

Observations on Electric Hybrid Bus Design

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Abstract

The work presented here deals with evaluation and optimisation of the tractive system in hybrid electric buses. The work is based on analytical simulation models that are verified via measurements.

The main results of the work are:

- An optimised composition of the traction system topology, regarding the size of the different components in the drive train with respect to the performance and emission at a given drive cycle.
- A charging strategy taking into account a predicted drive cycle, the SOC of the batteries and the instantaneous tractive power.
- A transient emission measurement (TES) method for Internal Combustion Engines.

The simulation model concerns all the major power flow, vehicle speed, temperatures and Internal Combustion Engine (ICE) parameters of the busses. The model is verified through measurements on two hybrid buses in Malmö and Stockholm. The ICE models are verified through test bench driving, both by an external partner and by Lund University.

The predicted drive cycle proposed here is based on position measurements of the bus relative to the route.

With the proposed changes in composition and charging strategy, one of the buses studied can reduce the battery weight with 60 %, the fuel consumption with 10 % and the size of the ICE with 60 %.

As a part of the work with measurements on the busses some practical experience of handling the vehicles have been gained, some of which are also presented in this report.

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Lund, a snowing day in April, 2001,

Christian Andersson

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Chapter 1

Introduction

1.1 Background

Electric traction of vehicles is an old technique and has been used for example 1894 in an electric train. Electrical motors have higher torque density than an ICE (internal combustion engine), and thus the electrical traction system can have a more compact design than the ICE counterpart, e.g. the electrical motor can be mounted in the wheel. The life cycle on an electrical machine is longer than that of an ICE, they do not need oil change and do not generate any emissions. Another advantage in a vehicle is that they can regenerate the kinetic energy when braking. As a traction motor, the electrical machine is more suitable than any ICE.

The problem with an electrical driven vehicle is the amount of energy that must be brought with the vehicle to reach a reasonable driving distance. The main energy storage is electro chemical (batteries), electro mechanical (flywheels) and electro static (super capacitors). No electric bus equipped with these energy storages can store an amount of energy on the bus that is comparable to e.g. the energy in the diesel tank of a pure diesel bus.

An important trend for the future of electric vehicles is the use of fuel cells that allow for direct conversion of a high-energy medium (gas or fluid) to electricity. In the future, the fuel cell vehicle may compete with conventional ICE vehicles.

One solution to the electrically driven vehicle's energy storage problem is to bring along an ICE and a generator, which can assist the electro chemical energy storage with electric energy from chemical energy with high energy

density. From a driving distance point of a view, such a vehicle has the same advantages as the pure ICE driven vehicles. From an emissions point of view the hybrid vehicle also has similar disadvantages as the ICE driven vehicle. But, there is a small and important difference, the ICE does not have to produce all the instantaneous power for driving, and there is a freedom to choose operating point for the ICE to keep the state of Charge (SOC) of the batteries within reasonable limits.

The battery assists with the difference between the total power used in the vehicle (including tractive power) and the power produced by the ICE-driven generator. The possibility of choosing the working points of the ICE more freely in a hybrid vehicle makes it possible to optimise some parameters. The energy consumption is one parameter and emissions another. To optimise the composition and use of a hybrid electrical vehicle, it is necessary to start by defining what qualities and performance or what combinations of these that is regarded as optimal.

Electrical hybrid vehicle can be built in any conventional type, like trucks buses and small cars. The electrical vehicle's qualities with a silent and emissions free (the ICE turned off) operation are particularly interesting in the centre of the city.

This licentiate thesis describes a scientific evaluation of two commercial hybrid buses, with special focus on the design and control of the traction system including the batteries, combustion engine and electrical machines. The work is requested by three bus fleet operators in Sweden (Malmö, Stockholm and Uppsala), and performed by IEA at Lund University and dept. of Physics at Uppsala University. IEA has earlier experience of hybrid vehicle project (Hemmingsson, 1999).

The main goal of the work behind this report is to increase the understanding of hybrid buses amongst bus fleet operators, in order to make them more competent buyers of hybrid buses.

To reach this main goal, a number of sub-goals have been set:

1. The creation of a simulation model that describes a hybrid bus in enough detail to facilitate evaluation of the effect of changes in the composition or control of the hybrid drive system.
2. Detailed measurements on two commercial hybrid buses for calibration of the simulation model. This in turn requires the design and installation of a measurement system.
3. Sensitivity analyses of the effect of changes in the composition or control of the hybrid drive system. Particular questions are:

- a. - What is the best size of combustion engine for a given power consumption?
- b. - What is the best size of the traction battery?
- c. - Which is the most suitable charging strategy, i.e. how to operate the ICE as a function of the operation of the vehicle?

There are several commercial simulation programs available for electro-hybrid vehicles. They are often made for specific customers or for specific hybrid structures, and do not allow the kind of changes in detail and/or topology that we anticipate to need. By the time the beginning of the project the Advisor program (Advisor) was not available. Thus we conclude that we need to build up our own simulation platform to be able to make necessary additions, because there is also pedagogic advantages with building a unique simulation model.

For all simulation programs a lot of parameters are requested like efficiency, consumption and emissions. The manufacturer of the components in a particular vehicle could supply these parameters, but often the manufacturers are not willing to supply key parameters, like the efficiency of their product. It is also required to have a good knowledge about the components in the vehicle as well as the driving cycle. This has been obtained in this work by measurements on the hybrid bus, both on the bus in traffic and directly on some of its components.

1.2 Main Results

The authors' main contribution with the work presented in this thesis is:

- A simulation program for a HEB (Hybrid Electric Bus), verified via measurements, taking all major power conversion processes into account, modelling efficiency and emissions, given a particular drives cycle and vehicle specification.
- A predictive charging strategy that utilizes the repetitive nature of a bus route to predict the power need and thus allow a smoother use of the ICE
- A method (TES) for determination of the transient limit, expressed as a bandwidth, within which the ICE performance can be regarded as stationary.

With the proposed changes in theoretical simulation model in composition and charging strategy, one of the buses studied can reduce the battery weight with 60 %, the fuel consumption with 10 % and the size of the ICE with 60 %.

1.3 Outline of the Thesis

A general introduction to hybrid vehicles and their main components is given in Chapter 2.

The two commercial buses of series hybrid type studied in this report, a Neoplan MIC N8012 and Scania/Dab 1200MKII, are described in Chapter 3.

A construction of a simulation model has been made that include the bus dynamics, the ICE and the power flow in the bus, see Chapter 4. The simulation model has been verified and calibrated with onboard measurements where comprehensive measurements were made on the buses and their ICEs (Internal Combustion Engine), see Chapter 5. With the simulation model a series of sensitivity analysis have been made, pointing out suitable motor sizes, charging strategies etc of the buses.

A number of different drive cycles are presented in Chapter 6. A particular way of using the drive cycle, as a function of position instead of time, is presented. The predicted drive cycle proposed in Chapter 7 is based on position measurements of the bus relative to the route.

A sensitivity analysis with respect to ICE size, battery size and charging strategy is presented in Chapter 7. A method for determination of the limit for transient behaviour of an ICE is presented in Chapter 8. The method is called TES-transient Emission Sampling and is based on emission sampling from a cyclic repetition of a torque/speed loop. A transient emission sampling technique and study is performed on an ICE in Chapter 8.

Chapter 2

Hybrid Vehicles

A definition of the entity hybrid vehicle is given by Michael Tamor at Ford Motor Company:

“A Hybrid vehicle is a conventionally fueled and operated vehicle that has been equipped with a power train capable of implementing at least the first three of the following four hybrid functions:

- 1) Engine shutdown when power demand is zero or negative.*
- 2) Engine down-size for improved thermal efficiency*
- 3) Regenerative braking for recovery and re-use of braking energy*
- 4) Engine-off propulsion at low power (when engine is inefficient)”*

A power train that fulfills at least the first three of the four functions above can be composed in a number of different ways, where series hybrid, parallel hybrid and variants of these are the most common. The ICE can be of different types, e.g. Otto, Diesel, Stirling etc. The electric energy storage can also be of several different types, like electro chemical (batteries), electro mechanical (flywheels) and electro static (super capacitors). The electrical machines can also be of several different types, although they are all rather alike in terms of efficiency.

In the following sections, these topologies and components of them are described as a basis for later simulation model creation.

2.1 Introduction

The aim with a hybrid-drive system is to run the ICE either at the best possible efficiency or at minimum emissions or a combination of both, while maintaining the desired vehicle performance. This goal can partly be reached already at the design phase, by a proper choice of ICE type and size, electrical machines type and size, battery type and size and charging strategy. The charging strategy is the strategy, with which the instantaneous ICE power is selected in relation to the driver's power request and the battery SOC (State of Charge) deviation.

The size of the ICE is crucial, since an oversized ICE means that it will probably run most of the time at too low efficiency. This is particularly important for a city bus since it runs and stops frequently and parts of the kinetic energy can be recovered to the battery when it brakes.

A too large battery-pack and ICE will make the bus heavy and expensive, while too small traction motors will make the performance too low. It is thus important to find the right combination of the different components.

In a hybrid vehicle the ICE with its fuelling system is the only prime source of energy. Night charging is not an alternative when the bus runs a whole day (for more than 10 hours). There are lots of possibilities to combine the ICE, battery and electrical machines in a drive-train series, such as series, parallel, or various combinations of series and parallel (here called complex).

2.2 Different Hybrid System

Series hybrid

The buses in the project are series hybrids. In this combination of the hybrid vehicles electrical machines supply all the tractive energy and there are no mechanical connections between the ICE and the wheels. The ICE drives a generator that charges the battery and supplies the traction motor with power, as shown in Figure 2.1 An advantage is that the ICE can be switched off when driving the vehicle in no-emission zones. The working point of the ICE (speed and torque) can also be chosen freely when running the ICE. (van Mierlo, 1999)

A drawback is that the prime energy from the ICE has to pass two electrical machines and power electronics on its way to the wheels. This makes the system efficiency relatively low. The energy may also have to be stored in a

battery, which further reduces the system efficiency. Another drawback is that the traction motors have to be able to convert the peak traction power.

An electrical vehicle supplied with a small ICE and generator as a range extender can be considered a simple series hybrid vehicle.

Most of the existing hybrid buses are series hybrids. One reason is the way they run with many starts and stops. Another reason is that electric wheel motors do not need a rear axis; this makes it possible to design the bus with a low floor even in the back.

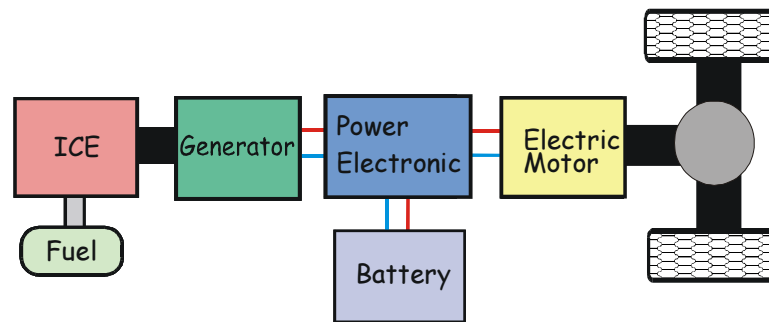


Figure 2.1: Series hybrid vehicle

Parallel Hybrid

The structure of the parallel hybrid is illustrated in Figure 2.2. The ICE is mechanically connected through a gearbox to the wheels; so is the electric motor. When braking the electric motor can regenerate power to the battery. One of the advantages in comparison with the series hybrid system is that all the energy from the ICE to the wheels does not have to be converted to electricity. This increases the system efficiency. Another advantage is that the electrical machine does not have to be so large that it can supply all tractive power. (van Mierlo, 1999)

A drawback with the parallel hybrid is that the operating point (speed and torque) of the ICE cannot be chosen freely due to the mechanical connection of speed through the gearbox to the wheels. This drawback can be neglected by using a CVT (Continuously Variable Transmission, a gear box with a continuously variable gear ratio) in the transmission. The CVT allows the ICE to be operated in other points in the speed-torque space.

A simple parallel-hybrid vehicle would be an ordinary car equipped with a large electrical starter-motor and a large battery. Several car producers have made various constellations of this hybrid. Honda Insight is the first parallel-hybrid vehicle in series production with 5-speed manual gearbox, 50 kW ICE and a 10 kW electric motor. (Insightcentral)

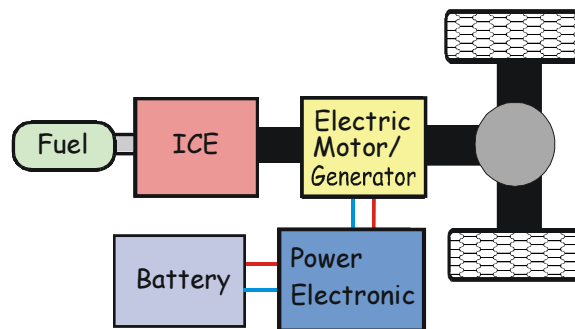


Figure 2.2: Parallel hybrid vehicle

Power Split Hybrid

It is possible to combine the advantages of parallel and series hybrid vehicle (Stridsberg, 1998) or by using a planetary gearbox (Kimura, 1999), as illustrated in Figure 2.3. Such a constellation uses two electrical machines and one ICE in connection to a planetary gearbox.

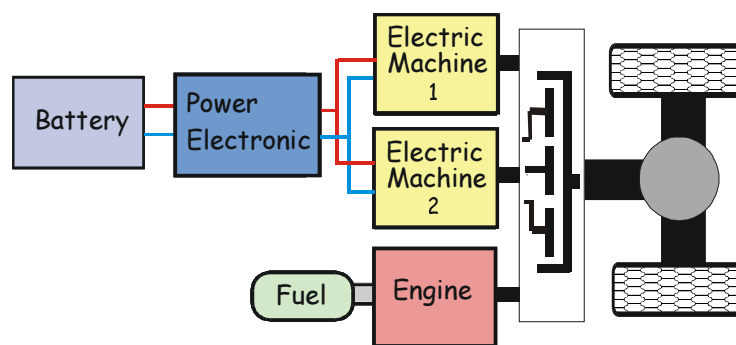


Figure 2.3: Complex hybrid vehicle

In the complex (power split) hybrids the ICE is connected to the planet carrier wheel, see Figure 2.4. The output axis is connected to the ring wheel. The electrical machines are connected to the solar wheel as well as the ring wheel. Both electrical machines are connected via separate power electronics to the battery. If the components in the drive train are well designed this technique allows the ICE to operate at optimal torque and speed for best efficiency. Only at one specific speed all the power from the ICE goes directly to the wheels and it acts like a parallel hybrid. In all other cases it acts more or less like the series hybrid. The choice of configuration depends on what performance the vehicle is designed for, and which complexity that is desired for the drive train.

The first passenger car in series production with this type of gearbox was Toyota Prius, with a 44 kW ICE and a 30 kW electrical motor, produced in 1998. (Hellman, Peralta and Piotrowski, 1998)

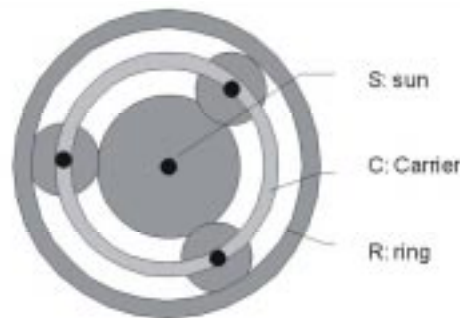


Figure 2.4: The planetary gear.

2.3 Prime Source of Energy

The prime source of energy can be a fuel cell (FC) or an ICE. The vehicle can also be connected to the electric grid over night for battery charging. This over night charging has little influence on the fuel consumption on a city bus in continuous traffic for 12 hours, since a fully charged battery in pure electric mode only will last for a small fraction of the travelled distance during a full days operation.

With generic FC's hydrogen is used as the primary energy storage, but heavy research efforts are made towards reformer based systems with e.g. methanol as the prime energy source. The combustion of hydrogen does not produce any other emission than water, and furthermore produces the necessary electrical energy. For a basic description of fuel cells in vehicles, see (Meyer, 1998). If hydrogen can be manufactured with favorable emission this technology could be very interesting for the future. There are still problems with hydrogen, e.g. it is not so easy to bring hydrogen in a tank on a vehicle. A FC has an efficiency of about 60%, but if the compressor and water pump also are included in the system, the efficiency is reduced to 30%. This value is comparable to an ICE. FC's are still too expensive compared to and ICE and a generator. (Törngren, 1998)

As alternative to the conventional ICE there are other types of ICEs like turbines and stirling motors. Volvo has built a hybrid bus with a gas turbine. (Malmqvist, 1998) In this thesis and in the hybrid vehicles in this project only conventionally fuelled ICE's have been modelled and evaluated.

There are many similarities between Diesel and Otto engines. One important difference is however the air/fuel ratio, called the lambda. A gasoline (spark ignition) ICE is meant to operate at stoichiometric relationship between air and fuel. The air/fuel ratio is controlled when throttling. In a Diesel engine the air flow is constant and the amount of fuel is controlled when accelerating. This makes the diesel engine run lean when idling and at low load. These are the reasons why an Otto (gasoline) engines run with $\lambda = 1$ (at the stoichiometric ratio) while the diesel ICE's require $\lambda > 1.4$ which is lean burn. The emissions in an Otto engine are illustrated in Figure 2.5.

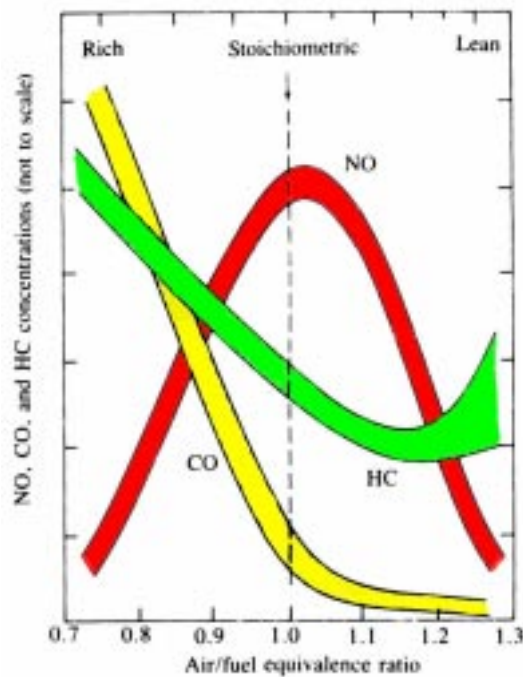
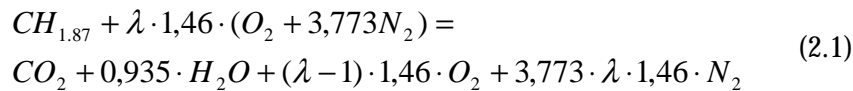


Figure 2.5: The emission by different lambda of an Otto engine before the catalytic converter.

In order to decrease the emission of carbon dioxides, hydrocarbons and nitrous gases there has to be both an oxidizing and reducing environment. This can be obtained by using a 3-way catalytic converter in the exhaust pipe. A modern air/fuel ratio control system controls the exhaust to be periodically rich and lean. In this way there is both an oxidizing and reducing atmosphere created in the exhaust pipe. The catalyst is active only at high temperatures but can in this way obtain a significant reduction of the three major components in the exhaust gas, CO, NO_x and HC. The exhaust gases will be reduced to 99 % from the emission after the catalyst reactions. (Heywood, 1988)

An ICE that is running lean and is connected to a 3-way catalyst will not be able to reduce the NO_x gases. A 2-way or an oxidation catalyst converter can be connected and do the same job by oxidising the HC and CO. With a proper air/fuel ratio that both oxidizes the hydrocarbons and the carbon dioxide and reduces the NO_x gases the principal composition of the exhaust gas is dominated by water and carbon dioxide. Here we neglect all the other

components that are present. Equation 2.1 shows a simplified summary reaction of the combustion between gasoline and air, in lean mixture as function of lambda. The coefficients in the equation represent the molar weight [g/mol] of the different substances. (Johansson, 2001)



In general gasoline can be replaced in the Otto engine with ethanol while diesel can be replaced with natural gas (CNG) in the diesel engine. When a gasoline ICE runs on ethanol, very small adjustments of the fuelling system is required, basically it only needs a higher amount of fuel. A diesel engine needs spark ignition plugs to run on natural gas, a new fuel system and fuel tanks. (Egebäck, Ahlvik, Westerholm, 1997)

The emissions from an ICE are very complex and are depending on many parameters such as combustion technology, thermodynamics and mechanical operations. To test and compare different ICEs standardised methods have been developed (Dieselnet). One of these methods is called ECE R49. The test contains 13 points where the ICE runs in different speeds and torques. First the ICE runs on idling and then on different speeds by the maximum torque, then idling, then by full power speed and final idling again, see Figure 2.6.

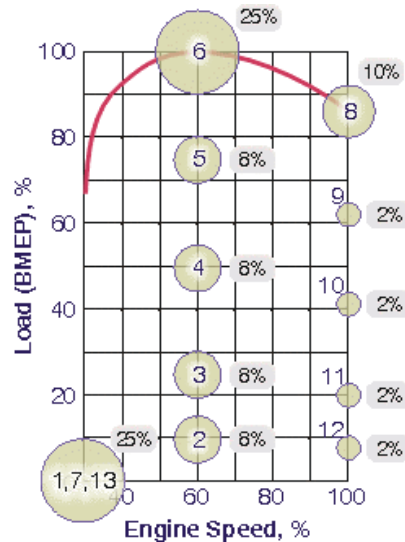


Figure 2.6: The ECE R49 ICE test

This mapping gives a good description of the fuel consumption and the emissions in stationary operation, but do not contain any information about the transient behaviour of the ICE when it is running up and down in speed and torque.

The traction system has to provide any transient power required by the driver. In a hybrid, these transients have to be supplied by the traction system to some extent. When the ICE runs in transient operation the emissions will increase.. Thus it is important to know the transient properties of an ICE when designing a hybrid traction system In Chapter 8 a new test procedure to measure the transient behaviours, proposed here in this thesis for the first time, will be tested on an ICE in a test bench. The test procedure gives a hint of how fast it is possible to move between different operation points. In a hybrid vehicle the ICE is not the only tractive power source like in an ordinary vehicle and power transients from the ICE can be avoided. In order to simulate the time varying behaviour of the hybrid vehicle it is obvious that the ICE has to be properly represented in the model.

An ICE in practical use may differ from the one in the test-bench; the ICE emission depends on many other things like the temperature, the flame speed in the combustion and the air/fuel ratio. Even in a test bench it is very difficult to measure the same emissions by the same working point two days in a row.

The most important reason for these behaviors is the Lambda variations. The Lambda alters between 0.97 and 1,03 with the average value 1,00 and when Lambda differs too much from 1,00 the emissions will increase fast. Another reason is also temperature variation in the combustion chamber and in the catalytic converter.

2.4 Electrical Machines

Most of the electrical machines used in hybrid vehicles are alternating current (AC) machines, that is induction or synchronous machines, which is due to the development of power electronics for high power and due to the faster control systems available with modern micro-controllers. In the beginning of the hybrid vehicle development process direct current machines were mostly used due to the simple control. One of the drawbacks with DC-machines was the shorter life cycle and problems with high speed. By having brushless permanent magnetic machines this problem is partly overcome (Alaküla, 2000)

The induction machine is the very most standardized and the most common of all the electrical machines. There are very few moving parts and the mechanical construction is simple. This gives this type of motor long lifetime and it requires a minimum of care. These advantages in combination with a low price make the induction machines very common.

Synchronous machines are similar in the mechanical construction to the induction machines. Most synchronous machines used in vehicle traction are permanent magnetic machines, which often uses an outer rotor in the permanent synchronous machine. This gives the motor a high torque density, typically one order of magnitude higher than that of an ICE.

The efficiency of a well-designed electrical machine for vehicle application is often higher than 90 % in most of its operating space. In best operating points the efficiency may reach 97 %. Generator and motor can be the same type of machine.

Electrical machines differ in behaviour from ICE in many ways. Electrical machines have generally good efficiency and can be overloaded for a short time when high power is needed. The ICE has a maximum torque by a certain speed while an electric machine has a constant torque during from zero speed to a certain maximum after which it drops as the inverse of the speed increase. This makes that an electrical driven vehicle feels stronger at low speeds. The torque density of an electrical machine is high, it can reach levels like 30 Nm/kg. (Anpalahan, 2001) In comparison, an ICE torque density is limited to 2 Nm/kg. (Heywood, 1988)

The Figure 2.7 shows the principal construction of a conventional induction- and an outer rotor synchronous machine.

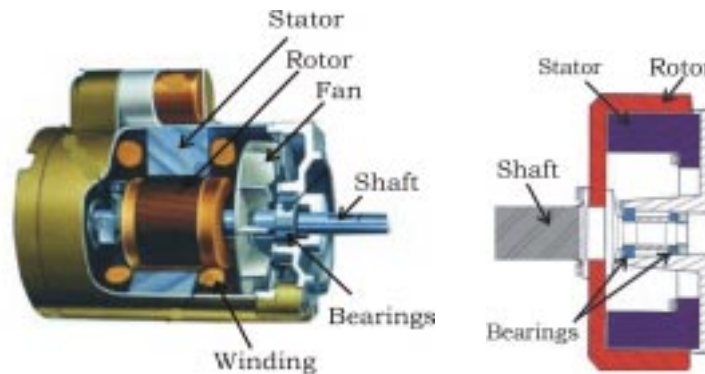


Figure 2.7: Induction- and synchronous-machine.

2.5 Power Electronics

To connect an AC-machine to a traction battery, the traction battery voltage has to be connected to some kind of power converter for conversion to AC. In some applications the power flows only in one direction, for example from the generator to the DC system. In other application e.g. the traction motor, where the power flows in both directions, more sophisticated power electronics is needed. When power goes from the generator to the traction motors there are two steps, the power from the generator is AC/DC converted and then DC/AC converted for the traction motors.

The converters are self-commutated with IGBT-transistor (Isolated Gate Bipolar transistor) or MOSFETs. In the power electronics the switches work by switch frequencies between 1 and 10 kHz. The efficiency of a well designed converter is often more than 98 % in most of the working area. (Blaabjerg, 1995)

2.6 Energy Storage

A hybrid vehicle uses per definition more than one energy source. If one is able to store regenerated energy, it is possible to improve energy efficiency and possibly emission decrease.

There are a number of energy storage types available with different drawbacks and advantages. Some of the energy storage still needs more development and testing to be commercialised.

Electrochemical energy storage is the most common one. These batteries belong to the type of storage where the energy is stored chemically. The drawback is the life cycle, size and weight.

Flywheels could be future mechanical energy storage. One advantage is a high peak power density (1 kW/l). (Manson, 1998)

Figure 2.8 illustrates some future and present energy and power storage technologies. The X-axis denotes the power density [kW/kg] in a logarithmic scale and the Y-axis shows the energy density [Wh/kg] in a logarithmic scale. The price is not included in this diagram. It would have been very difficult to evaluate that, since in most cases the storage is not yet produced in large series and the number of cycles that the battery can sustain is hard to predict. (HEV Team, 2000)

Since several of these technologies still are under development, there is a lack of predictions for large scale production pricing.

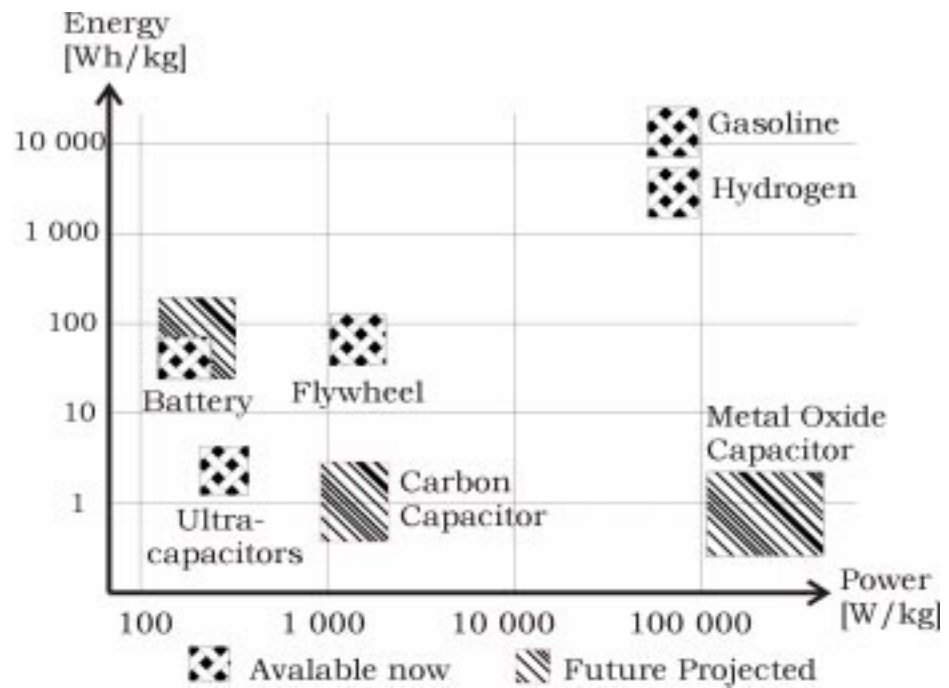


Figure 2.8: Different energy storage

Battery

The only energy storage commercially available today for use in hybrid vehicles is conventional batteries. The types of battery used are listed in Table 2.1:

Table 2.1
Battery types

Lead-Acid [Pb/ac]	Cheap, but not so long lifetime
Nickel-Cadmium [Ni/Cd]	Better than Lead-acid, environment problem
Nickel-Metalhydride [NiHM]	More energy and power than Ni/Cd
Lithium-polymer/iron [Li/p Li-ion]	Maybe the future, production just started
Sodium-Nickel-Chloride [Na/NiCl ₂]	Maybe the future but at present

The next table describes some relevant properties of different batteries for electric vehicles (Thisdale, 2000).

Table 2.2
Battery characteristics

Battery/Criteria	Pb/ac	Ni/Cd	NiHM	Li/p	Li-ion	Na/NiCl ₂
Energy [Wh/kg]	35-40	55	70	155	125	80
Power [W/kg]	80	120	200	315	260	145
Energy dens[Wh/L]	90	90	90	165	200	130
Life cycles	300	1000	600	+600	+600	600
Charge time [h]	6-8	6-8	6	4-6	4-6	4-6
Driveng range [km]	75	100	150	250	200	200
Price (SEK/kW/h)	1200	5000	7000	-	-	-

The use of the battery management system (BMS) should increase the batteries life and saving them from dangers like overcharging and discharging when driving and charging. One of the problems with a BMS is to establish relevant models of the state of charge (SOC), how full or empty a battery is for the moment (Hauck, Altimeier, 1998). Of course it is easy to measure the current in and out from the battery, but the SOC is also depending on several other parameters like resistive losses in the battery that are a function of the temperature, charging history etc.

There is also another way of handling the energy of the battery, having some kind of indication of the energy level of the battery. The energy level could both be a maximum or minimum level. The minimum level is interesting when the battery assist with power and the maximum level is interesting when power are going to be stored in the battery.

A battery consists of many cells that are connected in series. These cells are identical regarding the voltage and resistance in theory, but not in reality. When a battery is charged this may pose a problem with over-voltage in some cells and under-voltage in others. There are more advanced BMS systems that actively bypass the charging current from the over charged cells.

In this project the BMS of one of the buses has indicated out-of-range temperature or voltage in a battery cell-block, with the consequence that the bus did not move from the place. In that situation the question appears: how should a BMS system be implemented in a vehicle?

2.7 Accessories

In any vehicle, and certainly in a HEB, there are a number of systems that consume energy apart from the traction system. Examples of such systems are air conditioning, braking, steering and lights. Other such systems that are more specific to buses are the opening of doors and lowering of the bus at a bus stop. These systems could be electric, hydraulic or pneumatic. These different energy forms can be accomplished even when operating the system in pure electric mode on the battery.

Since most systems on board a bus are inherited from conventional buses, and thus made to be driven by the ICE, there is often a dual supply system. One example is the air pressure for opening doors etc. that is made with a compressor. The compressor can either be mechanically coupled to the ICE when the ICE is in operation or driven by a separate electric motor when the ICE is turned off. This kind of constellation naturally increases the complexity. In an electric-hybrid vehicle it would be preferable to have as many of the accessory systems as possible electric only. That would minimize the complexity, the cost and often the losses since e.g. an electrically driven compressor can be a variable speed drive, which is favourable from an efficiency point of view.

2.8 Driver

The drivers behaviour with respect to driving the bus is naturally a complicated function of very many parameters like traffic density, possible delays relative to schedule, time of the day, state of health, passenger behaviour etc. that is very hard to model correctly.

It is thus necessary to use a simplified model in the simulation work described later. There is an advantage though, with a simplified model, that the model will be repeatable which is very important when comparing different technical arrangements.

A particular note must be made regarding the drivers behaviour. After having done numerous measurements on the HEB's in the work with this report it is clear that the accelerator is used in mostly the same way by most of the drivers. The accelerator is basically operated in three levels, full way down, half way and not at all. When the bus starts and accelerates the driver pushes the accelerator to the bottom until the bus reaches the desired speed (50 km/h) and then releases the accelerator to halfway to continue at the same speed or just leave the bus rolling. When the driver breaks for a stop he doesn't push the accelerator at all.

Chapter 3

Case Studies

In the present work, the drive systems of two different types of hybrid busses have been thoroughly investigated. One is a Neoplan Metroliner MIC N8012 GE and the other is a Scania/Dab Citybus 1200 MKII. The purpose of the investigation has been to aid and verify modeling. Thus, comprehensive measurements system has been installed and all major energy paths in the vehicles, and a number of other quantities are also measured.

These buses are both pure series hybrid types, but represent different concepts in terms of battery size vs. ICE size. See table 3.1 for more detailed information about the vehicles.

Table 3.1
Vehicle specification

	Case I	Case II
Vehicle mass	8500 kg	12500 kg
Front area	8 m ²	8,5 m ²
Length	10 m	12 m
Generator type	PMSM	PMSM
Generator power	125 kW	55 kW
Electric motors type	PMSM wheel motor	IM
Electric motors power	2 x 55 kW	2 x 75 kW
ICE type	Natural gas	Gasoline & E85
ICE size	5.9 l	2.3 l
ICE power	145 kW	90 kW
Battery Type	NiMH	NiCd
Number of cells	280	270
Battery Energy	60 Ah	80 Ah

3.1 Case Study I – the Neoplan

Neoplan in Germany makes the bus in case I. It has a large ICE (5,9 l), generator and a battery (15 km at battery operation). The genset (ICE and generator) is able to supply all peak power needed for the traction-motors. The bus is designed to take 57 passengers. It is a low floor citybus, 10 meters long. The chassis is built of composite and coal-fibre. This makes the bus very light. The construction also is environmental friendly since it is 100 % recyclable.



Figure 3.1: Case I Neoplan bus

The ICE and generator are placed in the back of the bus, the fuel tanks on the roof and the battery on the floor in the middle of the bus.

The power-flow control and the name of the manufactures of the systems can be seen in Figure 3.2 in the Neoplan bus.

The Cummins system controls the ICE through the ICE sensors. The fuel/air ratio, the ignition and idling are controlled. The input signal like throttle-angle to the ICE comes from the MagnetMotor system.

The Varta BMS system measures, and to some extent, controls temperature, current and voltage of the battery. It also calculates the State Of Charge (SOC) of the battery that is delivered to the MagnetMotor system.

The MagnetMotor-control system controls all the other systems, the ICE, the battery, the generator and the motors, in a supervisory manner. The input to the MagnetMotor system comes from the driver. The driver's accelerator movements are registered and the MagnetMotor system decides how much and which power source (battery or generator) is going to supply the requested power. In this decision many parameters can be involved like the present State of Charge in the battery and the speed of the vehicle.

It must be noted that the description above on how the systems on board the buses interact is concluded from studies of the documentation that follows the bus. This information is not confirmed by Neoplan and there is a possibility that the real implementation differs from the one described in the documentation.

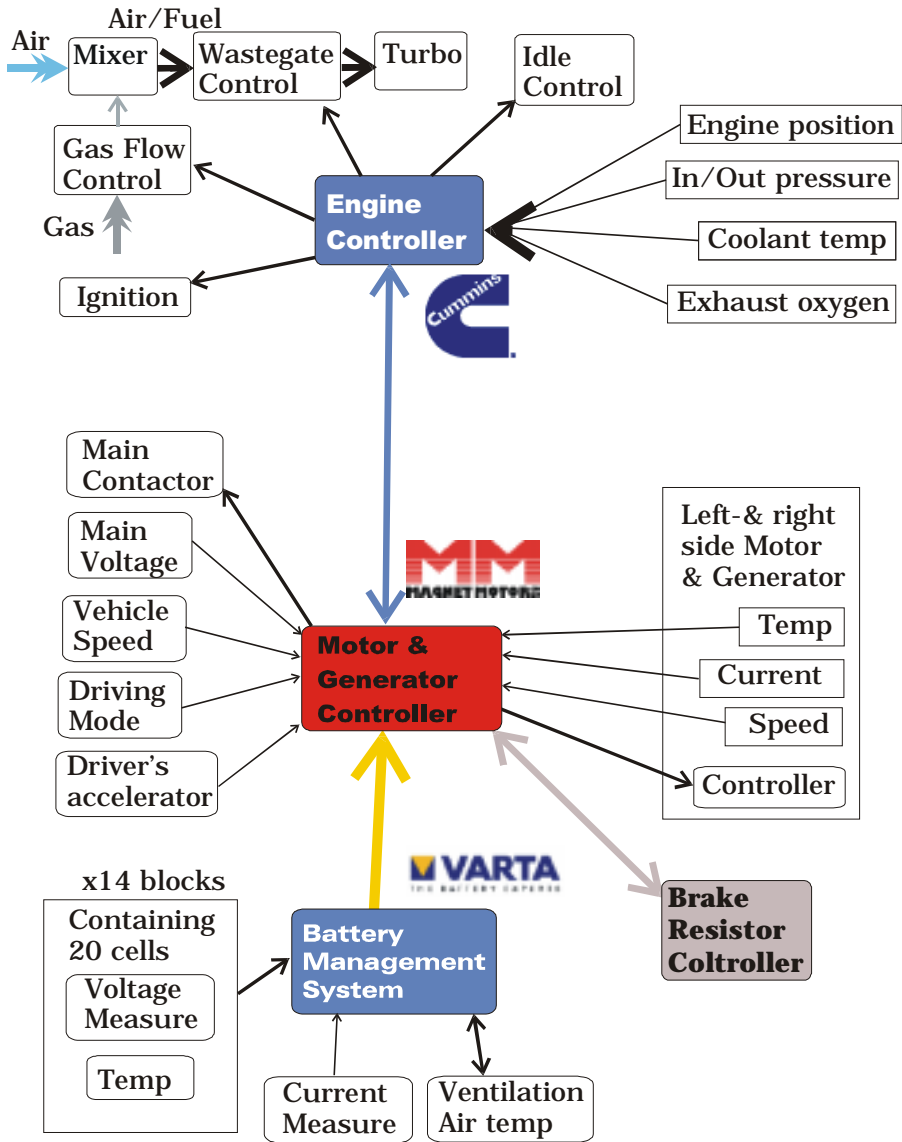


Figure 3.2: The control system and the manufactures of the Neoplan bus.

3.2 Case Study II – the Scania

In case II the bus is a Scania/Dab from Sweden. It is a full size 12 meters long bus with 66 passengers. The second case II is heavier than the first bus due to the size and the construction. It has a smaller ICE (2.3 l) equipped with a 3-way catalytic converter, from a commercial car, and a relatively large battery (10 km at battery operation). In the Scania bus, peak traction power must be collected both from the generator and the battery. Toreb makes the energy control system, which controls all the energy flow in the bus. Table 3.1 contains all other important information about the buses.

The ICE and generator are placed in the back of the bus, the gasoline fuel tanks in the back and the battery on the roof of the bus.



Figure 3.3: Case II Scania hybrid bus.

3.3 Differences and similarities

The main differences between the both the vehicles are the size of the chassis and the size of the ICE. The Scania is a full sized bus (12 m) and the Neoplan is a medium sized bus (10 m).

With the larger size the Scania bus can take more passengers, but with the smaller ICE it needs assistance from the battery to supply peak power to the electrical traction motors. The Scania bus is heavier and has a weaker traction motor compared to its weight, this makes the performance of the bus lower.

The Neoplan bus is both lighter and with the larger ICE it is able to supply the traction motors with peak power and simultaneously charge the batteries. The Neoplan bus also has the highest performance due to its higher ratio between peak tractive power and vehicle weight.

Since both buses are of the same type (series hybrid) only the size of the components and some parameters needs to differ between the simulation models.

No exchange of experience has taken place between the drivers of the buses in this project. The reason is that the different buses traffic two different cities.

Chapter 4

Simulation Model

The simulation model can be built in many different ways. To be able to use the model in as many situations as possible the model has to be based on physical principles. This gives more freedom to choose parameters in the model; not only to describe different choices of driving mode and components but also to be able to describe the way the vehicle operates.

In practical use two consecutive driving cycles on the same route are not equal. Stopping at a traffic light, a bus stop without passenger or stopping for a pedestrian crossing the road are unique actions. The distance, the acceleration behaviour and the total stops and starts during one cycle are approximately the same.

The “world model” means description of the external conditions around the bus operation. In principle the following types of information are necessary to supply:

1. the global movement of the vehicle which means acceleration, speed and position as the functions of time,
2. fuel consumption, emissions and the batteries state of charge as functions of time,
3. important components' efficiency and losses as functions of time.

The model has to include the ICE, the electrical traction machines and the power electronics and consider an adequate description of the vehicle's mechanic, electrical and ICE dynamics, efficiency and emissions.

The model does not consider things like temperature in the passenger compartment or the number of passengers. Actually, no difference was observed in the measurements between driving a bus filled with passengers and

an empty bus. One of the reasons to this is that the bus itself is so heavy that the passengers weight does not significantly change the tractive work. Another reason is the relation between aerodynamic and friction forces and of course the altitude variation.

4.1 Introduction to the Program-model

Different platforms for programming were evaluated and complete programs for vehicle simulation were evaluated. (van den Bussche, 1998). In some programs it was difficult to make modifications in the simulation program, e.g. with the simulation program Advisor (Advisor) and was not available by the beginning of the project. Other programs were too expensive (Nedungadi, 1997).

Matlab[®]/Simulink[®] was chosen as the platform for this simulation model. Matlab is well known in the scientific world and has already been used for many hybrid and electric vehicle simulations. The hybrid bus is modularly designed in Simulink[®] and fed with input values via Matlab[®]. The simulation program is, after calibration by extensive measurements, used for structural sensitivity analysis and evaluation of charging strategy improvements.

4.2 User Interface of the Program

The modules in the simulated vehicle constitute of batteries, ICE, generator, electric motor, power electronics, control block etc. Mechanical dynamics such as aerodynamics and rolling resistance components are modelled. All the components have been chosen to imitate the real bus and its conditions as good as possible. The electrical machines are modelled with look-up tables with current and voltage and efficiency as output parameter. The battery model includes a temperature depending resistance. In the simulation model the auxiliary load is considered a constant power.

The user-defined parameter that can be specified in the simulation model is:

- Choice of bus
- Driving cycle
- Charging strategy
- Size of the certain components

The choice of a special bus, defines the default value of ICE, battery and electric drive motor. These default parameters can then be scaled by reducing the number of cylinders, cells or using a scale factor.

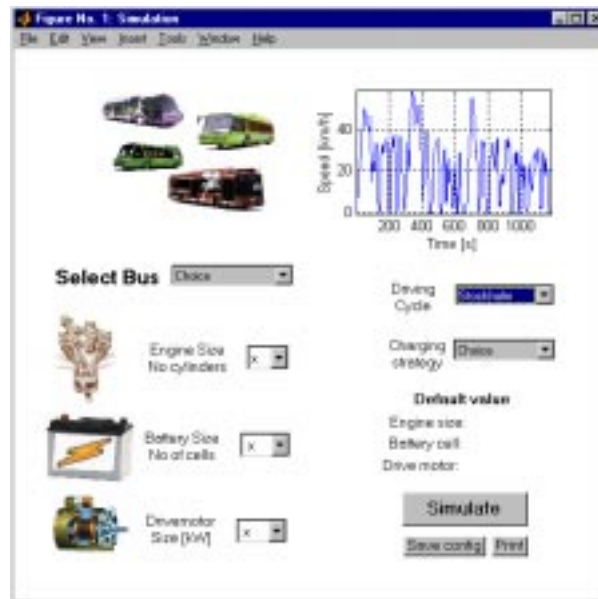


Figure 4.1: User interface of the hybrid bus simulation program.

The ICE simulation model includes all regulated emissions HC, CO and NO_x as well as the fuel consumption.

The simulated driving cycles use velocity as a function of time or distance. Using velocity as a function of time can give a wrong result due to accumulated errors. If the speed differs from the desired speed too much due to low performance of the vehicle, the bus stop will occur at the wrong place after a while. If velocity is used as a function of distance this problem will not appear, but there might be a problem with the pause time at the bus stop. To make it possible for the passengers of the simulated vehicle to get on and off the bus at the bus stop, a time delay is added at all bus stops.

It takes 20 seconds to run a complete simulation of 1800 seconds simulation on a hybrid bus with an average PC.

4.3 Program Model

The program's structure can be seen in Figure 4.2. This is an overview of the highest level of the Simulink® program. Each block can be opened and contains new structures. Here not all the details are described, but only the principal configurations are discussed. The full capability of the software is naturally experienced directly at the computer.

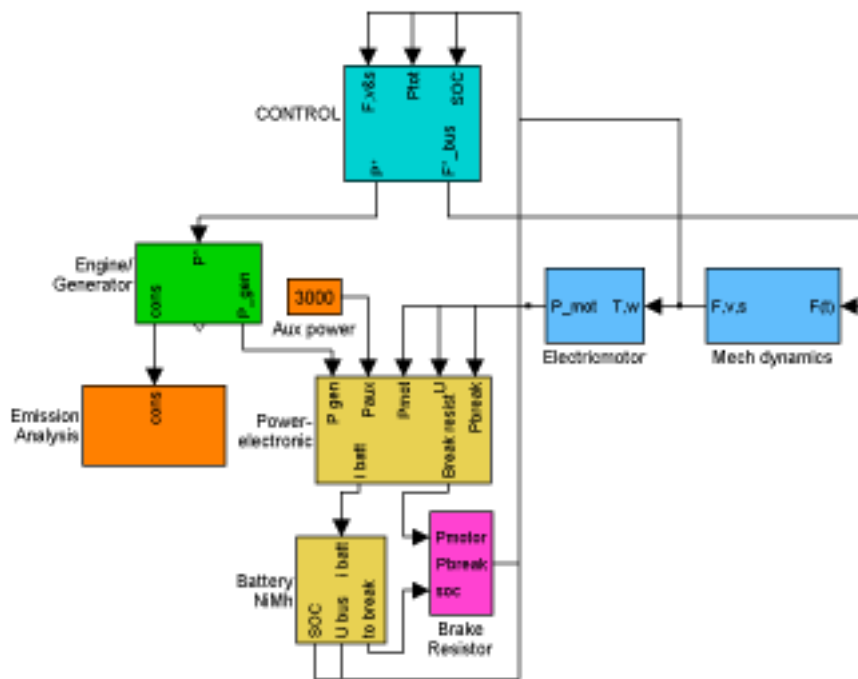


Figure 4.2: The highest level in the simulation program Simulink®.

Control

This block has two major functions, to control the vehicle traction force with a driver model and to control the ICE power.

The reference speed v^* comes from a table where the speed and distance are described. The speed reference is read from a vector in workspace and can be represented both as a function of time and of travelled distance.

The driver model used in the simulation program is a PI-regulator. It is selected due to its simplicity and the ease with which the parameters can be selected intuitively with realistic performance as the result.

The force of the driver model is described by the following equation:

$$F_{Traction} = K_p \cdot (v^* - v) + K_i \cdot \int (v^* - v) dt \quad (4.1)$$

where v is the velocity, v^* the set point of the velocity and K_p and K_i the control parameters of the controller. The proportional and integrative terms are selected according to Equation (4.2).

$$K_p = \frac{\text{Max tractive force}}{10 \% \text{ of max speed}} \quad (4.2)$$

$$K_i = \frac{\text{Max tractive force}}{33 \% \text{ of max speed}}$$

Equation (4.2) should be interpreted as a driver that request the full tractive force at a speed error of 10 % of the maximal speed, and doubles this request about every 3rd second as long as the speed error remains. An anti windup function stops the integration in case of a limitation of the requested tractive force. This driver model is not validated in any other ways than by showing that the vehicle behaviour is realistic with any of the driving cycles that have been used in this report.

The requested tractive force is limited as a function of the speed to account for the field weakening of the traction motors. The speed limit for field weakening is 20 and 30 km/h respectively in case I and II. This means that the tractive force is limited to the maximum that the traction motors can provide up to 20 and 30 km/h and the tractive power is limited above this speed, with correspondingly reduced tractive force.

The maximum braking force is always higher than the maximum force the traction motor can provide. When braking the traction motors are first used to

regenerate energy to the battery and the mechanical brakes are engaged in case higher braking force is needed.

Control of the ICE power corresponds to controlling the power from the generator, which supplies the traction motor with power and charges the battery. The generator power is selected based upon the instantaneous tractive power and the present SOC in the battery, but the exact charging strategy varies between the buses and is discussed in detail in chapter 7. As an example, the present charging strategy of the Neoplan bus can be seen in Equation 4.3.

$$\begin{aligned} P_{charge} &= [speed > 15km/h] = P_{Drivemotor} + 12 \text{ kW} \\ P_{charge} &= [speed < 15km/h] = 0 \text{ kW} \end{aligned} \quad (4.3)$$

To conclude; the control block provides the tractive force for mechanical propulsion of the vehicle, and the power request from the hybrid generator.

Mechanical Dynamics

In the simulation block called *mech dynamics*, all the mechanical forces in the vehicle are summed up. There is no compensation for wind speed or number of passengers. The input variable for the block is the traction force from the vehicle, which in this case is the tractive force of the traction motor and the braking force from the mechanical brakes. The output variables from this block are the traction force, vehicle speed and travelled distance.

In the block the forces on the vehicle such as friction, aerodynamics and slope are summed up together with the traction force.

$$F_R = F_{Traction} + F_{Friction} + F_{Aero} + F_{Slope} \quad (4.4)$$

where $F_{Friction}$ is a constant friction and F_{Aero} is the air resistance of the bus as specified in later Chapter 5.2.

Acceleration is calculated through Newton's law.

$$a = \frac{F_R}{m_{buss}} = \frac{dv}{dt} \quad (4.5)$$

The acceleration is integrated to speed. The speed is integrated to distance.

$$v(t) = \int_{t=0}^t a(t) dt \Rightarrow s(t) = \int_{t=0}^t v(t) dt \quad (4.6)$$

The new distance that is reached, as well as the speed, is sent back to the Control block to be used for the new reference speed and tractive force calculation. The speed is used in the block *Electricmotor* for calculation of the power use from the batteries and the motor losses.

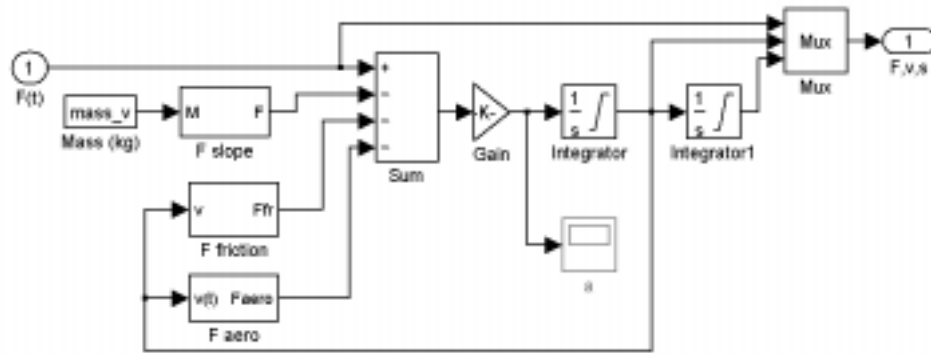


Figure 4.3: The mechanical level in the simulation program.

Electric Traction Motor

The block calculates the power needed for driving the motor, the power on the motor-axis and losses of the electric traction motor. The efficiency of an electrical machine is rather high but is dependent on how it is driven. The losses are mainly of two types:

- Resistive losses caused by the current in the copper-windings. The losses are depending on the current in square.
- Losses caused by the speed when the magnetic flux is changing, eddy current losses and friction when the motor turns. Some losses are linear and some are quadratic to the speed.

The sum of all losses is low compared to an ICE when the motor works at nominal torque and speed. When the motor power is low, the relative losses are higher. This is illustrated in Figure 4.4.

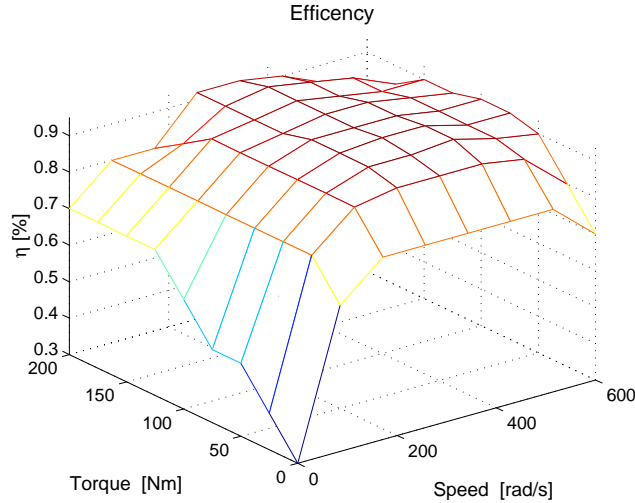


Figure 4.4: The efficiency of an electric motor.

The traction force and speed of the vehicle wheels are converted to traction motor speed and torque. The traction motor speed and torque are used in look-up tables for the efficiency of the traction motor and the electric input power is calculated. In Figure 4.4 the torque, speed and efficiency of a traction motor is plotted. Since the efficiency of well designed traction motors are very much alike, the same look up table for efficiency is used both for the generator and the traction motors. The specific data used are collected from a licentiate thesis on traction motors for electric vehicles (Helsing, 1998). Contact with the manufacturers was taken, but they did not supply with any data at all.

The same look-up table for efficiency is used both in motoring and generating mode, though in inverse ways, see Equation 4.7.

$$P_{in} = \begin{cases} \frac{\omega \cdot T}{\eta} & \text{when } \omega \cdot T > 0 (\text{motordrive}) \\ \omega \cdot T \cdot \eta & \text{when } \omega \cdot T < 0 (\text{generatordrive}) \end{cases} \quad (4.7)$$

ICE/Generator

The block *ICE/Generator* contains three different sub-systems: the ICE-control, the ICE and the Generator. The power request for the ICE/generator is supplied for the external *control* block, see Figure 4.2. The ICE is connected on the same shaft as the generator; this means that the ICE and the generator always have the same speed and steady state torque. One of the machines must be speed controlled and the other torque controlled by a control system.

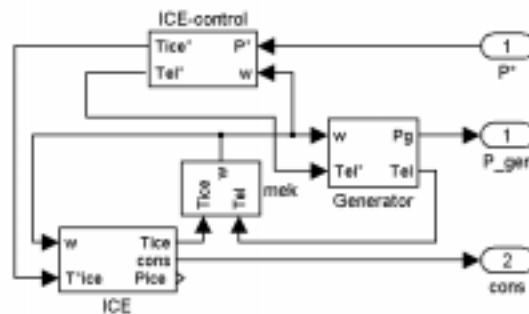


Figure 4.5: Inside the ICE/Generator block in the simulation program.

The ICE-control determines the most suitable speed and torque for the ICE and thus the generator. This torque and speed can be chosen arbitrarily to get the actual power.

$$P = \omega \cdot T \quad (4.8)$$

To minimize the fuel consumption it is well known that an ICE should be driven on high torque and low speed to have good efficiency. But it is not so obvious how the ICE should be driven (by what speed and torque) when low emission is desired. In the Figure 4.6 the optimal torque at a given power for different optimising criteria like minimal fuel consumption, minimisation of various emissions and the present implementation of the Neoplan hybrid bus are described for the Cummins ICE. The selection of these optimised operating points are based on steady state performance.

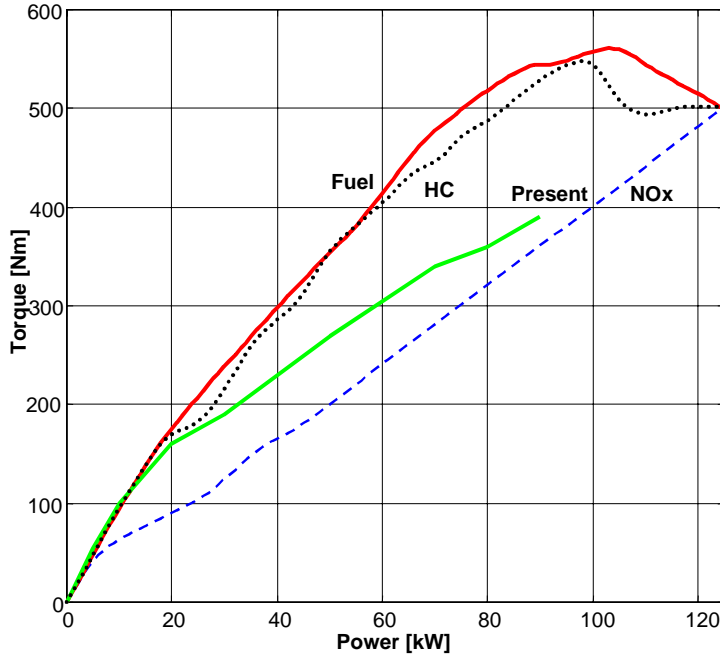


Figure 4.6: Optimal torque for several different optimisation criteria with the Cummins ICE used in the Neoplan Hybrid (case I).

The ICE-controller picks the best operating point for the ICE based on a look up table according to Figure 4.6. Based on the selected power and torque, the speed reference is subsequently calculated. Finally the generator torque reference is calculated by a speed controller. Both the ICE and the generator and a regulator adjust the speed to a stationary value.

$$\begin{aligned}
 T_{ice}^* &= \text{from look up table} \\
 \omega_{ice}^* &= \frac{P^*}{T_{ice}^*} \\
 T_{gen}^* &= K \cdot (\omega_{ice}^* - \omega_{ice}) + T_{ice}^*
 \end{aligned} \tag{4.9}$$

where T is the torque, ω the speed and P the power.

The mechanical dynamics is solved with Newton's 2'nd law, represented inside the block *mek* in Figure 4.5.

$$\frac{d\omega}{dt} = \frac{T_{ice} + T_{gen}}{J_{ice+gen}} \quad (4.10)$$

where $J_{ice+gen}$ is the inertia for the engine and generator.

The ICE subsystem is described in the simulation model with look-up tables. The model is depending on temperature, pressure, speed, fuel and air humidity (Heywood, 1988). There is often a catalyst converter connected to the ICE. This converter needs also to be modelled in some way. The catalyst is highly dependent on the working temperature.

Several considerations must be emphasized regarding the use of look up tables to represent the ICE in the HEB :

- The tables do only represent stationary operating points.
- The tables do only represent nominal working temperatures of the ICE, e.g. not cold starts.
- The tables are not valid when the ignition, air/fuel ratio or the compression is changed.

When the throttle of the ICE makes fast movements and creates transient torque or speed variations, the air/fuel ratio deviates temporarily from the desired level. This deviation becomes larger when fast transients of the speed and the torque are made on the ICE. Thus, a complete ICE model should describe these transient effects. This is however difficult and research is still needed, before reliable models can be implemented. Preliminary results indicate that transients, expressed as a bandwidth slower than 1 Hz, can be regarded as quasi stationary. See Chapter 8 for more information about the transient behaviour and measurement. Thus, look-up tables do not correctly model fast transients, but can be regarded as sufficient if the rate of change of operating point expressed as a frequency is lower than 1 Hz.

Torque and speed are used as in-parameters for the look-up tables and the fuel consumption or emissions are the output-parameters.

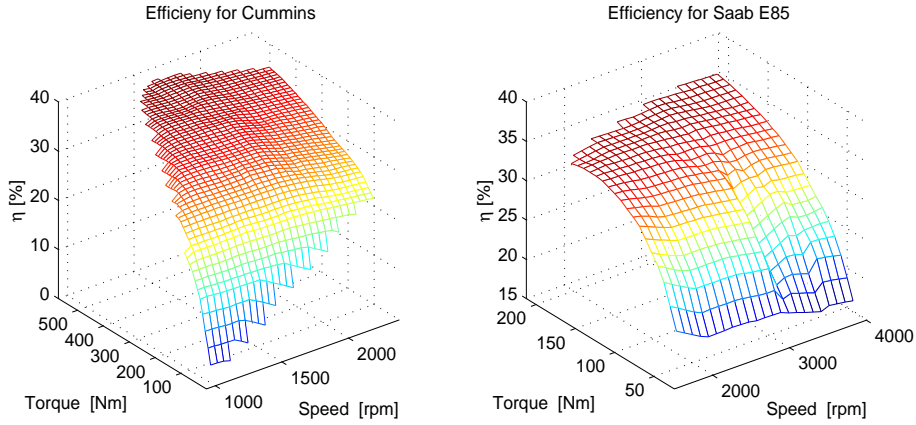


Figure 4.7: Efficiency look-up tables for the Cummins and Saab ICE.

The efficiency η for the ICE is looked-up at a certain speed and torque. The total fuel consumption is calculated by integrating the efficiency multiplied with the ICE power and divided by the specific fuel heating value Q_{LHV} :

$$Total_{Fuel-consumption} = \int \frac{(P_{ice} \cdot \eta_{ice})}{Q_{LHV}} dt \quad (4.11)$$

The generator subsystem is similar to the electric traction motor with look-up tables for the efficiency. The only difference is that the energy or power can only go in one direction, from the axis connected to the ICE via the generator and to the electrical system. Start of the ICE with the generator machine is not modelled.

Battery

The voltage and current in the battery are estimated from the power that charges or discharges the battery. The model of the battery is described as a voltage source where the voltage varies with the state of charge (SOC), Figure 4.8. The resistors in series with ideal diodes make it possible to model the battery with different internal resistances at charging and discharging. (Wiegman, 1998 & Sutanto, 1999)

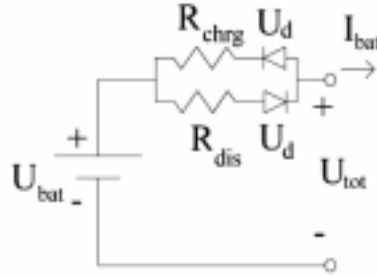


Figure 4.8: The battery model used in the simulation program.

The resistance does vary with the temperature of the battery. The battery manufacturer Varta has supplied values of resistance and internal voltage shown in Equation 4.12. A thermal model is included in the battery model.

$$U_{tot} = (U_{bat} + R_{chg/dis} \cdot I_{bat} \pm U_d) \cdot No_cells$$

$$\left\{ \begin{array}{l} U_d = 0.05V \\ R_{chg/dis} = \frac{0.85 + (20 - Temp)}{1000} \end{array} \right\} \quad (4.12)$$

The new SOC are calculated through integration and by using the number. The electro-chemical features of a battery cell are highly depending on the temperature. Most kind of battery cells has their best working point by 20°C. The resistance decrease with the temperature, as modelled in Equation (4.11). The losses in the battery, both with charging and discharging, contribute to heat the cells and is modelled in Equation 4.13.

$$\Delta Temp = \frac{P_{Losses}}{C \cdot m_{cell} \cdot n} \cdot H \quad (4.13)$$

where H is the heat transfer coefficient, C is specific heat capacity, m_{cell} mass of a cell and n is the number of cells in the battery.

Power Electronics

All electrical power of the vehicle is connected to the *Power Electronic* block in the simulation program, reflecting the actual structure of the power system in

the bus, where all major power consumers/generators convert electric energy via power electronic converters. This kind of power electronic converters has also some losses, where the most important ones are:

- In the power semi-conductor, when they are conducting current
- In the power semi-conductor, when switching (on < - > off)
- In passive components like coils and capacitors depending on the frequency and amplitude of the voltage and current.

The efficiency of power electronic converters is very high; the larger size the better efficiency. The converters used in this bus project are of medium-size with peak efficiency around 98 % and well above 90% at most operating points. (Blaabjerg, 1995)

This is implemented in the simulation model by using look-up tables with current and voltage as in-parameters and efficiency as out-parameter. This efficiency curve does vary from 90 to 99 %, with the lowest values when transforming low power.

In the block Power-electronics, all powers from the traction motors, generator and auxiliary load are added and divided by the voltage and multiplied by the efficiency for the certain component. Thus the total current for the battery is calculated. The total current is then divided or multiplied, depending on whether the battery is being charged or discharged, with the efficiency for the converter. See Equation 4.14.

$$i_{Total} = \left\{ \begin{array}{l} \frac{P_{motor}}{U_{dc} \cdot \eta_{motor}} \quad (P_{motor} < 0) \\ \frac{P_{motor}}{U_{dc}} \cdot \eta_{motor} \quad (P_{motor} > 0) \end{array} \right\} + \frac{P_{generator}}{U_{dc}} \cdot \eta_{generator} + \frac{P_{aux}}{U_{dc}} \cdot \eta_{aux} \quad (4.14)$$

$$i_{batt} = \left\{ \begin{array}{l} \frac{i_{Total}}{\eta_{PowerEl}} \quad (i_{Total} < 0) \\ i_{Total} \cdot \eta_{PowerEl} \quad (i_{Total} > 0) \end{array} \right.$$

where U_{dc} is the battery voltage, i the current, η the efficiency for the different component and P_{aux} the power consumption of the auxiliary system.

4.4 Auxiliary Power System

The auxiliary system is called *Aux power* in Figure 4.2. It has influence on the energy consumption of the vehicle, since it loads the energy system all the time, even during a stop. The auxiliary system drives ventilators, lights, steering, brakes and door openings.

It is very important that the help systems, like steering- and braking assistance, are built in an energy efficient way. On a hybrid electric vehicle there is always electric energy available. On an ordinary vehicle an ICE is running and mechanical pumps and compressors can be connected.

On the Neoplan bus there is a dual system with an air compressor and a servo pump mechanically connected to the ICE while the ICE is running. When the ICE is turned off there is another system with electric motors driving the servo pump and air compressor. This is a rather complex system where the energy is not used efficiently. For example it would be better to have an electric motor to assist the steering wheel instead of having a hydraulic system. This would replace the two servo pumps.

Figure 4.7 shows some real measurements on the Neoplan bus of the power of the auxiliary system when the ICE is on and off respectively. A small generator supplies power to the 24-volt system when the ICE is on.

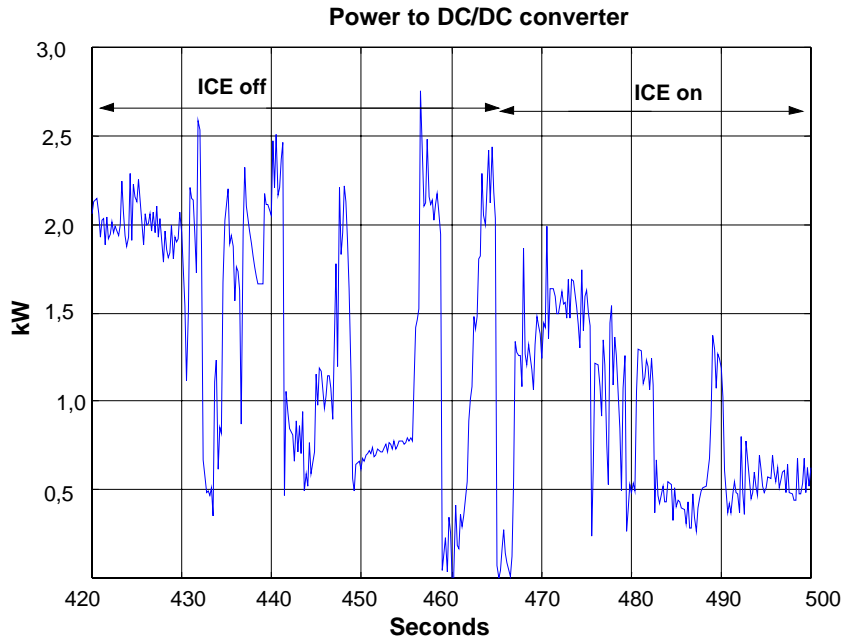


Figure 4.7: The DC/DC auxiliary power consumption on the Neoplan bus.

In the Scania bus there are only electric motors supplying the servo-pump and the air-compressor. These motors consume on average 0,6 and 1,0 kW during a normal driving cycle. The servo-pump is depending on how much turning the driver does and the air-compressor loads the system continuously. The other auxiliary system components (lights, fans, etc) consume about 1,5 kW. This makes a total consumption of 3,1 kW in the auxiliary system of the Scania bus.

In the simulation model the auxiliary power is modeled as an average power consumption that loads the electric system. In the future the simulation model has to be further developed in order to achieve a better accuracy. This also requires more sophisticated measurements of the auxiliary power consumers.

Chapter 5

Measurements

To calibrate the simulation model with measurements from the bus under real conditions, it is necessary to have a measurement system on the bus. The data from the measuring system is the reference and mean of calibration for the simulation model. If there is anything wrong or missing in this data, the calibration of the simulation model will be misguided.

5.1 Onboard System

The energy on the bus appears in many different forms like kinetic, electric and chemical energy. The measuring system is used onboard the vehicle to get information about the energy flow, vehicle behaviour, temperature and some ICE parameters like fuel consumption, speed and air/fuel ratio. From these data it is possible to derive and verify the energy flow as described in the simulation model so that the model can be verified.

A compact installation is desirable and the measurements system must be insensitive to vibrations, dust etc. The measurement systems in the buses are built around a commercial data acquisition system from National Instruments called SCXI[®]. A laptop computer is connected to the SCXI[®] system with the program LabView[®]. The analogue data-acquisition is done by 16 bits resolution. This means that 0 - 10 V will be resolved in steps of 160 μ V. It is important that the channels are sampled synchronously, since simultaneous measurements of most quantities is needed.



Figure 5.1: The computer and measuring system assembled in the Neoplan bus.

All quantities are sampled at a rate of 5 Hz. The data are stored on the hard disk of the laptop computer. During an ordinary day the total data storage requirement will be 30 MB. The transfer to a stationary computer is done with a “zip-drive”.

When the ignition is turned off (during the night) the data acquisition system goes into a sleeping mode.

Data Acquisition Program

The program used for data acquisition is called LabView[®]. LabView[®] is a graphical program language for collecting data, viewing data and controlling instruments. From the beginning it was made for the Macintosh computers and later on ported to the PC platform. It is a user-friendly environment, which a person without large programming experience can use. There are advantages and drawbacks with a graphical user interface compared with text-based systems. One example is when the program grows too big, and then it is hard to get a good overview of the program. If the LabView[®] program environment is used for viewing collected data, the program is very user-friendly and allows simple ways of viewing data.

In the project it has been found that the computations inside the LabView[®] programme in the on-board measurement system should be

minimized, due to the complexity of the data handling of the program environment. It is recommendable to store the data on disk as fast as possible without making too many calculations.

In the subsystem on the highest level of the program all sensor signals are sampled as primary variables. They are scaled by the DAQ system and sampled with 5 Hz. During 60 seconds a number of (5 x 60) 300 values per variable are stored in the variable *Lager*; see Figure 5.2.

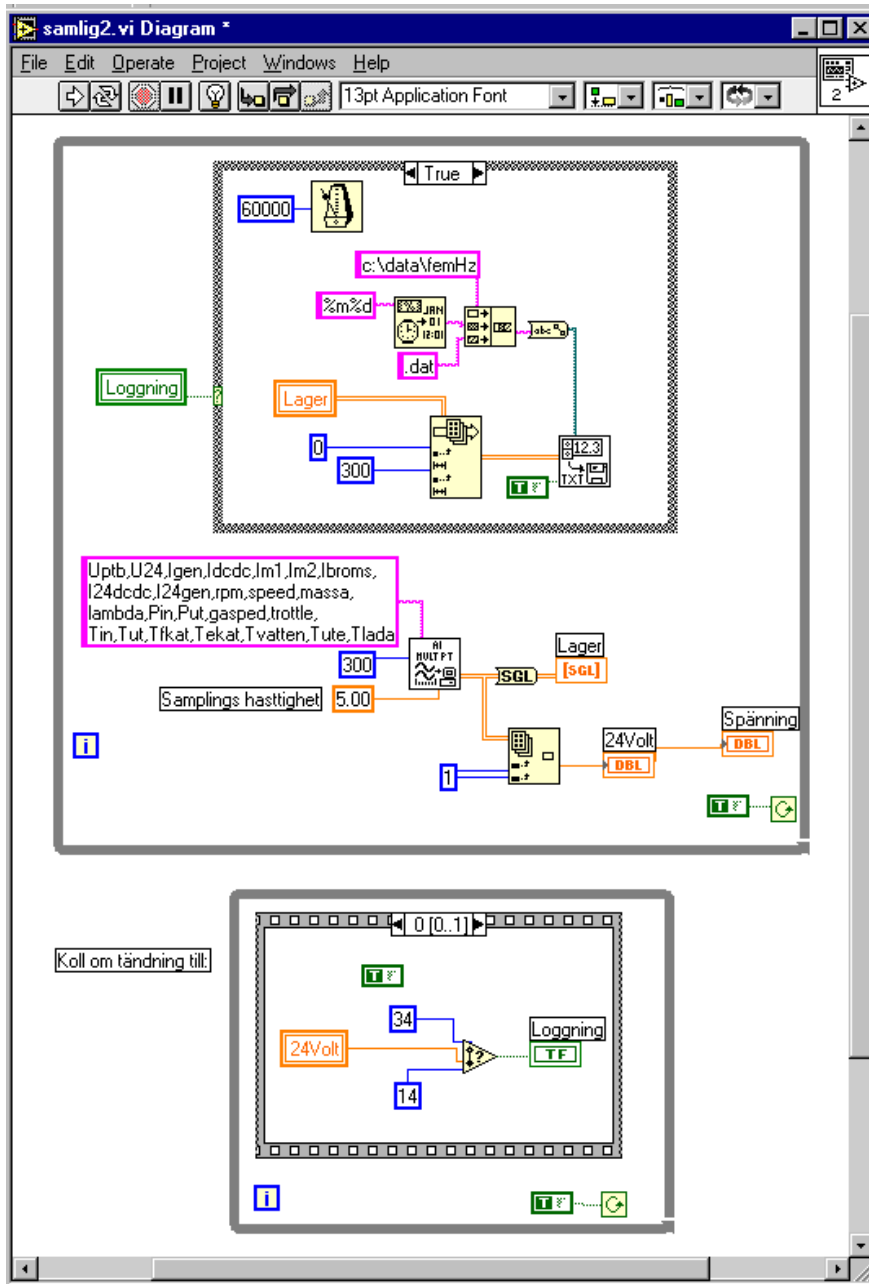


Figure 5.2: One page of the LabView[®] program used for collecting data.

Sensors

All sensors are mounted after the bus was built, see the Table 5.1.

Table 5.1
Sensor specification

Unit	Remark
Voltage (traction system)	To calculate the power flow
Voltage (24 V system)	"
Current from generator	"
Current to DC/DC (traction system)	"
Current to motors 1 & 2	"
Current to brake resistor	"
Current to DC/DC (24V system)	"
Current from generator (24V system)	"
Speed ICE	ICE behaviour
Speed Vehicle	Vehicle behaviour
Lambda	Air/Fuel ratio
Mass gas	Fuel consumption
Pressure inlet	Corresponds to the torque
Diff. Pressure Catalyst	Check catalyst condition
Accelerator	Drivers activity
Throttle	ICE parameter
Temperature inlet	ICE condition
Temperature exhaust gas	"
Temperature before & after Cat.	Catalyst condition
Temperature Cooling	ICE condition
Temperature Outside	Condition
Temperature in the bus	"

The current and voltage sensors measure the electrical power flow in the bus. The manufacturer of these sensors is LEM. The sensors use the Hall effect and they are galvanically isolated from the respective system. The inaccuracy is $\pm 0,8\%$. This will make the voltage error at 500 V to ± 4 V, and the current error of 100 A to $\pm 0,8$ A. See Figure 5.3 for the connection points of the current and voltage transducers.

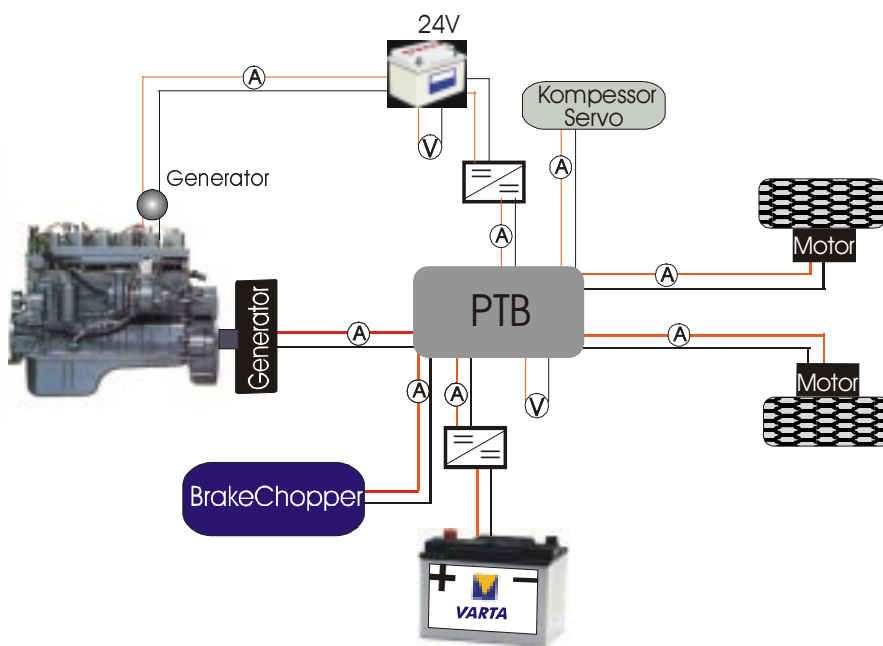


Figure 5.3: The current and voltage transducer placement in the Neoplan bus.



Figure 5.3: The current transducers around the cables in the power connecting points in the busses. At the top the “PTB”-box in the Neoplan bus and at the bottom “Grundbulten” in the Scania bus.

The temperature sensors measuring less than 150 degrees Celsius consist of PT-100 elements, which are resistive sensors. The temperature sensors measuring above 150 degrees are thermo elements of type K, and are only used on the exhaust gases from the ICE. The temperatures on both sides of the catalyst are measured to determine whether the catalyst is working or not, as illustrated in Figure 5.4.

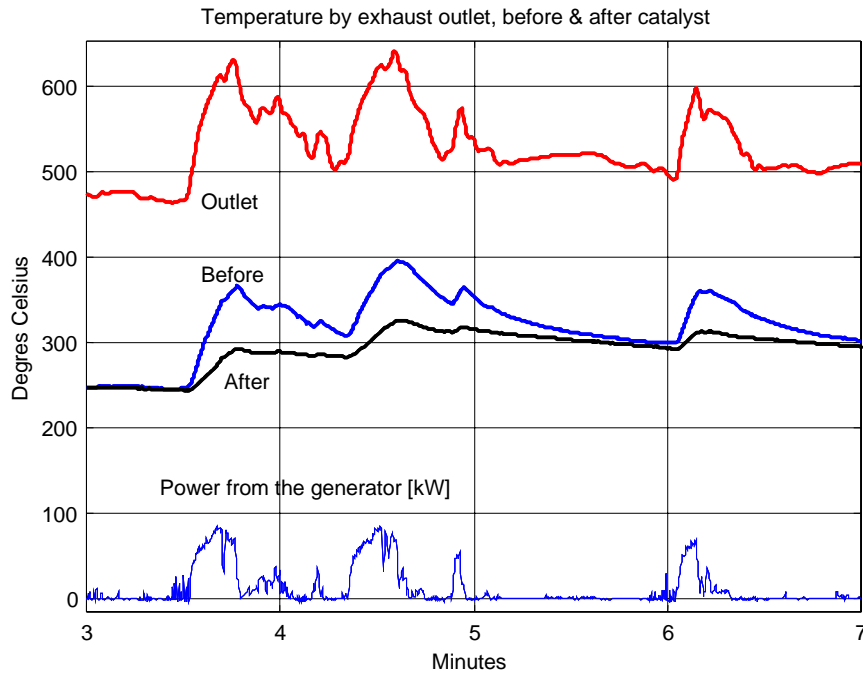


Figure 5.4: Examples of different ICE exhaust temperatures

The temperatures right before and after the catalyst in Figure 5.4 are within the operating range for the catalyst, according to correspondence with Cummins (Lainig, 1999). The low temperature after the catalyst indicates that it is probably not working properly, since the combustion within the catalyst is expected to be exothermic. Some weeks after these measurements were done the catalyst broke down and was dismantled.

The lambda-sensor with attached electronic equipment with a very fast responding time (<10 ms) is mounted on the ICE. The sensor has been installed by the exhaust outlet, to measure the ratio between fuel and air. With a fast responding (high-band-width) lambda-sensor it is possible to measure during transients, i.e. when the ICE changes working points. The fuel/air ratio is important for the emissions from the ICE. The lambda-sensor comes from ETAS.

The fuel-flow sensor for the fuel consumption comes from BRONKHORST HI-TEC. The sensor measures the massflow of natural gas. The working range is between 0 – 36 kg/h. The measurement principle is thermal. The sensor are neither sensitive to vibrations nor do they need long straight pipes. The response time is below 1 second.



Figure 5.5: The massflow sensor for natural gas.

Pressures in different locations are also measured. The differential pressure over the catalytic converter is recorded. One reason for this is that in the previous bus a fire started in the back of the bus and a stop in the exhaust pipe by the catalyst was suspected to be the cause. The intake pressure is also measured since it is directly linked to the torque of the ICE.

Other sensors like speed sensors, position sensors and a GPS unit are also installed in the bus.

The speed sensors get pulses from the internal bus system and convert to a dc-voltage, which is recorded by the data-acquisition system.

The position sensors are used to get the positions for the throttle and the accelerator pedal of the driver.

A GPS unit was also installed to log the speed, position and the altitude variation; this sensor, however, was too slow and could only be used for calibration of the speed sensor.

5.2 The Rolling Test

To get the forces on the vehicle, when driving at a constant speed (no acceleration), rolling tests are done. The air and friction forces are speed, mass and air density dependent.

The rolling test is performed like this:

- The bus accelerates to 70 km/h on a long flat road. After that the traction motor is turned off.
- Rolling with the vehicle begins with all brakes released while the speed is logged.
- The vehicle is rolling until it stops.
- The same procedure is done from the other direction.

Some calculations now need to be done. The acceleration is calculated through the speed. Newton's law calculates the force by multiplying the vehicle mass and acceleration:

$$F_{Newton} = m_{bus} \cdot a = m_{bus} \frac{dv}{dt} \quad (5.1)$$

The resulting force on the vehicle by constant speed will be:

$$F_R = m_{bus} \cdot g \cdot \mu_{friction} + A \cdot C_d \cdot \frac{\rho_{air}}{2} \cdot v^2 \quad (5.2)$$

where the first term corresponds to frictions forces and the second one the aerodynamic damping. The coefficients are:

F_R [N]	Resulting force
m_{bus} [kg]	Weight of the bus
g [m/s ²]	Gravity
$\mu_{friction}$	Rolling friction coefficient
A [m ²]	Bus cross-section area
C_d	Aerodynamic coefficient
ρ_{air} [kg/m ³]	Air density
v [m/s]	Speed

The resulting force with the coefficients inserted for the Neoplan bus will be:

$$F_R = 1050 + 1,46 \cdot v^2 \quad (5.3)$$

In Equation 5.4 the measured force in relation to the speed and the coefficients can be seen. The equation is calculated by doing linear regression in the measured values.

$$F_R = 600 + 50 \cdot v + 0,62 \cdot v^2 \quad (5.4)$$

The measured and theoretical results can be seen in Figure 5.6. The practical and theoretical equations do match reasonably within the speed interval of interest, but the assumption of quadratically dependent air resistance loss seems to need improvement. The manufacturer supplied with no information regarding the rolling test.

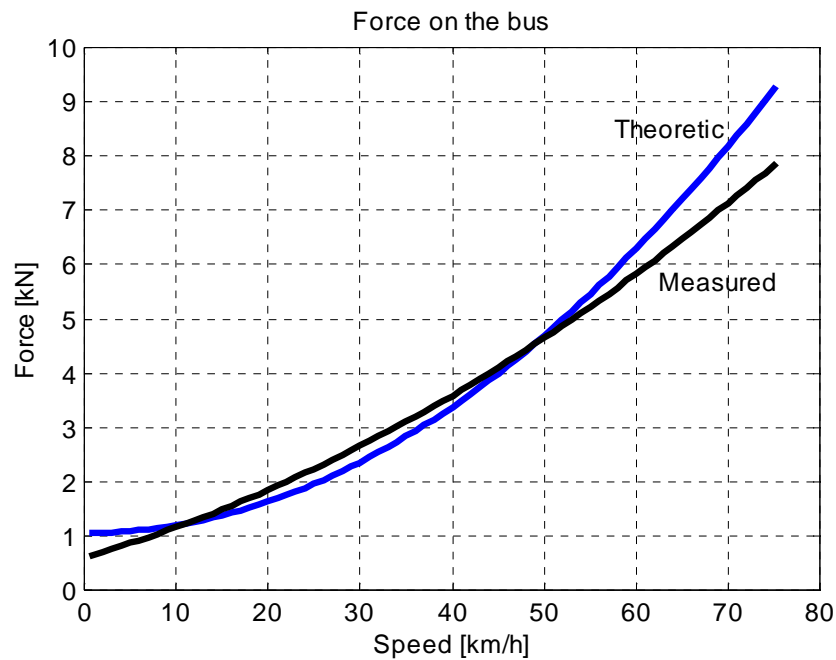


Figure 5.6: Aerodynamic and friction force during the rolling test on the Neoplan bus.

5.3 ICE in Test Bench

The stationary characteristics of the ICE's used in two dimension look-up tables in the simulation program are based on measurements from test bench driving. Torque (Nm) and speed (RPM) is used as the in parameter and for example NO_x emission (g/kWh) as out parameter. The bench testing gives a good knowledge about how the ICE works in stationary operation, but is not valid when the ICE moves too fast in torque or speed. Transient operation is evaluated in Chapter 8.

Cummins ICE

The Cummins ICE in the Neoplan bus has been run in a test bench by VTT, the Technical Research Centre of Finland. (Westerholm, 2000) All regulated emissions, particles and some other unregulated emissions have been measured, and some results are shown in Figure 5.7. These measurements are also used for simulation model calibration.

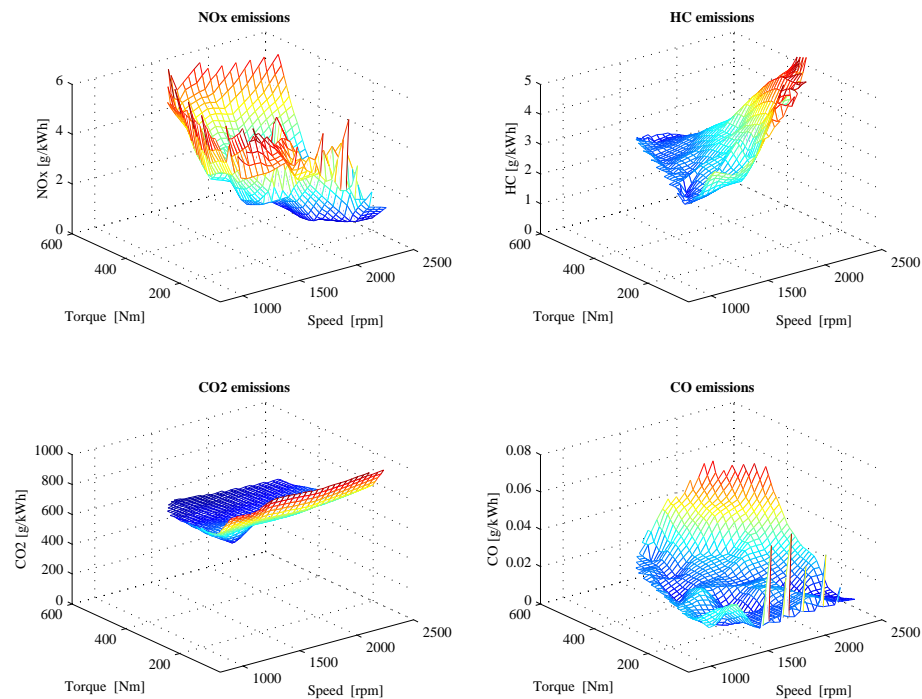


Figure 5.7: The emissions from the Cummins natural gas ICE

Saab ICE

The regulated emissions, the CO_2 and the efficiency have been measured on the Saab ICE of the Scania bus. The department of Heat and Power Engineering together with the department of Industrial Electrical Engineering and Automation at the Lund University made the tests. Both gasoline and E85 (85 % ethanol) have been used as fuel for the ICE during the bench testing (with corresponding adjustment of the fuel injection system). All these measurements are performed in 46 working points, before and after the catalyst.

Only stationary measurements were made on the SAAB engine. The analysis and detection of CO and CO_2 are made with an infrared instrument

called NDIR. HC was analysed with a flame ionisation detector FID and NO_x was analysed with a chemo luminescence instrument CL. (Einewall, 2000)

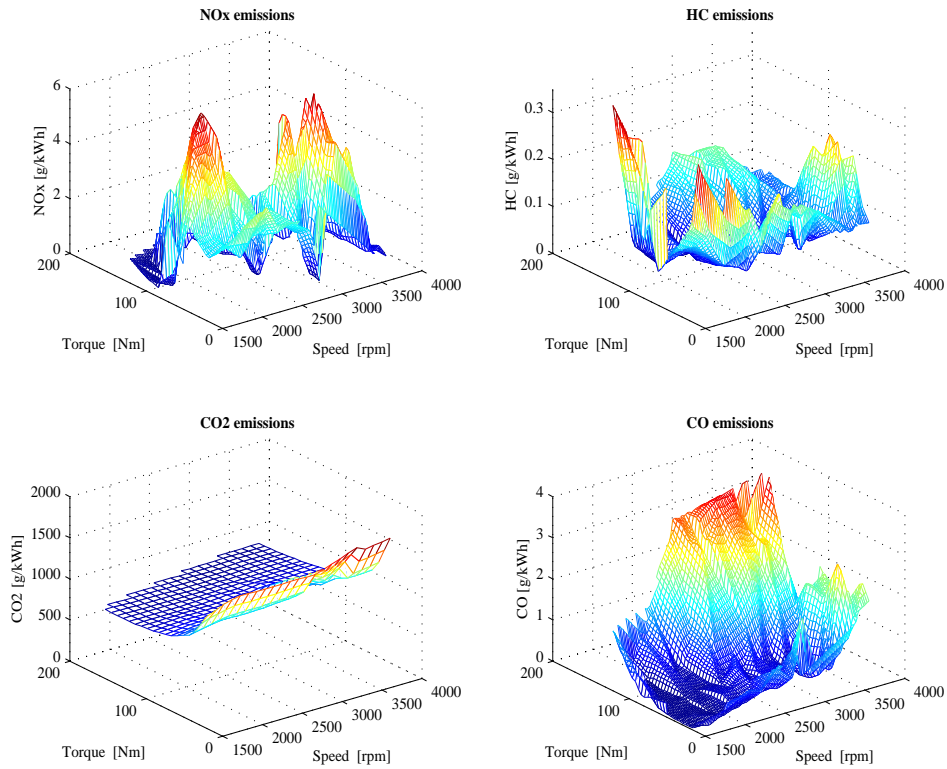


Figure 5.8: The emissions from the Saab ICE with gasoline, measured after the 3-way catalyst.

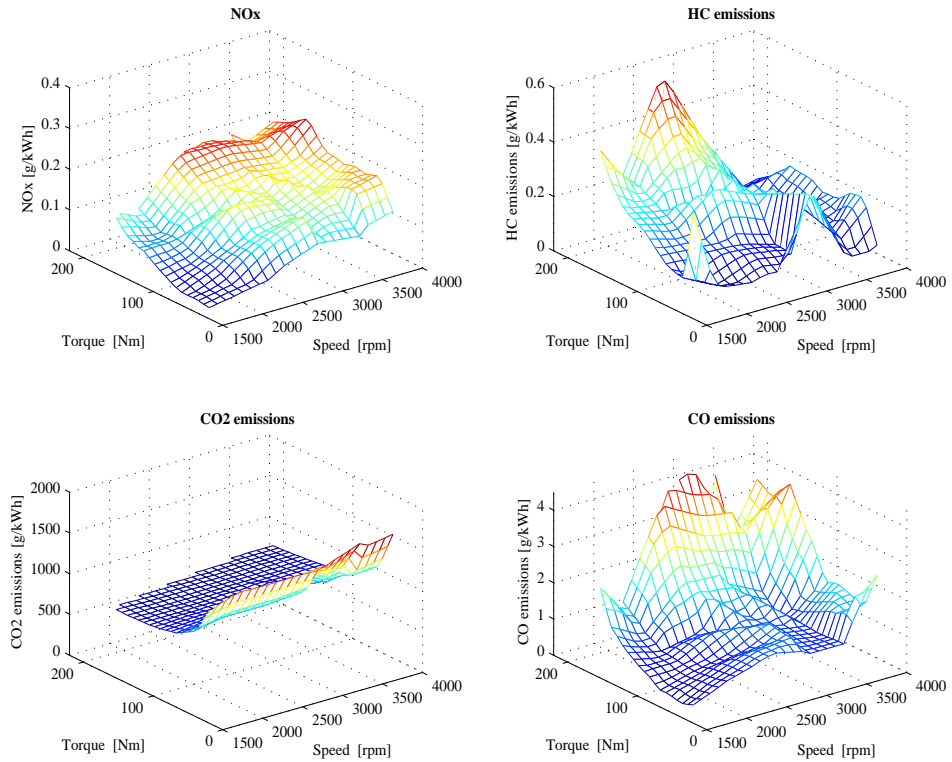


Figure 5.9: The emissions from the Saab ICE with ethanol, measured after the 3-way catalyst.

The emissions of NO_x and HC are significantly lower for the Saab ICE than for the Cummins ICE. The reason for this is that the emissions are measured after a 3-way catalytic converter on the Saab ICE. The Cummins ICE is equipped with an oxidizing catalyst, with less efficiency. The Cummins ICE is a lean burn ICE and cannot be equipped with a 3-way catalyst.

Chapter 6

Driving Cycles

When specifying a HEV or choosing the individual components performance and size, it is important to know the performance requirements, like speed limits, acceleration and hill climbing etc.

6.1 Standard Cycles

There are a number of different standard driving cycles for chassis dynamometer testing. For example the Braunschweig cycle and the ECE15. The Braunschweig cycle was developed at the Technical University of Braunschweig. It is characterized by a lot of starts and stops and high acceleration. The ECE 15 cycle is a standard cycle used by car manufacturer the measure fuel consumption, it is a theoretical recorded cycle with low acceleration.

Recently the transient behaviour and the real driving cycles have drawn attention. This is the reason for the discussion whether the ECE15 is a representative driving cycle for a bus, since it emanates from a car cycle. The cycle is used for emission certification of light-duty vehicles in Europe. This cycle can easily be optimised by a good chassis dynamometer driver and does not give a good indication of the real fuel consumption and the emissions of the vehicle in real operation.

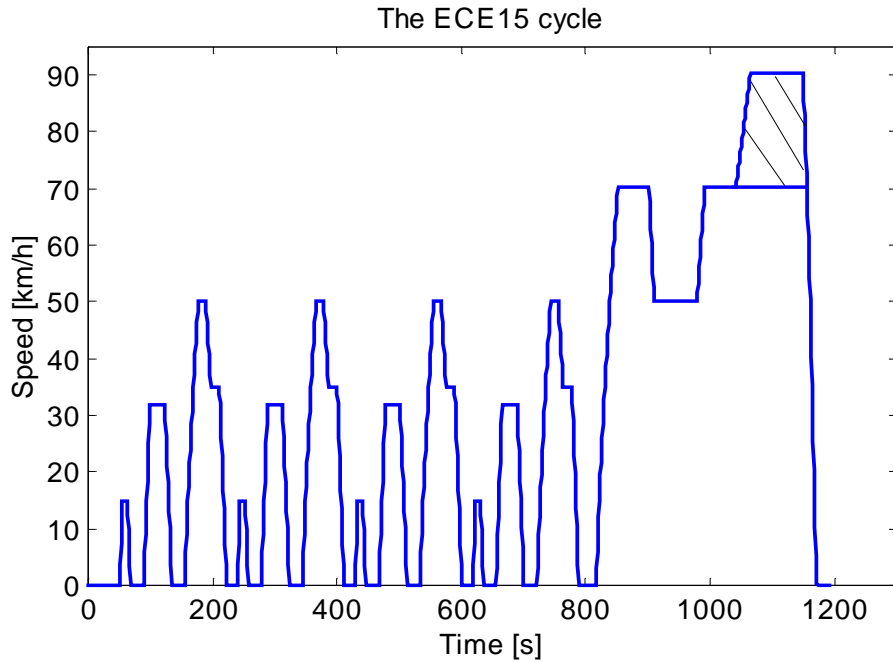


Figure 6.1: Speed as a function of time during the ECE15 cycle.

The speed limits for light-duty vehicles are 90 km/h and 70 km/h for heavy-duty vehicles. This will make the driven distance slightly shorter for heavy-duty vehicles, i.e. 9.94 vs. 10.5 km. The average speed for heavy-duty vehicles is 30 km/h while it is 31.7 km/h for the light-duty ones. The maximum (read: all) acceleration in the ECE15 is rather low, 1.04 m/s^2 . This low acceleration makes it easier to optimise the fuel consumption by smooth driving.

The Braunschweig cycle was developed at the Technical University of Braunschweig, Germany to simulate and test an urban bus driving cycle, especially when a vehicle is tested on a chassis dynamometer. The cycle is frequently used in research when comparing simulation models. This cycle is demanding and contains quick accelerations and retardations. The maximum acceleration is 2.14 m/s^2 . The maximum speed is 58.2 km/h and the average speed is 22.4 km/h. The driving distance is 10.8 km.

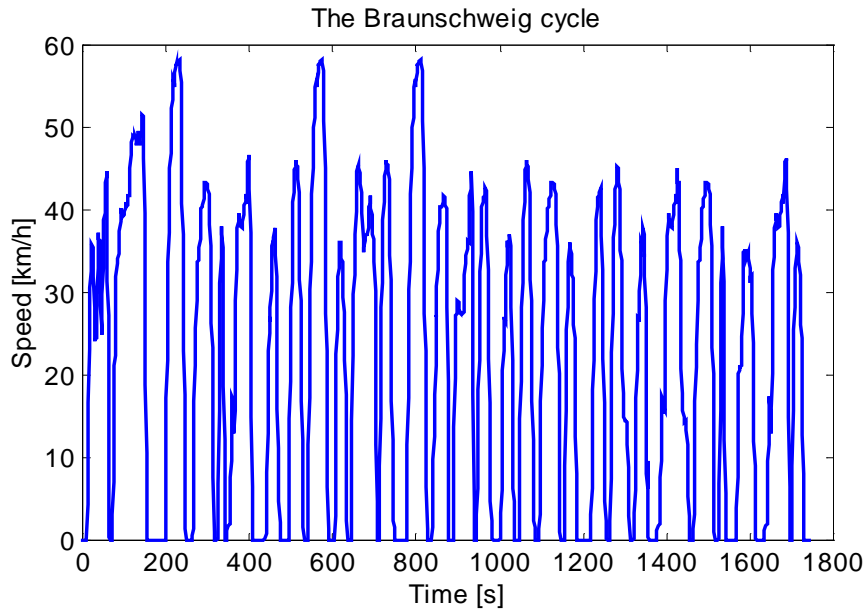


Figure 6.2: Speed as a function of time during the Braunschweig cycle.

6.2 Local Cycles

The Malmö cycle is a randomly selected recording of the bus velocity going from the town centre to an exhibition site at the Öresund-bridge at the outskirts of Malmö. The cycle is depicted in Figure 6.3. It is not as demanding as the Braunschweig cycle, partly reflecting that Malmö is a relatively flat city. The maximum speed is 49.7 km/h, the average speed is 20.9 km/h and the cycle is 10,5 km long. The maximum acceleration is 1.36 m/s^2 . It is important to note that when using a standard driving cycle like the Braunschweig City Driving Cycle, this will impose too high demands on acceleration on the HEV specified. This result in an overpowered vehicle not able to run near optimal operation with respect to fuel consumption, exhaust emissions etc.

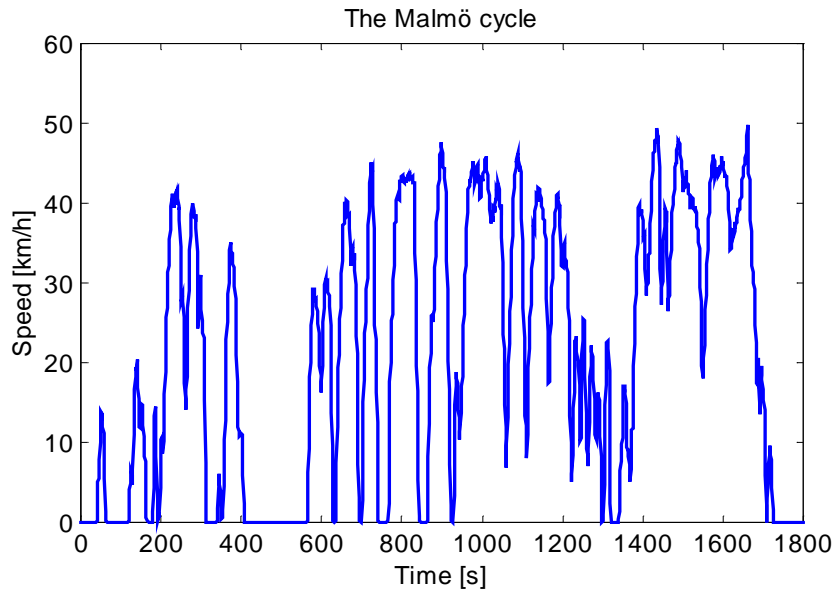


Figure 6.3: Speed as a function of time during the Malmö cycle

The Stockholm cycle is a recording of bus line 57 in Stockholm. See Figure 6.4. This line is usually trafficked by the hybrid buses. In Stockholm there is a large altitude variation with many up- and down hills as opposite to the Malmö city cycle. The altitude variation has large impact on the tractive power when driving the bus, this effect is discussed in the next Chapter, section 7.2. The maximum speed is 58 km/h, the average speed is 21,6 km/h and the cycle is 7,0 km long. The maximum acceleration is 1.3 m/s^2 .

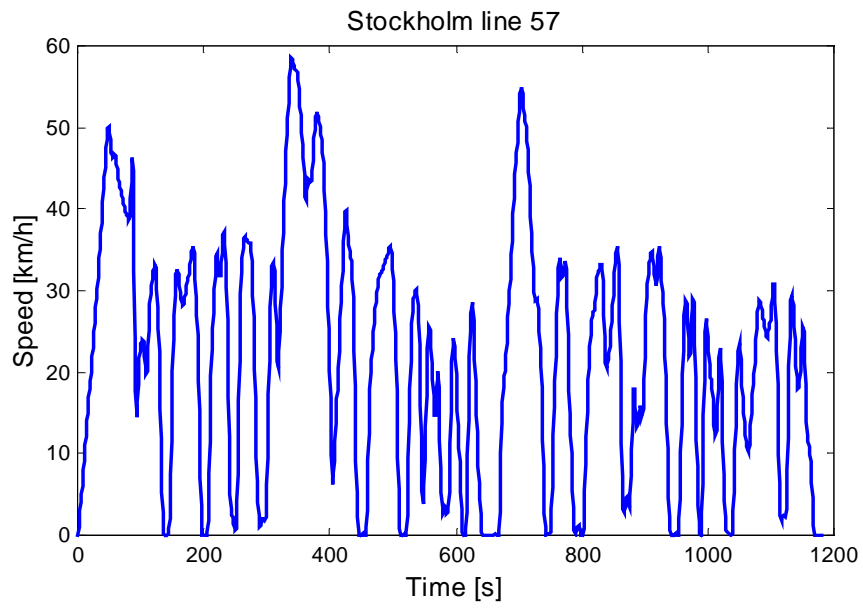


Figure 6.4: Speed as function of time during Stockholm line 57.

Chapter 7

Charging Strategies

The charging strategy for an HEV is defined as the way the ICE and generator are producing power with respect to the instantaneous power demand of the driver and the auxiliary system, and the SOC deviation of the electric energy storage. In a HEV this is one of the most important design parameters when optimising a HEV drive train. The choice of charging strategy influences the size of the different components in the drive train. In a series hybrid vehicle the operating point of the ICE, defined by speed and torque, can be chosen freely, since no mechanical connection to the wheels exist. This gives a great flexibility in choosing charging strategy for a HEV.

A simple charging strategy is obtained as the ICE and generator deliver a constant power (average driving power) to the traction motor and the battery. In this way the battery will deliver all the dynamic variation in tractive power. The losses will be large in the battery due to the power exchange when braking and accelerating.

A more energy efficient charging strategy is the ICE and generator delivering as much as possible of the instantaneous tractive power. The ICE and generator should not produce any power at all when braking. When the ICE produces all the instantaneous power, the operating point of the ICE has to vary fast. Transient operation like that is a source of some of the excess emissions of the ICE.

An intermediate solution is a charging strategy where the ICE and generator deliver a low pass filtered version of the tractive power and the battery supplies the difference to the instantaneous tractive power. The degree of transient operation is well defined by the cross over frequency used in the low pass filter. This reduces the electrical power requested and avoids the fast

transients in speed and torque range by the ICE. The battery handles only the transient power. In this way the losses in the battery and thus the battery size will be reduced.

This charging strategy with a small battery will only allow a relatively short distance in the emission free zones. The idea with emission free zones can be questioned, to drive the bus in the center of a city in pure electric mode and let the suburbs take care of the emissions from the ICE.

7.1 Present Charging Strategies for the Neoplan bus

The charging strategy, when driving in Hybrid Mode with the Neoplan bus, works as follows:

The bus runs on reduced battery power up to 25 km/h. All the power (max 50 kW) to the wheel motors comes from the battery and no power comes from the generator. The power limitation to 50 kW is set to protect the batteries since they cannot provide the 90 kW that the traction motors could use themselves, but need assistance from the ICE.

When the bus is driven faster than 25 km/h the ICE starts to deliver power via the generator. Then all the power for the wheel motors (max 100 kW) comes from the generator. Power from the generator also charges the battery. The charging power is then approximately 12 kW, when going faster than 25 km/h and 0 kW when going slower than 20 (i.e. the ICE turns off). This is depicted in Figure 7.1. The consequence of this is that the battery state of charge is kept at a high-level (SOC=90%).

When the bus slows down and the motors begin to act like generators, energy is fed back into the traction battery. Then the battery may already be charged to a high level and cannot absorb much more regenerated power. The excess regenerated power is then dissipated as heat in a brake resistor. The brake resistor only heats the water, used for cooling the ICE. As a result the power is just put away as heat, and could be better utilized for charging the battery.

Example:

The wheel motors deliver 40 kW when braking. The battery was charged with 10 kW the seconds before and has the state of charge of 90 %. The power for the battery is low 10-15 kW and 25-30 kW goes to the brake resistor. This is of course not energy efficient.

A better way to handle this problem with overcharged battery would be to charge the battery with the generator power only up to SOC 70 or 75 % and

then stop charging. When the bus is breaking, the battery will have a better chance to absorb all the power that the motors generate.

To verify the simulation model for the Neoplan bus the simulation result is plotted in Figure 7.2 under the measured energy flow. There are obvious similarities between the experimental data and the simulation. Still there are some minor differences that can be explained by local winds, vehicle turns and small height variations that influence the vehicle behaviour and energy consumption.

To get a better verification of the energy consumption the fuel consumption is integrated during a measured cycle. Verification is then possible between the simulated and the measured integrated values of the cycle.

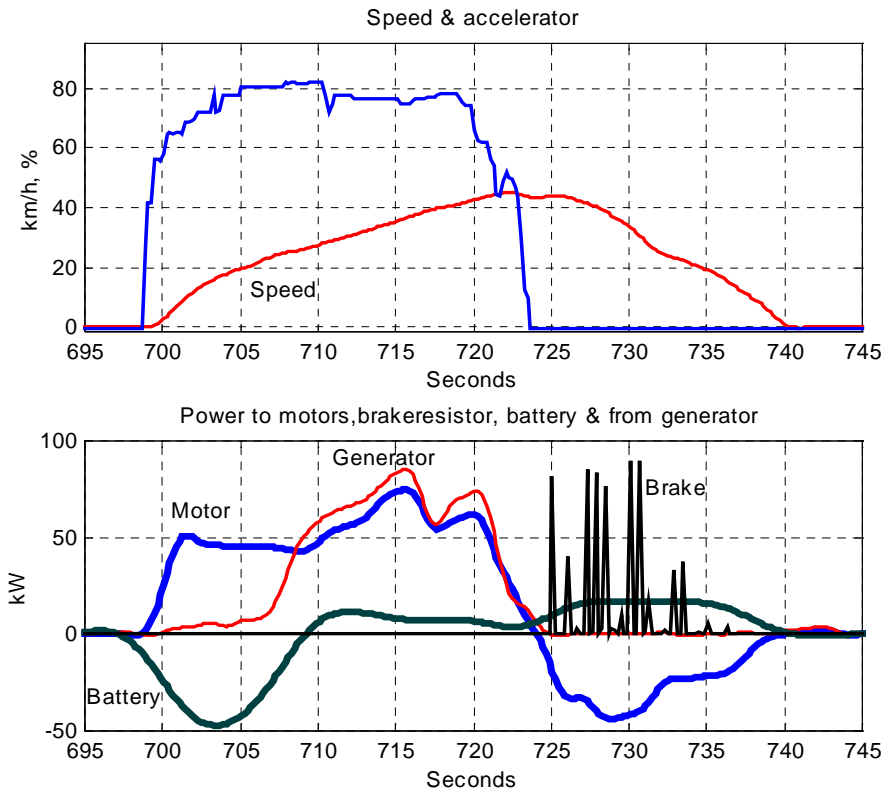


Figure 7.1: The present charging strategy, measured on the Neoplan bus

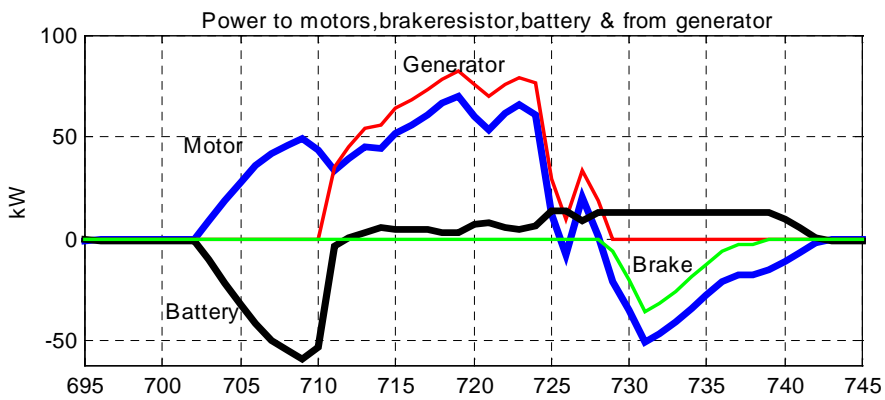


Figure 7.2: The present charging strategy, simulated on the Neoplan bus

The differences between the measured and simulated the motor power curves is the local altitude and wind variation. The generator and battery power differences can partly be depending on the differences in the state of charge in the battery and the different motor power. There is also a little time delay in the simulated, the reason for this is that the simulated cycle was extended by 3 seconds in the beginning. The brake resistor is an on/off module, but is simulated as an average power consumer. The total (integrated) power consumption of the different components for a cycle is the same in the both cases.

7.2 Present Charging Strategies for the Scania Bus

When driving the Scania bus in hybrid mode, the voltage of the battery controls the ICE and generator. If the voltage of the battery is below a certain level the ICE is started and if the voltage exceeds a certain level the ICE is turned off. When the ICE is off the peak power for the traction motor is reduced by 50 %. Both the generator and the battery supply the traction motor with power at peak load when the ICE is on. The ICE produces a power of 35 kW or 50 kW when running. The generator is consequently charging the battery when the tractive power is less than 35 kW or 50 kW respectively.

The ICE operates at two different speeds, 2500 rpm and 3500 rpm with constant torque. The speed of the ICE goes down to 2500 rpm when the speed of the vehicle is below 8 km/h and increases to 3500 rpm when the vehicle speed exceeds 8 km/h, as illustrated in Figure 7.3. This reduces the noise emissions from the ICE at the bus stops

This charging strategy needs a large battery, as the battery has to take care of all the tractive power variations of the traction motor. With this charging strategy recharging by the traction motors is not allowed. The reason is that too much power would charge the battery, when the generator delivers 50 kW and the traction motors generate 90 kW. If the ICE had been controlled in another way or turned off by the braking, then regeneration would be possible. This charging strategy makes the gasoline consumption rather high. In a normal city cycle the average gasoline consumption is 0,6 kg/km.

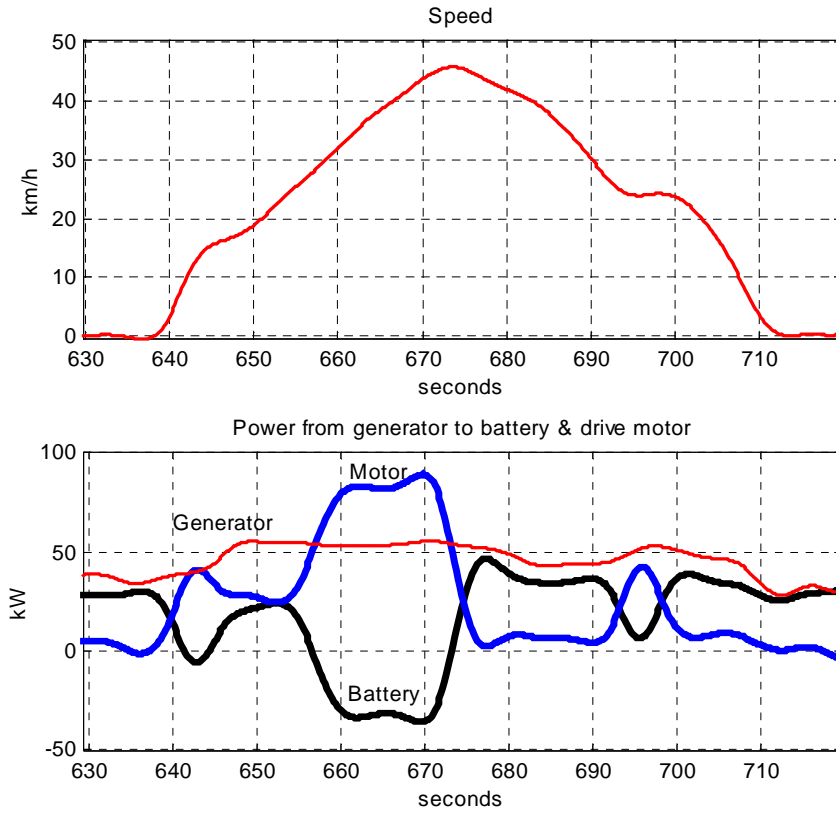


Figure 7.3: The present charging strategy, measured on the Scania bus

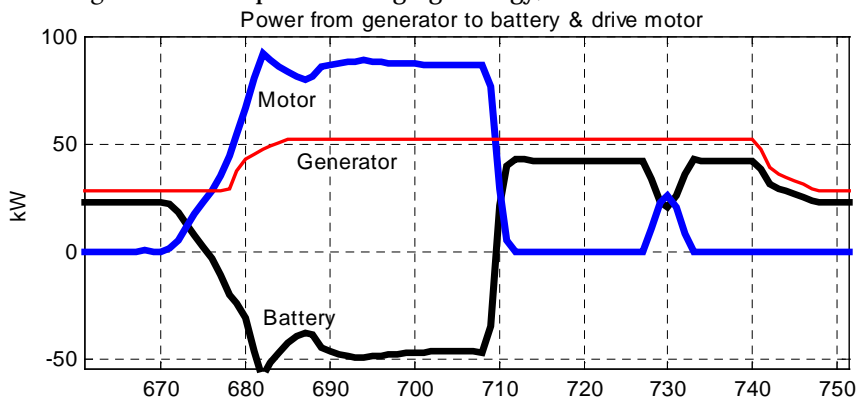


Figure 7.4: The present charging strategy, simulated on the Scania bus

There is a delay in the simulated cycle of 30 seconds. The differences in the motor power are due to the Stockholm area has large altitude variation, having some measurement and compensation for that in the simulation model would have been recommended, but was not feasible due to technical problems with the measurement system in the Stockholm bus. There are also differences in the SOC between the measured and the simulated batteries of the buses. The total (integrated) energy consumption of the different components for a cycle is the same in the both cases.

7.3 Alternative Charging Strategies

The simulation of any of the following driving cycles is arranged for SOC to end at the same level as it started, in this case 75 %. This makes the fuel consumption and emissions of different cycles comparable. Therefore a peak may appear in the ICE-power at the end of each driving cycle, if the SOC of the battery is too low. The different charging strategies are tested on the Neoplan bus.

Average Power

This charging strategy is very simple. The ICE and the generator supply the battery and traction motor with the average power, consumed by the traction motors. In this way the ICE and generator can be made small, since the battery will take care of all the dynamic power. When breaking the peak power will become very large as both the traction motors and the generator will charge the battery. This will create large losses in the battery, so a large battery will be needed. This is illustrated in Figure 7.5 and Table 7.1. A large battery is heavy and expensive. The lifetime of the battery is short, so this charging strategy is not so good for busses working continuously during 8 – 12 hours.

The average power might be good in a HEV if this power source is for example a fuel-cell, which peak power is expensive (SEK/kW), or in an electric vehicle that is charged once in a while by the grid and has not so long daily usage time as a city-bus. A small ICE and generator (range extender) might then be adequate.

On/Off Power

A large ICE and generator deliver power to the battery and traction motor by the ICEs highest efficiency point during the charging time. During the rest of the time the ICE is switched off. This will make the battery losses large since

the battery has to supply the traction motor with all the tractive power variations. When the ICE is switched off, this charging strategy will need large battery capacity. One of the advantages with this charging strategy is that the fuel economy is good when the ICE drives by the optimum efficiency point. This charging strategy is similar to average power but a larger ICE and generator are used. See figure 7.5 and table 7.1 for number of the fuel economy and battery losses.

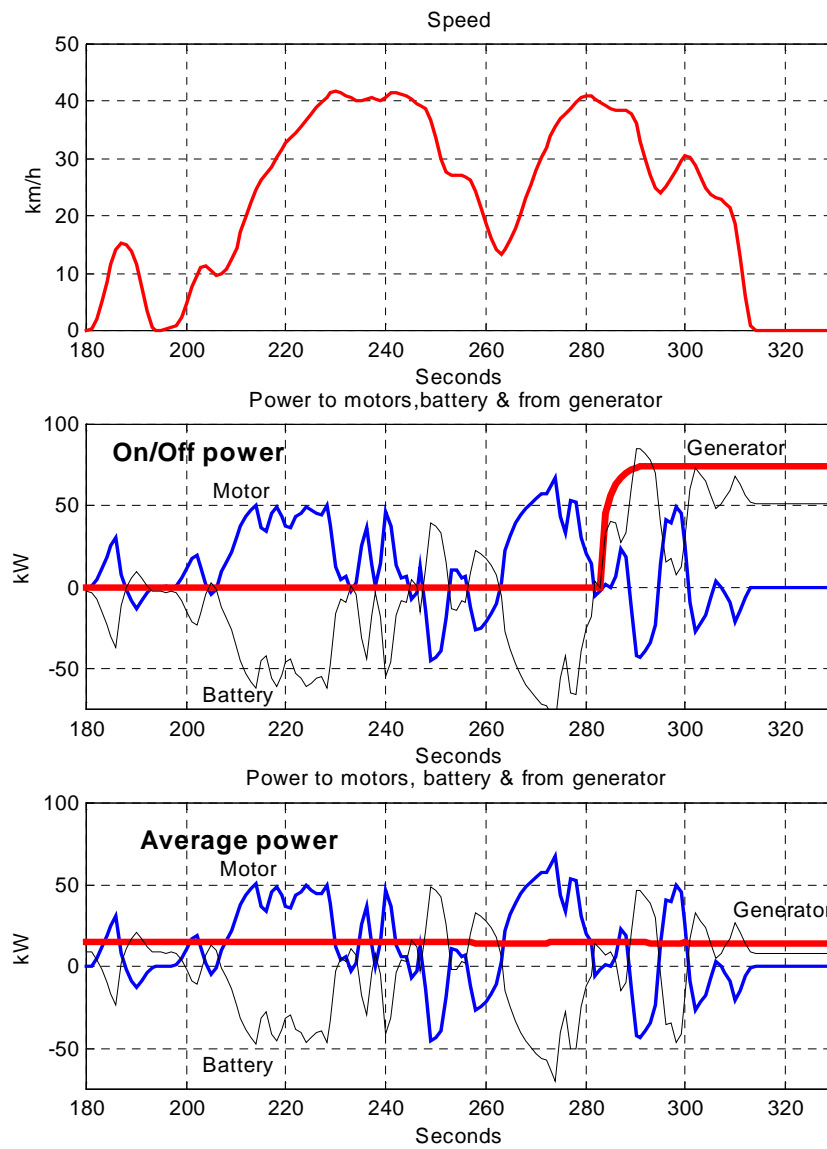


Figure 7.5: Simulated on/off & average charging strategies on the Neoplan bus

Low-pass Filtered Power

With this charging strategy the ICE and generator deliver a low pass filtered version of the tractive power and the battery supplies the rest of the required instantaneous tractive power. This reduces the electrical power requested and avoids the fast move in speed and torque by the ICE. In this way the losses in the battery as well as the battery size are or can be reduced.

When an ICE is forced to change operating point fast, the instantaneous emissions increase significantly, see Chapter 8. Since one of the motivations to design a hybrid drive system is to minimise emissions, such dynamic operation must be avoided. The strategy presented below is as simple as effective in limiting the dynamic operation requirements for the ICE.

The proposed charging strategy, used in the simulation model, sets the ICE power (P_{ice}) as a low-pass filtered sum of the tractive power ($P_{tractive}$) and a proportion of the state of charge error ($SOC^* - SOC$). This gives the required ICE power.

$$\frac{dP_{ice}}{dt} = \frac{P_{tractive} + k(SOC^* - SOC) - P_{ice}}{\tau_{ice}} \quad (7.1)$$

τ_{ice} is the low-pass filter time constant for the ICE. The emissions are strongly depending on the selection of τ_{ice} . A small τ_{ice} entails a quick change of the ICE operation point and vice versa. The simulations have been made with τ_{ice} equal 1, 3, 10, 100 and ∞ seconds. At a choice of $\tau_{ice} < 1$ second the analysis must be made with the reservation that transient effects of the ICE operation are not fully represented.

The choice of τ_{ice} also affects the minimum battery size needed. Smaller battery capacity of course means a lighter battery, but the ability to run in an emission free zone will also be reduced. It should be observed that the SOC varies very little during the driving cycle, no matter which cycle is used. This implies that the present battery size, in both the tested buses, is too large for hybrid operation, but it may still be needed for pure electric operation, e.g. in emission free zones. The distance could be reduced from 15 km to a couple of km, for example 5 km. The central part of a city is usually not so large. The battery will then have to contain higher power density. The size of the battery can be reduced with 60 %.

A drawback with the low-pass filtered charging strategy is that the ICE power set point cannot easily be predicted. The ICE power is thus some seconds too slow, when accelerating and breaking. The ICE will still charge the

battery but causes unnecessary big losses in the battery. A possible solution to this problem is presented in the following paragraph.

Forwarding the Driving Cycle

The best chance to optimise the charging strategy of the ICE and the generator on a hybrid vehicle is when the driving cycle, the road topologies and the emission-free zones are known in advance. In the hybrid bus, where the bus often runs the same route many times a day, this would not be too difficult to implement.

Implementation

It would be possible to connect the information of the bus stops as a priori information to the system. This can, for example, be connected to the GPS system for feedback information. It could also be a connection to the system that shows the bus stops for the passengers or a combination of the GPS and the display systems. The bus stop information system is connected to the door opening and to the distance between the bus stops.

When the driver starts on a new route, he also chooses the route for the passenger stop-display. The input signals to the stop display system are velocity and door opening. The velocity is integrated to a distance that is connected to the stop-display showing the name of the bus stop. When the bus stops and the doors are opened for passengers entering or getting off, the distance is reset and in a second and a new bus stop shows on the display. If the bus passes a bus stop and the distance increases too much, a new bus stop is shown on the display automatically.

The requested power for driving the bus is the sum of the power of the traction motors and all auxiliary systems. This power could be stored together with the position the first time the bus travels the route specified by the driver. The information could then be used the second time the bus travels the route. Compensation by the new requested power could also be done between the first and second time the bus travels the route.

When the system for power in advance fails or something else happens it can automatically go back to the normal charging strategy.

Example:

In Figure 7.6 a simulation with low-pass filtered power from the generator is shown. The requested power is the same as the previous time but forwarded the same number of seconds (10 s) as the low-pass filter constant. The low-pass

filtered charging strategy behaves very well in combination with the feed forward power information. The following examples show how.

- When the bus climbs a hill or accelerates and the traction motors need a lot of power, the power is supplied by the battery and the generator. If the ICE and generator are low-pass filtered, there will be a time delay by the ICE- and generator power and the battery will supply the requested power. If the power request is known in advance the ICE- and generator power could be increased the seconds before the acceleration. This limits the peak power supplied by the battery.
- When braking or running down a steep hill the traction motors produce power for charging the battery. The power from the ICE and the generator is low-pass filtered. The generator will still charge the battery when braking. The charging power for the battery will be large and cause unnecessarily big losses in the battery. If these power requests are known in advance, the charging power to the battery could be limited to the power from the traction motors.

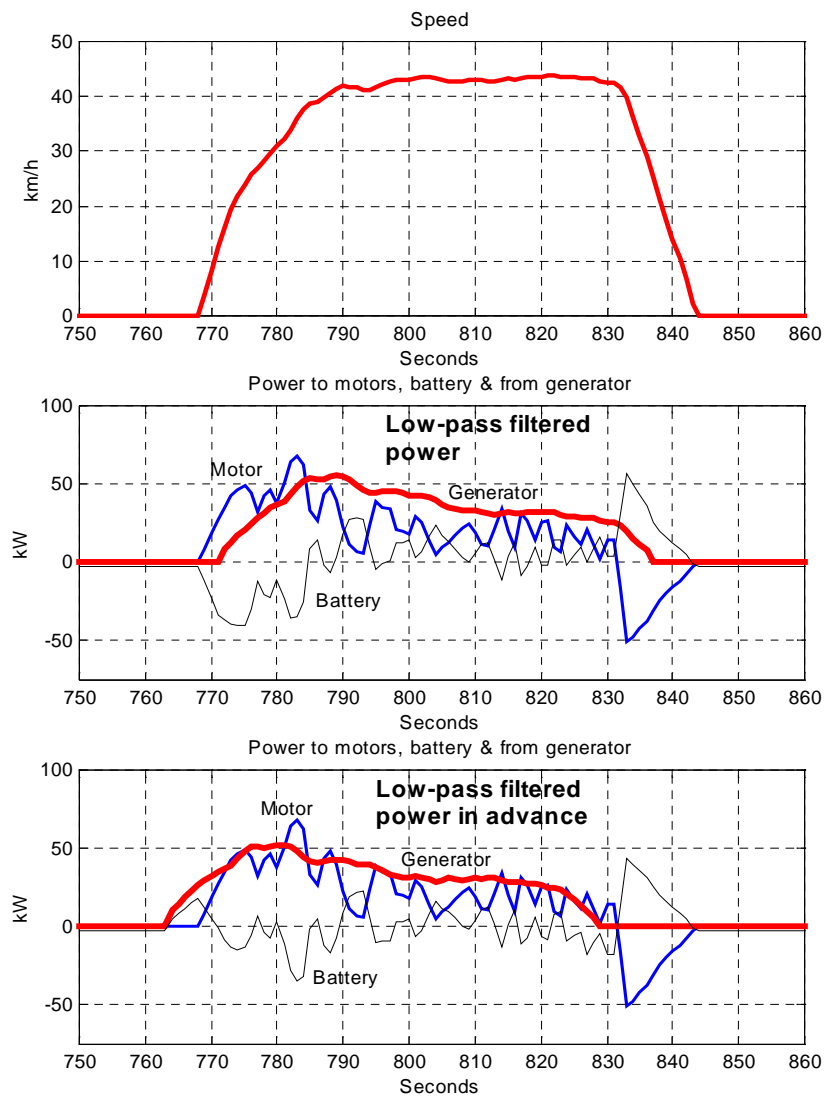


Figure 7.6: Top: Low-pass filtered power with the time constant $\tau_{ice}=10s$
 Bottom: Low-pass filtered ($\tau_{ice}=10s$) feedforward charging strategy on the Neoplan bus.

Comparing different strategies

With aid of the simulation program, a sensitivity analysis with respect to charging strategy, ICE size and battery size, has been made. The results, for Case I (Neoplan in Malmö) in one route, are presented in table 7.1. The bus is running the Malmö cycle in all simulations. The reason why this bus was chosen for modification was that the bus design is the most modern.

The over all efficiency of the driving cycle in the simulation is the same as the fuel consumption, when the final SOC in the battery is the same.

The following strategies were tested in table 7.1:

- The first simulation is called MM (MangetMotor). This charging strategy is the original in the Neoplan bus. The size of the components in the drive train has the original dimensions.
- The charging strategy, "on/off", is run with the ICE off at the beginning and in the later part of the simulation with the ICE on, with constant power (75 kW).
- The low-pass filtered charging strategy is altered in steps of 1, 3, 10, 100 and ∞ seconds. With the ∞ time constant this strategy corresponds to the average power discussed in section 7.3. Note that the fuel consumption is not significantly affected by the charging time constant. All the other strategies do involve the time constant τ_{ice} . The battery losses on the other hand are significantly reduced if the ICE is "taking more responsibility" for transient traction power.

$\tau_{ice} = 1$ is believed to possibly excite transient behavior. This is supported by results such as presented in (Cowart-Cheng, 2000) where $\tau_{ice} = 3$ is regarded as being on the verge to transient operation of the ICE.

$\tau_{ice} = 10$ is regarded as *not* exciting any transient operation of the ICE. The peak power of the ICE is still reduced significantly compared to the tractive power.

$\tau_{ice} = 100$ the ICE runs almost on average power and battery losses get too large.

$\tau_{ice} = \infty$ the ICE runs on a constant (average) power.

- Secondly, the size of the ICE is used as a variable parameter. The size cannot be altered continuously, but in steps of cylinders. Even if one cylinder is removed, the fuel consumption and exhaust emission per cylinder will remain almost the same (ref discussions with Rolf Egnell). The efficiency at a given torque- and speed combination is modelled as

unchanged when a cylinder is removed or added. However, a smaller motor (cylinders removed) must operate at a higher torque/cylinder for the same power, thus increasing the efficiency. See Table 7.1.

Table 7.1
Charging strategy is changed

#	τ_{ice} [s]	No. cyl.	Fuel [kg]	Max ICE Power [kW]	HC [g]	NOx [g]	Bat los [kWh]	Max Power fr./to Bat [kW]
1	MM	6	2,30	87	24*	24*	0,35	40/51
2	on/off	6	2,02	75	24	24	1,31	93/88
3	1	6	2,33	79	24*	24*	0,22	40/32
4	3	6	2,33	76	25*	24*	0,31	62/40
5	10	6	2,37	61	25	26	0,52	68/51
6	100	6	2,47	33	25	37	0,73	61/70
7	∞	6	2,44	15	23	48	0,76	51/72
8	∞	2	1,95	15	24	17	0,76	51/72
9	10	4	2,22	61	24	22	0,52	68/51
10	10	3	2,16	60	23	24	0,52	68/51
11	10p	6	2,32	60	24	26	0,35	56/40
12	100p	6	2,47	26	23	41	0,70	56/75
13	10p	3	2,04	57	23	22	0,35	53/68

Comments to the results of the simulations by number:

- 1 The original charging strategy of the Neoplan buss. The ICE supports with most of the dynamic power. In the model there is no transient operation compensation that would have made the emissions from the ICE larger.
- 2 With the on/off charging strategy, the battery has to take care of all the tractive power, parts of the time. This gives relatively high battery losses but a good fuel economy since the ICE runs only at high efficiency. An additional problem is that long intermittence may cause the catalytic converter to go out, with correspondingly high emissions in the beginning of the next start.

- 3 - 7 Low-pass filtered power from the ICE. The low-pass filter time constant (τ_{ice}) should be small from the battery losses point of view, but not too small, as the ICE will gradually create transient emissions, as the time constant gets shorter. The limit where the ICE starts causing transient emissions is somewhere between 3 and 10 seconds. These are the reasons why $\tau_{ice} = 10$ seconds is selected.
- 7,8 When $\tau_{ice} = \infty$ the ICE will run on an average power during the whole drive cycle. This power is relatively low and it is thus possible to reduce the ICE size. The ICE has higher efficiency if the whole torque register of the ICE is used. Cutting off cylinders will reduce the ICE size, but retain the torque-speed characteristics per cylinder. When only 15 kW is needed a 2-cylinder ICE is sufficient. The fuel economy will be good but the battery losses will be large, since the battery will take care of the tractive power dynamics.
- 9, 10 In this case the ICE power request is not constant but slowly varying and without the high peaks like in example #1 and #2. With the lower power requests from the ICE, a smaller ICE can be used, see 7,8. In this case, the number of cylinders is reduced from 6 to 4 and 3. This also changes the fuel economy and the emissions.
- 11-13 The last three simulations, marked with “*p*”, are simulated with the predicted cycle. The lower battery losses are of special interest in these simulations. When the battery does not need to exchange so much energy, the overall efficiency is increased.

Concluding Remarks

The different charging strategies presented in this section are simple in nature and can all be implemented as software changes. The only exception from this rule is the predictive cycle that would need a GPS-unit with the additional hardware that follows.

An important consideration in the choice of charging strategy is the need for emission free driving distance as this sets the lower limit for the size of the battery. If the emission free driving distance can be disregarded, it is shown that the 13 charging strategy will improve the fuel consumption with 11 % as well as reduce the ICE size with 60 %. The size of the battery can be reduced with 60 % corresponding to a theoretical reduction of the emission free driving distance from 15 km to 5 km.

Chapter 8

Transient Emission Sampling (TES)

A hybrid vehicle offers the freedom to choose between the ICE and/or the battery as power source. The conclusion from the previous chapters is that the ICE should operate as near its transient limits regarding emissions as possible. Thus, knowledge of this transient limit is crucial. However, conventional methods for emission measurement are made for stationary operation. (Egebäck-Westerholm, 1997) In fact, most emission measurement techniques are unable to detect transient changes within the time frames necessary for establishing the transient emission limitation of an ICE in real time. The instruments response time is too slow. Fast responding instruments, used by the industry, are very expensive and in some cases not so reliable.

To overcome this problem, a transient emission measurement technique is proposed here, called TES (Transient Emission Sampling).

The ICE measurements are done together with the Department of Heat and Power Engineering, Division of Combustion Engineering. Fast throttle movements are performed and a special technique for sampling the emission is applied. The ICE, used to test this TES-method, is a 2,3 l SAAB ICE, the same as in the Scania hybrid bus.

8.1 Method

The idea with TES is to measure transient emissions with standard emission measurement equipment, used for stationary measurements. This does not request use of fast responding equipment that is expensive and does not have the same performance.

The TES method is applied to an ordinary ICE. The ICE is mounted in a test bench with additional measurement equipment. The test bench's brake is speed controlled and the ICE is torque controlled. The ICE is forced by controlling the speed and torque to continuously change operating point by changing the torque and speed references. A repeated behaviour is possible to achieve and in a controlled manner repeatedly excite transient operation. Figure 8.1 illustrates how the speed and torque changes.

Emissions from a certain selected part (torque and speed) of the transient operation can be "sampled" by a valve on the exhaust pipe. The valve is opened intermittently in a specific time interval. These samples can be gathered for analysis with conventional instruments, in a stationary manner.

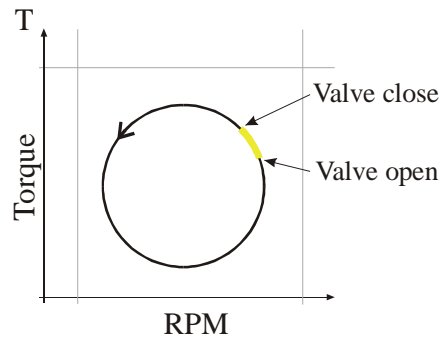


Figure 8.1: TES principle for emission sampling.

8.2 Implementation

The test bench consists of an electrical brake of eddy current type. The brake is connected to the outgoing axis of the ICE. The brake controls the speed variations. It tries to limit the speed of the ICE when it is throttling by increasing the braking torque.

The ICE is torque controlled by a throttle servo connected to a tone-generator for torque reference. The tone generator can give triangular or sinusoid reference signals by a chosen frequency, amplitude and dc-level. These voltages can easily be adjusted for acting as torque references for the throttle servo. An example is ramping the throttle like a triangle forward and backward.

When the speed or torque reaches a certain level a valve by the exhaust pipe is opened for a short time. A sample of the emissions is taken by a certain

torque and speed under a bit of the transient loop. This is done over and over again until a plastic bag is full of these samples. Ordinary emission tests can be done on the emissions in the bag as illustrated in Figure 8.2. A time-delay can be added to the opening condition of the valve and the emissions in another speed- and torque level around the loop can be collected.

A complete ICE measuring system is connected to the ICE. The sensors are as described in Table 8.1.

Table 8.1
Sensor specification of the engine test bench

Sensor	Unit
Speed	rpm
Fuel flow	g/s
Pressure inlet	bar
Fuel pressure	bar
Torque	Nm
Valve	Open/Close
Temp cool water	•C
Temp oil	•C
Temp fuel	•C
Temp brake	•C
Temp inlet	•C
Temp before cat	•C
Temp after cat	•C
Lambda sensor	Air/Fuel

The reason why so many temperatures are measured is to check that the ICE, fuel and cooling has the right working temperature. The catalyst temperatures before and after are very important to control that the catalyst has lightened and is active.

The inlet pressure is depending on the ICE torque, and is also used for controlling the magnetic valve by the exhaust pipe. The torque measured on the electrical brake is not the same as the ICE torque. The ICE's torque is also used for accelerating the inertia of the brake and the ICE. This is the reason why it is important to measure the inlet-pressure. In stationary operation

(constant torque and speed) the brake torque and the ICE torque would be the same. In this case the ICE torque will be calculated afterwards by using the inertia (J) for the brake and the ICE multiplied with the speed variation and the measured brake torque, as described by Equation 8.1.

$$T_{ice} = T_{Brake} + J \frac{d\omega}{dt} \quad (8.1)$$

Lambda

A broadband lambda sensor with very fast response time is also used in the measurement system. The lambda sensor makes it possible to see how the ratio between air and fuel changes, when throttle movements are performed. When lambda differs from 1 for a long time, emissions will increase a lot after the 3-way catalyst.

Example: The ICE tries to control the air/fuel ratio to an average value, in this case 1, for the 3-way catalyst. The operation is performed as a limit cycle around the stoichiometric air/fuel ratio 1.0. The lambda value (air/fuel) is lean (over 1.0) and the ICE makes lambda richer (goes down) until it reaches a certain level (0.97). The ICE changes strategy and starts to make the lambda leaner (goes up) until it reaches a certain level (1.03). This is repeated as long as the ICE applies lambda control and will make the lambda average value to 1. It is important that the average lambda is 1.00, but not that important that the actual value is exactly 1.00.

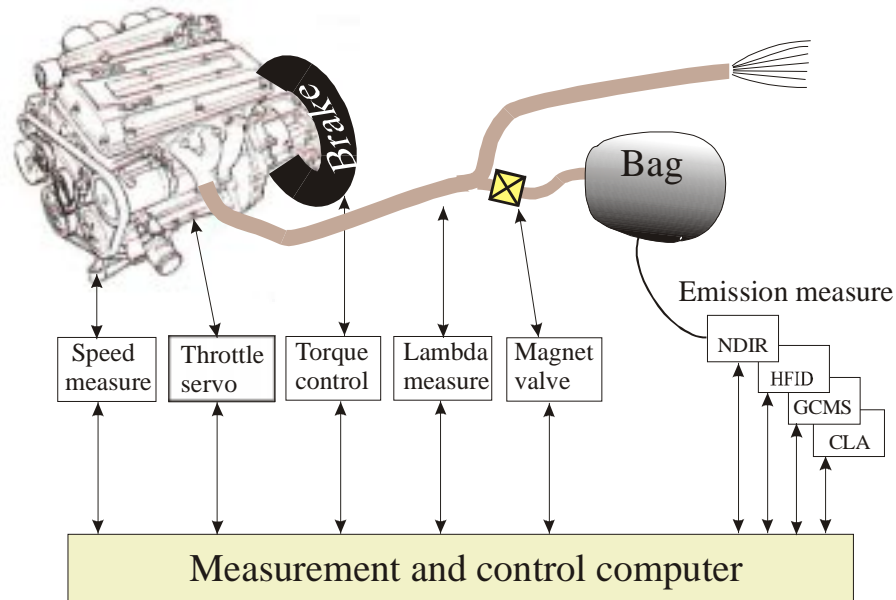


Figure 8.2: TES major equipment for emission sampling. (NDIR: infrared analysis instrument detection of CO and CO₂, HFID: flame ionisation detector for HC, GCMS: gas chromatograph and mass spectrometer for emissions detection, CLA: chemiluminescence instrument for detection of NO_x)

8.3 Result

A number of tests with the TES-method have been performed where the DC level, amplitude and frequency of the throttle servo have been changed. The magnetic sample valve can be controlled by speed or torque. In the torque case the ICE inlet pressure is used as reference for timing of the sample valve.

Emissions at Slow Transients

In Figure 8.3 one of the tests is performed where torque, speed and lambda with very slow throttle movements are shown. The repetition time for one cycle is in this case 20s. The small squares show the magnetic valve opening for measurements in both these both points.

By these slow movements the ICE lambda control still works. The lambda control keeps the air/fuel ratio near an average of 1.0. The 3-way catalyst converter works and there are no transient emissions due to the very slow transient behaviour.

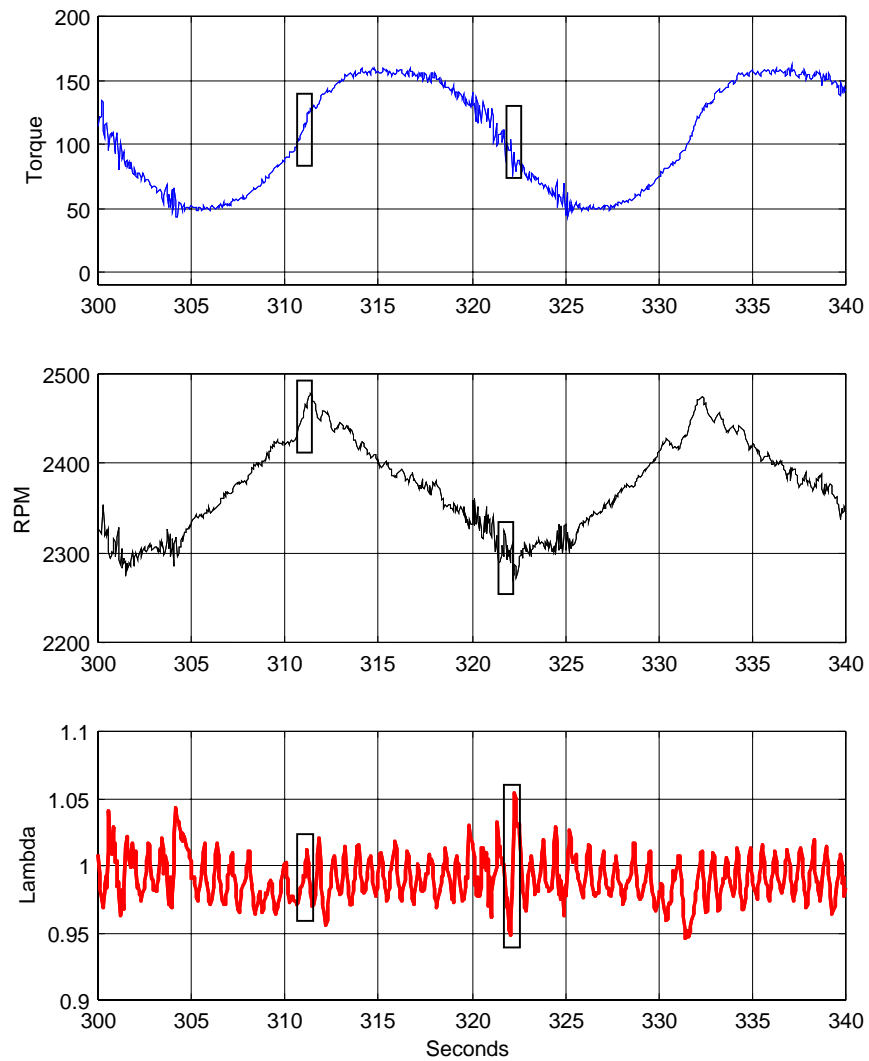


Figure 8.3: TES torque, speed and lambda measured by slow throttle movements.

In the next figure the same speed and torque variations are used as in the previous figure, but plotted in a different way, torque as a function of speed. The cycle is run through counter clock-wise.

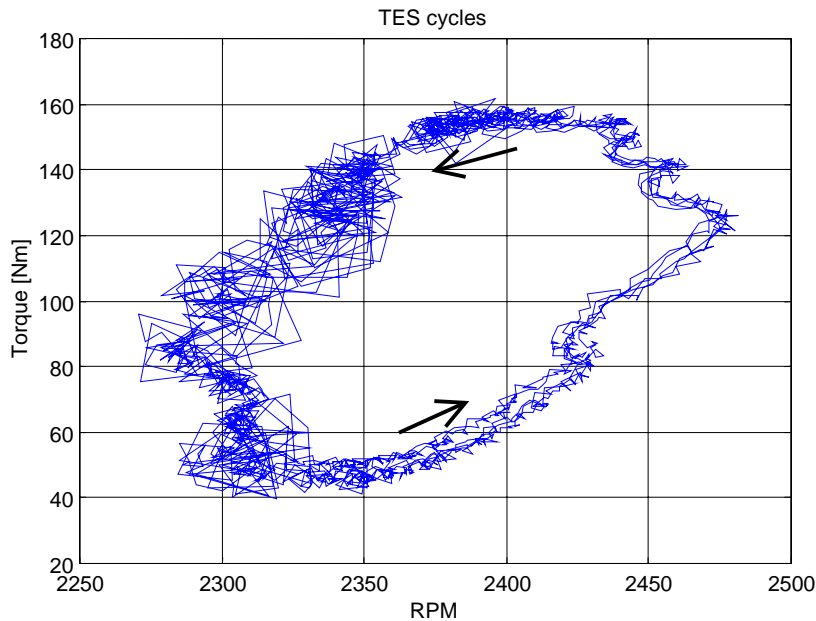


Figure 8.4: TES torque as a function of speed by slow throttle movements.

These cycles make a very low variation per time unit in both speed (ω/dt) and torque (T/dt). The speed is going between 2280 rpm and 2480 rpm and the torque is going from 50 Nm to 150 Nm, this makes a power variation of approximately 30 kW.

Higher Transient Emissions

In the following example the cycle time was 2,5 seconds, the speed and torque has thus been varied with higher frequency (0.4 Hz) than the previous example (0.05 Hz). The lambda variation is clearly increased. This is a source of transient emissions.

The ICE speed and torque are plotted in Figure 8.5. The emissions were measured both at load increase and load decrease. The magnetic valve was opened during 0.5 seconds each cycle.

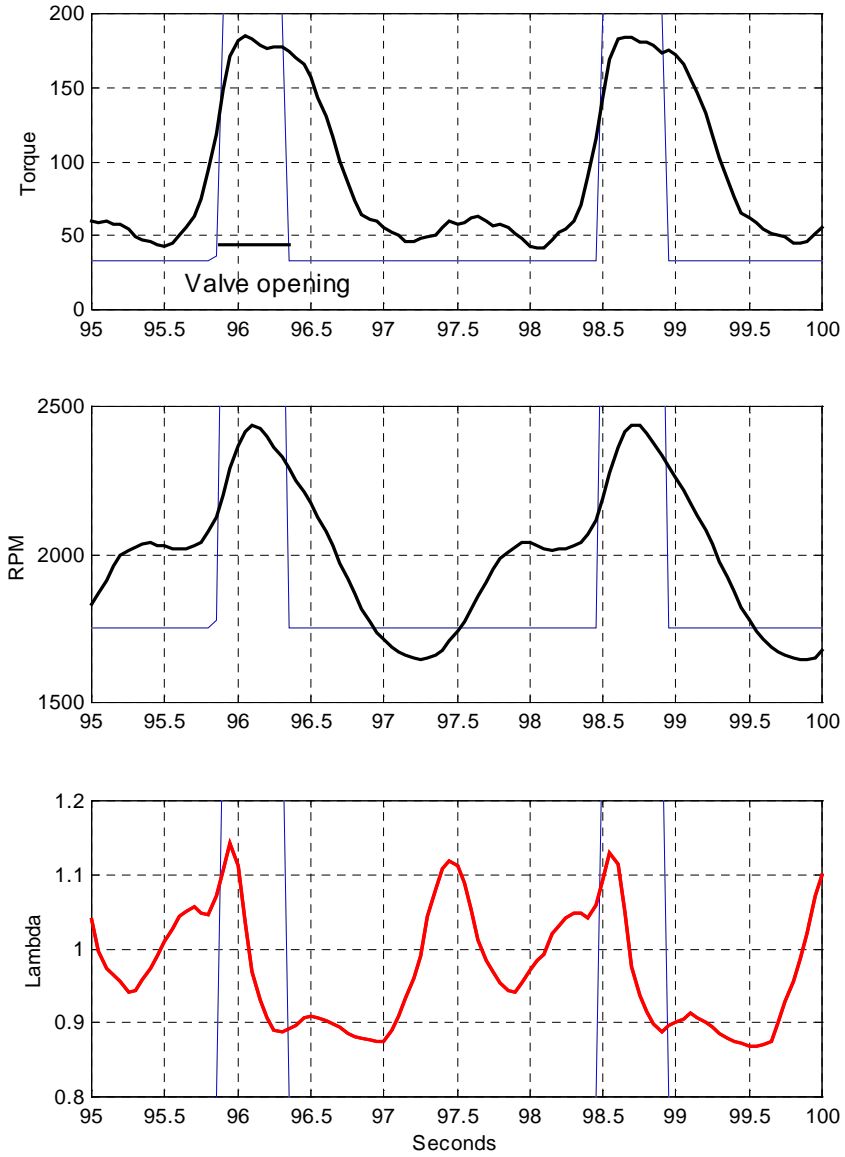


Figure 8.5: TES torque, speed and lambda measured by fast throttle movements.

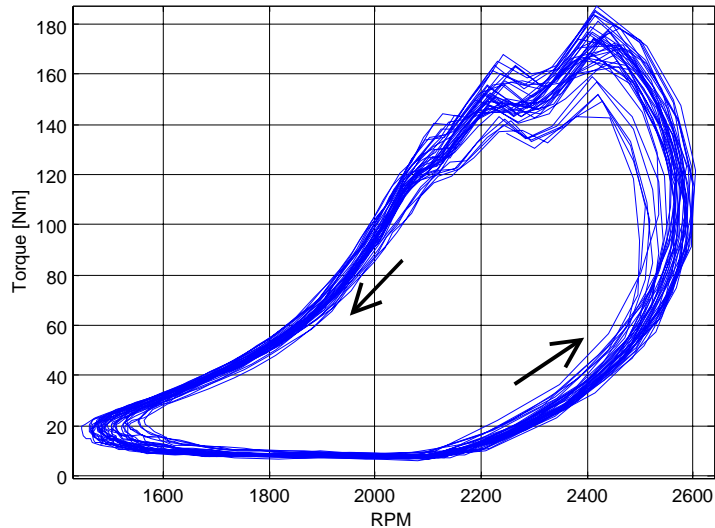


Figure 8.5: Torque as a function of speed by fast throttle movements.

These cycles make a high variation per time unit in both speed (ω/dt) and torque (T/dt). The speed is going between 1550 rpm and 2500 rpm and the torque is going from 10 Nm to 180 Nm, this makes a power variation of approximately 40 kW.

In table 8.2 and 8.3 the emissions measured with the TES principle as described in this section are compared with the emissions produced in stationary operation at the same operating points as the average torque and speed of the sample valve opening interval.

Table 8.2
Emissions in stationary and transient operation with the same average torque, @ increasing torque.

Emission	Transient operation	Stationary operation
CO [%]	2.25	0.4
HC [ppm]	1200	1880
O ₂ [%]	2.0	0.88
NO _x [ppm]	2200	3500

The results from these measurements give a hint that the emissions by the certain load have an overflow of fuel. This is also indicated by the lambda sensor.

Emissions by load reduction can be seen in Table 8.3.

Table 8.3
Emissions in stationary and transient operation with the same average torque, @ decreasing torque.

Emission	Transient operation	Stationary operation
CO [%]	3.3	0.8
HC [ppm]	1000	720
O2 [%]	1.0	0.72
NOx [ppm]	1400	2500

The lower emission by NOx can be explained by Figure 2.5,. The both measuring points has probable a rich mixture of air and fuel.

Stationary Measurements

The reason for this performance test is that there have been questions about the influence of the TES-equipment on the emissions. To verify and confirm that the emission measurements by the TES-method have not been influenced by the cooling of the exhaust gases in the bag or any other things in the TES system, a stationary test has been done. The ICE was run at a constant speed (2200 rpm) and torque (80 Nm) and the emissions were measured, both with the TES-equipment and in the ordinary exhaust pipe. In these two different places the emissions were the same. So the TES-equipment had no influences on the emissions.

Conclusions of TES

Fast throttle movements can excite the transient behaviour where the lambda control of the ICE has a problem to control the air/fuel ratio average to 1. For the ICE used in the preliminary tests of the TES method reported here, the limit for this behaviour starts somewhere in the region between 5 to 10 seconds. Faster throttle movements than this limit on a hybrid vehicle with this particular ICE and engine control system, where the electric traction system

can reduce the transient power from the ICE, is thus not recommended from an emissions point of view.

The limit for transient emission generation, expressed as a bandwidth, in an ICE is most likely different in different ICE drives. It is also possible that this limit may be different for different operating regions of the ICE torque-speed plane. The TES method as presented here is a first and preliminary evaluation of the TES method, and must only be taken as a indication supporting the intuitive assumption that there must be a limit where the lambda control no longer works properly. Other reports do support this assumption (Cowart-Cheng, 2000).

Chapter 9

Experience of the Vehicles

9.1 In General

In this chapter some general experiences of working with the vehicles used in this project are discussed. To have one or two special vehicles in a larger conventional bus fleet causes some problems. The vehicles are unique and have several kinds of unusual properties. When a failure occurs in one of these special vehicles, special repair methods are needed. Service and repair is also needed for the ordinary vehicles in the fleet; the special vehicle's needs are placed last or beside the queue. If not somebody, like the one who is in charge of the bus workshop, is particularly assigned to care for the vehicle it might stay out of service for an unusually long time. When the vehicle is not in use some other complications does also appear, like the battery becoming discharged.

A larger fleet with special vehicles, like hybrid and electric buses, would be preferable to collect in one place, compared to have them spread out at many places in Sweden.

9.2 Drive and Control System

It is very important that the vehicle control system limits the number of warning messages for the driver. Too many warning lamps and alarms may cause the driver to reduce attention to them. The bus must not lose tractive power control when a side-cover is indicating opened. These alarm limits

should be very carefully chosen and if possible diverted from the driver to the workshop.

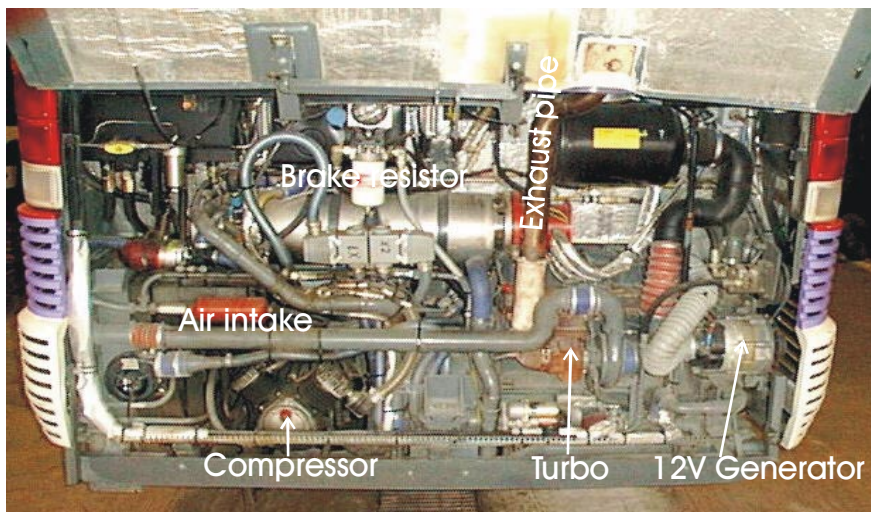


Figure 9.1: The back of the Neoplan bus showing the complexity of a hybrid system.

The complexity has to be watched carefully. Having too many computer systems talking to each other depending on too many sensors is a dangerous solution. One of the buses was not able to run on batteries at all when one of ten temperature sensors in the battery was short-circuited.

A cold day when the bus was parked outside during the night, the battery signalled too low temperature. The consequence was that the bus was not able to run on battery. The cooling fan kept pumping cold air from the outside, which works very good during all seasons but winter. The result of this was that the bus could not run on battery that day. If the air during the cold season instead were taken from the passenger compartment this problem would not appear.

The different parts used in hybrid vehicle construction must be of the right size and made for the use in the certain application. In the ICE case it is neither good to use a too big ICE, which can deliver the power for long time without service nor use a small car ICE of the right size but not constructed for this kind of use. A small car engine that is used in a hybrid bus is designed to

run with peak power for a short time under acceleration in a car and then run with reduced power for a longer time. It is also designed to run 15-20.000 km between the services. During one day a hybrid bus will run 12 hours or (12h x 20km/h) 240 km consuming approximately 6 times as much fuel as a small car. This will be equivalent to run the ICE (6 x 240km) 1440 km. This means that the ICE during two weeks in the hybrid bus will run as much as it would do in a small car during one year. The ICE bearings, valves and other moving parts will be worn out in advance when the ICE is not designed for this application.

These kinds of failures or design mistakes may not appear on a commercial bus, and it shows that the hybrid busses still are somewhere between experimental and commercial state of development.

9.3 Views on the Driver of the Neoplan Hybrid bus

The driver of a special vehicle should not be randomly selected among hundreds of drivers. It is important that the driver will get a special education and information about the vehicle that he is appointed to drive. When a new driver comes to a new vehicle and is not used to the vehicle and some small failure appears (some lamp flashing) he is not prepared to solve this kind of problem. The driver immediately calls for another bus. These kinds of situations do not appear as often when the driver is used to the vehicle and has some experience to handle the particular problems related to hybrid buses.

The drivers are generally negative to changes compared to their ordinary bus. For example, some drivers had opinions about the steering wheel and the brake pedal, both being too heavy to operate compared to other buses. Some had opinions about the place to hang the jacket. These things can many times be easily adjusted or changed. It is a pity that such small things could affect the general impression of a hybrid buses.

9.4 Views on the Driver of the Neoplan Electric bus

In Uppsala there are 12 electric busses that also were a part of the project from the beginning. No data collection from these buses has yet been made.

The drivers of the electric bus were not randomly selected; they were purposefully selected. Among the drivers it was seen as a privilege to drive these electric buses.

The battery was charged in a special charger, see Figure 9.2. The driver had to change the battery when it was empty. This procedure meant some extra work. The bus has to be stopped by the charging station, the driver has to go

out of the bus and manually operate the switching of batteries. Among the drivers it has been a challenge and competition to drive as long as possible without the battery exchange procedure. In other words: to drive as energy efficient as possible, which is a good thing. If the driver could be challenged to drive efficiently like in this example, somehow even on other kind of vehicles, it would of course be a great advantage.

One of the drivers also told that the batteries behaved like individuals. He was able to drive many routes with battery no. 5 while he was only able to drive one route with battery no. 7. This demonstrates that the battery technology is still the weakest link in the driving chain. There is still a lot of work to be done in this area.

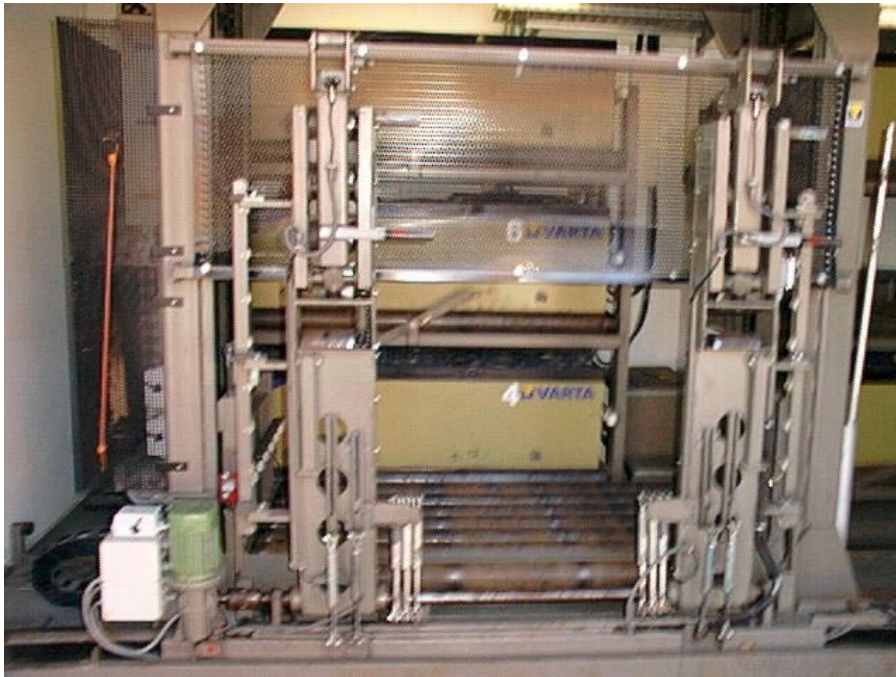


Figure 9.2: The battery changing station for the electric busses in Uppsala.

Chapter 10

Conclusion and Future Work

Conclusions

Several lessons have been learnt from these half experimental vehicles. Some of these are just minor problems with details, and some are on the system level. The major conclusions are:

1. To be able to write “near optimal” specifications for a hybrid bus it is important to know the driving cycles, what kind of traffic, how steep hills and how many passengers the bus is expected to carry. Without such “a priori” knowledge, the hybrid drive train is likely to be overpowered with significantly less than optimal performance in terms of emissions, fuel consumption and battery losses. The ICE must be selected and purposefully designed with regard to average and peak power production. This in turn requires a well-defined charging strategy. The battery size must be limited to a minimum with respect to either the charging strategy or the minimum zero emission driving distance.
2. The charging strategy is important to minimize exhaust emissions and fuel consumption. The goal should be to supply instantaneous power to the traction and auxiliary systems, but without exceeding the limit for transient emission generation with the ICE. With such a goal, the battery will be minimized with respect to the charging strategy.
3. A prediction of the drive cycle should be taken advantage of to improve the charging strategy. This is especially feasible in a city bus route due to

the repetitive nature of its operation, e.g. by using information from the GPS-sensor or the bus stop information system. The simulations made in this work indicate a reduction of the battery losses with more than 30% when applying prediction to one of the better charging strategies.

4. The transient emission limit, expressed as a bandwidth, needs to be determined for a particular ICE before implementing the charging strategy. Methods for determination of this limit, like the TES method discussed here, needs to be developed and applied.
5. The error message handling must be made to minimize the number of error situations that disturb the driver or cause the vehicle to cease operation. The less important error messages should be available to the workshop personnel only.
6. The job to be a driver of a hybrid bus should be given a positive image, it should be regarded as an honour to be picked as a driver of test vehicles like the ones used in this project. If such an image is obtained, and the driver is properly educated, the number of undesired stops due to technical problems is reduced due to the driver's higher willingness and ability to solve problems "on the spot".

Proposals for Future Work

Based on the work presented in this report, some particular suggestions for additional effort within the field of hybrid buses are recommended.

1. Equip a hybrid bus with a drive line according to the results in this work, i.e. a considerably smaller engine and battery pack, of course including the proposed charging strategy.
2. Implementation of the proposed route predictive charging strategy in a hybrid bus.
3. Further development of the TES method as presented in this report. In particular, testing different types of ICE's with a comprehensive evaluation of the size, position and repetition speed of the loop in the torque-speed-plane.

Chapter 11

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Appendix A

The MagnetMotor charging strategy

The measurements on the Neoplan bus were performed during an 8-hour shift in traffic between the central station of Malmö and the exhibition by the Öresund bridge. Under these tours the power from the generator, the fuel consumption and speed of the ICE were measured. The torque, power to ICE and efficiency of the generator and the ICE can be calculated in all these points.

The number of operating points visited by the ICE with a certain rpm and torque can be seen in figure A.1. As expected the highest peaks are by idling with zero torque. These peaks are set to zero, to see the others that are more interesting. There is also an apparent ridge of small peaks by 700 rpm that goes high up in the torque register; the generator causes this when it starts to deliver power.

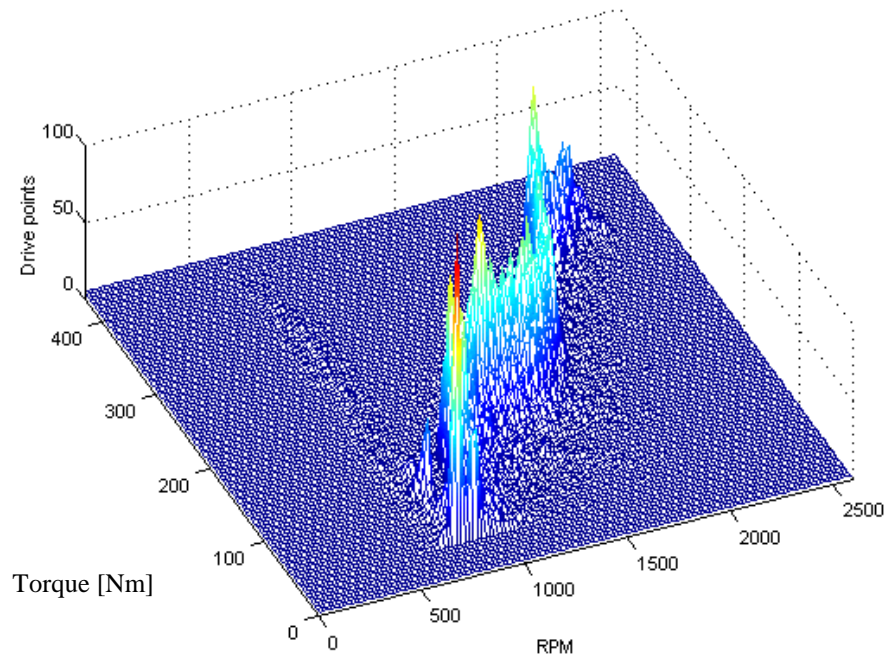


Figure A.1: ICE driving points on the Neoplan bus during one day.

The ICE have visited these operating points more than 25 times during 8 hours. This is a normal driving point for the ICE. All efficiencies by a certain rpm and torque are summarized and an average efficiency values are calculated. In figure A.2 the efficiency of the most frequent visited working points are plotted. The efficiency increases as more torque is requested from the ICE. When the torque is high, the efficiency over the ICE and the generator is the highest.

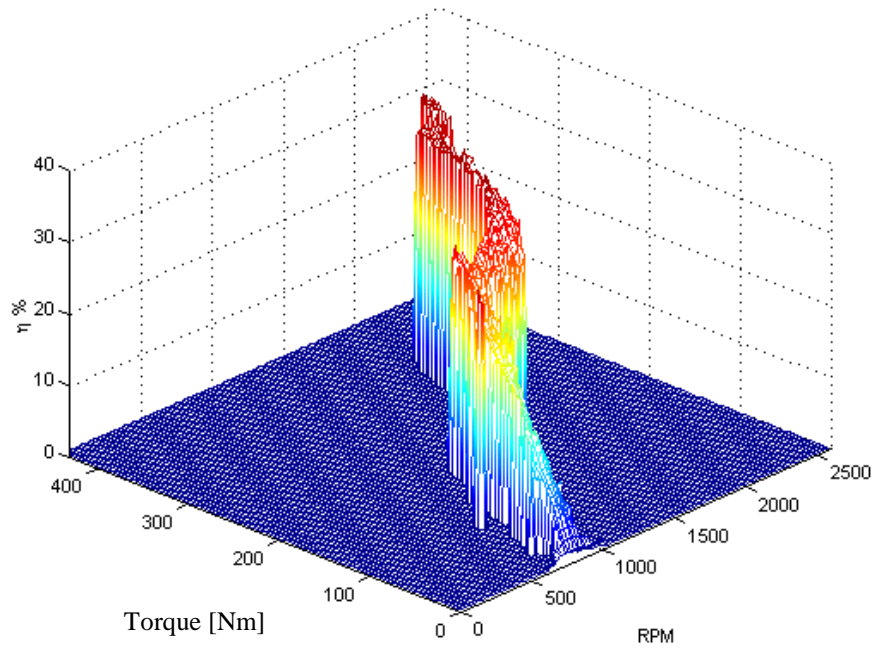


Figure A.2: ICE efficiency on the Neoplan bus during one day.

Appendix B

User Manual

This is a description of the user manual for the simulation program. It is a manual that a person with some computer experience and only little knowledge about Matlab/Simulink® can handle. It could also be interesting to have a description of the simulation program on another level, where modification of the software and more advanced use can be executed. This more complicated use has been described in some way in the thesis. Here the purpose is to present a quick introduction into the use of the simulation program,

Instructions

- Start the Matlab program on the computer.
- Go to the directory where the file “*simulate*” is placed.
- Write: “*simulate*” and press return.
- Now Matlab starts its graphical user interface where the simulation program runs. A new window opens with buses, a piston, a battery, an electric motor, a diagram and different buttons. The interface is shown in Figure 4.1.
- A choice between different buses can be done, by clicking on the popup-menu "Select Bus". A selection between Neoplan and Scania/DAB hybrid buses can be done. When a bus is chosen, a picture of that bus appears in the figure.

- When a bus has been selected all its default values appear by the different components. This is the number of cylinders, number of battery cells and the size of electric motor. These numbers can be changed by the popup-menus for each component. For example, if the ICE size is to be reduced with 50 percent the default value number of cylinders can be changed from 6 to 3 by the popup-menu.
- The driving cycle, which the bus is going to run during the simulation, can be selected by the popup-menu "Driving Cycle". The driving cycle available for the moment is: Malmö (to the Öresund bridge), Stockholm (line 57) Braunschwig and ECE15. When a cycle is chosen it appears in the plot.
- The "Charging strategy" is the way the ICE should charge the battery and the electric motors. The selection by this popup-menu is between the original and different low-pass filter constants.
- The simulation can now be saved or printed by clicking on the proper buttons.
- To run the summation program press the button Simulate.

Result of the Simulation Program

In the simulation result view of the simulation program there are 5 different subplots and some text information. The text informs about the total driving range and average speed, total fuel consumption and the different emissions.

All subplots can be zoomed by clicking on the magnifying glass and mark the interesting area with a square around it. The first subplot shows the reached speed in m/s of the bus. The second subplot shows the variation (%) in state of charge in the battery. The third subplot shows the power (kW) from the ICE. The fourth subplot is the ICE's fuel consumption (kg). And finally the fifth subplot shows the power (kW) to the electric motor requested to run the driving cycle.

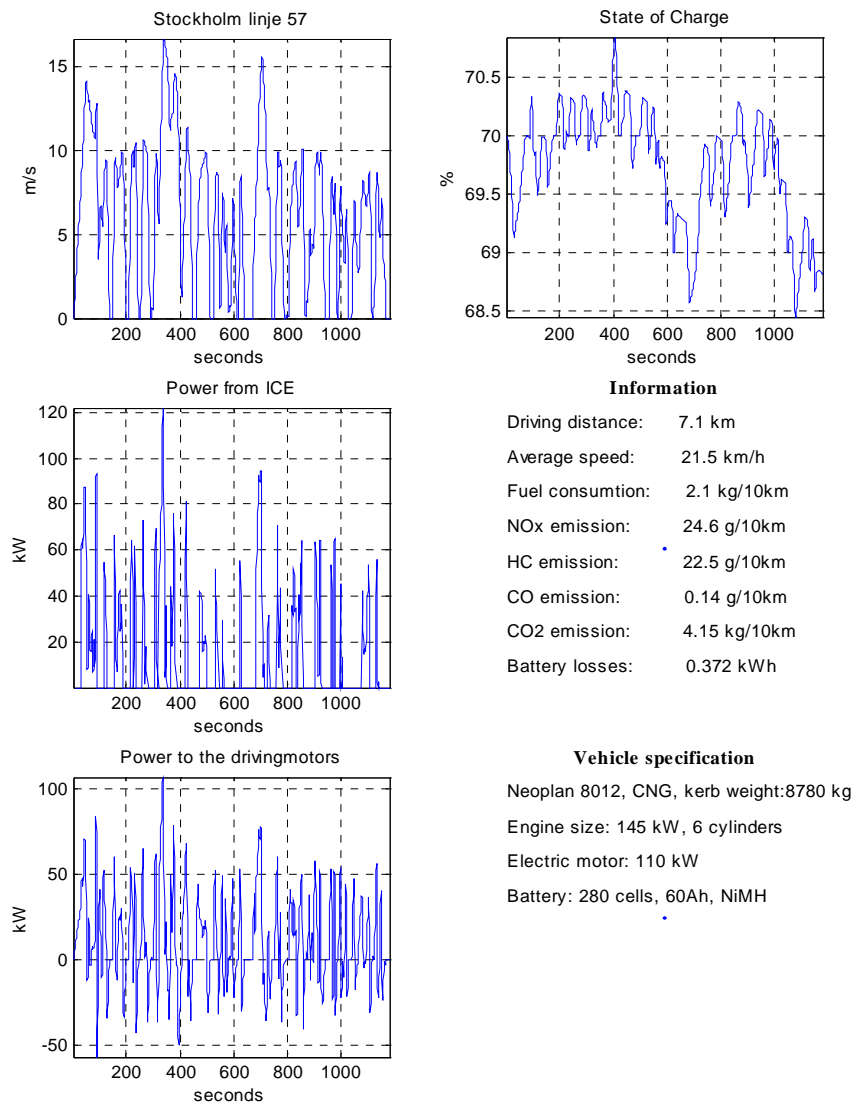


Figure B.1: The result view of the simulation program.