14	32.3	32.3	32.3	32.3
Mode 2 ICE ω [rad/s]	140	231	231	231	208
Mode 3 ICE P [kW]	32.3	-	-	-	-
Mode 3 ICE ω [rad/s]	231	-	-	-	-
Max battery SoC	0.85	0.85	0.85	0.85	0.85
Min battery SoC	0.5	0.5	0.5	0.75	0.5

from the electric motor exceeds the sum of the peak power of the battery and power level in Mode 2. In battery charge mode, Mode 2 is used. Finally using Strategy 6 the system peak power becomes the sum of the battery peak power and power level in Mode 3.

Strategy 6 to 9 uses optimal set points from the optimisation section. Strategy 10 uses a non optimised set point in order to give the possibility to study how good the loss function from the optimisation section is. The motor speed that is used in Strategy 10 is the motor speed that gives maximum torque of an engine output power of 32.3 kW.

Simulations

The account of the simulation results of series hybrid vehicle configuration 2 begins with some plots that shows how the battery SoC and the battery temperature varies with time when the vehicle is following the FHF cycle.

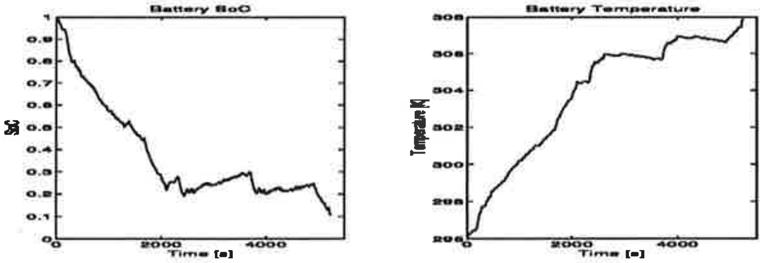

Figure 22: Battery SoC and battery temperature when Strategy 6 is used to operate Configuration 2.

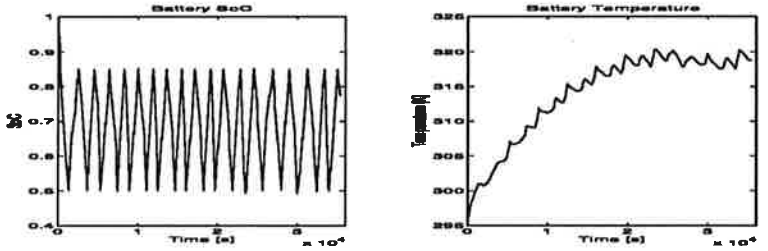

Figure 23: Battery SoC and battery temperature when Strategy 7 is used to operate Configuration 2.

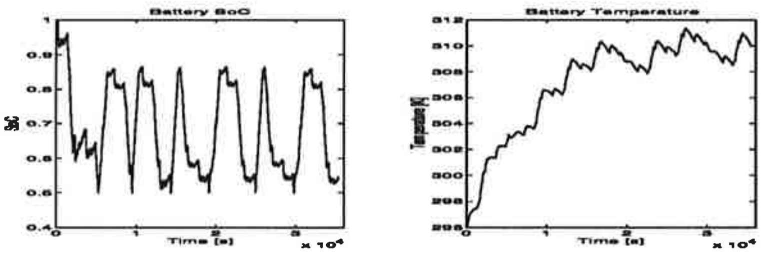

Figure 24: Battery SoC and battery temperature when Strategy 8 is used to operate Configuration 2.

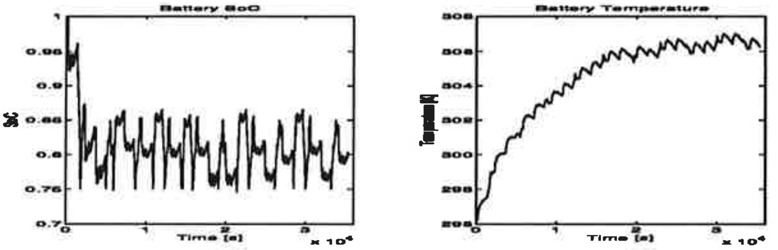

Figure 25: Battery SoC and battery temperature when Strategy 9 is used to operate Configuration 2.

Figure 22 shows that the power level 14 kW is too low to manage to keep the battery SoC within the specified limits. This was also the case for Configuration 1 (cf. Figure 15) and it is thereby possible to conclude that Configuration 1 and Configuration 2 consumes more power than 14 kW in average over a drive cycle. Further vehicle configuration 2 seems to be more temperature sensitive than vehicle configuration 1 since only Strategy 9 manages to keep the temperature

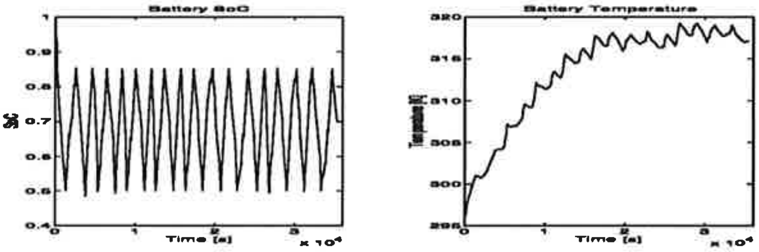

Figure 26: Battery SoC and battery temperature when Strategy 10 is used to operate Configuration 2.

within reasonable limits.

The account of the emission and fuel consumption calculations is listed in Table 13. The emission and fuel consumption calculations are based on the distance covered between the first and the last peak of the SoC plots in Figure 23 to 26. This table is quite discouraging reading since a comparison with Table 3 gives that hybrid vehicle configuration 2 does not show any improvement compared with a conventional car. Further a comparison between Strategy 7 and Strategy 10 shows that also for configuration applies that the optimised set point gives a reduction in fuel consumption, CO and HC emission and an increase in NOx emission compared with the non optimised set point.

Table 13: Simulation results of hybrid vehicle configuration 2.

	Strategy 7	Strategy 8	Strategy 9	Strategy 10
Drive cycle (repeated)	FHF	FHF	FHF	FHF
Total distance covered [km]	369.7	284.4	362.8	366.6
Drive time [s]	32400	24710	31705	32105
Fuel cons [g/km]	111.3	103	100.7	118.11
CO emiss [g/km]	7.452	7.96	7.823	31.9
HC emiss [g/km]	1.47	1.432	1.411	2.567
NOx emiss [g/km]	5.557	5.196	5.054	3.134

The account of the simulations is finished, also for this configuration, with some energy flow results of the system. The different energy flows in series hybrid vehicle configuration 2 are defined in Figure 27, the simulated energy flows are listed in Table 14 and some efficiencies of the system are listed in Table 15.

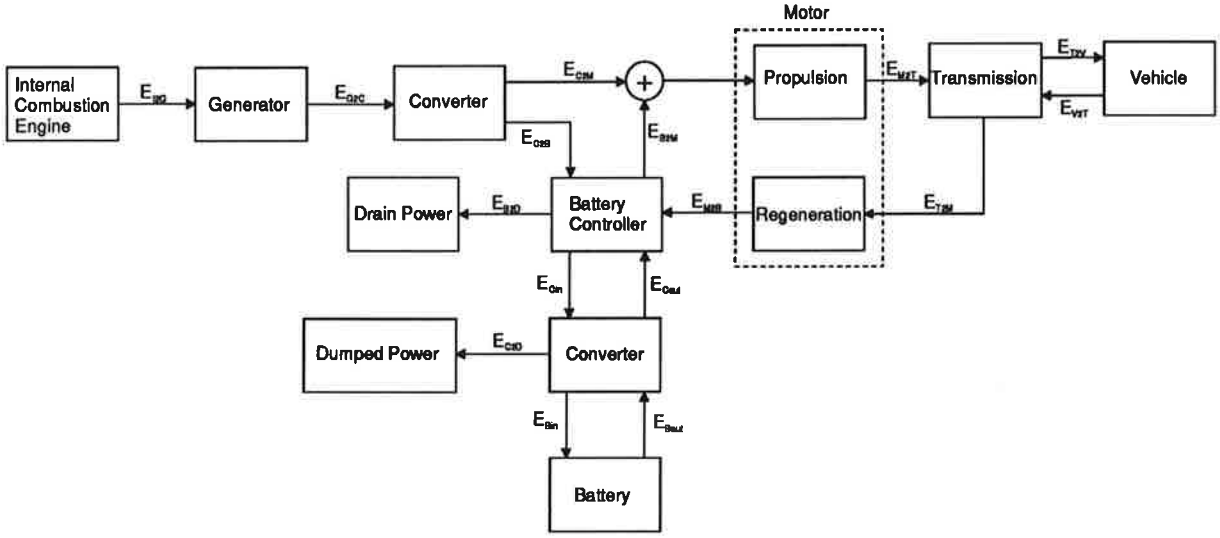

Figure 27: Energy flow diagram of hybrid vehicle configuration 2.

Table 14: Simulated energies of hybrid vehicle configuration 2.

	Strategy 7	Strategy 8	Strategy 9	Strategy 10
E_{I2G} [MJ]	545.94	444.60	557.09	548.89
E_{G2C} [MJ]	401.76	285.46	354.87	393.85
E_{C2M} [MJ]	132.49	126.98	172.23	135.89
E_{C2B} [MJ]	249.18	144.20	164.90	238.26
E_{B2M} [MJ]	140.94	82.45	96.17	135.54
E_{M2B} [MJ]	35.56	27.04	34.71	35.22
E_{B2D} [MJ]	81.01	61.79	79.28	80.28
E_{Cin} [MJ]	241.35	133.46	148.89	230.41
E_{Cout} [MJ]	178.56	106.47	124.73	172.74
E_{C2D} [MJ]	12.34	4.55	4.79	10.39
E_{Bin} [MJ]	216.94	122.24	136.66	208.50
E_{Bout} [MJ]	188.95	112.07	131.29	181.83
E_{M2T} [MJ]	202.78	155.44	199.16	201.36
E_{T2M} [MJ]	48.63	36.94	47.43	48.13
E_{T2V} [MJ]	194.67	149.22	191.19	193.30
E_{V2T} [MJ]	50.65	38.48	49.41	50.14

Table 15 shows that also Configuration 2, like Configuration 1, gives a remarkable low electric efficiency. Moreover a comparison with Table 10 shows that the electric efficiency is quite lower for Configuration 2. This is probably one of the reasons why Configuration 2 gives higher emissions and fuel consumption than Configuration 1.

Table 15: Some efficiency highlights of hybrid vehicle configuration 2.

	Strategy 7	Strategy 8	Strategy 9	Strategy 10
$(E_{C2M}+E_{C2B})/E_{I2G}$	0.6991	0.6099	0.6052	0.6816
$E_{M2T}/(E_{C2M}+E_{B2M})$	0.7416	0.7422	0.7420	0.7418
E_{M2B}/E_{T2M}	0.7312	0.7320	0.7318	0.7318
E_{Bout}/E_{Bin}	0.8664	0.9168	0.9607	0.8721
$E_{T2V}/(E_{I2G}-E_{V2T})$	0.3930	0.3674	0.3764	0.3876
$E_{M2B}/(E_{C2M}+E_{B2M})$	0.1301	0.1291	0.1293	0.1298

3.5.4 Some software and hardware experiences

As mentioned before, the model is developed in the Matlab/Simulink environment. The program versions that have been used are Matlab 4.1.1 and Simulink 1.2. This simulation environment has a very nice user interface that makes the writing of the models fairly simple. However during the simulations it has been noticed that the Matlab/Simulink tool is not completely reliable. For example, a small change of the logging interval in a "To Workspace" block may radically change the simulation result. It is therefore necessary to be extremely careful when interpreting the simulation results. Another major drawback with Matlab/Simulink is that it is not possible to convert an input signal to an output signal or vice versa without rewriting the whole model. This makes it very hard to write general reusable models.

The simulations have been performed on a Silicon Graphics Indigo 2 work station. Even if this computer is quite fast the simulation times have been long. The ratio between the simulated time and the real time taken has been around 1 and the average simulation has taken about 10 hours.

4 Summary

The purpose of this project was to evaluate if a Volvo 850 GLE in series hybrid configuration gives any environmental improvements compared to an ordinary Volvo 850 GLE. For this evaluation a simulation model developed by Ricardo Consulting Engineers has been used. The simulation model had to be modified in several ways so a considerable amount of time was spent on improvement and testing of the model.

In order to tailor the Ricardo simulation model for simulation of a Volvo 850 GLE in series hybrid configuration several new subsystem had to be implemented. The new subsystems were implemented in such way that they could easily be inserted in the original Ricardo model without causing too much interference with the rest of the model. However, during the work it turned out to be very hard to include components that performed well individually into the original model. Due to the great complexity of the system it was fairly difficult to predict the consequences of small changes in certain subsystems.

The implementations of the new subsystems have, as far as possible, been based on data from existing commercial components. A consequence of this is that some components not are perfectly suited for operation in the modelled hybrid vehicle. As an example of this, the internal combustion engine can be mentioned. The top power that is taken from the engine when using the operating strategies in Section 3 is around 32 kW. The peak power of the engine is however 90 kW indicating that the engine is far too powerful. If a more tailored engine was used, the emissions and the fuel consumption would probably decrease considerably.

In the implementation of the new subsystems it has been desirable to limit the complexity of the models in order to obtain reasonable simulation times. As a result of this, fast components as the motor, the generator, the engine and power electronics, have been modelled by static models while slow systems as the battery and the vehicle dynamics have been modelled by dynamic systems. The basis in the choice between static and dynamic models has been considered features that are crucial for the system behaviour over larger time scales.

The resulting model from the model improvement phase in this project has been used for the study of some basic operating strategies for series hybrid vehicles. The aim has been to find a strategy that accomplishes the following four goals:

- Minimise the emissions
- Minimise the energy consumption
- Maximise the battery life time
- Optimise the vehicle performance

To accomplish the first and second goals the set point of the internal combustion engine has been chosen to give a reasonable compromise between emissions and fuel consumption. The third goal has been taken into consideration through the following actions: Firstly the battery charge current was limited so that the battery voltage stayed below a certain level in order to not over load the battery. Secondly the battery temperature was kept within reasonable limits through limitation of the SoC variation during a run.

The main result from the simulation study is that when all input energy to the vehicle is supplied by gasoline, the hybrid version of the vehicle consumes about 10 % less fuel than the corresponding conventional vehicle. This result is quite interesting since the hybrid version of the vehicle is 50 % heavier and has a considerably lower efficiency than the conventional version of the vehicle. The conclusion is that a carefully chosen engine set point can compensate for increased mass as well as decreased efficiency.

Finally it must be mentioned that a simulation study of this kind has a severe limitation. It has not been possible to validate the results with measurements from a real series hybrid vehicle. Therefore it is not possible to judge whether the assumptions and approximations that have been done are reasonable or not. There are however at the present time work proceeding at Volvo in building prototype vehicles so hopefully in a not too far distant future it will be possible to decide if this report belongs in the dustbin or in the bookshelf.

References

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A Some key features of the modelled vehicle

When the series hybrid vehicle simulation model was developed the aim was to use data that as far as possible corresponds to measurements from a real Volvo 850 GLE. In Table 16 some the key data that has been used in the model is collected.

Table 16: Some key features of the modelled vehicle.

Vehicle model	Volvo 850 GLE
Transmission mass [kg]	50
Chassis mass [kg]	280
Body mass [kg]	410
Other mass (seats, panels, etc.) [kg]	340
Maximum brake force [kN]	10
Rolling resistance [kN]	0.2
Frontal area [m^2]	2.12
Drag coefficient [-]	0.36
Tyre rolling radius [m]	0.3
Engine model	Volvo N1
Engine mass [kg]	245
Engine peak power [kW]	90
Generator model	Siemens
Generator mass [kg]	140
Generator peak power [kW]	90
Converter mass [kg]	15
Battery model	DAUG
Battery type	NiCd
Number of battery cells	180/270
Battery mass [kg]	245/360
Battery peak power [kW]	40/80
Motor model	Siemens
Motor mass [kg]	140
Motor peak power [kW]	90

B Californian emission limits

In order to reduce the intolerably high air pollution level in California the California Air Resources Board in September 1990 issued new regulations on vehicle emissions. The following vehicle classes were defined:

- Transitional low emission vehicles (TLEV)
- Low emission vehicles (LEV)
- Ultra low emission vehicles (ULEV)
- Zero emission vehicles (ZEV)

To every vehicle class there is certain emission levels connected. Those levels are shown in Table 17.

Table 17: Maximum emissions in g/km after 80000 km of use per vehicle in California.

	TLEV	LEV	ULEV	ZEV
NOx [g/km]	0.25	0.12	0.12	0
HC [g/km]	0.08	0.05	0.03	0
CO [g/km]	2.11	2.11	1.06	0

There are also specifications how many vehicles a certain car producer must sell within every vehicle class. Table 18 shows how the number of sold cars shall be distributed over the different vehicle classes.

Table 18: Demanded percentage of sold vehicles in different classes in California.

	TLEV	LEV	ULEV	ZEV	Others
1995 [%]	15				85
1996 [%]	20				80
1997 [%]		25	2		73
1998 [%]		48	2	2	48
1999 [%]		73	2	2	23
2000 [%]		96	2	2	
2001 [%]		90	5	5	
2002 [%]		85	10	5	
2003 [%]		75	15	10	

The figures listed in Table 18 concerns car producers that sell more than 35000 vehicles per year in California. Producer that sells among 3000 and

35000 vehicles has to follow the rules from year 2003 and producers that sells less than 3000 vehicles does not have to follow the rules. More information about Californian emission limits can be collected from [3].