On auxiliary systems in commercial vehicles

Christian Andersson

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Department of Industrial Electrical Engineering and Automation

Department of Industrial Electrical Engineering and Automation
Lund University
Box 118
SE-221 00 LUND
SWEDEN

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Abstract

As more and more focus is put on the environmental questions and the request for cleaner transportation the demand on the vehicles increases. Especially the environmental request of the public transportation that is visible to the public and operates in the centre of the city. The demand on the buses used for public transportation will increase. The whole bus must be optimised, usually only the propulsion system is on focus. The optimisation does concern the vehicle and driveline not only the diesel engine that usually are used in those buses. As the driveline get more and more efficient, for instance by hybridisation and the passenger demand for comfort increases the auxiliary systems part of the energy use of the driveline increases. That will make the auxiliary system energy use more important.

This study is focused on energy consumption by the auxiliary systems. In this study, detailed vehicle simulation in ADVIS0R, ADvanced VehIcle SimulatOR using MATLAB™/SIMULINK™ is used to investigate how to reduce the auxiliary sub system systems energy consumption. The simulation model that is used is verified by measurements on a Scania hybrid fuel cell concept bus.

The methods used for reducing energy and fuel consumption are better control of the auxiliary system loading vehicle driveline and selection of more energy efficient components for the auxiliary systems. The control of the auxiliary systems involves: recover some of the kinetic energy when braking and switching off, if possible, the auxiliary system load in peak load mode.

Acknowledgements

First, I would like to thank my colleague in this project, Anders Folkesson the Department of Chemical Engineering and Technology, Royal Institute of Technology, KTH, Stockholm. I have worked, studied and traveled with Anders the last three years during this project. It is great to have someone in the same situation to bandy ideas and thoughts.

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I am very grateful to my college Karin Jonasson. We have shared office for some years. She always has to take my spontaneous outbursts.

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I would especially like to thank my supervisor, Professor Mats Alaküla. Professor Alaküla, who has been my main supervisor, has shown much enthusiasm, even if his schedule is tight.

I do not know how to thank my family enough. My parents, Manne and Rose-Marie have helped me with all kinds of practical issues and especially when I was fighting an uphill battle.

Christian Andersson

Contents

Chapter 1

Introduction

Buses and other large vehicles consume large amounts of energy, thus limiting their range and causing pollution. This is true whether the vehicle is conventional, hybrid or pure electric. In Stockholm, the bus fleet operator SL (Stockholms Lokaltrafik) annually covers 100×10^6 km, consuming 60×10^6 litres diesel and 13×10^6 litres ethanol. Reducing fuel consumption, even by just a few percent, would result in significant savings.

There has been a great deal of research into reducing the energy consumption of internal combustion engines (ICE). In the research studies the energy consumption of the auxiliary systems in the vehicles is seldom addressed. According to the author's knowledge the auxiliary system has not been investigated. In city buses the energy used by the auxiliary, such as the air conditioner (AC), cooling fan, compressor, water pump, servomotor and 24 V system, represent a significant load. In a hybrid electric urban bus equipped with AC, the auxiliary systems might well consume as much energy as the propulsion system. While the power of the auxiliary system loads together is less than 10 % of the driving power when accelerating, it can be close to 30 % of the average load power. Some of the systems, i.e. the alternator, the servomotor and water pump, run continuously when the ignition key is on, thus making the total energy consumption of the auxiliary systems considerable. In a conventional vehicle, where the crankshaft drives most auxiliary systems via a belt or a gear pinion, the energy consumption of the auxiliary loads is less visible. In a hybrid electric vehicle the energy must first be converted to electricity and thus the consumption is more visible.

When a standard heavy vehicle brakes, the retarder and the brake system are used to transfer the kinetic energy to heat. The kinetic energy in a hybrid or electric vehicle is re-generated into electric power via the electric driveline. The electric braking energy in a hybrid vehicle is normally stored in a battery.

The energy consumption of the auxiliary systems is heavily dependent on the technology selection, the control strategies and driving pattern.

1.1 Energy systems in buses

Conventional

A simple model of a conventional vehicle is showed in Figure 1. The fuel tank stores the chemical energy, which is the energy source. The fuel tank is connected to the fuel converter. The fuel converter is the source of the mechanical power in a conventional vehicle. The fuel converter module usually contains an internal combustion engine (ICE), and a mechanical transmission. The transmission can however also be electric (generator–motor) and then the ICE-generator can be replaced with a fuel cell system [11]. The wheels are mechanically connected via a gearbox to the fuel converter. The auxiliary systems are also mechanically connected to the fuel converter.

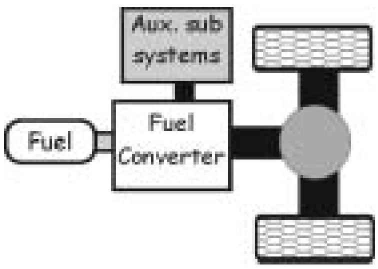

Figure 1: Driveline of a conventional vehicle.

Electric Series Hybrid

The model of a electric hybrid vehicle is showed in Figure 2. The Fuel tank is also the source of energy in a hybrid vehicle. The Fuel thank is connected to the Fuel Converter. The Fuel converter converts the chemical energy to electric energy. This is done by an ICE and a generator, but it can also be performed by a fuel cell. The Electric Motor, Battery, Fuel Converter and the Auxiliary systems are electrically connected to the Power Electronics. The wheels of the hybrid are mechanical connected to the electric motor that converts electric energy to mechanic energy.

The electrical connection to the auxiliary system is the only alternative if the ICE under certain driving conditions is turned off or a fuel cell is used as the fuel converter. If, on the other hand, the ICE in the fuel converter module is running all the time during the operation of the vehicle, the auxiliary systems can be mechanically connected to the ICE. The advantage with the mechanical connection is the simple system design and the low mechanical losses when there are no separate electric motors that run the auxiliary systems. The drawback is that there are fewer control possibilities.

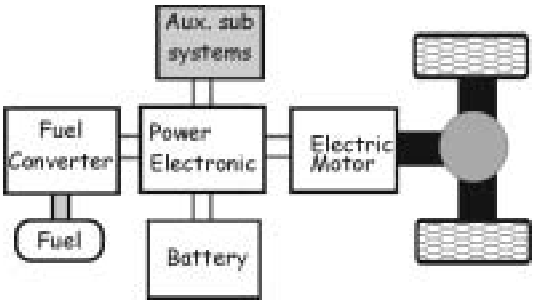

Figure 2: Driveline of a series hybrid vehicle.

The number and diversity of loads that are used either in the basic operation of the vehicle or to increase its comfort and usefulness is steadily increasing. Some of these loads are mechanically driven from the crankshaft of the ICE, and others are electrically driven. In hybrid vehicles it can be beneficial or necessary to drive the auxiliary loads with electric power. The advantages are:

- The auxiliary systems can be more freely placed within the vehicle since they do not have to be mechanically connected to the ICE.
- The energy conversion efficiency can be significantly increased, since the possibilities to control power consumption are more numerous when power electronically controlled is driving the load. The AC compressor, for example, can be driven at the optimal speed all the time. In a conventional vehicle the AC compressor is

connected to the ICE speed, which is related to vehicle speed rather than to climate-relative AC demand.

Other auxiliary systems

Another option is to drive the auxiliary systems by a fuel cell [8]. The fuel cell is called APU, Auxiliary Power Unit. The truck manufacturers are interested in driving the cooling system of the trailer this way. For the 24 V (12 V) system the fuel cell APU will have low energy conversion losses. When the large diesel idles, only some of the auxiliary systems run and the efficiency of the diesel engine is very low. Fuel consumption and emissions are relatively high when the ICE runs at idle for a long time, i.e. overnight, in order to supply power to the driver's compartment or to cool a trailer.

Some APU projects go one step further and include a reformer [50]. The reformer makes hydrogen from either diesel or gasoline, so when the driver visits the filling station, he or she must only fill up with one sort of fuel.

1.2 The approach to auxiliary systems used in this thesis

To evaluate possible savings with altered designs and control strategies, simulation models are used. Many vehicle simulation programs simulate auxiliary systems as a constant parasitic load. This is often an incorrect simplification, since the load is usually heavily dependent on the driving pattern.

In this study, the simulation model MATLAB™/SIMULINK™ is used as a platform for auxiliary system simulation model development in order to study reduced auxiliary system energy consumption. In this simulation model it is easy to modify the installation and simulate the developed system.

A fuel cell bus that Scania built together with several partners in a European project was the platform for the experiments. All the vehicle simulation models are designed in ADVIS0R, ADvanced VehIcle SimulatOR. ADVIS0R is a complete vehicle simulation program and it was shareware until 2003.

The methods used for reducing energy and fuel consumption involve better control of vehicle driveline loading and selection of more energy efficient components for the auxiliary systems. Using a full vehicle simulation program, extended with a proper definition of auxiliary systems, the potential of intelligent 1) New technology selection and 2) Control has been analysed [28].

1. New technology selection: The auxiliary systems often have low efficiency [47]. A pneumatic system with a compressor in one end and, for example, a bus door-opening piston in the other end has very low energy transfer efficiency. The door opening work could be performed by an electric motor instead. Changing door activation from pneumatic to electrical results in considerable energy savings. In a conventional bus there are several other systems that can be changed to more efficient systems.

2. Control of auxiliary system loads can improve total fuel consumption without decreasing the energy consumption of the auxiliary system. If the auxiliary systems are loading the driveline of the vehicle when it is braking, the energy could, for example, be used for the alternator (or DC/DC converter) to charge the 24 V battery or for the AC-system to cool down the compartment. If all the auxiliary system “buffers” are filled up when braking, this would result in an optimal use of braking energy with high efficiency. When the propulsion system needs full power, i.e. during acceleration, the auxiliary system power is reduced, so-called peak shaving. This is included in the Control of the auxiliary system, by turning off the auxiliary system (if possible) when high power is requested to the propulsion system. Such shutdowns are only necessary, for example, during acceleration and only for a limited time. Control of auxiliary system loads will reduce the driveline peak power requirement and improve fuel consumption. Scaling down the energy buffer would be one of the side effects in a hybrid or electric vehicle. In conventional vehicles, where no regeneration is applied, the energy savings would be even larger, as braking energy is not recovered.

1.3 The project

The goal of the hybrid fuel cell bus project was to create and construct a demonstration vehicle. The project was supported by money from European Unions (EU) Non-nuclear energy (JOULE) programme. The EU fuel cell bus project started in 1996 and the project proceed until 2002.

Several partners were involved in the project:

- Air Liquide (France), -Fuel cell module and hydrogen storage system design and construction.
- Scania (Sweden), -Bus construction.
- SAR (Germany), -Power bus controller and DC/DC electrical converter design
- Nuvera Fuel Cells Europe (Italy), -Fuel cell design and construction
- Universita diGenova (Italy), -Air compressor module design
- Commissariat à l'Energie Atomique (France), -Fuel cell tests

The fuel cell bus testing, modelling and evaluation activities were a research project, supported by funds by the Swedish National Research Programme for Green Car Research and Development ("Den Gröna Bilen" or DGB). The aim of this project, named "Scania Hybrid Fuel Cell Bus", is to gather knowledge and experience in using fuel cells and hybrid technology in urban buses. The project involves Scania, Lund University and The Royal Institute of Technology (KTH, Stockholm).

- Test planning and testing of the hybrid fuel cell bus
- Vehicle and auxiliary system analysis and modelling
- Auxiliary system simulation and improvements

1.4 Contribution

The contributions of this work are given in Chapter 2, 4, 5 and concluded in Chapter 6. The main results from the simulations are summarised in Chapter 5.

- A data acquisition system is designed and installed on a bus to evaluate the present auxiliary system on a hybrid bus.
- Through simulation models the present auxiliary systems and alternative more energy efficient auxiliary systems are evaluated both for a hybrid bus and a conventional bus.
- A load control method is developed for the auxiliary system with different conditions for running and stopping the auxiliary systems.

This work will result in reduced energy consumption of the auxiliary systems. As the total energy consumption of the vehicle decreases the fuel economy will improve and the emissions will be reduced.

1.5 Outline of the thesis

In Chapter 2 it is described how the auxiliary systems work in relation to the driveline power with the Control of the auxiliary system. The conditions and selections for switching on and off the auxiliary systems are described.

In Chapter 3 it is described how the major components in the simulation program of the bus work. The losses and measurements of these components in the bus are also presented in this chapter.

In Chapter 4 it is described how the different auxiliary systems of the bus work and how the simulation models are constructed.

In Chapter 5 the results are presented from the simulations, and the cost calculations of the two different buses, hybrid and conventional, are presented.

In Chapter 6 the conclusions of the simulation results are described.

1.6 Publications

The following papers regarding Observations on Electric Hybrid Bus Design was presented in my Licentiate thesis:

C. Andersson, M. Alaküla, "A Matlab/Simulink Simulation Model of a Hybrid Electric Bus", *European Power Electronics and Applications conference, EPE99, Lausanne, Switzerland, Sept. 6-9, 1999.*

C. Andersson, K. Jonasson, P. Strandh, M. Alaküla, "Simulation and verification of a hybrid bus", *Power and Industrial Electronics, IEEE conference, NORPHIE, Aalborg, Denmark, Jun. 13-16, 2000.*

C. Andersson, M. Alaküla, "A Simulation Model comparing two different Hybrid Electric Buses", *Electric Vehicle Symposium (EVS) 17, Montreal, Canada, Oct 16-18, 2000.*

C. Andersson, M. Alaküla, “Different charging strategy Hybrid Electric Buses”, *Electric Vehicle Symposium (EVS) 18, Berlin, Germany, Oct. 21-23, 2001*.

The results presented in this thesis regard the fuel cell bus and auxiliary systems are also presented in the following papers:

A. Folkesson, C. Andersson, P. Alvfors, M. Alaküla, L. Overgard, “Real Life Testing of a Hybrid PEM Fuel Cell Bus” *European fuel cell conference, GROVE, Amsterdam, Netherlands, Sept. 2002.*

C. Andersson, M. Alaküla, L. Overgard, “Test and Improvement of Auxiliary sub systems.” ”, *Electric Vehicle Symposium (EVS) 20, Long Beach,California., Nov. 15-19, 2003.*

A. Folkesson, C. Andersson, P. Alvfors, M. Alaküla, L. Overgard, “Analysis of test results from a hybrid electric fuel cell bus”, *Electric Vehicle Symposium (EVS) 20, Long Beach,Californi., Nov. 15-19, 2003.*

Chapter 2

Load control of auxiliary systems

This chapter describes how the auxiliary system Control works.

The propulsion system power is fundamental for the development of a Control strategy of the auxiliary system. Figure 3 shows the power spectrum for the propulsion system, on four different driving cycles. The speed profiles of the driving cycles are described in Appendix D. The positive power is the power flow from the fuel converter or electric motor to the wheels for example when accelerating. The negative power is the power flow from the wheel to the brakes or the energy storage (battery) when the bus is slowing down. The most common power in the cycles is zero power, the bus is parked or free rolling. Information about the duty cycles can be found in Appendix D. The graphs indicate that more power is needed to follow the Braunschweig and FTP75 cycles than the ECE15 and the IDIADA cycles. There are also more negative power (regenerated power) in the Braunschweig and the FTP75 cycles due to the heavy brakes in the duty cycles. The regenerated power can be used for regenerative applications as driving the auxiliary systems. In a conventional bus the negative power of the spectrums in Figure 3 is equal to brake power. In a hybrid bus the negative power, with in limits of the energy storage and the electric motors, is stored as energy in the energy storage (driveline battery).

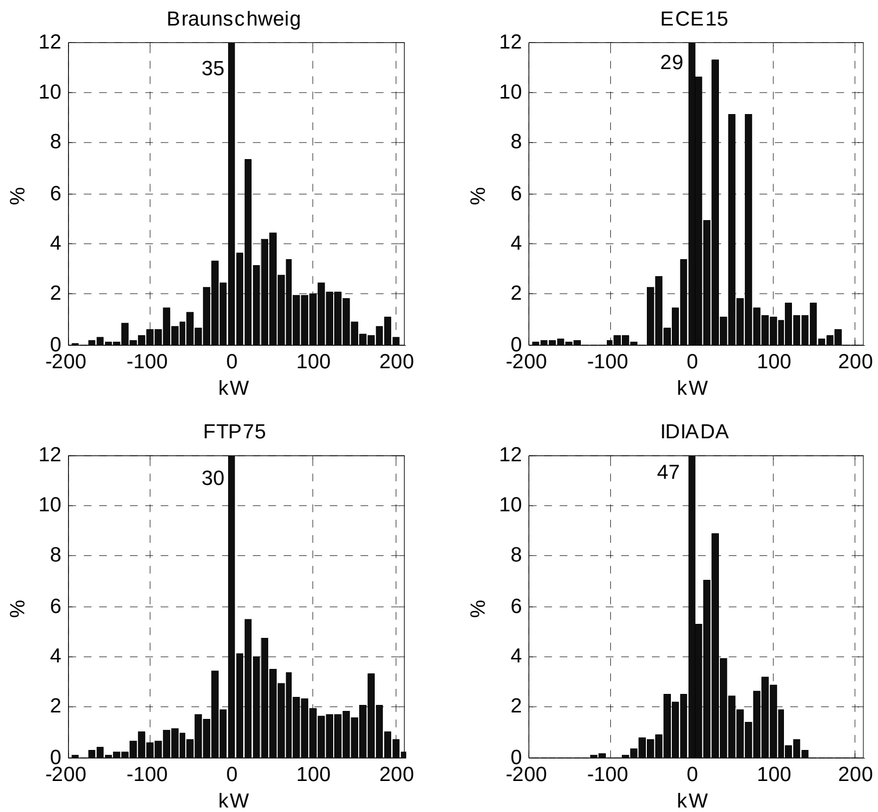

Figure 3: Simulated power spectrum of the propulsion system for the different duty cycles.

2.1 Control principles for auxiliary systems

Some of the auxiliary systems need to be on "always", systems like the servo steering, fuel pump and engine cooling system. There is no room for controlling these systems by switching the systems on and off.

Some auxiliary systems can be run more or less intermittently, systems like the air compressor, AC compressor and alternator for the 24 V system. Such loads can be controlled with e.g. an "on/off"-control, within limits, without compromising passenger comfort. In most buses these usually represent the larger part of the auxiliary system energy. The reasons for controlling the power supplied to, or used by, the auxiliary system are:

- Minimised fuel consumption
- Minimised emissions
- Limitation of the peak power used by the drive train

Possible methods to accomplish these improvements are:

- Recover some of the kinetic energy when braking
- Turn off, if possible, the auxiliary system load in peak load mode
- Optimise operation of the auxiliary systems with respect to the instantaneous efficiency of the fuel converter (ICE).

In a conventional vehicle without the Control methods some auxiliary systems are used when braking, but these systems are not running at full power.

Energy storages

In a series hybrid electric bus, an electric energy storage is necessary in the tractive power path e.g. a driveline battery or the super capacitor. The size of the energy storage varies with the driveline storage technology. A reasonable energy storage size of a battery for a series hybrid bus will be about 45 MJ (maximum power 150 kW, 260 kg NiMh) [39]. The energy of the super capacitor is typically 1.4 MJ (maximum power 150 kW, 100 kg) [34].

The conventional bus and the hybrid bus have additional energy storage possibilities, via the thermal capacity of the air in the passenger compartment, the compressed air in the pneumatic supply tanks and the 24 V battery. A temperature difference of 10 ºC in the passenger compartment of a bus corresponds to an energy difference of 0.7 MJ (volume 70 m^3). The volume of the pneumatic tank in a standard bus is approximately 120 l air by the pressure of 10 Bar. The energy used by the compressor to fill up the tanks from 0 to 10 Bar is 0.8 MJ. The 24 V battery stores 19 MJ. It is not possible to use all the energy in these buffers, but it is realistic to vary the stored energy by 10–20 % of the total energy in these systems.

Selected load Control methods

In this context, the following load control methods are suggested and used, in the following context it is just named Control.

1. Peak shaving, by switching off the auxiliary systems power consumption, will increase the propulsion power when the total power (propulsion + auxiliary system) is limited. The peak shaving increases the peak performance of the vehicle, is has no or very small effect on the fuel consumption of the vehicle, since the control system subsequently compensates for the off switching. The peak shaving for the auxiliary systems switches off the compressor, 24 V alternator and the AC system when the propulsion power and the auxiliary systems reach the peak power of the fuel converter (ICE), see equation (2.1). The driveline power is then limited by the fuel converter power.

$$\begin{aligned} &P_{ICE} = P_{\text{Propulsion}} + P_{aux} \\ &if\ P_{\text{Probulsion}} + P_{aux} > P_{ICE,MAX}\, , P_{aux} = 0 \end{aligned} \tag{2.1}$$

   In this example, a conventional bus equipped with an ICE (200 kW peak power), the auxiliary systems (max ≈40 kW) are switched off when more than 160 kW of peak power of the ICE (200 kW) is used and switches these system on again at less than 120 kW are used, see Figure 4. The difference between controlled and non-controlled power to the auxiliary system is shown in Figure 5 by the two circles on the left. When the propulsion system power reaches 160 kW, the AC, the controller switches off compressor and 24 V alternator. The controller then switches on the auxiliary systems when the propulsion system power goes under 120 kW. The on switching limit is lower than the off switching limit to avoid oscillation, see equation (2.2). The oscillations will occur for example when the bus performs gearshifts and the working points changes.

$$P_{aux} = P_{aux,cont.} \cdot \frac{(1 - sign(\frac{P_{\text{Probulsion}}}{P_{ICE,MAX}} - \begin{bmatrix} P_{\text{aux off limit}}\ decr. \\ P_{\text{aux on limit}}\ incr. \end{bmatrix}))}{2} \tag{2.2}$$

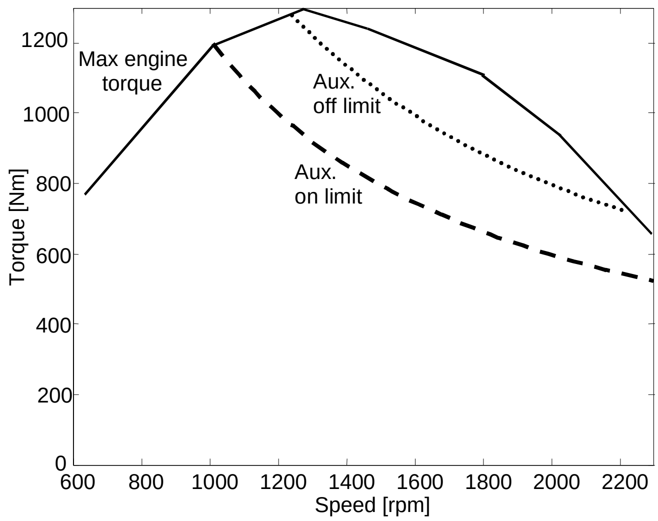

Figure 4: The maximum torque as faction of speed and the auxiliary on/off limits of the engine.

The effect of peak shaving on the hybrid vehicle is very dependent of the hybrid set up. On a hybrid vehicle the peak shaving will limit the maximum power from the fuel converter and the energy storage or increase the performance of the vehicle.

2. Regenerative brake power usage. When the propulsion system power is negative, the bus is braking, see Figure 3. According to the Control strategy of the auxiliary systems, the systems should consume as much as possible of the negative power. The power of the generator or the DC/DC converter to the 24 V system can freely be selected between zero and a maximum and the energy can be stored in the 24 V battery. The compressor and AC systems can only be switched on and off. When there is negative power enough to cover the compressor and AC system power consumption they are switched on. The compressor will fill the air tanks and the AC will cool down the compartment. The generator or DC/DC consumes the remaining negative power up to peak power of the generator or DC/DC. When the propulsion system power in Figure 5 in the two right side circles goes negative and the bus starts to brake, the control of the auxiliary systems starts. When the propulsion system power is less than -20 kW (AC + compressor power) the 24 V alternator consumes 20 kW. When the negative power of the

propulsion system is less than -20 kW the AC system and the pneumatic system compressor are switched on. The AC system and the pneumatic system compressor consume totally 20 kW.

$$P_{AC+Pneum} = P_{AC+Pneum,\,MAX} \cdot \frac{(1 - sign(P_{Driveline} + P_{AC+Pneum}))}{2} \tag{2.3}$$

$$P_{24V\ gen} = P_{Driveline} \cdot \frac{(1 - sign(P_{Driveline}))}{2} - P_{AC+Pneum},\ P_{24V\ gen} \leq P_{24V\ gen\ MAX} \tag{2.4}$$

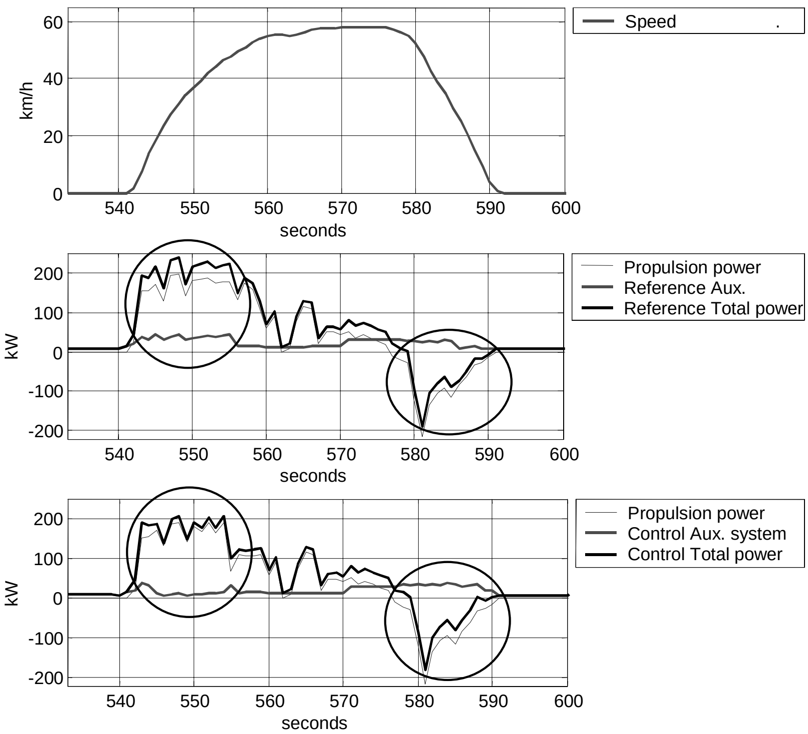

Figure 5: Speed and power of the propulsion system and the auxiliary systems with AC on at 50 %.

2.2 IMPLEMENTATION ASPECTS

A complex and expensive implementation of the auxiliary system Control is no alternative. The implementation should be kept as simple as possible; with few sensors connected to the all ready existing CAN (Controller Area

Network) system in the vehicle. The CAN bus information need to be expanded by more detailed information about the auxiliary systems e.g. temperature in the passenger cabin, pressure in the pneumatic tanks and 24 V battery current and voltage. The vehicle computer should do most of the control of the auxiliary system; the performance of the vehicle computer in some cases needs to be up graded. Additional sensors to perform the Control of the system are the 24 V battery current and voltage sensors, to control the SOC (State Of Charge) of the battery.

The Control for switching off auxiliary systems units (peak shaving) should be controlled by the fuel converter (usually the ICE) “Reference” power. The simplest way is to use the accelerator pedal position. When it is pushed more than a limit of the range the peak shaving will start to shut off the possible auxiliary systems if the engine speed increases over a certain limit. The engine has smaller power potentials at low speeds. The accelerator pedal position sensor is usually already installed and the information available in the CAN system.

The Control for switching on auxiliary systems to full load, when the propulsion system power is negative and the bus is braking could be using the brake pedal information. When the brake pedal is pushed the Control system switches on the auxiliary systems, if they are not already fully on.

If any thing goes wrong in the Control of the auxiliary systems the Control should just be switched off and the auxiliary system should work in normal way.

Chapter 3

Vehicle model design

This chapter describes how the major components in the simulation model of the bus are designed. The losses and measurements of these components in the bus are also presented in this chapter.

All the simulation models are designed in ADVIS0R, ADvanced VehIcle SimulatOR [1]. It is a set of model, data, and script text files for use with MATLAB^{TM} and SIMULINK^{TM}. It is designed for rapid analysis of the performance and fuel economy of conventional, electric, and hybrid vehicles. The user interface is described in Appendix B.

The verification data for the models comes mainly if not specifically noted, from the test vehicle, which is a hybrid fuel cell buss. The test bus is described in Appendix C, data acquisition system in Appendix A and some test results are shown in Chapter 3.3.

3.1 Vehicle specification

Three different buses were used for the test and simulations. The buses are:

- A hybrid electric fuel cell bus, 9 m, 12 500 kg, for testing.
- The conventional Scania Omnicity bus, 12 m, 15 300 kg, for simulation.
- A hybrid electric ICE bus, 12 m, 15 900 kg, for simulation.

The simulations of the conventional and hybrid buses should be as comparable as possible. The size, weight, number of passengers and fuel should be the same. The Scania Omnicity (conventional) bus is a larger bus than the hybrid fuel cell bus that was tested. The size of the hybrid bus in the simulations is adjusted to be comparable to the conventional bus. The hybrid electric fuel cell bus is described in Appendix C.

The Conventional bus

The Scania Omnicity bus is a typical conventional city bus. It has a conventional driveline, two axles and a mechanically driven auxiliary system. The Scania OmniCity bus is a modern commercial bus that is available on the market. The bus is completely built by Scania. The bus is larger than the hybrid fuel cell bus and can take more passengers. The length is 12 m, width 2.5 m, height 3 m and the service weight is 15 300 kg. All the simulation parameters for the OmniCity bus come from Scania.

The Hybrid electric ICE bus

The simulated hybrid bus is defined to be as close as possible in comparison with the conventional bus. It has the same chassis and the same ICE as the conventional bus. The only exception is the driveline that composes a series hybrid setup with generator, battery and electric motors. The hybrid bus has the same auxiliary systems setup as the tested hybrid fuel cell bus.

3.2 Simulation environment

The simulation tool used is ADVISOR running in the MATLAB^{TM} SIMULINK^{TM} environment. The ADVISOR models take the required/desired speed as an input, and calculate which drive train torque, speed, and power that are required to meet the required vehicle speed. Because of this flow of information back through the drive train, from tire to shaft to gearbox and so on, ADVISOR is a so-called backward-facing vehicle simulation program. The top level of the ADVIS0R model of a conventional vehicle is showed in Figure 6 and an electric series hybrid vehicle is showed in Figure 7. The hybrid set up has more components, which will make it more complex to simulate.

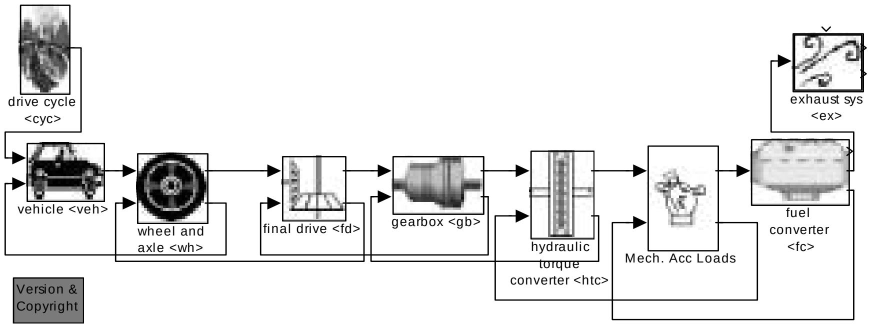

Figure 6: A model of a conventional vehicle in ADVIS0R.

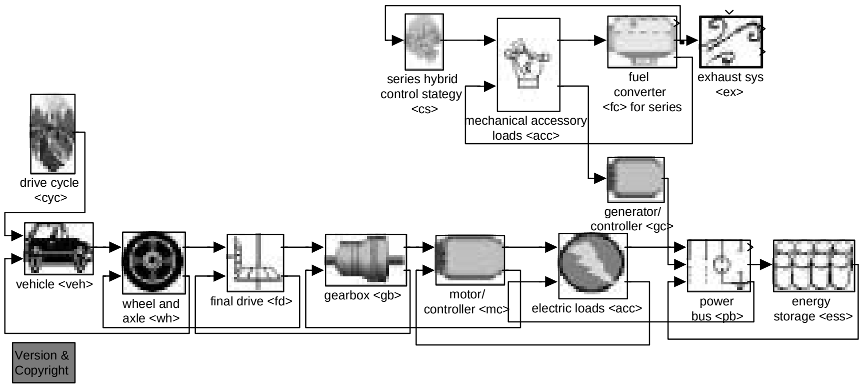

Figure 7: A model of a series hybrid vehicle in ADVIS0R.

Descriptions of the ADVISOR block diagrams are available by opening the block diagram of interest and double-clicking on the green ‘NOTES’ block in the bottom right or left corner. Note that most blocks have two inputs and two outputs. It is possible to open the blocks like all SIMULINK™ block diagrams, so the models can be described in a hierarchical way. It is also possible to make changes in the block definition. Each block sends and transforms a torque and speed request, and each block also sends an achievable or actual torque and speed. The arrows are feeding left-to-right. The drive cycle requests or requires a given speed. Each block between the driving cycle and the torque provider, in these cases the ICE or energy storage, then computes its required input, given its required output, by applying losses, speed reductions and performance limits.

At the end of the line (right side), the energy source, ICE and battery in these examples, uses its required torque output and speed to determine how much torque it can actually deliver and its maximum speed. The information is passed back to the left; each component determines its actual output given its actual input, using losses computed during the ‘input requirement’ phase described above. The vehicle block computes the vehicle's actual speed given the tractive force and speed limit it receives, and uses this speed to compute the acceleration for the next time step.

Driving cycle

The driving cycle block contains the reference speed as function of the time during the duty cycle. This block also determines the roadway grade of the cycle and the elevation as a function of the distance travelled. The roadway grade information of the driving cycle is optional. If the information is missing the grade is set to zero. Output from this block is speed [m/s] and elevation.

Vehicle and wheel axles

These blocks contain parameters for the bus chassis, tires and shafts. To get knowledge of these parameters a rollout test has been performed with the hybrid electric fuel cell bus. The vehicle block uses the required vehicle speed with vehicle parameters and the previous speed to determine the tractive force required at the tire/road. The wheel axles block determines the required axle torque and speed given the tractive force and speed required to meet the driving cycle, and determines the available tractive force and possible vehicle speed.

The main idea with a rollout test is to map the dynamics of the vehicle and the wheel axles. The conditions require minimal wind and no road gradient. By analysing the rollout data, it is possible to split-up the dynamics of the vehicle wheel axles into the elements of aerodynamic drag and rolling resistance. The contribution of speed (v) to the power losses (P) can be expressed as [48] [6]:

$$P(v) = C_r \cdot m \cdot g \cdot v + 0.5 \cdot C_x \cdot A \cdot \rho \cdot v^3 \qquad (3.1)$$

In the wheel and axles model the friction C_r and in the vehicle model the aerodynamic parameter C_x (C_d) are central. C_d is empirically determined by measuring the air drag in wind tunnels tests. The wind speed is important for the air drag. In real life testing the wind direction and wind speed are quite difficult to determine. As the direction and magnitude of the wind is fluctuating, most measurements of C_d and simulations of the vehicle loads neglect the contribution from the wind. If there is a side wind the incoming airflow experiences the vehicle as being broader, resulting in an increase in the product of the apparent frontal area and the drag coefficient. Also the turbulence around the bus can be increased as a result of side wind. These effects lead to an increase in the air drag in the presence of side wind, e.g. an 15-40 % increase in air drag for an attack angle of 15 degrees for a long bus [48].

The power P is equal to the constant drive power (P_{drive}), when rolling, change in kinetic energy ($P_{kinetic}$) and power losses in the transmission (P_{losses}).

$$\left.\begin{array}{l} P_{drive} = 0 \\ P_{kinetic} = v \cdot \left(m + m_j\right) \cdot a \\ P_{losses} \end{array}\right\} \; P = P_{drive} + P_{kinetic} + P_{losses} \tag{3.2}$$

Where m is the moving mass of the vehicle, m_j the equivalent mass of rotating inertia, v the speed and a the acceleration.

During a rollout test, the energy stored in the wheels and in the electric motors, “act like propulsion” and make the vehicle roll longer, due to the moment of inertia in these parts. The kinetic energy is dependent on the rotating speed in the different parts. The mass that is the source of kinetic energy is divided in two parts, moving mass (m=bus mass) and rotating parts mass (m_j). Each rotating part has its moment of inertia J_i, gear ratio U_s and equivalent radius r_r:

$$m_j = \frac{\sum (J_i \cdot U_s^2)}{r_r^2} \tag{3.3}$$

The kinetic energy (Q) is calculated using the mass (m, m_j) and the speed of the bus:

$$\left.\begin{aligned} Q &= \frac{m \cdot v^2}{2} \\ Q_j &= \frac{m_j \cdot v^2}{2} \end{aligned}\right\} \quad (3.4)$$

A calculation of how the kinetic energy is stored in the bus, as an example at v=80 km/h, can be found in Table 3-1. It is based on input data from Michelin regarding the moment of inertia of the tires and rims and the dynamic rolling diameter of the tires, and based on data from ZF [49] regarding moment of inertia of the motors and the transmission ratio.

Table 3-1 Kinetic energy; at 80 km/h (22.2 m/s).

Part	U_s [ ]	r_r [m]	J [kg m^2]	m_j, m [kg]	Share [%]	Q, Q_j [kJ]
Wheels	1:1	0.514	2x42.3	137	0.9	34
Electric motors	1:25.5	0.514	0.92	2260	15	558
Moving bus				12500	84	3080

Table 3-1 show that the wheels and the electric motors contribute with approximately 16 % of the total moving energy and 84 % comes from the kinetic energy of the bus mass.

Figure 8 describes the power losses in the planetary gear. The planetary gear loss data comes from ZF [49], the gearbox manufacturer. The figure also shows the power in the deceleration of the rotating parts in the wheel drive in the rollout test.

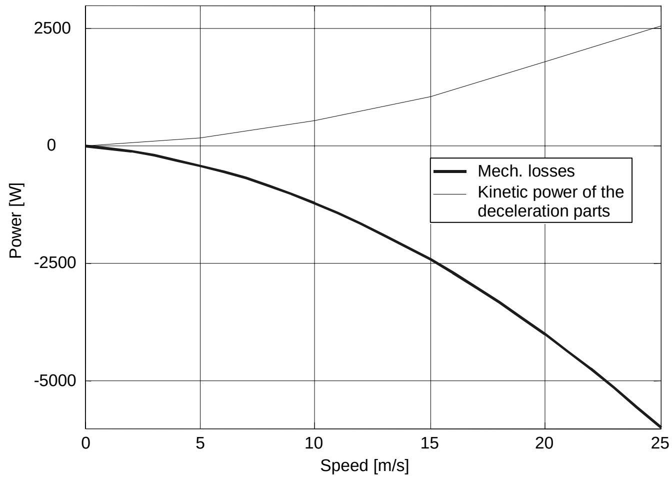

Figure 8: The mechanical losses of the planetary gearbox and the additional power produced by the decreasing rotation speed of the inertia of the rotating parts (wheel, planetary gearbox and electric motors).

In the third and fourth subplots of Figure 9, the thick lines are calculated using non-linear regression and correspond to the measured speed and power, while the theoretic thin lines are calculated using equation (3.1)

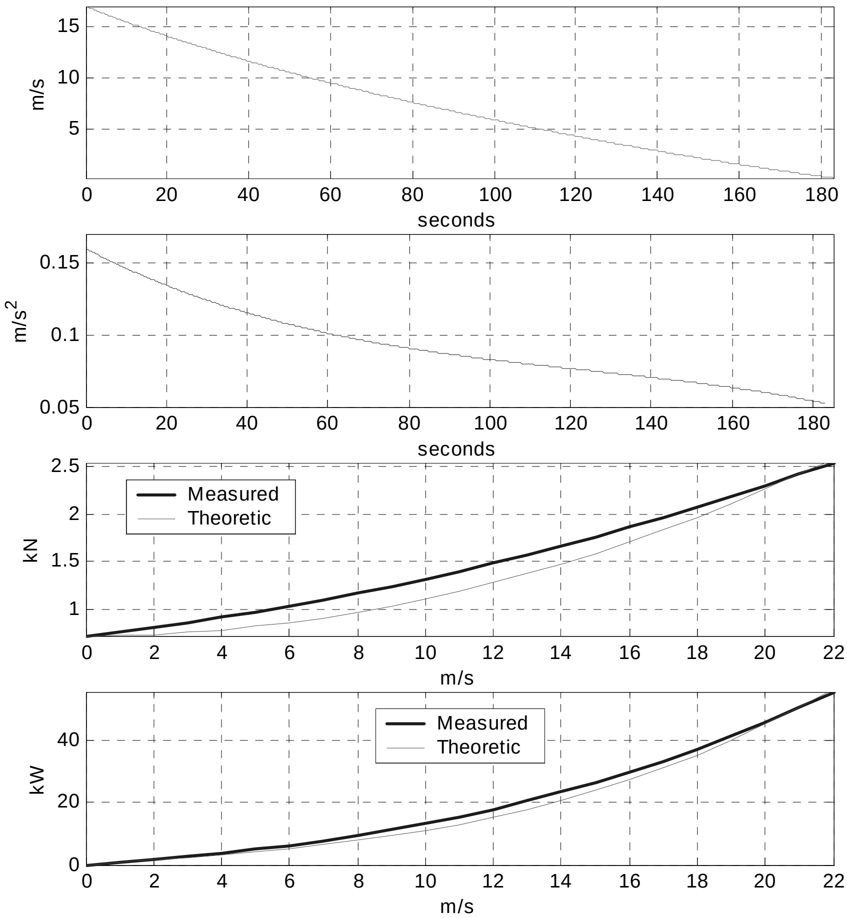

Figure 9: Rollout test, the first subplot shows the speed as a function of the time, the second subplot the de-acceleration as a function of time, the third subplot is the force as a function of speed and the fourth subplot power as a function of speed.

Non-linear regression of the measured speed and power in last subplot of Figure 9 gives the theoretic line (thin):

$$P(v) = C_r \cdot m \cdot g \cdot v + 0.5 \cdot C_x \cdot A \cdot \rho \cdot v^3 \Rightarrow \begin{cases} C_r = 0.0052 \\ C_x = 1.00 \\ C_d = 1.00/1.15 = 0.87 \end{cases} \quad (3.5)$$

Note that in equation (3.5) [48] [6], the dependence on the speed in square (v^2) is missing and the modelling error cause by leaving out the square term maybe too large. If this term is introduced, a more detailed equation is presented, equation (3.6) [1][43]. The quadratic dependence comes from the tires rolling resistance. Rolling resistance changes with speed:

$$P(v) = C_{r1} \cdot m \cdot g \cdot v + C_{r2} \cdot m \cdot g \cdot v^2 + 0.5 \cdot C_x \cdot A \cdot \rho \cdot v^3 \qquad (3.6)$$

The coefficients describing the rolling resistance and the aerodynamic drag of the test vehicle were:

$$\begin{cases} C_{r1} = 0.0067 \\ C_{r2} = 0.00007 \\ C_X = 0.855 \\ \mathrm{C_d} = 0.855/1.15 = 0.74 \end{cases} \qquad (3.7)$$

With equation (3.6) and the constants of (3.7) the plotted rolling resistance is covered by the thick line of subplot 4 in Figure 9.

The simulated buses, conventional (Omnicity) bus and the hybrid electric ICE bus, have different mass (*m*), front area (*A*), aerodynamic drag (C_d), and rolling friction (C_r), see Table 3-2. These values are manufacturer specifications.

Table 3-2 Vehicle and wheel and axles specification.

	m [kg]	*A* [m^2]	C_d	$\mathrm{C_{r1}}$ x10^{-3}	C_{r2} x10^{-5}
Convetional bus, simulated	15300	7.1	0.65	6.14	0
Hybrid electric ICE bus, simulated	15900	7.1	0.65	6.14	0
Hybrid electric fuel cell bus, tested	12500	6.4	0.74	6.795	7

Final drive, Gear box and Hydraulic torque converter

The final drive model includes loss data, rotational inertia, and a gear reduction. The conventional bus has a 5-speed automatic gearbox and the hybrid buses have a 1-speed gearbox. The gearbox model includes loss data, rotational inertia, and a gear reduction. The data in the simulation model comes from the gearbox manufacturer Voith [46]. A hydraulic torque converter makes the gear shifting possible.

Motor/controller - Traction motors

The hybrid test bus is supplied with two-wheel hub drives from ZF [49]. It is high-speed induction motors with disk brakes and a planetary gear, see Figure 10. The water-cooled induction motors having a maximum speed of 11 000 rpm. The driveline inverter is also water cooled and fully controlled by the driveline controller. The driveline controller is handling the inputs from the accelerator and brake pedals converting and applying these inputs to the controlled movement of the bus. Both acceleration and deceleration are performed in a transition less way.

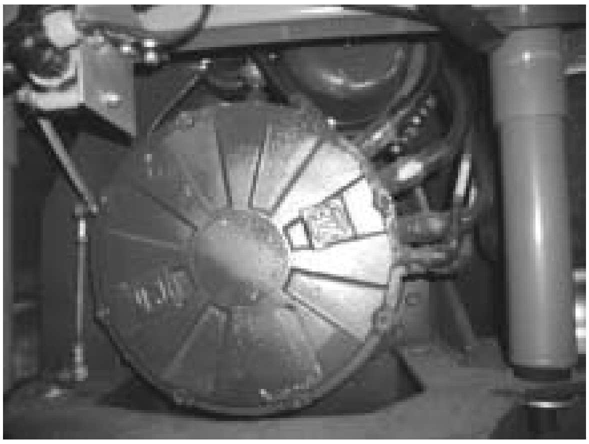

Figure 10: An water-cooled induction machine.

Full acceleration and hill climbing test were performed to evaluate the field weakening and the efficiency of the electric drive motors [2].

As illustrated in Figure 11, the power increases approximately proportional to the speed up to 270 rad/s. The power then remains constant to the maximum motor speed of 1150 rad/s (11000 rpm), indicating a field-weakening region. The effect of field weakening is that the torque decreases as the speed increases while the electric power is kept constant.

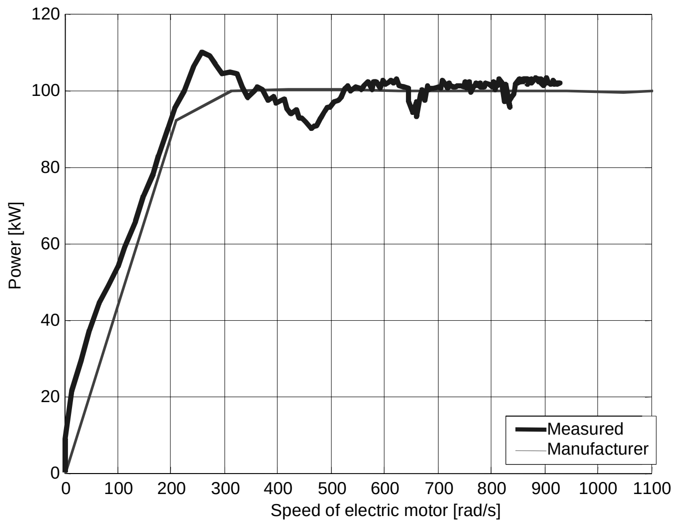

Figure 11: Power and speed of the electric traction motors. The thick line describes the measured power of the bus and the thin line is the manufactory specification. The field-weakening region starts at about 270 rad/s.

The maximum motor speed is 1150 rad/s, corresponding to a vehicle speed of 76 km/h.

One method to measure the efficiency of the electric motors is to measure the electric energy input to the motors and the work performed by the motors. When hill climbing the potential energy of the bus is increased and the motors consume energy. The efficiency of the motors can be defined as the potential energy increase divided with the electric energy consumed by the motors with compensation for the friction losses.

The hill climbing tests were performed in test hills with grades of 12 and 18 %. The altitude difference between the lower area and the higher area is approximately 17 m. Figure 12, a 12 % grade ability test is displayed. The first subplot displays speed as a function of time, the second subplot shows power to the electric motors as a function time and the third subplot respectively drag force from the electric motors (thick line), gradient drag force (line marked with “xxx”) and acceleration (thin line).

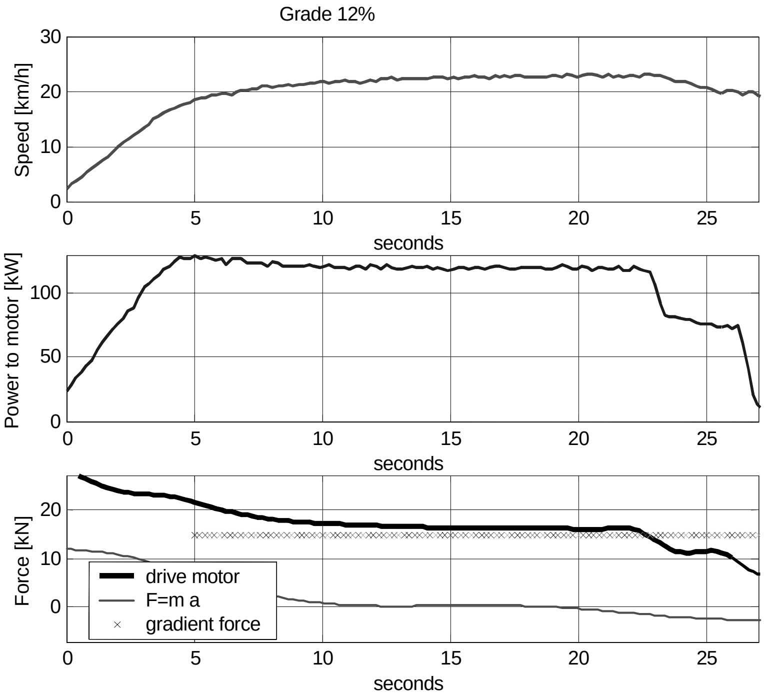

Figure 12: Hill climbing in a 12% ability test. The first two sub plots are measurements and the third are calculated results

The efficiency of the propulsion system is calculated as:

$$\eta = \frac{m \cdot g \cdot h + \int P_{\text{friction}} + \frac{m \cdot (v_1^2 - v_0^2)}{2}}{\int P_{\text{Driveline}}} \tag{3.8}$$

In the nominator the terms indicate the increase in potential energy, the friction losses and the change in kinetic energy. The denominator denotes the total energy delivered to the propulsion system. The losses are calculated, empirically from the power needed for driving the bus at 20 km/h on a flat road, see Table 3-3.

Table 3-3: Hill climbing test results.

Test	Grade	Weight [kg]	Height [m]	$m \cdot g \cdot h$ [kWh]	v_0 [km/h]	v_1 [km/h]	Energy [kWh]	Efficiency [%]
1	12%	12506	16.8	0.573	2.4	18.6	0.798	85
2	18%	12506	17.2	0.469	2.8	0	0.598	85
3	18%	10646	17.2	0.497	3.3	10.1	0.691	81

The efficiency in Table 3-3 is from the 500 V DC electric powers to mechanical power that will include both DC/AC inverter and electric motor. The efficiency of the DC/AC inverter is assumed to be about 95 %, which gives the electric motor efficiency 90 %. Note that this is the average efficiency of the motor in a certain operating condition regarding speed and torque, specifically when doing the hill climbing tests. The value of the efficiency is however the value is normal for an electric drive of this size [2].

In the simulated hybrid electric ICE bus, a lager motor from Voith [46] for the propulsion system is selected for the simulated hybrid ICE bus. One of the reasons is the increase of the weight, from 12 500 kg to 15 900 kg. The motor has different characteristics from the induction machine that was used in the hybrid fuel cell test bus. The peak power, speed, torque and efficiency are: 150 kW, 2400 rpm, 2800 Nm, and 95 %, respectively. Manufacturer specification of the efficiency map is used in the simulation model.

Energy storage - battery

The function of the driveline battery is:

- To supply power to the propulsion and sub systems, partly together with the fuel cell system
- To store regenerated energy during braking
- To store energy from the fuel cell during low consumption phases

The Exide Maxxima 900 battery used in the tested hybrid bus, is a Valve Regulated, Lead Acid (VRLA), gas recombinant 12 V battery, with energy density of 35 Wh/kg and power density of 380 W/kg [14]. The battery has a low internal resistance.

44 battery modules are arranged in series leading to a nominal voltage of 528 V, see Figure 13. The battery pack frame is designed for optimal balance between strength and the cooling requirements. A cooling module with radial blower is integrated together with temperature sensors, current sensors, voltage sensors, fuses and a security switch. Battery management, which includes thermal management, SOC calculation and diagnostics, is handled by the microprocessor-based supervisor, which receives all data from the battery via a CAN (Controller Area Network) data bus.

Figure 13: Driveline battery box with 44 units of 12 V batteries.

During the battery tests the energy consumption was measured during a whole test drive, from the workshop and back again. After each test the energy amount charged into the battery was measured (charged). The difference between total charged energy (charged + regenerated) and the energy from battery (discharged), corresponds to the energy loss in the batteries:

$$E_{\text{loss battery}} = E_{\text{charged}} + E_{\text{regenerated}} - E_{\text{discharged}} \tag{3.9}$$

The energy efficiency of the batteries is calculated as energy from battery (discharged) divided with total charged energy (charged + regenerated):

$$\eta_{\text{battery}} = \frac{E_{\text{discharged}}}{E_{\text{charged}} + E_{\text{regenerated}}} \tag{3.10}$$

The results are summarised in Table 3-4. The average battery efficiency is approximately 85 %. There are no significant differences in the energy efficiency of the batteries between test cycles with regenerative braking on and off, respectively.

Table 3-4: Battery test results.

Test cycle name	Reg. brake on/off	Energy to battery, [kWh]	Energy from battery,[kWh]	Charged after, [kWh]	Battery (energy) efficiency, η_{battery} [%]	Average battery temperature, [°C]
battnore0609	off	0,00	11,93	14,85	80,3	27
battre0609	on	2,23	12,27	12,13	85,5	27
braunschwA10	on	2,88	14,19	13,30	87,7	32
malmoB0614	on	2,27	13,12	12,37	89,6	37
ftp72Ano0629	off	0,00	12,04	14,47	83,2	25
ftp72Ano0628	off	0,00	11,93	13,94	85,6	34
ftp72B0629	on	2,07	11,00	10,84	85,2	25
ftp72Bno0629	off	0,00	10,93	13,00	84,1	24
Average					85,2	

Note that this is the cycle efficiency, i.e. the efficiency in storing and later reusing the energy. The efficiency of just storing energy can be estimated to:

$$\eta_{\text{storage}} = \sqrt{85} \approx 92\,\% \tag{3.11}$$

The driveline battery model in ADVIS0R for the simulated buses comes from the manufacturer. The average efficiency of the simulated battery is 83 % in the Braunschweig driving cycle. This value is within our battery test results.

The efficiency is also used as a constant in the simple battery model of the 24 V system in the ADVIS0R auxiliary simulation model. The battery model has two constants for one for charging power and the other for discharging power.

The battery efficiency in the measurements is correlated to the temperature of the batteries. A higher temperature, gives a higher battery efficiency. This phenomenon has to be further examined before secured conclusions can be drawn, but is in line with other experiences of traction batteries. A problem is that excessively high temperature also reduces battery lifetime. Further investigations with regards to the balance between battery temperature, performance and lifetime are necessary to set-up the optimal thermal management of a VRLA battery.

Generator/controller

The driveline generator model includes loss data, rotational inertia, and performance limits. The model computes the output electric power from the input mechanical torque and speed from the ICE. The generator map used in the look-up table block is similar to the traction motor map. The generator used is a permanently magnetised synchronous machine with peak power of 180 kW [4]. The peak torque, speed and efficiency are 1200 Nm, 2400 rpm and 95 % respectively. The efficiency map used for the generator the simulations for the hybrid electric ICE is bus obtained from the manufacturer, Voith [46].

Fuel converter and exhaust system - ICE

This block models the ICE, which includes inertia effects, performance limits, auxiliary loads, and temperature transient effects on fuel use, engine emissions, and catalyst efficiency.

To be able to compare the simulations of the hybrid and conventional set up, the same engine has been used in both simulations set-ups. The conventional bus (OmniCity) and the hybrid electric ICE bus are equipped as standard buses with Scania’s 9-litre Euro 3-engine. The engine is mounted transversely in the back of the buses.

The engine is a 4-stroke, liquid cooled, direct fuel injected turbo charge diesel engine. More engine specifications can be found in Table 3-5.

Table 3-5 Specification of the Scania engine.

Cylinder capacity	9.0	l
Number of cylinders	6	
Valves per cylinder	2	
Cylinder bore	115	mm
Stroke	144	mm
Max. output power	191	kW
Max. torque	1250	Nm
Min. fuel consumption	200	g/kWh
Weight, approximately	875	kg

3.3 Test result with the hybrid bus in driving cycles

The Braunschweig driving cycle is a typical bus duty cycle, with fast accelerations and hard braking. The actual speed and the reference speed of the bus during the Braunschweig cycle are shown in Figure 14.

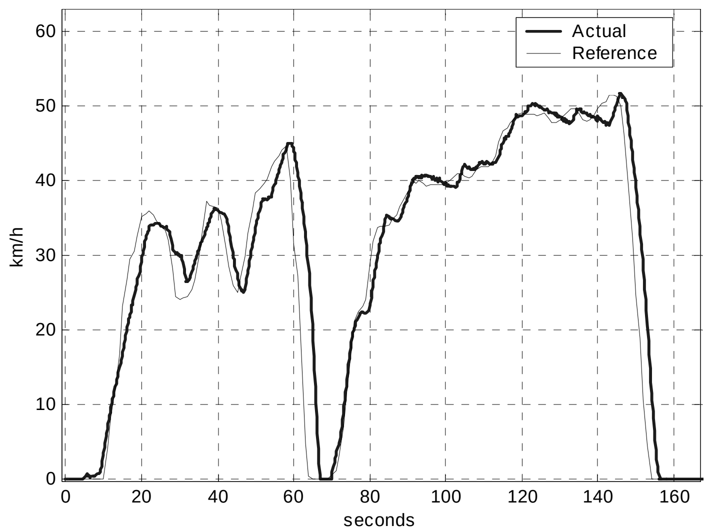

Figure 14: The first 160 seconds of Braunschweig duty cycle with the fuel cell bus. The complete cycle can be found in Appendix D.

The mean power consumption for the 12.5 tons fuel cell bus is approximately 17-24 kW during the Braunschweig, ECE15, FTP75 and IDIADA duty cycle, see Appendix D. This means that a fuel converter (fuel cell) with a nominal power output of approximately 35-50 kW would be sufficient for a full size (12 m) hybrid electric city bus. The energy buffer and power booster system, consisting of batteries, super capacitors, or a mix of both, would then handle power peaks of 120 kW.

The energy flows in the bus during a duty cycle are visualised in Figure 15. Note that the values are time average values for the whole Braunschweig duty cycle and not the true values at any particular time.

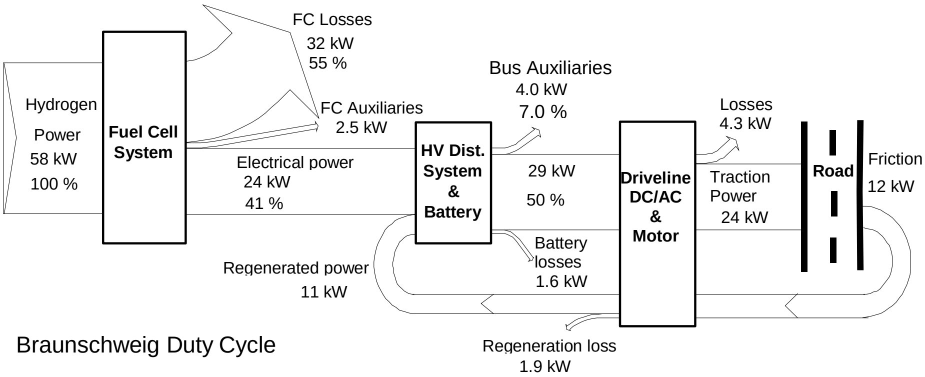

Figure 15: Sankey diagram of the average measured and calculated power flow in Braunschweig duty cycle with the fuel cell test bus.

The bus Auxiliaries of 4.0 kW, 7 % in Figure 15 will be further analysed in Chapter 4. This Braunschweig cycle example with the hybrid fuel cell test bus is performed ordinary bus auxiliary systems without AC.

In the hybrid set up with battery (energy storage), the propulsion system (traction motor and DC/AC) consumes more power than the fuel cell supplies, see Figure 15 and Table 3-6 and the battery thus supplies the difference in power for the propulsion system. Table 3-6 shows this energy balance for some duty cycles.

Table 3-6: Overview of the duty cycles measurements.

Duty Cycle	From FC [kW]	Regenerated [kW]	To Propulsion [kW]	Aux. System [kW]
Braunschweig	22.1	10.5	28.6	4.02
ECE15 or EDC	25.2	6.50	29.6	2.77
FTP 75	29.8	11.3	37.2	3.60
IDIADA	17.7	5.66	19.0	4.41

Many of the installations in the fuel cell concept bus are not optimised for automotive use concerning weight, size and lifetime. Nor is the bus designed for gaseous fuels from the beginning. Consequently, there is an optimisation potential in the general bus concept design.

Chapter 4

Auxiliary model design

In this chapter the different auxiliary system, mechanical and electric, of the bus and the corresponding auxiliary systems simulation models are described.

In the simulation model description there are references to constants and component information that are set in a special data set up file. MATLAB™ runs the set up file before the simulations. These setup files for the auxiliary systems are presented in **Appendix B**.2.

4.1 New subsystem models developed for ADVIS0R

There are two different sets of auxiliary systems developed for ADVIS0R, **Mechanical** for a conventional bus and an **Electric** for a hybrid or electric bus.

The mechanical load model for the conventional vehicle in Figure 16, uses the requested shaft torque [Nm] and speed [rad/s] of the driveline as primary inputs. The achieved shaft and belt torque [Nm] and speed [rad/s] of the ICE (prime mover) are the secondary inputs. The wheel and transmission are connected to the shaft. Auxiliary loads are attached to the belt. The first outputs from this block are the requested shaft and belt toque [Nm] (propulsion + Aux system) and speed [rad/s] of the engine. The second outputs are the achieved shaft torque [Nm] and speed [rad/s] to the driveline.

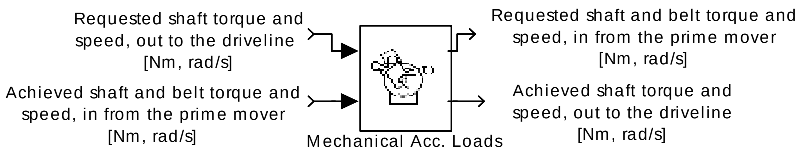

Figure 16: The subsystem model for a Conventional bus (Mechanical Aux. Loads).

The electric load model for the hybrid vehicle in Figure 17, uses requested electric power [W] to the driveline as primary inputs. The achieved electric power [W] from the battery and the generator (power source) are the secondary inputs. The first output from this block is requested electric power [W] (propulsion + Aux system) from the power source. The second outputs are the achieved electric power [W] out to the driveline.

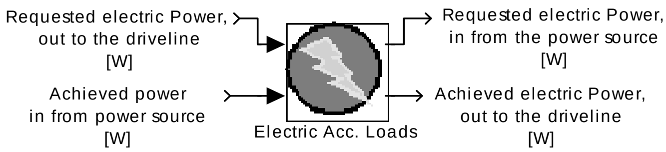

Figure 17: The subsystem model for a hybrid bus (Electric Aux. Loads).

In the auxiliary system models there are up to 8 sub levels. The major difference between the Mechanical load model and the Electric load is the use of speed and torque in the Mechanical auxiliary system model instead of electric power in the Electric auxiliary model, see Figure 17.

Between the second to fourth sub levels of the mechanical auxiliary model, the interface to the AVISOR simulation program is set and no calculations are performed.

In the fifth level of the mechanical auxiliaries, see Figure 18, all the different mechanical and electric loads are added and used as input to the "Auxiliary mechanical torque and power calculations" block. The different belt driven loads are:

- The power to the "Cooling fan" that is driven by the belt is calculated via a look-up table with the engine speed [rpm] as input and the belt load as output.

- The power of the belt driven "Steering system" is calculated with the vehicle input speed [m/s] as input and belt load as output.

- The “Pneumatic system” has five inputs; the speed of the vehicle [m/s], busstop information [1/0], DoorEcas [1/0], the engine speed [rpm] and a power calculation signal [1/0]. The belt load [W] is the output signal.

- The engine speed [rpm], electric power consumption [W] and power calculation signal are defined as parameters to the “24 V system” block. The “24 V system” contains the alternator (generator), battery SOC control and 24 V battery. The belt load [W] from the alternator is output signal.

- The “Air condition” block have engine speed [rpm] and Power Control [1/0] as input. The power of the compressor [W] and the AC power load of the 24 V system [W] are the output signals.

- The “Power calculation” block sends a control signal to consumer systems that have some kind of buffer. The buffer makes it possible to turn on and off the supplier of air or electricity. The power calculation signal is described in Chapter 4.8.

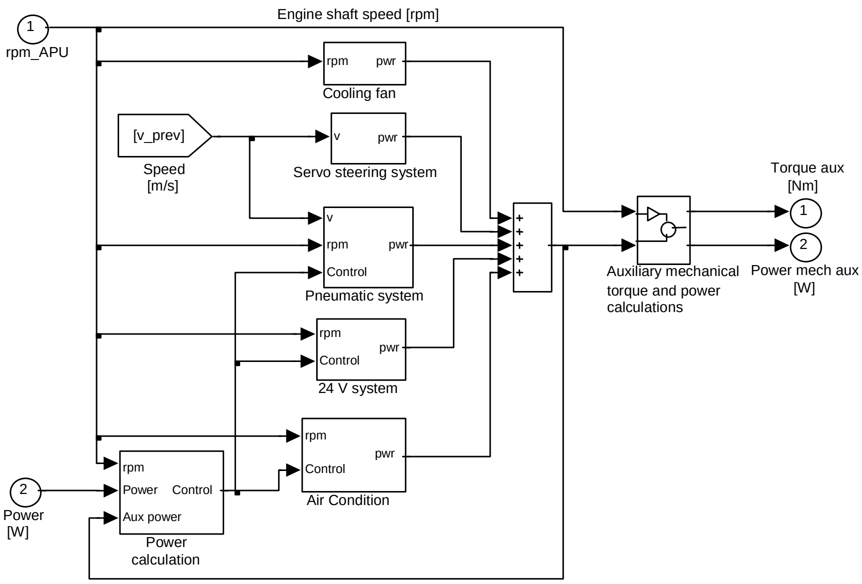

Figure 18: Fifth level of the mechanical auxiliary system, “mechanical auxiliaries”.

In the sixth level of the mechanical model, see Figure 19, the mechanical loads of the auxiliary system are divided with the mechanical (belt) efficiency [5] and then converted to belt load in torque [Nm] and speed [rpm]. The speed, power and torque of the mechanical loads are input parameters to the "Auxiliary mechanical torque and power calculations" block. The total torque and power consumption for the auxiliary systems are finally calculated as the sum of all auxiliary loads.

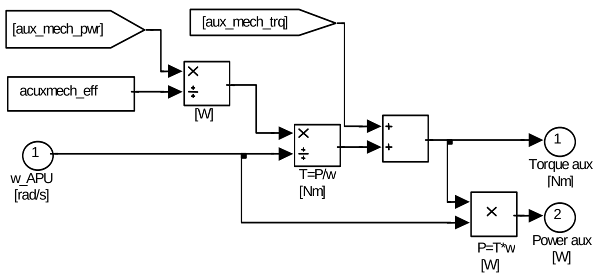

Figure 19: The sixth level of the mechanical auxiliary system, Auxiliary mechanical torque and power calculations.

In the second and third levels of the electric auxiliaries model, the interface to the AVISOR simulation program is set and no calculations are performed.

In the fourth level of electric auxiliaries, see Figure 20, all the different electric loads are added and the total Electrical Power [W] used by the auxiliary system is calculated. The propulsion system power [W] is the input to this block, while the electric auxiliary power and total electrical power (propulsion + auxiliary) requested from the power source are outputs. The following auxiliary systems are modelled:

- The "24 V system" block contains the DC/DC converter, the battery SOC control and 24 V battery. This block uses the electric power consumption [W] and the power calculation signal. The power calculation signal is described in Chapter 4.8. The electric power consumption [W] for the 24 V system is the output of the block.
- The "NEW Doors Ecas & Parking" block describes an alternative energy saving technology instead of the conventional pneumatic system. The electric energy consumption of the 24 V system is the output signal.

- The “Power calculation” block sends a control signal to the consumer systems that have some kind of energy buffer. The buffer makes it possible to turn on and off the supplier of air or electricity.
- The “Air condition” block has the power calculation control signal [1/0] as input. The AC power load of the 24 V system [W] and the power of the compressor [W] are output signals.
- The “Servo steering” system model use the vehicle speed as input and the electric load [W] as output.
- The “Pneumatic system” has four inputs: the speed of the vehicle [m/s], busstop information [1/0], DoorEcas [1/0] and a power control signal [1/0]. The electric load [W] is output signal.
- The “Water pump” and the “Cooling fans” are represented by a constant load [W].

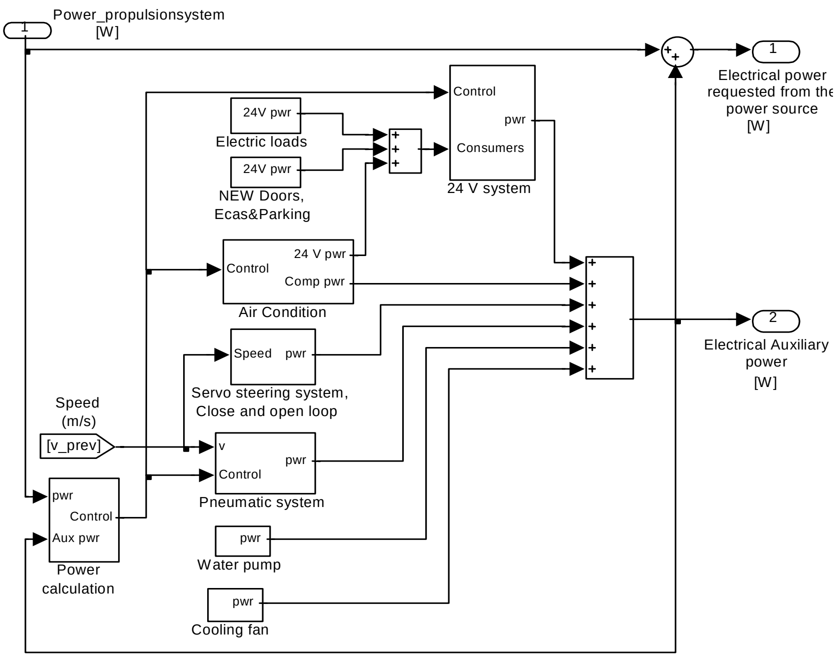

Figure 20: The fourth level of the electric auxiliary system.

4.2 Subsystem test result

The energy consumption of different sub systems in the bus was measured in order to map the energy flow in the bus and to identify optimisation potentials. The measurements included the pneumatic system (compressor, brakes, doors and suspension), the hydraulic system (servo steering), the 24 V DC/DC converter (24 V grid), the water pump and the cooling fans on the roof (driveline system cooling). The mean power consumption for the sub systems is 2-4 kW depending on the duty cycle, which is 4-10 % of the lower heating value of the consumed hydrogen or 10-25 % of the net power out from the fuel cell system. The measurements include ordinary bus stops at city driving but no air condition system. An air conditioning system for a 9-meter bus consumes up to 25 kW, which is more than the average energy consumption for most duty cycles.

Figure 21 shows the result of these measurements during a Braunschweig cycle. For this cycle the sub systems consumed 18 % of the total power for the bus.

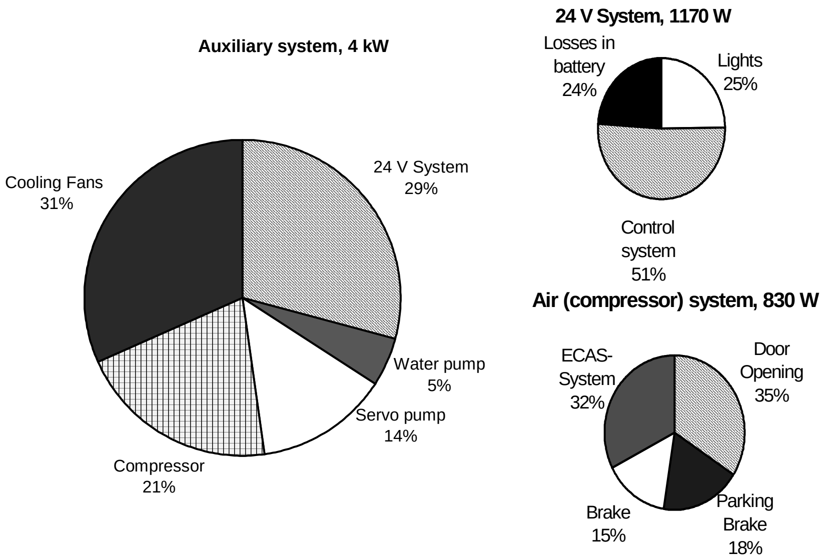

Figure 21: Average power consumption of the auxiliary system in a Braunschweig duty cycle.

4.3 Air Condition

The AC-system is the largest energy consumer of the auxiliary system. Due to design and aerodynamic reasons modern vehicles are equipped with large windows and windows that are very inclined. The increased windows size will increase the cooling demand. The AC-system at full power in a large bus consumes up to 25-30 kW. This can be compared to the power demand in small cars, approximately 4 kW [15]. This energy consumption of the AC system is also a large part of the total vehicle's energy.

Figure 22 shows the working principle active the parts of the AC system. The AC system performance is strongly influenced by the efficiency of the compressor. In an AC system the compressor is the most energy consuming part.

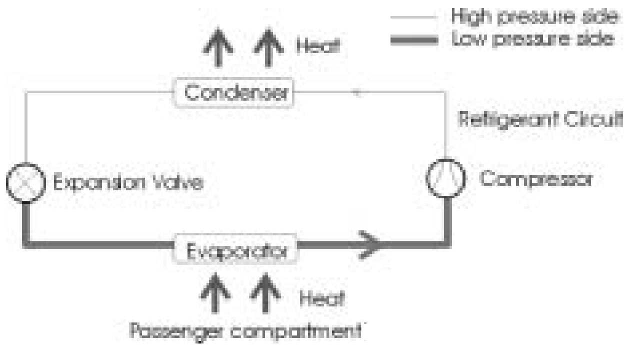

Figure 22: AC system with condenser, compressor and evaporator.

The AC compressor working principle can be described by the following, see Figure 23:

While A => B the evaporator absorbs the heat to the refrigerant circuit and cools the air of the compartment. During this phase the temperature is constant and the refrigerant goes from liquid to gas.

While B => C the compressor increases the pressure and the temperature rises while the refrigerant flows through the compressor.

In the transition C => D the condenser heats the ambient air and cools the refrigerant circuit. The temperature is constant and the refrigerant is transformed from a gas to a liquid phase.

The expansion valve decrease the pressure and the temperature will fall during the phase D => A.

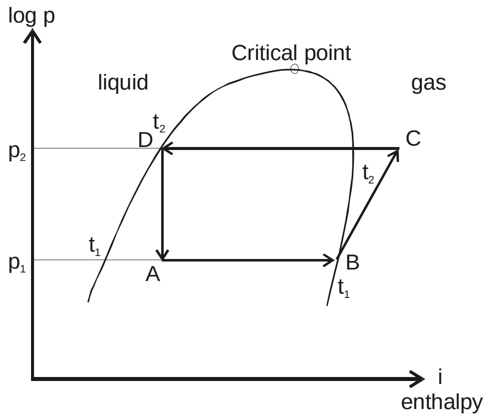

Figure 23: Ideal cooling process with evaporation.

In the real process there is often a pressure drop in the heat exchanger and an enthalpy increase in the compressor. In a closed system the control cannot follow the path D-A-B to a 100 %. If the condenser during the cooling phase has an additional cooling area after the medium has condensed, the D point will move in the left direction.

If overheating occurs, the B point will move towards right. The over heating will decrease the system efficiency, increase the temperature in the compressor exhaust pipe and increase the power consumption. A temperature control unit will control the temperature by increasing the area of the expansion valve. The pressure and the temperature in the evaporator will increase.

Compressor

The compressor in the air condition system is used to transfer the vapor between the different pressures zones in the AC system [15]. It is connected to the engine crankshaft shaft via a belt. The AC compressor is also connected via an electro mechanical clutch, and can be disconnected when the AC compressor is turned off.

The compressor, used in the AC system, is a rotary piston compressor. Screw compressors are also getting manufactured in series production. The advantage are: low noise emissions, need less maintenance and increased efficiency. The strongest drawback is their price.

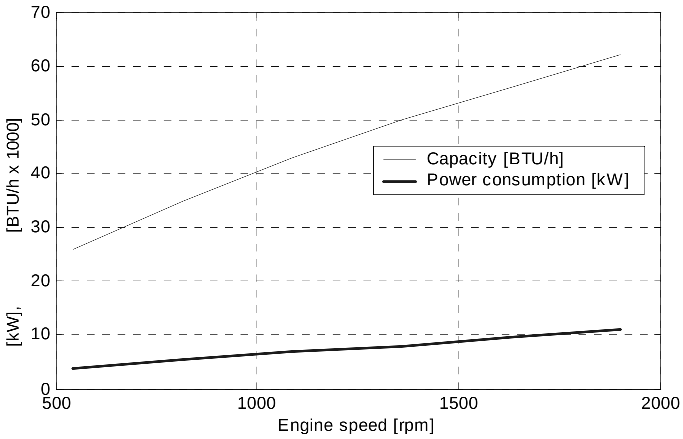

Figure 24: Engine speed vs. power consumption and cooling capacity of an AC compressor.

In Figure 24 the power consumption [kW] and the cooling capacity [BTU/h] of a compressor is plotted. The cooling capacity ratings are in British Thermal Units (1 BTU = 1.055 kJ) per hour. The relation between cooling capacity [BTU/h] and power consumption [kW] in Figure 24 indicates that the compressor speed should be kept low for best cooling efficiency. The compressor is used in medium size buses. In larger buses and buses in warmer areas two compressors are used. The power and capacity are very dependent of the engine speed. It is a problem when the engine is idling for long times. A solution to the idling problem with AC systems is a special engine to drive the compressor, which secures the cooling capacity in all driving points.

Cooling media

The gas in the refrigerant circuit should fulfil certain criteria: cheap, safe, non-toxic and have good thermal performance [30]. Today's AC system manufacturers use "R134a" gas in the refrigerant circuit. R134 satisfies most of the criteria, but it still not environmentally friendly. Earlier AC systems used gases with more freon content. When the system gets old leakages will appear and the compressed gas will leak out. The freon gas breaks down the ozone layer which has a consequence for the global warming. The risk for flames and explosion of the refrigerant may not be too large. For the thermal performance such aspects as reasonable pressures and temperatures in the refrigerator circuit must be considered.

Environmentally friendly refrigerants have been tested in practical applications. They do not contribute to the depletion of the ozone layer and have negligible global warming effect. Some examples of these environmentally friendly gases are: R600a (iso-buthane), R290 (propane), R717 (ammonia) and CO_2. The use CO_2 gas in AC system is still in the experimental phase. One of the main problems is the high operating pressure that requires expensive installations.

Electric driven AC

In the UITP conference in Madrid 2003, Termo King [44] presented a High Voltage Air Condition (HVAC) system for hybrid or electric buses. It would also be suitable for conventional buses with a special alternator. A smaller unit for truck cabins was also presented. The smaller unit used the 24 V system @ 70 A. All parts of the AC system are packed in a one-piece rooftop.

The largest air condition manufacturer Denso [12] is supplying the second generation of the Toyota Prius hybrid car with an electric driven AC system. The electric AC provides cooling when the engine is shut down during the stops. The size of the system is reduced by 40 % and the weight by 53 % [20] in comparison to a belt driven compressor. The compact design will also contribute to a reduction of the leakage in the refrigerant by 25 %.

The advantages with all in one unit are: the operation is independent of engine speed and works even if the engine is stopped, there is a plug-and-play installation and the unit is ideal for high-pressure refrigerants like CO_2. The plug-and-play function is important for the bus manufacturer.

Often the bus manufacturer has to hire a special company to make the final refrigerant installation and testing. With one single unit there will be no leakage in pipes and hoses and higher pressure will be possible. The technique with HVAC is well tried in rail applications.

Measurements of the dynamic

A three-axles, 18 m, articulated bus (sv: led-buss) was equipped with AC sensor, temperature sensors and a speed sensor by Scania. The signals were sampled at 10 Hz and the measurements lasted for two days.

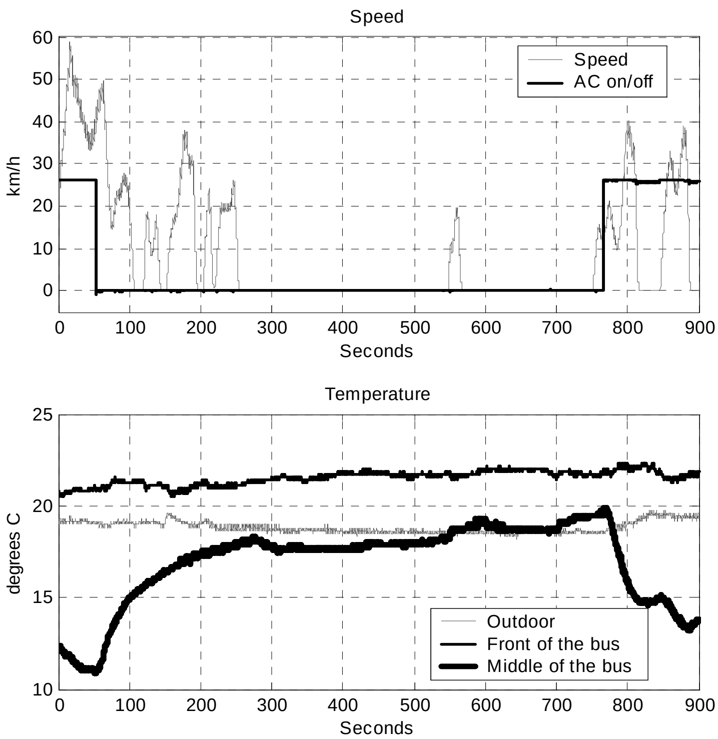

Figure 25: AC and temperature measurements.

At 50 seconds the AC is switched off, as depicted in Figure 25. As a consequence the temperature in the passenger compartment starts to increase. The temperature in the middle of the bus increases fast in the beginning when the difference is large between inside and outside and slower when the difference was smaller. Such behaviour is expected due to the heat transfer dynamics.

At 770 seconds the AC was switched on, in Figure 25. When the AC was started the temperature in the middle of the bus decreased fast in the beginning when the difference was large and slower when the difference was larger. The thermal time constant τ_{th} is estimated from Figure 25.

$$\tau_{th} = 70 \text{ s} \tag{4.1}$$

This shows the dynamic of the temperature inside the bus when the AC is turned on and off.

Simulation model

Figure 26 shows the “Air Condition” model of the AC system in a conventional bus. The model calculates the power consumption of the compressor and the cooling fans in the Air Conditioning system. This block uses the engine speed [rpm] in a look-up table for the power consumption [W] of the compressor. The power consumption look-up table of the compressor is set in an m-file. A Control signal with information about the power need from the propulsion system exceeding a limit [1/0] and information about regenerative braking [0/1], is used by the “Duty cycle Generator” to control the compressor. The “Duty cycle Generator” switches on and off the compressor so that the compressor gets a duty cycle that corresponds to the constant **acc_Aconoff**, [%] specified in an m-file.

The fans of the AC system load the 24 V system. The fans should be switched off when large power is needed for the propulsion system and run at full speed when regenerative power is available. The AC system should not be turned off by the control signal when the Duty cycle of the AC system is more than 90 %.

The power consumption of the compressor and load of the 24 V system are the outputs from the AC block.

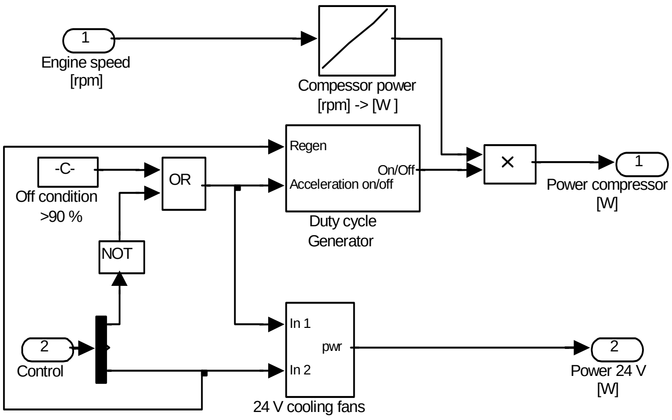

Figure 26: The subsystem Air Condition of the mechanical auxiliary system.

The hybrid model in Figure 27 is almost identical to the mechanical model, with one exception, the engine speed. The compressor is driven by an electric motor, which makes the speed and power consumption constant. The compressor size is set in the m-file.

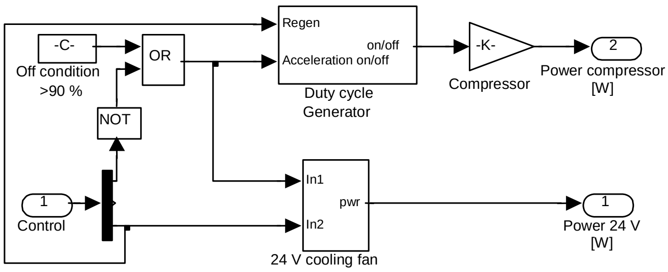

Figure 27: The subsystem Air Condition of the electric auxiliary system.

In the “Duty cycle Generator” in Figure 28, the “Pulse” generates a pulse that has the duty cycle [**acc_Aconoff**] and the period of [**acc_ac_pulse**] seconds that is used for controlling the compressor. The “Pulse” signal in combination with other conditions, as if the bus is braking and regenerated power (Regen) is available and has the AC system should be running at full speed and if the propulsion system power reached a certain limit (AC Onoff) and the AC it should be switched off.

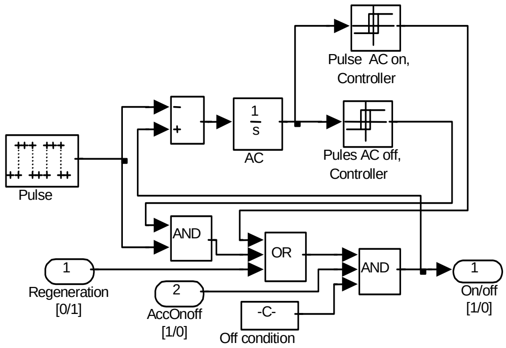

Figure 28: The subsystem Duty cycle Generator of Air Condition.

In Figure 29 an output from the "Duty cycle Generator" is graphically displayed. The first sub plot shows the propulsion system power and the limits for high power limits and regenerative power limit. The second subplot shows the reference and actual output from the "Duty cycle Generator". If the integrated value of the difference between the "Pulse" and the output of the "Duty cycle Generator" grows too high, the AC system runs too much, (one pulse extra) and the system is turned off for the next pulse. If the system runs too less an extra pulse appears at the end of the normalpulse. This system minimises the on/off switching.

Implemented conditions:

- The actual output from the "Duty cycle Generator" is subtracted with the reference value from the "Pule" and the difference is integrated.
- When the integral becomes a whole pulse, [**acc_ac_pulse*acc_Aconoff**], the "Pulse, AC off, Controller" is turned off until the integrated signal is 0.
- The "Pulse, AC on, Controller" turns on one pulse when the integrated signal is one negative pulse [−a**cc_ac_pulse*acc_Aconoff**], until the integrated signal is 0.

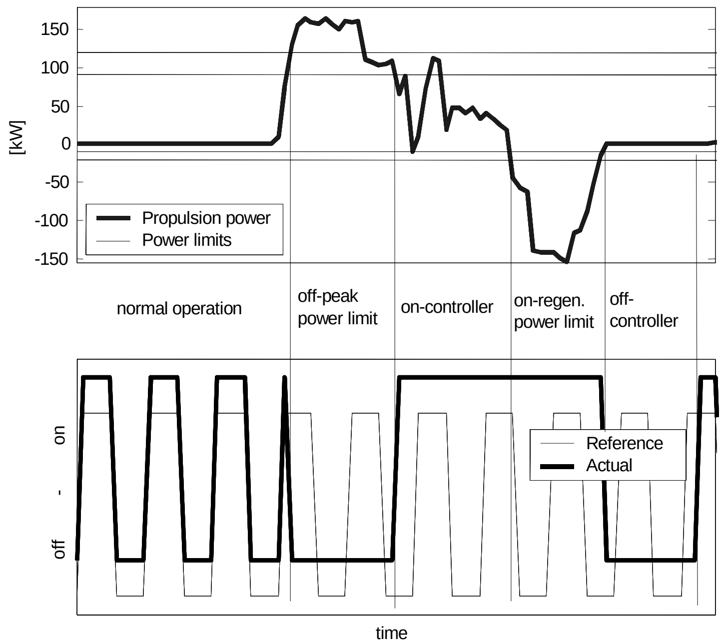

Figure 29: The propulsion system power in the first subplot and the output from the Duty cycle Generator of Air Condition, Reference and Actual output at 50 % duty cycle in the second subplot.

4.4 Pneumatics

Pneumatic systems are used in most commercial vehicles. The purpose is to facilitate power braking or remote opening/closing of doors. Other application of pneumatic technology is used in are EGR (Exhaust-Gas Recirculation) valve control and operation of other engine valves. The use of pneumatically controlled engine valves is increasing to meet stronger emission regulations.

Most commercial vehicles use pneumatic brake systems. Laws and regulation are controlling the number of full brakes that the air tanks should supply. They also control the time the compressor needs to refill the tanks.

Air treatment

The pneumatic system and components of a truck is showed in Figure 30 The air produced by a compressor must be dried and cleaned before it is used in order to protect the entire pneumatic system from freezing and internal corrosion, to ensure reliable operation of the compressor and increase the overall life [27]. The air dryer has no air space of its own for regeneration. For this reason, an external tank is used for the regenerated air. This smaller tank (4-8 l) is located close to the air dryer. The air from the regeneration tank is blown back through the desiccant (sv: torkmedel), bringing the moisture out into the open air via the relief valve. Air dryers, pressure regulators, circuit protection valves and pressure limiting valves, ensure the operational safety of pneumatic braking systems.

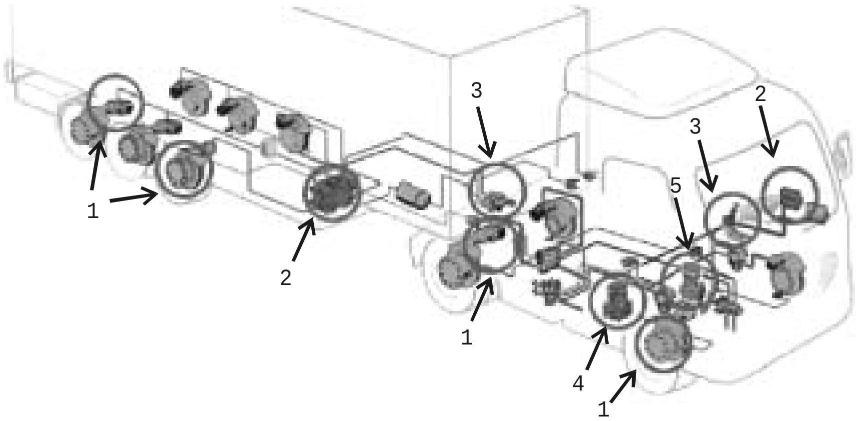

Figure 30: Components in the pneumatic system, 1 Brakes, 2 Electronic control system, 3 Valves, 4 Air dryer and 5 Compressor.

Reference system and model

The air system in Figure 31 is modelled with a Compressor that produces compressed air for different consumers. Air storage tanks, controller valves and an on/off controller are also parts of the Air system model.

The Air system contains four different air consumers:

- Door opening/closing system
- Brake system
- Parking brake
- Suspension (Ecas) system

On the hybrid fuel cell concept bus all main air consumers are logged. Dedicated tests were performed to monitor the energy consumption of each single sub system in the pneumatic system. The air consumption of doors, service brake, parking brake and suspension (ECAS-system) are listed in Table 4-1.

Table 4-1: Main consumers of air.

Use	**Volume [l_n]**
Door (one pair, open & close)	21.0
Brake pedal (maximum force)	40.0
Parking brake	25.0
Suspension (ECAS)	42.0

The Speed [m/s] is input to the brakes and Busstop information [0/1] and Busstop on/off [1/0] are inputs to the other consumer models of the air. The air tanks are connected to the output of the consumption models. The second input to the air tanks are connected to the supply of air from the compressor via a control valve. A signal full [0/1] and empty [0/1] is connected from the storage tanks model. The “On/off Controller” controls the compressor and uses the request for more air, tank full and power control signal as inputs. The Compressor uses engine [rpm] and the control signal [0/1] as inputs. The power consumption [W] and the airflow [l_n/s] are outputs. The airflow is connected to an Air control valve that chooses the air tank that has the highest request priority.

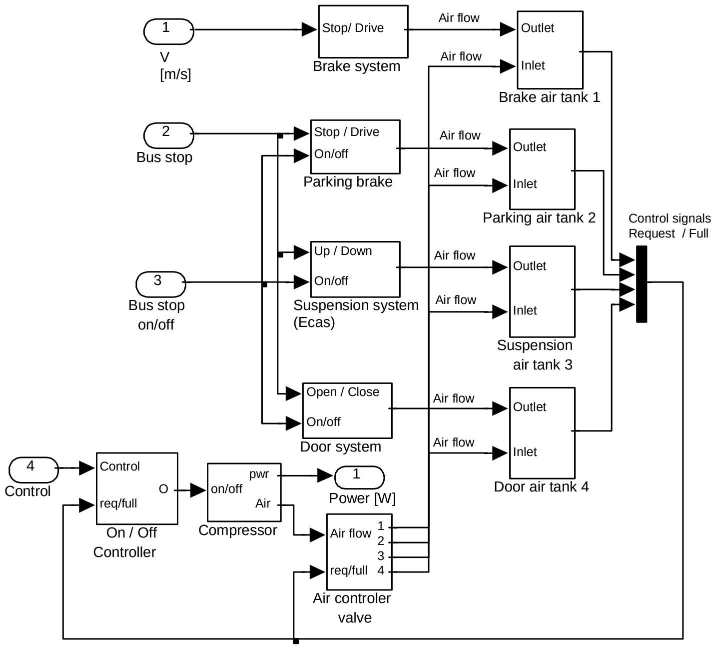

Figure 31: The subsystem Air system.

In the “On/Off controller” block in Figure 32, logic operators are used to calculate if the compressor is going to run or stop. Considerations as if a tank sends out a request signal and if all the tanks are filled, are taken. A selector chooses if the control of the subsystem is on or off.

If the control is off:

- The compressor starts to run if the request signal is set to 1 in one tank and not all the tanks sends the stop signal. An integrator will make the compressor start as it reaches its max value 1.
- If all tanks are filled, the integrator is initialized to zero and the compressor is stopped.

If the control is on:

- The first signal, the power control, indicates that the magnitude of the propulsion system power (big/small = 1/0). If this signal is set to

1 (high power in propulsion system), the Not block turns the signal to 0 and the And block will turn off the compressor. If the high power signal is 0, the Not block turns it to 1 and the compressor then will run if the tank send a request signal. The compressor will run until the request signal turns to 0.

- The third signal of power control indicates that regenerative power is available and the compressor should run at full power if not all of the tanks are full.

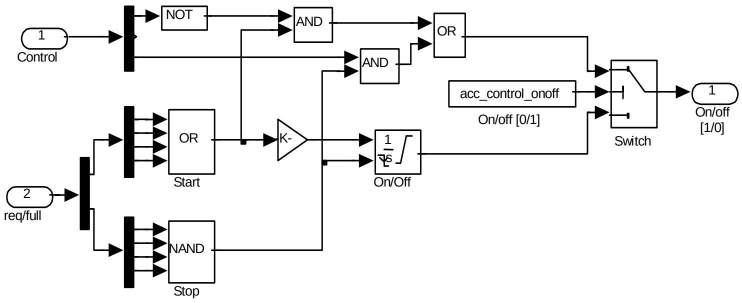

Figure 32: The subsystem On/Off controller of the Air system.

The “Air controller valve” in Figure 33, controls the destination tank of the air produced by the compressor. The airflow [l/s] and the full air tank signal [0/1] are inputs to the Air controller valve. The “Air controller valve” gives priority to the Brake air tank and then the second priority to Parking brake, Suspension (Ecas) and Door air tank. The airflow will go to this tank when the Brake air tank is not full. When the Brake air tank is full the airflow will go to the Parking brake tank if this tank is not full.

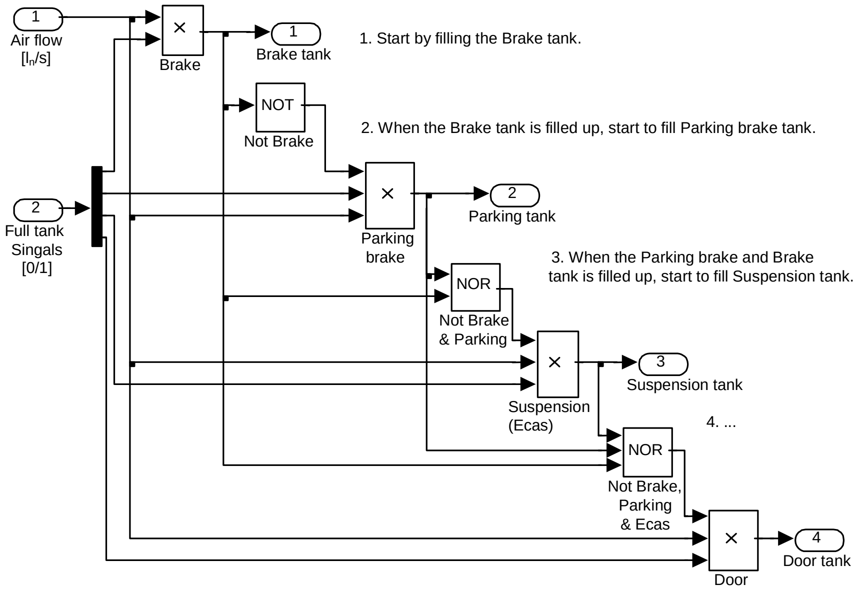

Figure 33: The subsystem Air controller valve of the Air system.

Compressors

The compressor is used to produce compressed air to the pneumatic system [15]. The compressor is usually connected to the engine's crankshaft via a belt in a conventional vehicle. The compressor development began in the early 19th century. The compressors had slow speed, low efficiency and heavy weight. The first types of compressors were piston compressors. The piston compressor is still very common, but the speed and capacity has increased and the weight has been reduced.

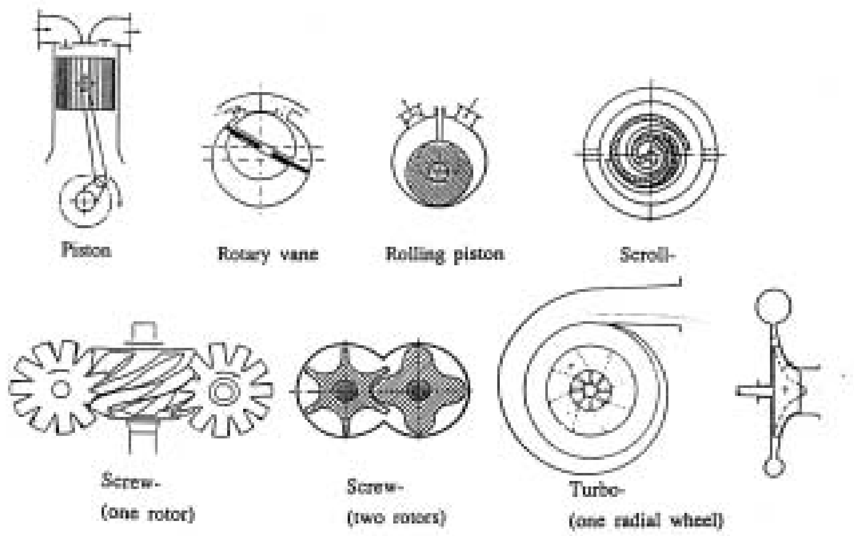

Figure 34: Different compressor.

Some of the compressor principles are shown in Figure 34 and the most important ones are:

- Piston or reciprocating compressor
- Screw compressors
- Rotary (rotary vanes or rolling pistons) compressors
- Scroll compressors
- Turbo compressors

All the compressors types, except the turbo one, are positive displacement devices. This means that a certain volume of gas is reduced during the rotation. Due to the volume reduction the pressure of the gas will rise, and the gas will be delivered to the high-pressure side. The turbo compressor, on the other hand, is a "dynamic compressor". The pressure is enhanced by the rotating centrifugal field, which is produced by the high-speed impeller.

An important difference between the compressors is the use of valves for controlling the gas flow. The valves are very sensitive and important for the life expectancy.

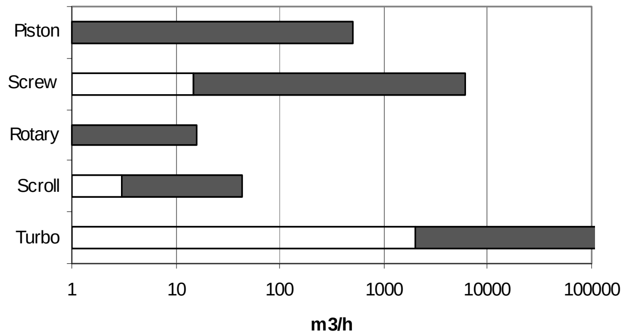

Figure 35: Swept volume of different compressor types. In the dark area the compressors have proven to be most suitable for use.

The way to define a displacement compressor is the “swept volume”. The swept volume is defined as the volume that geometric is formed to be filled by gas at the inlet of the compressor. It can also be expressed as “swept volume per revolution”. The units for the swept volumetric flow will be m^3/sec in the SI-system. Figure 35 shows some typical values of the swept volume for different compressor principles.

Different designs of compressors have different applications.

Piston compressors are the most common ones but their market is decreasing in favour of large screw compressors. The flow rates are up to 500 m^3/h. One of the problems in the vehicle is carbonised coal that will appear in the cylinder. It causes the cylinder to be too hot and the mixture of oil to be too high.

Screw compressors with two rotors are available with max flows from 180 to 6000 m^3/h, requesting 50 to 1700 kW operating power are available. This type of compressor has high efficiency due to the design with small compression space that gives high volume metric efficiency. It has low noise level and may be used in vehicles instead of piston compressors in the future. The drawback is a higher prize, due to the manufacturer costs, than piston compressors.

Rotary compressors are used for smaller units to about 15 m^3/h. The rotary compressor can also be built in as a booster in a two level system. It is very silent, 60 to 70 dB and most of the noise comes from the cooling air. Te rotary compressor can be operated without a buffer.

Scroll compressor has increased in the last decades and both size and market are expected to grow. The volumetric flow is about 2 to 40 m^3/h.

Turbo or centrifugal compressors are used for the largest capacities with inlet flows of more than 2000 m^3/h. with limited pressure.

Reference system

The compressor used in the conventional bus is a water-cooled two-cylinder piston compressor used for supplying the pneumatic system on a truck or bus. The compressor performance is showed in Figure 36. The compressor consumes a lot of power even when it is off load. To reduce the off load power some kind of energy saving system can be used. The energy saving system used here is based on closing of the compressor output valve and may reduce the off load power by as much as 50 %. When the compressor has filled all the air tanks, a pneumatic valve automatically closes the outlet. This does not open until the system needs filling again. During this relief phase the compressor works with a backpressure in the cylinders and consumes less engine power. If a mechanical clutch were mounted between the compressor and the engine it would be possible to reduce the off power load to zero, by turning the compressor off when not needed. The reason for not mounting the clutch is that the connection torque will be too large. The AC compressor has a mechanical clutch to control the on and off operation.

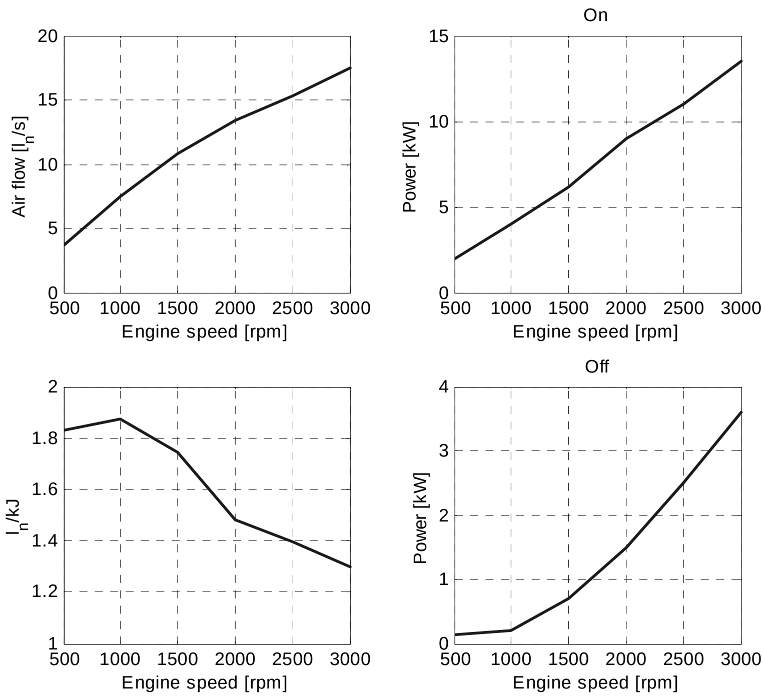

Figure 36: Compressor performance.

The compressor needs to blow out (back) unwanted dirt (water, oil and dust). This regeneration (blowing) can be implemented in different ways. In the hybrid fuel cell bus the regeneration is done every time the compressor is turned off. A special tank is used for blowing back [10]. The tank is refilled when the compressor is restarted. The implementation of the regeneration in the model is done as follows:

1. Every 25 l of compressed air produced by the compressor, a 4.5 l tank is used for regeneration (blowing backwards). These values are defined in an m-file.

2. The compressor directly refills the air tank again.

In the “Compressor” model in Figure 37, power consumption and airflow of the compressor in a conventional bus are calculated. The engine speed [rpm] and the control signal [0/1] are used as inputs to the “Compressor”.

Three look-up tables are used to calculate airflow [l/s] and power consumption [W] when the compressor is on and off. The airflow and power consumption of the specific compressor is set in an m-file. The airflow is multiplied with the control signal [0/1] and a thermal coefficient. The temperature of the output air from the compressor is decreased before it reaches the storages. The outputs from this block are airflow and consumed power.

A regeneration tank that blows out (back) unwanted oil and water is included in the model. The regeneration tank model is composed of two integrator blocks and a memory block. If 25 liters of air has been delivered to the left integrator a signal is sent to the right integrator via the memory block. The right integrator is cleared, the tank (integral) is refilled and the output signal is set to 1 when the tank is full.

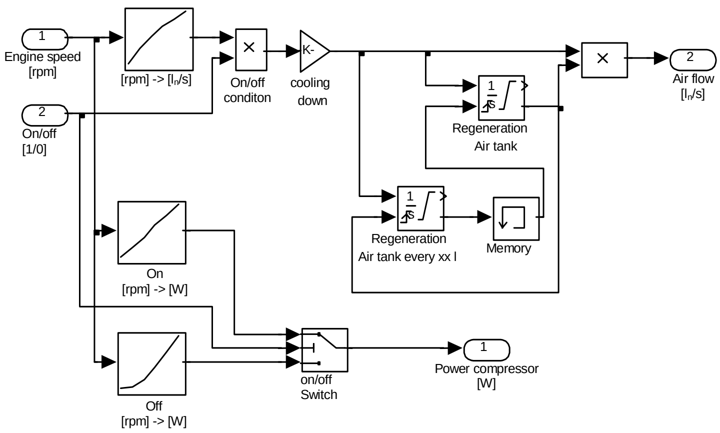

Figure 37: The subsystem Compressor of Air system in the mechanical auxiliary system.

On a hybrid vehicle a separate electric motor drives the compressor. A compressor of lamella type from Hydrovane has been used in the hybrid fuel cell bus. An asynchronous motor and a DC/AC inverter drive the compressor. Figure 38 shows the electric motor and compressor.

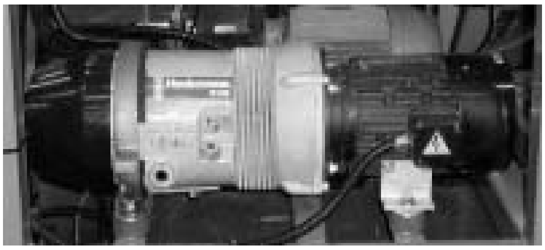

Figure 38: The compressor and the electric motor.

Hydrovane 502 lamella compressor
Weight: 35 kg
Air flow: 3.4 l_n/s @ 10 bar (manufacture), 3.0 l_n/s @ 9 bar (measured)
Power consumption: 2.2 kW (manufacture & measured)
Efficiency: 1.3–1.6 l_n/kJ

The pneumatic sub system consumes approximately 830 W (time average) during a Braunschweig duty cycle, when both doors and the ECAS-system are activated at each bus stop, see Figure 39. A considerable amount of air is used for the brake system. The air compressor is driven by an AC electric motor, powered by the high voltage grid, via a DC/AC inverter. The compressor is a lamella type due to the requirements of low noise level.

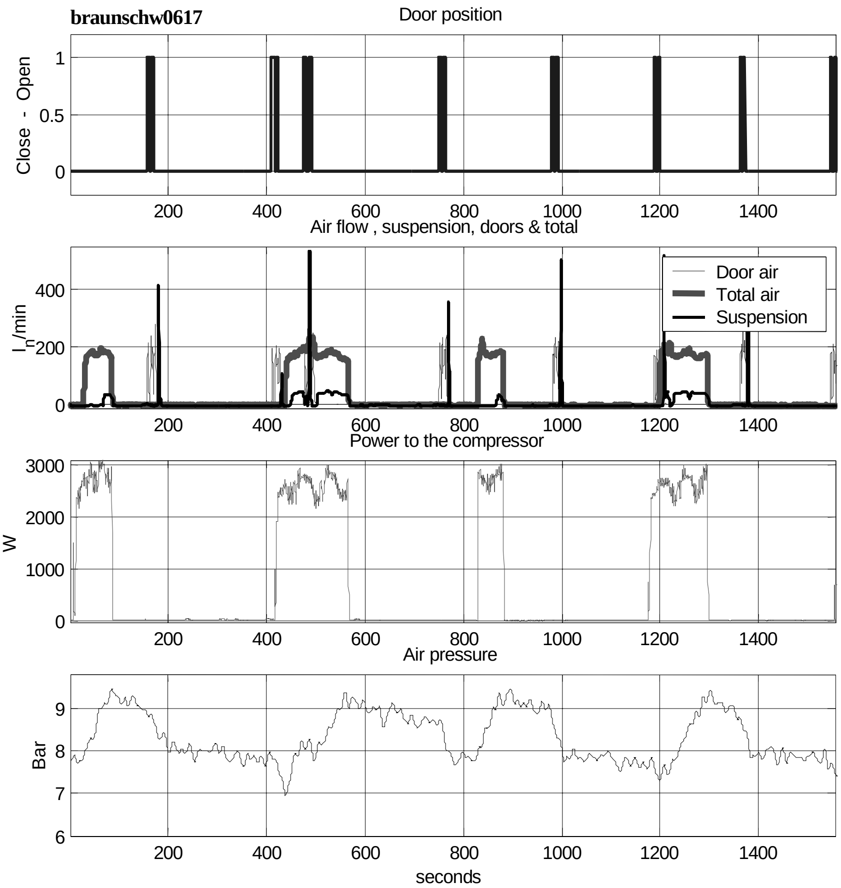

Figure 39: Pneumatic system air consumption in the tested hybrid electric fuel cell bus. The first subplot shows the door position over time, the second subplot the air consumption as a function of time, the third subplot the electric power consumption of the compressor sub system as a function of time and the fourth subplot the air pressure in the pneumatic system as a function of time.

The hybrid vehicle (electric) compressor model is similar to the conventional vehicle (mechanical) model, with the exception that it is run by an electric motor that runs at a constant speed, see Figure 40. The airflow [l/s] and the power consumption [W] are constant when the compressor is on. The airflow is calculated by multiplying the rate limited control signal [0/1] with a coefficient for cooling down with the flow rate [l/s] at the constant speed of the electric motor. The electric power is calculated by multiplying the control signal [0/1] with the electric motor power [W]. The power of the electric motor and the airflow rate are set in the m-file. A regeneration tank that blows out (back) unwanted oil and water is also included in the model. For descriptions see the mechanical compressor model, previous section. The airflow and the consumed power are outputs from this block.

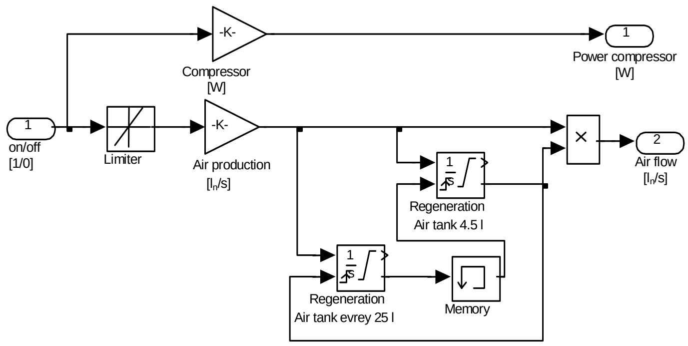

Figure 40: The subsystem Compressor, Hydrovane 502, Electric motor of Air system for the electric auxiliary system.

New improved compressor technique

There are new alternative compressors types with reduced emissions significantly of noise and less use of oil. The screw compressor is the most promising candidate. Up to recently such compressors have been rather expensive, but lately the prices are dropping [15].

In a conventional vehicle the compressor cannot be disconnected from the engine. When the use of the pneumatic system is low, the compressor losses are related to the engine speed. An electric driven compressor avoid this problem [41].

Pneumatic brakes

Cars use hydraulic or a boost hydraulic brake system [6]. Most heavy commercial vehicles use however pneumatic brake systems. One of the drawbacks with pneumatic brakes compared to hydraulic brakes is the response time. The benefits with pneumatic brakes are that the connection between the truck and the trailer is safer and more environmental friendly, since no spill of hydraulic fluid can occur when connecting or disconnecting the trailer.

The brake system includes:

- Service brakes
- Secondary brakes
- Parking brakes
- Retarding system
- Self actuated braking system (on trailer only)

Law requirements

The brake system is a part of the vehicle safety system. The requirements on the systems in vehicles are strongly regulated both by individual country laws, EU Directives and ECE and EEC regulations. The European brake directions divide the vehicle into classes and subclasses. The classes depend on weight, number of wheels and passenger capacity.

The service brakes should be applied step by step without the hands being released from the steering wheel. The maximum time to achieve 75 % of the full brake power has to be 0.6 s. The safety or secondary brake system may use part of the service or parking brake systems and may be applied by keeping one hand on the steering wheel. The power of the safety brake system should be 50 % of the service brake system. If the parking brake is engaged it should hold the vehicle by a gradient of 18 % without the driver present.

Reference system

All city buses are equipped with service brakes and parking brakes. The simulation model for the hybrid and conventional bus contains the same service and parking brake models. The consumption during the fuel cell bus tests was 25 l_n air for the parking brake and 40 l_n air for the service brake (100 % brake force).

In the model, Figure 41, the “Brake system” consumes air only when the speed [m/s] is decreasing and the derivate (acceleration) of the speed consequently is negative. The more negative acceleration that is needed, the more air is used. In the gain module “Brake” there is a compensation for the mass of the vehicle.

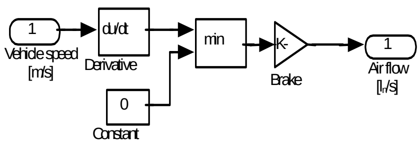

Figure 41: The subsystem Brake system in the Air system.

The “Parking brake system”, see Figure 42, uses the Busstop information [0/1]; The symbol 0 ⇒ 1, represents the beginning of the bus stop and 1 ⇒ 0 represents the end. When the parking brake is applied and realised in the beginning and at the end of a stop it will consume 25 l_n air.

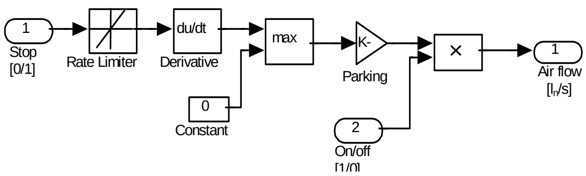

Figure 42: The subsystem Parking brake in the Air system.

New improved system

The pneumatic controlled parking brake and service brake for heavy-duty vehicles can be replaced by pure electrical or electrical/hydrostatic solutions. However, the pneumatic technology has been the solution long time, for example the truck industry have to serve millions of trailers with pneumatic parking- and service brakes. Electric controlled parking brakes are becoming more common on luxurious passenger cars. An electric servomotor, mounted on the rear wheel, which presses the brake calliper directly onto the brake disc [40]. There are also ongoing projects aiming at the to replacement of the ordinary brake, system like the eBrake project [19]. The eBrake is based on an electric powered controlled friction brake with high self- reinforcement capability. These solutions have a great potential for saving energy and in the end eliminate the use of pneumatics in vehicles. However, the brake system will probably be the last system to change from pneumatics to alternatives.

The electric “Parking brake system” in Figure 43 is similar to the pneumatic system, but electric power is consumed instead of air. The Parking brake uses the Bussstop information [0/1], when it goes from 0 ⇒ 1, at the beginning of the bus stop and 1 ⇒ 0, at the end of the bus stop. When the parking brake is applied and realised in the beginning and the end of a stop it will consume 20 A and 26 V during 1 second, which means 560 J.

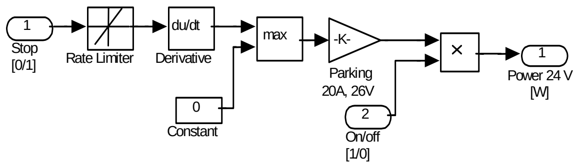

Figure 43: The Parking brake system of the NEW Doors Ecas & Parking.

Suspension

The pneumatic suspension system, see Figure 44, maintains the bus at a constant level regardless of load [26]. The system can lower the front boarding step, the whole side or the entire front. Increasing passenger demand for low entrance step will cause the driver to lower the bus more frequently. The lowering movements start when the switch for kneeling is pressed. The largest draw back with the suspension is the efficiency. Pressurised air is released during the lowering phase. To raise the vehicle again the suspension is filled with air from the compressor.

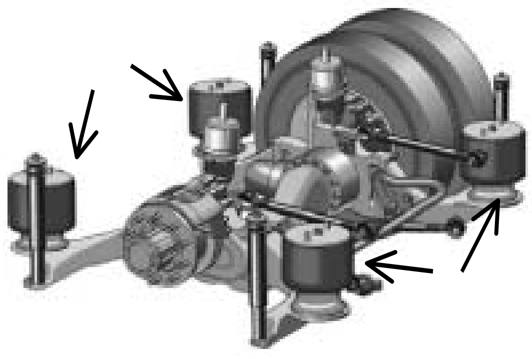

Figure 44: Rear bus axis pneumatic suspension system.

Reference system

This suspension system uses a lot of "air energy" at a very low efficiency. When lowering the bus 65 mm and lifting it back to normal level, the suspension consumes 42 l_n of pressurized air. The energy consumption to produce the air is 41.4 kJ and the work lifting 4500 kg, 65 mm is equal to 2.87 kJ, which yields the efficiency approximately 7 %, see equation 4.2.

$$\eta = \frac{m \cdot g \cdot h}{E_{\text{comp}}} \approx 7\% \qquad (4.2)$$

The "suspension (Ecas) system" in Figure 45, controls the levelling of the bus. In the gain module "Front org:" there is a compensation for the mass on the vehicle front axle. This compensation is set in the m-file.

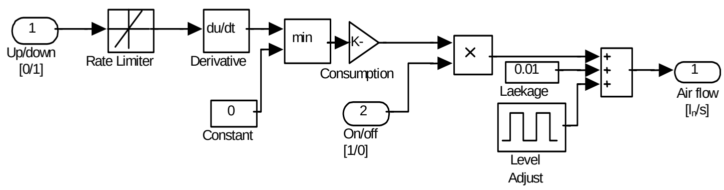

Figure 45: The subsystem suspension (Ecas) system of the Air system.

New improved system

Replacing the pneumatic suspension (down/up), a hydrostatic semi active solution would be more energy efficient. Haldex [18] produce small electrically (24 V DC) driven servo pumps that would be suitable for this application, see Figure 46 and Figure 47. The servo pumps are for example used in trucks for the back lift. This modification would increase the system from 7 % to approximately 75 %.

Figure 46: Compact electric servo pump.

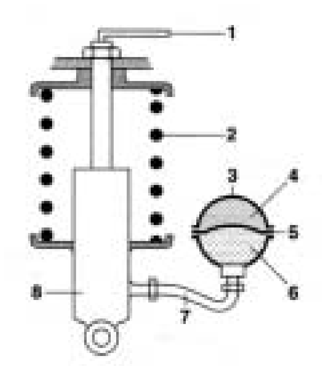

Figure 47: Hydropneumatic levelling system, 1.Fluid supply, 2.Steel spring, 3.Accumulator, 4.Gas volume, 5.Rubber diaphragm, 6.Fluid, 7.Hose, 8.Shock absorber.

Releasing pressurized air when the bus is lowered at a bus stop is not an energy efficient operation. An energy saving solution for both the pneumatic and the hydraulic suspension would be to store the pressured air when going down and use it to lift the bus again. If the height of the opposite side were raised by 65 mm and the door side were lowered by 65 mm, the centre of gravity would not be changed, see Figure 48 and equation 4.3.

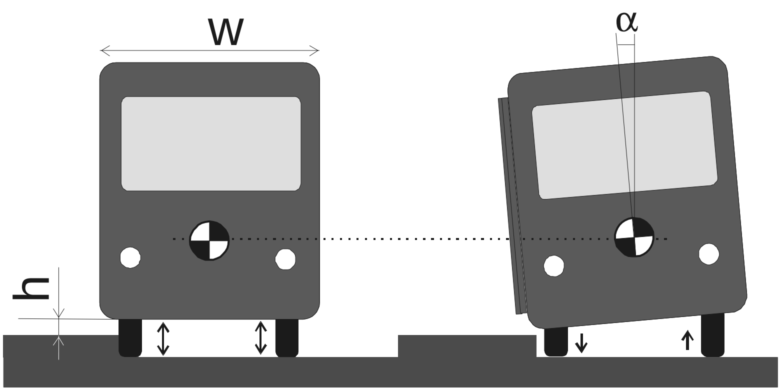

Figure 48: A suspension alternative.

$$\left.\begin{array}{l} w = 2.40\ m \\ h = 2 \cdot 65 \cdot 10^{-3} m \\ \alpha = ?° \end{array}\right\} w \cdot \sin(\alpha) = h \Rightarrow \alpha = 3° \qquad (4.3)$$

Thus, when the position of the centre of gravity is not changed a minimum of input power is needed to perform the “kneeling”. This alternative would be simple to realize with an electro servo system. However, the passenger comfort must be respected when the bus are “kneeling”, in particular as the floor angle is doubled for the same reduction of *h* when the centre of gravity is maintained.

The improved system (the new “Ecas system”) in Figure 49, controls the suspension of the bus. The model design is equal to the pneumatic model where the front of the bus are level adjusted, with the exception: electric power is consumed instead of air. This model does not use the advantage with the centre of gravity maintained. When the bus front rises in the end of a stop it will consume 75 A and 26 V for 3 seconds. With an efficiency of 55 % in the electric motor and hydraulics the energy consumption will be 5.6 kJ.

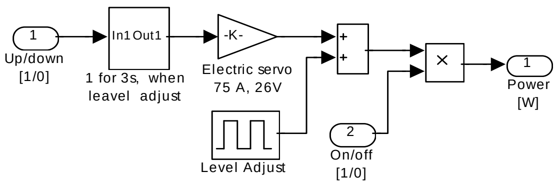

Figure 49: The subsystem Ecas (suspension) system of the NEW Doors Ecas & Parking.

Doors

The doors of the bus are operated by double acting control cylinders [6]. The action of the piston is transmitted to the door leaf. Alternating pressurization and depressurization of the two cylinders opens and closes a door. The closing force must be deactivated at to high travel resistance. The closing force must be limited to 150 N or be interrupted upon encountering resistance. In buses with more than 2 door pairs, the rear third door is controlled automatically. The driver only releases the door for passenger opening and automatic closing.

Reference system and model

A door energy and air consumption test in the fuel cell bus was performed. A pair of doors were opened and closed 10 times. The consumption of one single opening and closing operation was 21 l_n.

The doors are opened at the bus stop and subsequently closed just before leaving the bus stop. The “Door system” of Figure 50 uses the Busstop information; when it shifts from 0 ⇒ 1, the door is opened at the beginning of the bus stop and when it changes again from 1 ⇒ 0, the door is closed at the end of the bus stop. In the gain module “two doors” there is a variable “Doors” that sets the number of doors pairs used when stopping. This variable is set in the m-file.

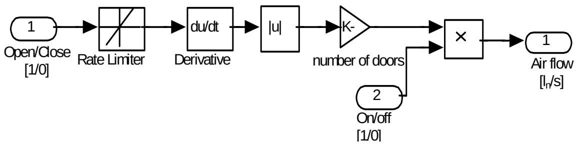

Figure 50: The subsystem Door system of the Air system.

New improved system

The use of electrically powered doors is increasing. The two largest manufacturers of electric doors systems are: Bode GmbH & Co KG, Europe and Vapor Bus International, North America [45].

An electric prime mover transmits motion to the door through connecting rods and door shaft levers. The mover limit the doors forces, regardless of the door position.

The advantages of electrically operated doors are:

- Low energy consumption.
- No air tubes and air leakage.
- No maintenance components.

The drawbacks are that they are not as reliable from the operator point of view as pneumatic doors.

The improved doors, see Figure 51, are opened and closed in the same way as the pneumatic door system. When the doors are opened and closed they will consume 3 A and 26 V during 3 s, corresponding to 230 J. In the gain module “two doors” there is a variable “Doors” that sets the number of pair doors used when stopping. This variable is set in the m-file.

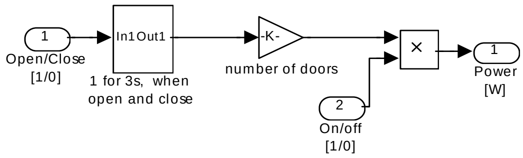

Figure 51: The NEW subsystem Door system.

Validation

Figure 52 shows simulated and measured data of the pneumatic system. The total airflow and the mean power consumption of the simulated and the measured bus are close to each other. Also the number of starts and stops of the compressor are equal. The air produced by the compressor, energy consumption and number of starts and stops are of high importance for the validation, but the time of the starts and stops has less importance.

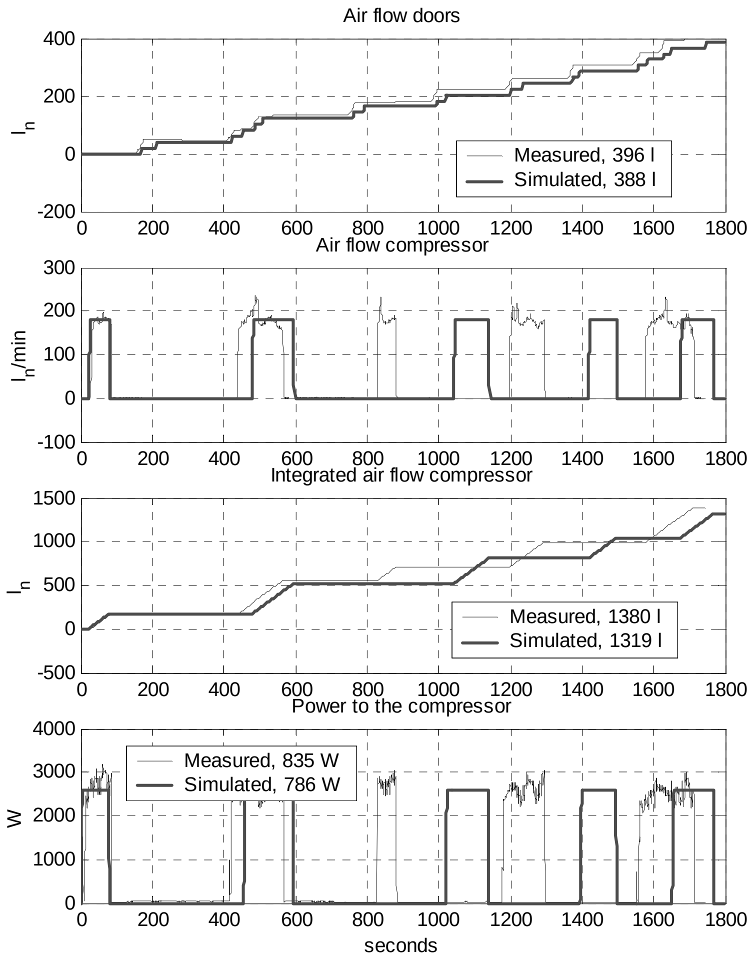

Figure 52: Validation of the pneumatic system, measured and simulated results.

4.5 Hydraulic steering systems

Two types of steering [6] have become established:

Rack and pinion steering consists of a rack and a pinion (sv: kuggstång och kugghjul), see Figure 53. The steering ratio is defined as the number of steering wheel revolutions to rack travel. The number of teeth can be adjusted to change the steering ratio and the force of the steering wheel.

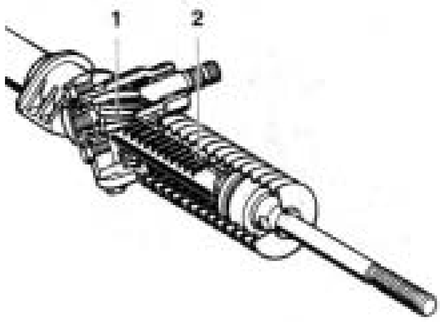

Figure 53: Pinion (1) and Rack (2).

With *recirculating ball steering* (sv: styrsnäcka), Figure 54, the forces generated between steering worm and steering nut are transmitted via low friction recirculating row of balls. The steering nut acts on the steering shaft via gear teeth. The steering box can change the ratio by changing the number of teeth.

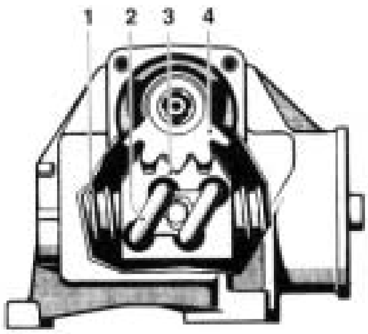

Figure 54: Steering system, Steering worm(1), recirculating balls(2), steering nut(3), steering shaft with gear teeth.

Power assisted steering

Hydraulic power assisted steering

A vane (sv: centrifugal) pump powered by the engine or an electric gear or roller pump on smaller vehicles, is the energy source in the system. The pump must be dimensioned so that it is possible to turn the steering wheel when the engine is idling. The temperature of the oil in the circuit may not exceed 100 ºC. The system also contains an oil reservoir, flow regulator and control valves. An electric powered pump is easier to locate in the modular design.

Electric power assisted steering

It is possible to use an electric power assisted steering in small and medium sized cars. The electric servo unit works directly on the pinion of the steering gear, see Figure 55. Only the torque exerted on the steering wheel is transmitted via the steering column, intermediate shaft and universal joints. The sensors and torsion bars sit directly on the steering gear pinion. The advantages for the driver, compared to the normal hydraulic system, are more precision, improved ride comfort and safety. Other advantages are: 80 % power savings compared to standard hydraulic power steering systems, power supply independent from vehicle's engine and no maintenance. Depending on the vehicle type various installation alternatives are possible. Additional performance potential is available for larger cars if the vehicle power supply increases from 12 V to 42 V.

The electric power assisted steering will probably be the best solution for a hybrid electric vehicle with high voltage. The electric power assisted steering is not available on the market for commercial vehicle.

Figure 55: Pinion electric power assisted steering system.

Hydraulic electric power steering

Hydraulic electric power steering use a combination of an electric motor driven hydraulic pump instead of an engine shaft driven operation, see Figure 56. The steering will not be dependent on the power supply from the vehicle engine. Driving characteristics will be as a standard hydraulic power steering system. The power-savings is about 70 % compared to standard hydraulic systems. This steering system will also be suitable for hybrid vehicles. The drawbacks are that such a system needs more maintenance and is more power consuming.

Figure 56: Hydraulic electric power steering.

Law requirements

The steering system of vehicles is regulated in a European Directive. The regulations aspects are:

- Fast response
- Operating force
- Road surface damping
- The steering wheel should go back to neutral position

The steering system has some unique requirement of the performance quantities:

- No playing in the straight position.
- Low friction
- High rigidity.
- Readjustment ability

Some of these requirements are not so easy to combine; this is the reason why only two types of steering have become established to this date.

A European directive defines three types of classifications of steering system:

- Muscular energy steering system, which is only powered by human, used in small vehicles. This system is used in small cars and lighter vehicles.
- Power assisted steering system that uses both the human driver and the source of energy. For example is used in higher speed vehicles.
- Power steering system that uses only the source of energy in the vehicle. This system is not used in vehicles that can move faster than 50 km/h.

Reference system - open loop

The present hydraulic steering system, the Open loop system, the hydraulic pump is always operating and the oil is constantly flowing regardless of whether the steering wheel is moving or not [3]. This generates a large amount of heat and wear on the hydraulic system and the engine or electric motor. Only the pressure difference will vary with the steering power. If the pump is driven by an electric motor, like in a hybrid vehicle, the constant flow on even more losses as the electric motor has low efficiency when the load is close to zero.

In the fuel cell bus the hydraulic pump is driven by an electric motor, powered by the high voltage grid, via a DC/AC inverter, see Figure 57. The total idling losses were measured to be 0.5 kW, including idle losses of the electric motor 0.2 kW and the servo pump 0.3 kW. These values were close to the average energy consumption when measured over a full drive cycle. The electric motor was a 3-phase asynchronous machine, 2.2 kW, 1390 rpm. The servo pump produces 12.6 l/min at 1400 rpm. The hydraulic system on the fuel cell bus is an open loop system with constant oil flow. A closed loop system would consume less energy.

Figure 57: The servo pump and the electric motor.

A power steering system test is displayed in Figure 58, where the power steering was tested at different speeds.

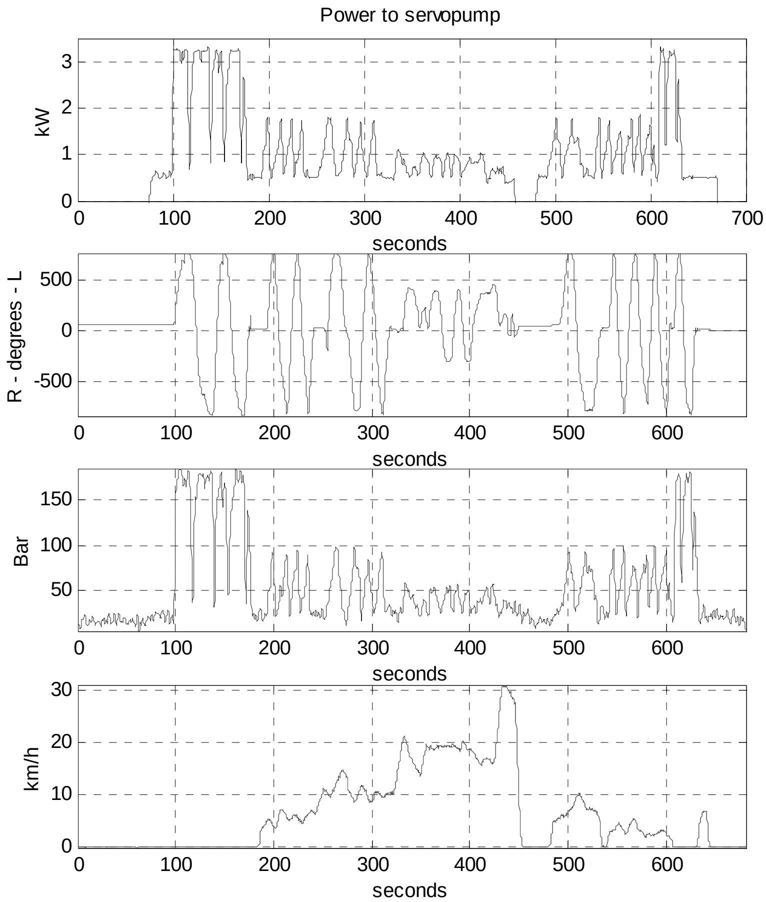

Figure 58: Measurements of the power steering system test at different speeds of the hybrid fuel cell test bus. The first subplot shows power to the electric motor as function of time, the second subplot the steering wheel angle as a function of time, the third subplot hydraulic pressure as a function of time and the fourth subplot bus speed as a function of time.

The speed of the hydraulic pump is close to constant, only varying some percent over the load curve of the electric motor. Consequently the power consumed by the hydraulic sub system must be close to proportional to the hydraulic pressure in the system.

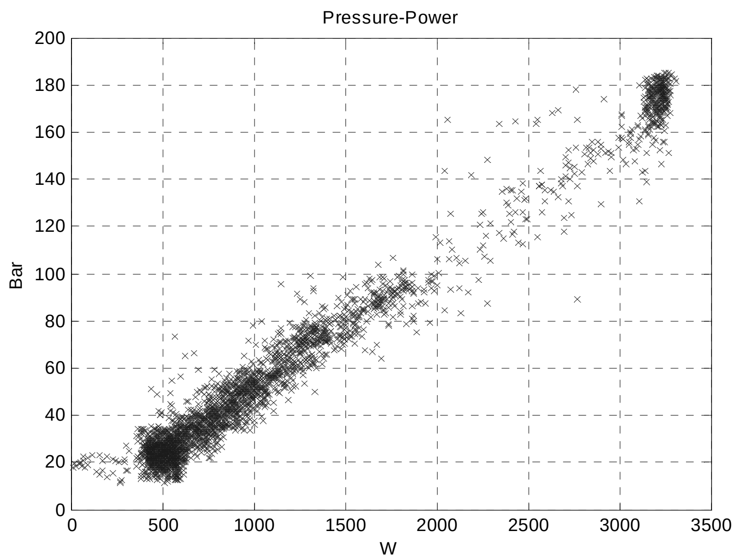

Figure 59: Power versus hydraulic pressure.

In Figure 59 the hydraulic pressure as a function of power to the hydraulic sub system is displayed. The plot shows the proportionality between the hydraulic pressure and the power consumption. An idle pressure of approximately 20 bars shows the resistance in the hydraulic steering system. The range of the current sensor is ±6 A, which is equal to ±3.2 kW, why all measurements above 3.2 kW are non-proportional.

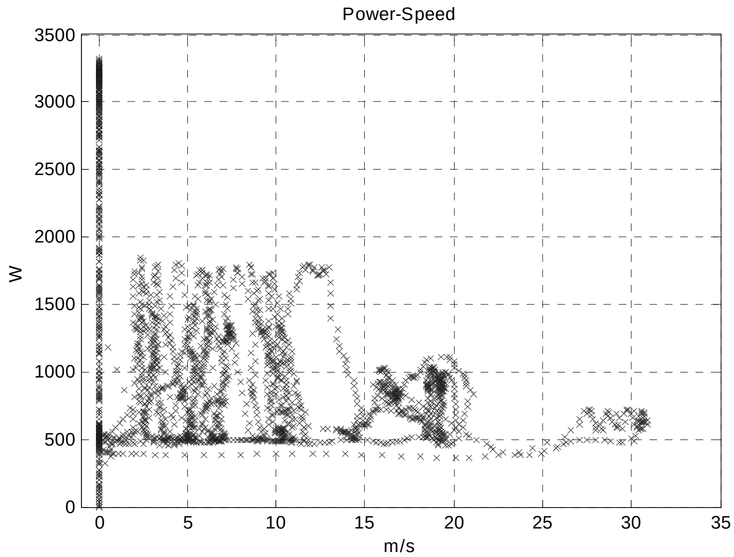

Figure 60: Power consumption dependence on speed.

In Figure 60 the power consumption as function of bus speed is showed. At standstill the peak power consumption is very high. At different speeds there is a rather linear relationship with decreasing power consumption at increasing speed. The power consumption and maximum power requirement are also very dependent on the ground surface.

The “Steering system” model in Figure 61 uses look-up tables with input speed of the vehicle [m/s] that is used to get the power consumption. A switch controlled by the variable **acc_NewSystem** (set in a m-file) chooses between the closed loop and open loop steering, see next paragraph. The steering power output is set in a m-file. The electric load [W] is output of “Steering system” block.

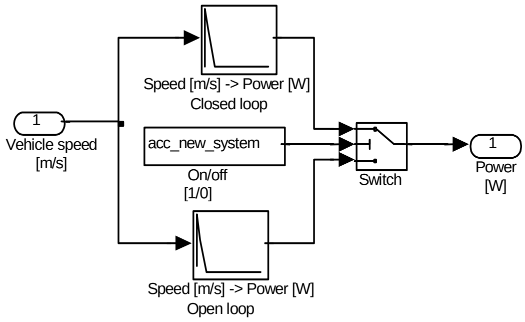

Figure 61: The Steering system of the electric model.

The primary advantages of an open loop system are the lower cost. Further more the components are already available on the market.

New improved system - closed loop hydraulic system

The alternative to an open loop hydraulic system is a closed loop system. In the closed loop hydraulic system the pressure is constant and the flow of oil varies with the power consumption of the steering [3]. The hydraulic oil is only pumped when the steering wheel is turned leading to less wear and heat generation. As the closed loop system is sealed there is less risk of debris getting into the hydraulic system that would result in accelerated wear on the system. The reduction in the heat and wear generated leads to a more reliable system.

The closed loop system also has drawbacks. The closed loop hydraulic system compared to an open loop system has a substantially higher component costs and need for a higher level of oil maintenance and service [37].

4.6 Electrical systems (12 V & 24 V)

The electrical system has a voltage of 12 V in small cars and 24 V in commercial vehicles [7].

Most vehicles are equipped with open lead-acid batteries where it is possible to refill the electrolyte with water. In some demanding applications sealed lead-acid (e.g. Optima) are used, having a higher power density and higher cost. The battery capacity is rated in Ah. In small cars the size of the battery is approximately 50 Ah (12*50 = 600 Wh).

Commercial vehicles use two 12 V batteries connected in series. The capacity is usually as high as 200 Ah (24*200 = 4800 Wh). The battery must supply the starter motor with sufficient electric energy in a limited duration during all conditions. Critical conditions are outside temperatures and load variations by engine idling. The voltage of the battery should be as stable as possible.

The alternators are all engine mounted and are driven by a belt. The current from the alternator increases with the speed.

Important alternator requirements are:

- Supply to the electric system with enough current and constant voltage during all conditions (low speed - high consumption).
- Robust design, in the aspect of vibration, dirt and high temperature.
- Minimal operating noise.
- Low weight, small dimensions and long service life.
- High efficiency.

The development has gone from DC to AC generator with rectifiers. The latter are also referred to as alternators and are cheaper with 50 % less weight. The construction varies depending on the application between claw-pole, compact, and salient-pole alternators. A diode rectifier converts the three-phase alternating current into direct current. The diodes also prevent the battery from discharging when the engine is stopped. A large-scale alternator application becomes feasible with the introduction of low cost, powerful silicon diodes.

In small cars the alternator is air-cooled, see Figure 62. The price is under 1000 SEK for this kind of alternator [29]. An integrated fan or an attached radial fan supplies the alternator with the airflow. In a commercial vehicle the entire collector-ring and carbon-brush assembly is usually encapsulated in order to prevent dust, dirt and water to penetrate the system. The lager alternators for commercial vehicles are hand made, which makes the price increase by three times compared to an alternator for small cars [29].

There are always losses when converting mechanical energy to electric. A normally operated alternator has the average efficiency of 50 %. At higher speeds the efficiency decreases. The losses are related to iron losses (hysteresis and eddy current), copper losses (resistance in the windings), friction (bearings) and aerodynamic losses (cooling fan) [2]. The relatively high losses are compensated by the lightweight, compact design and low investments costs. More emphasis should be placed on optimization of the efficiency than on optimization of its mass. Any load supplied with electric power suffers from low system efficiency due to the low generator efficiency. An industrial drive electrical machine of the same rated power can have an efficiency of at least 80-90 %, i.e. there is room for significant improvement of the generator efficiency.

The maximum output current from alternators vary from 80 A (80*14 = 1.1 kW) in small cars to 300 A (300*28 = 8.4 kW) in larger buses. The charging capacity at idling speed is 50 % of the maximum power. The demand for electric power in vehicles is increasing as more electric auxiliaries are connected in the vehicles.

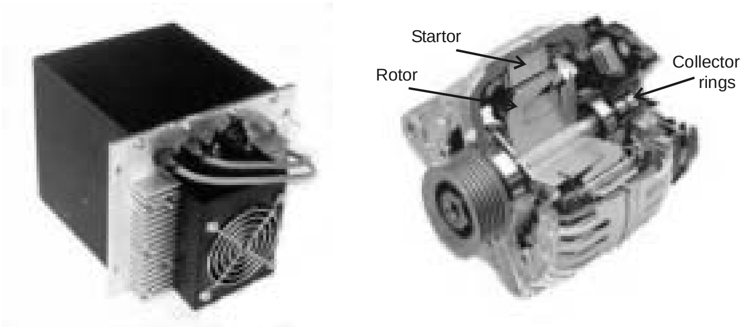

Figure 62: DC/DC converter from Brusa and an alternator for small cars from Bosch.

In a hybrid vehicle a DC/DC converter will be used instead of an alternator [9]. A DC/DC converter has no moving parts accept for a small cooling fan, see Figure 62. All transformations from high voltage to low voltage are done by power electronic components. The efficiency will rise dramatically if it is possible to use a DC/DC converter instead of an alternator. A DC/DC converter converting power from 500 V to 12 V will have an efficiency of about 90 %. There is a Swedish DC/DC manufacturer called Nira Components AB. They supply very compact liquid cooled high power DC/DC for automotive application [33].

Table 4-2 Technical Characteristics of a DC/DC converter

Max. voltage capacity	900	V
Operating input voltage range	250-750	V
Output voltage	11-14.5	V
Max. output current	125	A
Continuous output current	80	A
Standby power consumption	< 1	W
Degree of protection	IP54	
Efficiency up to	91	%
Weight	3.5	kg

New improved system - Higher voltage (42 V) and improved efficiency

The mechanical load of the alternator can be reduced by increasing the efficiency of the alternator (electric load to mechanical load). An efficiency of realistic 88 % would be possible compared to now day's efficiency of 50 %. As more and more electric load is used in the vehicles the efficiency of the alternator will be important. Some of the components in a high efficiency system require liquid cooling. Such an alternator has less noise (no fan), and is sustainable for higher temperature and is waterproof. The drawback is of course higher installation and components costs [29]. Some of these power electronic components are also used in the 42 V system. When (if) the 42 V system is used in the small cars the component cost will decrease significantly. The potential for changing to an improved alternator will increase when the fuel price goes up and the component price goes down.

One way of reducing the losses in the system is to decrease the current (and the losses) by increasing the voltage in the system. Previously 42 V has been an option. Due to practical problems with installation like electric arcs and EMC (electro magnetic compatibility) the 42 V is emerging slowly with the vehicles manufactures.

Meanwhile, a higher voltage in the electric system than the 42 V has been discussed. The high voltage system would accept even larger electrical loads like electric driven AC and heater and electric assisted steering.

Consumers in the electrical system

The consumers in the 24 V system are:

- Fans, AC cooling and other compartment fans (max 2.8 kW).
- Head lights
- Wipers
- Driveline control system
- Fuel converter systems.

The consumers of the 24 V system in the hybrid fuel cell test bus are showed in Figure 63. During these tests the bus was not equipped with AC system.

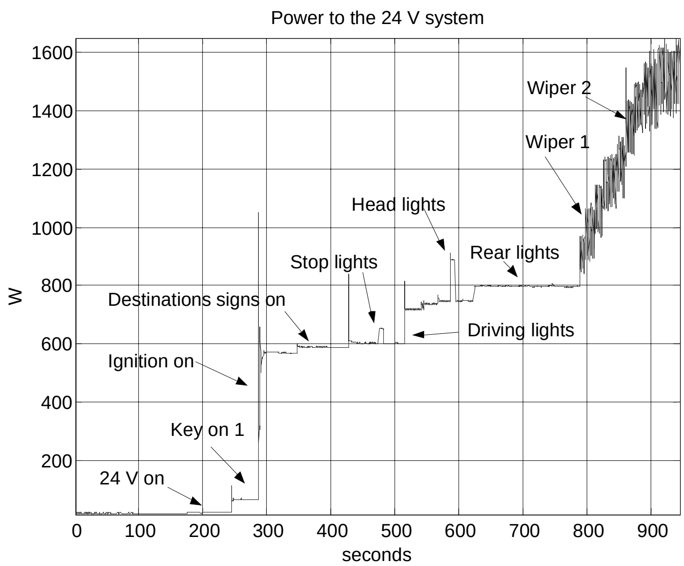

Figure 63: Results from 24 V system test.

"24 V on" indicates that the main switch for the 24 V battery is on. Than the key is switched on at the first stage, only some small consumers like lamps and radio are activated. The "Ignition on" means that the key is turned to the second stage and all computer control systems are activated.

The consumption of the control systems is considerable, more than 400 W. Then some of the lights, fans and wipers are tested. The large wipers in the front window uses up to 800 W, one of the reasons for the large power consumption is that the window was dry.

Reference system

The currently installed system in the conventional vehicle is a 280 A alternator. The characteristics of the alternator are shown in Figure 64.

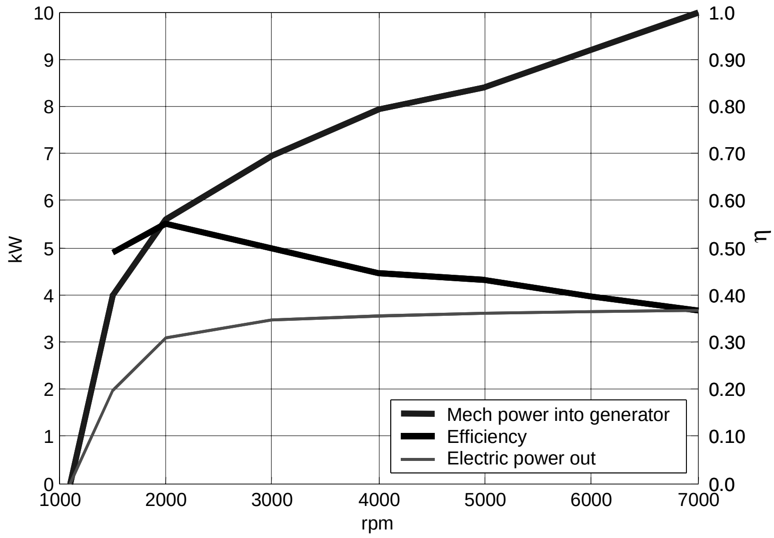

Figure 64: Alternator characteristics, alternator speed versus capacity and efficiency. The alternator to engine coupling is 3.02:1.

The “24 V system” model in Figure 65, is the same for the conventional and hybrid model, with the exception that in the hybrid model the engine speed is not used. In the 24 V system model the consumption and the production of power in the 24 V circuit are added. The sum is fed to a battery. The inputs to the 24 V system are the electric power Consumption [W], the engine speed [rpm] (conventional only) and the Power control [0/1]. The consumed power [W] is subtracted from the Produced power [W] of the alternator or DC/DC. This value is multiplied with the battery efficiency, Charging or Discharging, positive or negative power for the battery. An integrator block is used as a battery model. The battery size, initial SOC (State Of Charge) and charging efficiency are set in the m-file. Finally the present battery energy is related to the full charged battery energy to calculate the SOC of the battery.

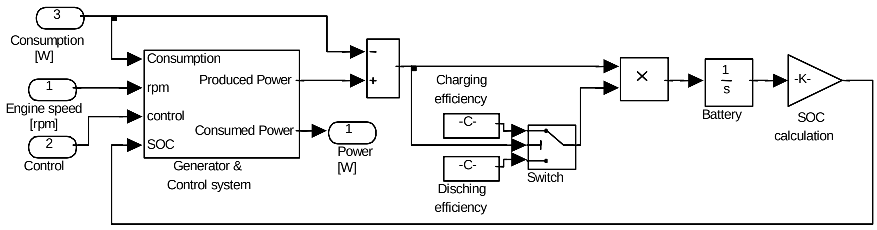

Figure 65: The subsystem 24 V system of the mechanical model.

In the “Generator & Control” system of the conventional vehicle in Figure 66, the the efficiency and mechanical power consumption of the alternator are calculated. The engine speed is used in look-up tables for alternator efficiency and mechanical belt load. The alternator parameters are set in the m-file.

The system performs two different calculations, and the selection is made by the parameter **acc_ControlOnOff** [1/0] that is set in the m-file. Both systems contain control algorithms for the alternator.

In the first system the alternator delivers the consumed power, if possible. If the alternator cannot deliver the requested power at a certain rpm, the SOC Controller will limit the alternator to deliver its max power. In this way the SOC variations of the battery within limited range. The battery limits are set in the m-file.

In the second system the battery SOC is used for controlling the energy of the battery by switching on and off the alternator [1/0]. If the regenerated power in the propulsion system [W] is larger than the mechanical load of the alternator [W] the Regen Controller [1/0] switches on the alternator. If the power consumption of the propulsion system is large the alternator is switched off. The different conditions [1/0] are multiplied with the mechanical load [W] to calculate the consumed power of the alternator [W]. The Produced power [W] of the alternator is calculated by multiplying the alternator efficiency [%] with the Consumed power [W].

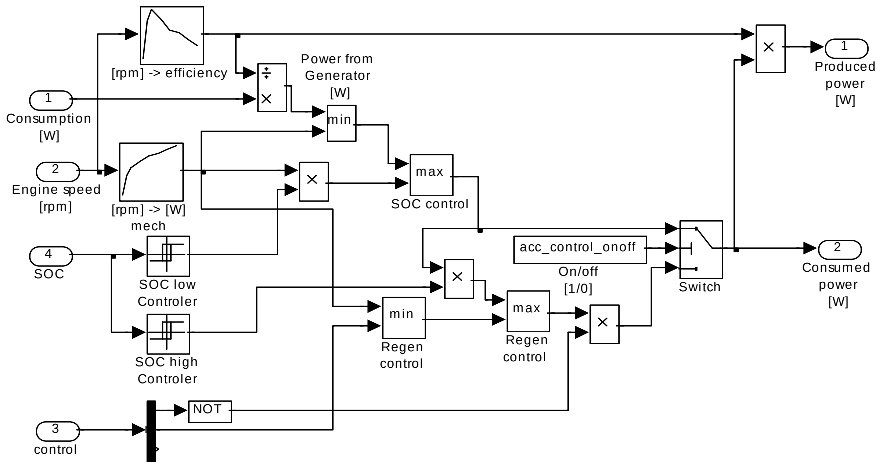

Figure 66: The subsystem Generator & Control system, 280 A, 24V of the 24 V system

The "DC/DC & Control system" of the hybrid vehicle in Figure 67, contains an algorithm for the control of the DC/DC converter. Inputs to the DC/DC & Control system are battery SOC [%] and Power control [1/0]. If the battery SOC [%] is low/high the DC/DC converter is switched on/off. If the power consumption of the propulsion system is large (80 % of the peak fuel converter power) the DC/DC is switched off. If the regenerated power in the propulsion system [W] is greater than zero the controller switches on the DC/DC unit. The DC/DC power in the regenerated case has to be smaller than the regenerated or DC/DC maximum power. The power is multiplied with the DC/DC efficiency and the power production is calculated. The DC/DC efficiency and the limits for the SOC Controllers are set in the m-file. The power used when regenerating is also calculated and logged.

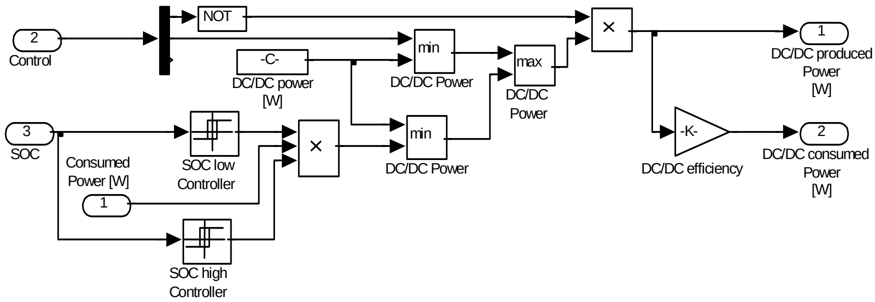

Figure 67: The subsystem DC/DC & Control system of the 24 V system.

4.7 Cooling systems

Consumers

The cooling demand of the engine is large [38]. It is also very depending on the load and the climate where the vehicle is used. When the engine is producing 100 kW on the crankshaft it also produces approximately 200 kW of heat. One part of the heat exits together with the exhaust gases, approximately 100 kW. The rest is directly cooled by the surrounding air and by the cooling system, approximately 100 kW. The size of these fractions does of course vary widely depending of the working point. Almost all passenger cars and heavy-duty vehicle engines are water-cooled. Antifreeze (glycol) and corrosion inhibitors are added to the water in the coolant mixture. The cooling system consists of: a water pump that makes the coolant circulate in the circuit, coolant radiator, cooling fan, and a radiator tank that ensures that the coolant is distributed through the blocks, see Figure 68. In most vehicles the water pump is connected via a belt to the crankshaft of the engine. The cooling system normally consumes 3-4 % of the energy output from the engine.

The retarding system in commercial vehicles is often equipped with an alternative brake system, retarder or exhaust brake. These systems may be used for example when going down a steep hill. The retarder / exhaust brake may be operated in two different ways: with the control lever on the instrument panel or with the brake pedal. The brake pedal function can be disengaged with a switch.

The hydraulic retarder delivers a high braking torque, 3000 Nm. The high braking torque enables the driver to maintain higher speeds on long descents without inflicting wear on the service brakes. The retarder creates a great deal of heat when braking which has to be cooled by the cooling system. The retarder is a compact unit mounted integrally with the rear section of the gearbox.

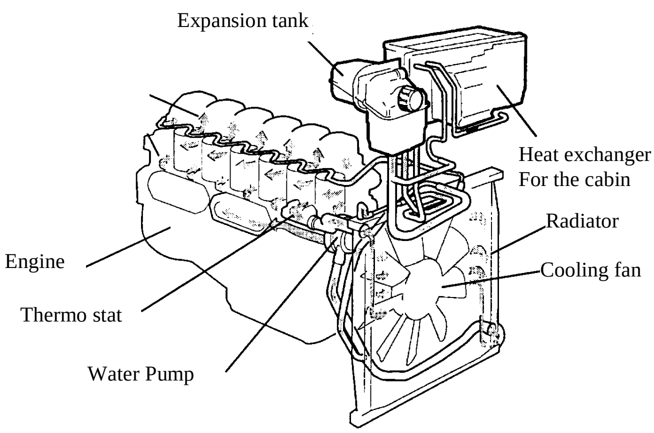

Figure 68: The engine cooling system.

Despite the wide range of climate conditions and the fluctuation of the engine loads, the temperature must remain in a narrow range. A thermostat incorporated with an expansion tank is used to control the temperature, independent of the pressure variation in the cooling system, performs the control of the coolant temperature.

The design factors involve minimizing the fan power and aerodynamic drag and maximizing the airflow to the radiator. If the size of the radiator is increased, the size and power consumption of the fan will decrease. The cooling fan is driven directly by the crankshaft via an electro-mechanic clutch or a Visco coupling. The Visco coupling is the most common one in heavy vehicles in Europe. It is controlled by the thermal management system and is used to reduce the fan speed to the optimal speed, see Figure 69. The Visco coupling slips so that the outgoing speed of the fan is lower than the incoming. The coupling transmits a torque to the fan that is dependent of temperature in the coolant. The cooling fan speed has a large influence on the power consumption while the relation between power consumption and speed is cubic. The radiator must provide a reliable thermal transfer discharge of the engine heat to the surrounding air.

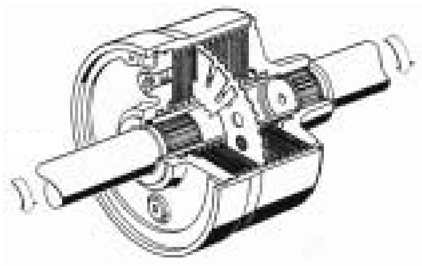

Figure 69: The Visco coupling of the engine cooling system.

In a hybrid vehicle there are more than one coolant circuit. The engine or fuel cell has a higher temperature and the electric motor, battery and electronics have separate liquid cooling with lower temperature. All cooling fans in hybrid vehicle can be electric powered since electric energy is available.

In common bus chassi layouts it is not possible to connect the fan directly to the engine crankshaft, as the cooling radiator and fan are not placed in front of the engine. Instead of the direct drive, and Visco coupling, a hydraulic drive system is used, see Figure 70. The fan speed is also variable with this drive, but handled via hydraulic valves instead of a visco coupling.

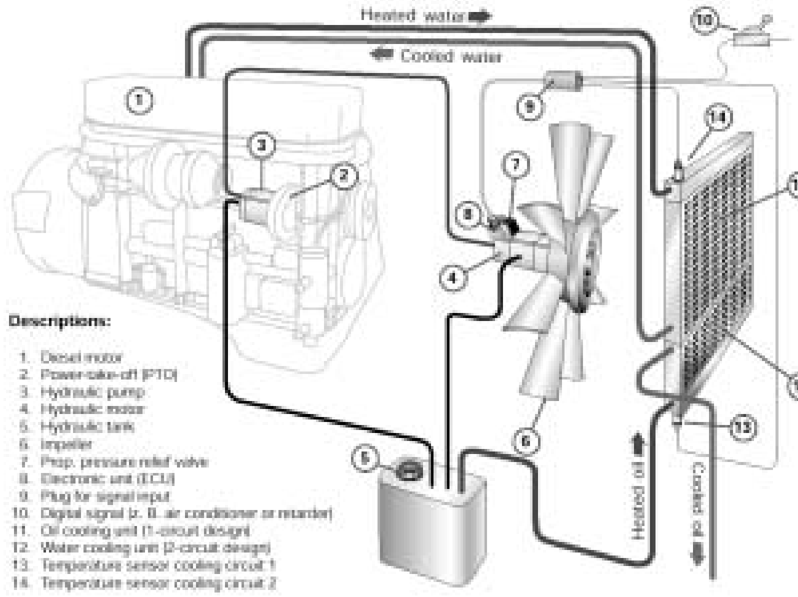

Figure 70: Hydraulic fan drive.

The engine is mechanically connected to the hydraulic pump. The latter drives the hydraulic motor that is mechanically connected to the fan. The relation between the hydraulic pump displacement [cc/rev] and the hydraulic motor displacement [cc/rev] represent the maximum gear ratio of the pump/motor. A bypassing (slip) valve controls the oil flow in the circuit. Slow speed of the hydraulic motor is achieved by opening the bypassing valve. From an efficiency and energy point of view it would be preferable to control the oil flow with a variable displacement pump instead of using the bypassing valve, which is subject to greater losses.

The efficiency of the hydraulic fan drive system is calculated from the mechanical torques and speed (power out) of the servomotor divided with the mechanical torque and speed (power in) of the servo pump. The maximum efficiency of the system is approximately 70 %. The efficiency will decrease when the bypassing valve is opened, and the power consumption of the fan will also decrease. The power consumption of the fan is dependent on the fan speed in cubic and the power consumption of the bypassing valve is dependent of the pressure drop and the flow, see equation (4.4). The pressure over the pump will be related to the square of the speed of the motor.

$$\left.\begin{array}{l} P_{pump} = P_{valve} + P_{fan} \\ P_{fan} \sim n^3 \\ P_{valve} = \phi_{valve} \cdot p \\ \phi_{fan} \sim n \\ \phi_{fan} = \phi_{valve} = \dfrac{\phi_{pump}}{2} \end{array}\right\} \Rightarrow p \sim n^2 \tag{4.4}$$

Reference system

The maximum power consumption of the cooling fan designed for the Scania DC9, 9 liter engine is plotted in Figure 71. The engine speed to hydraulic fan speed is 1:1.2. The displacement of the pump is 45 cc/rev and the displacement of the motor is 33.1 cc/rev, which makes the total engine to fan ratio will be (1.2*45/33.1) 1.63.

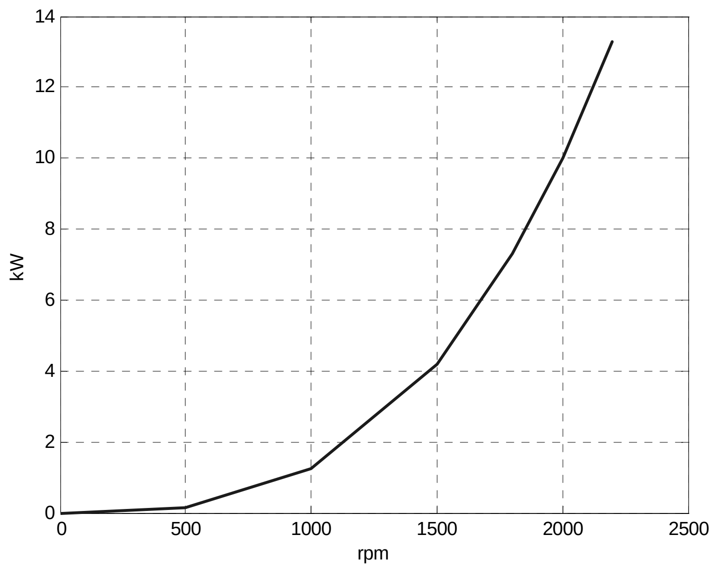

Figure 71: The Cooling fan maximum power consumption vs. fan speed.

In the simulation model of the “Cooling fan” in conventional vehicle, see Figure 72, the engine speed is used as input. The speed is changed with the gear ratio from the engine to the hydraulic pump. In the second step, adjustment is made according to the displacement ratio between the hydraulic pump and hydraulic motor. The speed of the fan is also compensated for the hydraulic motor slip and the speed limitation of the fan. The “Cooling fan” uses look-up tables with the speed of the fan [rpm] as input. The output from the look-up table is the hydraulic motor power [W]. The power is multiplied with the compensation for slip losses and efficiency of the hydraulic drive system (motor and pump).

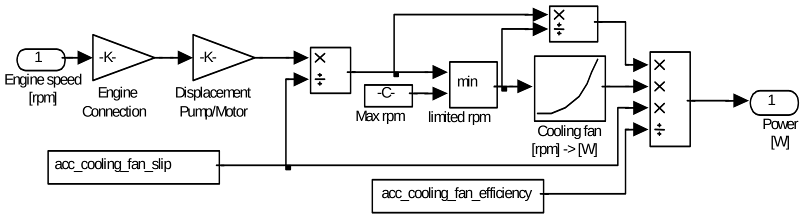

Figure 72: The Cooling fan model of the conventional vehicle.

For maximum cooling power in the hybrid fuel cell bus used a fan power of 1.3 kW. In the hybrid model the cooling fan is a constant load of 600 W. The load is set in the m-file.

Figure 73 shows the electric driven water pump used in the fuel cell bus. The “Water pump” is modelled as a constant load of 200 W for the conventional and hybrid model. The load can be changed in the m-file.

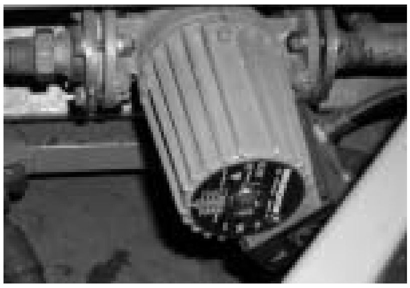

Figure 73: The Water pump used in the fuel cell bus.

4.8 Control of the auxiliary systems

The “Power calculation” module, see Figure 74, controls the power of the auxiliary systems with respect to the power in the propulsion system. When large power requests or regenerative (negative) power is available, a control parameter is set to 1. The input variables to the Power calculation system are the propulsion system power [W], the engine speed [rpm] (not in Electric aux.) and the power consumption of the auxiliary systems, except for the alternator (DC/DC

In the block “Power slip Conventional” compensation is made for the closed throttle power of the ICE. When the bus is braking the ICE also brakes. The ICE uses friction power when it is kept running by the wheels via the gearbox. In the electric (hybrid) auxiliary module there is no Power slip block, because of the engine slip.

The Power calculation system computes three different parameters for the AC, alternator and compressor:

- The first parameter controls the peak shaving. If the propulsion system requests a large amount of power, more than a limit of fuel converter peak power the first parameter is set to 1. If the power of the propulsion system decreases below 20 kW the limit the parameter will be changed to 0.
- The second control parameter controls the alternator. When the bus is braking the alternator uses the remaining power after all other non-electrical systems have taken their part of the available braking power.
- The third control parameter turns from 0 to 1 when regenerative power is available. This is used for controlling the AC system and the compressor. The control limits, high propulsion system power and regenerative power are set in the m-file. The limit for turning on the control signal should be the same as the AC system and compressor power, approximately 20 kW. A hysteresis level of 50 % of the turn on level should be used a s turn of level, to limit switching on and off of the AC system.

The control information can be switched on/off by multiplying with **acc_ControlOnoff** [1/0], which is set in the m-file.

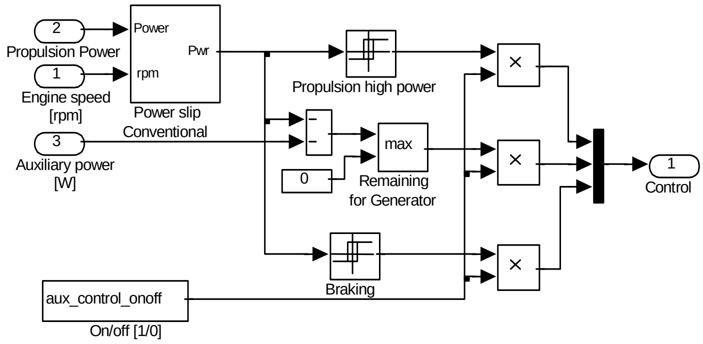

Figure 74: The subsystem Power calculation.

The "Power slip Conventional", see Figure 75, compensates for the engine slip when the bus is braking in the Mechanical aux. module. Propulsion system power [W] and engine speed [rpm] are inputs to the "Power slip Conventional". In the block "Power slip Conventional" compensation is made for the closed throttle power of the engine and calculated in a look-up table. The engine slip occurs when the propulsion system power is negative. The remaining power after the slip compensation may not be larger than zero. The selector <0 kW connect the slip function when the propulsion system power is negative.

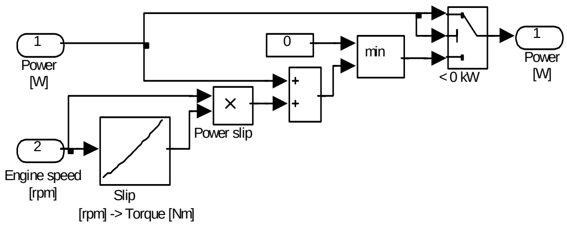

Figure 75: The subsystem Power slip Conventional of the Power calculation.

4.9 Summary

The AC system has the largest Control potentials. It is possible to turn on and off the system within reasonable passenger comfort limits. The power range is 0 to 30 kW. The new electric powered AC system with carbon dioxide would be a large improvement both for the conventional and hybrid vehicles.

The largest improvements would be to change as many as possible of the pneumatic system consumers to other more efficient energy carriers, e.g. electrical assisted doors, alternative electric/hydraulic suspension and parking brake. It is possible to use the proposed concept “Control” with the compressor in the pneumatic system. The power consumption of the compressor is 0 to 13 kW.

The electric system (12 V & 24 V) has large improvement potentials to use the proposed concept “Control”, with improved efficiency of the alternator and with higher voltage. The power consumption of the alternator is 0 to 20 kW and the DC/DC consumes 0 to 6 kW.

The hydraulic steering system is not possible to involve in the proposed concept “Control”. An option would be to make a closed loop hydraulic system or for a hybrid vehicle electrical assisted steering.

The cooling system is difficult to improve with the proposed concept “Control” and efficiency improvements. The system is very dependent of the climate and the driving conditions.

Chapter 5

Simulation results

In this chapter, some results from the simulation studies and cost calculations for two different bus driveline configurations are presented, the conventional bus and the series hybrid ICE bus.

5.1 Conventional bus

In Table 5-1, the simulation results for the auxiliary systems are presented for a conventional bus without AC system. The following cases are studied:

- The "**Reference"** case represents the standard system and control of a conventional bus, as described in Chapter 4. All improvements that will be done are compared to this reference case.
- In the Control case the auxiliary system has been controlled as described in Chapter 2, with peak shaving and with the intelligent timing of the loads.
- The "**New"** case uses conventional control as in the "Reference" case but with more energy efficient auxiliary systems, see Chapter 4.
- The "**New+Control"** case combines the control methods of the "Control" case with the more efficient auxiliary systems of "New".

The "Reference" case for the auxiliary system of the conventional bus is composed of different mechanical loads that are connected to the engine. The "Reference" system for the conventional bus set-up includes:

- Open loop hydraulic steering with a mechanically (belt-) driven hydraulic pump;
- A belt driven alternator for the 24 V system;
- Pneumatic suspension, brake, parking brake and open/close assistance of the doors. A compressor produces the compressed air. The compressor is mechanically connected to the ICE;
- A hydraulic drive system for the ICE cooling fan. The hydraulic pump is mechanically connected to the ICE;
- A mechanically driven water pump.

The "New" system that uses more energy efficient auxiliary systems than the conventional bus includes:

- Closed loop hydraulic steering;
- Improved efficiency of the 24 V system alternator;
- Alternative electro-hydraulic suspension;
- Electrically driven opening/closing assistance of the doors;
- Electrically assisted parking brake;
- Reduced compressor size resulting from reduced air consumption and reduced off load power demand.

Table 5-1 Simulation results of a conventional bus without AC on the Braunschweig duty cycle. The average power of the auxiliary systems are showed. The right column shows the improved fuel economy for the bus, with the “Reference” as a starting point.

System set up	Steering [kW]	Cooling [kW]	Compr. [kW]	24V el. [kW]	Σ Aux [kW]	Improved fuel cons.
Reference	0.269	3.511	1.166	4.093	9.300	-.- %
Control	0.269	3.503	1.166	4.375	9.572	3.2 %
New	0.065	3.449	0.259	2.557	6.787	5.6 %
New+ Control	0.065	3.493	0.259	3.159	7.404	8.2 %

The Control case consumes more total auxiliary power (Σ Aux) than the “Reference”, but the total fuel consumption still decreases. The reason for the lower fuel consumption is that the auxiliary systems are running at full power when the bus is braking and the propulsion system power is for free.

On of the advantages with the Control is peak shaving, reduced power for the auxiliary systems and more power for the propulsion system. Table 5-2 shows simulation results with the peak shaving Control case, i.e. switching off (if possible) the auxiliary systems when more than a limit (160 kW) of the fuel converter power is requested by the propulsion system. The Control does reduce the power requirement for the propulsion system and the auxiliary systems by 5–14 kW compared to the “Reference” set-up, depending on the AC duty cycle. The consequence of the peak shaving (Control) is improved acceleration and performance of the bus. The acceleration improvements due to the peak shaving of the bus are largest when the AC is in operation. The acceleration improvement is 8.7 %, for an acceleration 0-50 km/h, when the AC is running 75 % of the time.

Table 5-2 Peak shaving (Control) effects of a conventional bus on Braunschweig cycle and acceleration test 0-50 km/h.

AC duty cycle [%]	Peak power req. Propulsion+Aux. [kW]		Reduction of peak power [%]	Acceleration. 0–50 km/h [s]		Improved Acc. [%]
	Reference	Control		Reference	Control	
0	239	234	2.1	14.4	14.0	2.8
75	250	234	6.4	17.3	15.8	8.7

The “New” more energy-efficient auxiliary systems save a total of 2.5 kW or 27 % of the power for the auxiliary systems, see Table 5-1. The largest energy savings will occur at the 24 V system with improved efficiency of the alternator (55 % improves to 88 %), see Chapter 4.6. The reference 24 V alternator consumes 4.1 kW compared to new alternator that consumes 2.5 kW, with the same output.

In the second place of the energy saving potentials comes the compressor or pneumatic system, which are replaced by an electric system. In Table 5-3 the pneumatic systems of the “Reference” bus are compared to the “New” more energy efficient technology that is selected, see Chapter 4.4. The improvement of the power consumption in a Braunschweig duty is showed. The improvements by changing the systems will be similar for the hybrid bus.

Table 5-3: Improvement by changing the pneumatics to electric/hydraulic.

System	Pneumatic [W]	New electric [W]	Improvement [%]
Doors	230	20	91
Suspension	260	25	91
Parking brake	150	10	93

The open loop hydraulic steering system that is replaced by a closed loop system, without idling losses, comes at the third place of the energy savings potentials, see chapter 4.6.

The combination “New+Control”, without AC, will improve the total fuel consumption of the conventional bus by 8.2 %.

Other alternative improvement

With the Control case the improvement depends on the size of the buffers and the suppliers. The capacity of these systems should be large enough to accommodate all available braking energy in normal operating conditions.

Increasing volume of the air tanks in the pneumatic system has no effect on the fuel consumption. As the air tanks are not over charged when the Control of the auxiliary systems is used with the pressure limits (7 – 10 bar).

A larger compressor will increase the fuel consumption and the losses during off-load will also be larger. A smaller compressor is more suitable if the air consumption is reduced. The compressor may not be too small. An important reason is legal demand for refilling the air tanks used for the brakes sufficiently quickly.

The ideal operating conditions for an alternator is if it only has to work while the bus is braking. In the Braunschweig duty cycle, without AC, the optimum output electric power would be:

$$\overline{P}_{24\,V\,out} = \frac{24\,V\ \text{Average electric power consuption}}{\text{Duty cycle regenerated power share}} \approx 10\,kW \quad (5.1)$$

The “Reference” alternator output has an average output power of 3.4 kW. If the size is increased 3 times to approximately 10 kW this will have positive influence on the fuel consumption, a reduction of 1.2 % for the Control set-up.

The buffer in the 24 V system, the battery, is large enough to accommodate the power variation.

AC system influences

The AC system is the largest consumer in the auxiliary system for the conventional bus. At full power the compressor will consume 13.4 kW of the mechanical load and the electric cooling fans 2.5 kW from the 24 V system. The 24 V electric power is produced by the alternator with low efficiency, 55 % in the “Reference” set up. In Figure 76 the improved fuel consumption related to the “Reference” set up in [%] as a function of AC system duty cycle is shown.

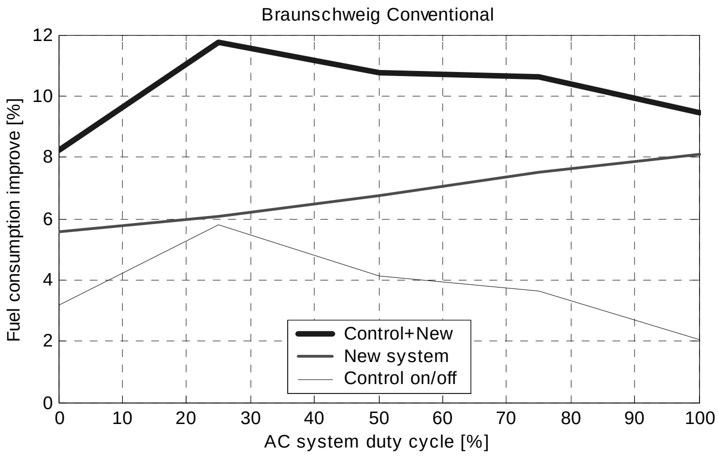

Figure 76: Reduction of fuel consumption on the Braunschweig cycle as a function of the AC duty cycle.

The improvement of the fuel consumption for the Control case reaches a maximum at 25 % AC system duty cycle. The explanation is that the regenerated braking power is available for the AC system during approximately 19 % (engine slip included) of the Braunschweig duty cycle. The generative value is lower for the conventional bus than for the hybrid bus. The reason is has to do with the engine slip. When the bus is slowed down, the bus also has to rotate the engine and the available regenerated power for the auxiliary system will decrease slightly.

The "New" systems fuel consumption improvements will increase as the AC system duty cycle increases, since the inherently better efficiency of an electric A/C dominates more at a higher A/C power. The load of the 24 V system will also increase as the cooling fans of AC system also load the 24 V system. The improved efficiency of the alternator compared to the "Reference" set up will be more important to the fuel consumption as the load on the 24 V system increases.

5.2 Hybrid bus

The simulated system specifications for the hybrid bus are:

- The **"Reference"** case represents the base hybrid vehicle, as described in Chapter 4. All the improvements are compared to this set-up;

- The **Control** case with control of the auxiliary system as described in Chapter 2, with peak shaving and use if intelligent timing of the loads;
- The **"New"** case with more energy efficient systems, as described in Chapter 4;
- The "**New+Control", which** is a combination of the "New" system and the intelligent control of the auxiliary system.

The "Reference" system for the hybrid bus set includes:

- An open loop hydraulic steering with an electrically driven hydraulic pump;
- A DC/DC converter supplying the 24 V system;
- Pneumatic suspension, brake, parking brake and opening/closing of the doors. A compressor produces the compressed air. The compressor is driven by an electric motor;
- An electrically driven cooling fan for the ICE or fuel cell;
- An electrically driven water pump.

The "New" system that uses more energy efficient auxiliary systems of the hybrid bus includes:

- Closed loop hydraulic steering with an electrically driven hydraulic pump;
- Alternative electro hydraulic suspension;
- Electrically driven opening/closing of the doors;
- Electric parking brake.

In Table 5-4, the simulation results of the auxiliary systems, except for the AC system, of a hybrid bus are presented.

Table 5-4 Simulation results for a hybrid bus on Braunschweig without AC. The mean power of the auxiliary systems is displayed. The right column displays the improved fuel economy for the bus, with the “Reference” as a starting point.

System set up	Steering [kW]	Cooling [kW]	Compr. [kW]	24V el. [kW]	Total [kW]	Improved Fuel cons.
Reference	0.537	1.700	0.856	2.154	5.247	-.- %
Control	0.537	1.700	0.869	2.378	5.443	0.2 %
New	0.067	1.700	0.037	2.219	4.022	3.4 %
New+ Control	0.067	1.700	0.046	2.449	4.261	3.5 %

The Control case consumes more total power than the “Reference” case, but the total fuel consumption is still lower. One of the reasons for this is that the 24 V battery power (both charging and discharging) will increase the battery losses. The battery is charged with full power when braking and not charged at all when accelerating. This will cause losses in the 24 V battery, but the losses will decrease by the same size in the driveline battery. The energy storage losses will then appear in the 24 V battery instead of the driveline battery.

In a hybrid bus there is less energy saving potential with the Control strategy since most of the kinetic energy is stored in the driveline battery thus reducing the corresponding potential benefits with storing energy in the other energy storages like the pneumatic tanks or the 24 V battery.

The “New” case with more energy efficient auxiliary systems save a total of 1.2 kW or 23 % of the power for the auxiliary systems. For the hybrid bus the “New” system set up alternative is the most energy saving alternative.

The largest energy savings potential appear will occur in the Compressor or pneumatic system, which is replaced by an electric/hydraulic system, see conventional bus Chapter 5.1 and Chapter 4.4.

The second largest energy saving potential appears in the open loop hydraulic steering system that is replaced by a closed loop system, without idling losses, se Chapter 4.5.

The combination “New+Control” will improve the total fuel consumption of the hybrid bus by 3.5 % compared to the “Reference” set-up.

AC system influences

At full power the compressor will consume 14 kW of the mechanical load and the electric cooling fans 2.5 kW of the 24 V system. The 24 V electric power is produced by the DC/DC inverter with the efficiency of 92 %. In Figure 77 is depicted the improved fuel consumption related to the "Reference" set-up in [%] as a function of the AC system duty cycle.

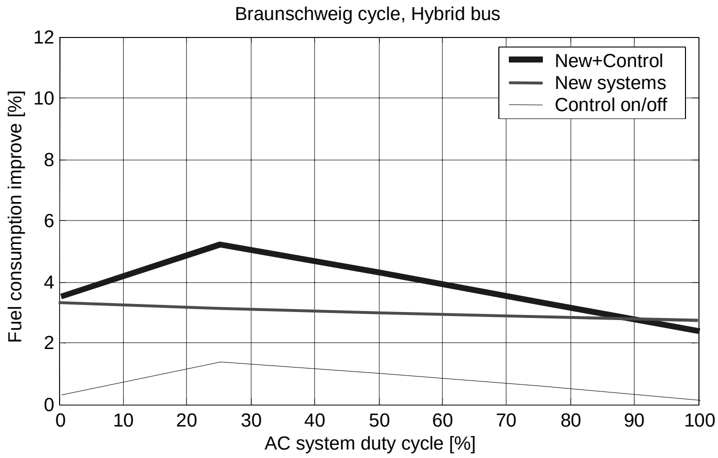

Figure 77: Reduction of fuel consumption on the Braunschweig cycle as a function of AC duty cycle.

The fuel consumption improvement increases for the Control guided systems when the AC system duty cycle goes from 0 % to 25 %. Further on, from 25 % to 100 % the improved fuel consumption decreases. The explanation for this is that the regenerated brake power becomes available during approximately 23 % of the Braunschweig duty cycle.

The "New" systems fuel consumption improvements will decrease as the AC system duty cycle increases. The explanation is that the fuel consumption of the bus goes up as the duty cycle increases and the AC system will dominate the power consumption of the auxiliary systems.

Alternative energy storage

The efficiency of the energy storage in a hybrid drive train is essential to the hybrid constellation. If there are no losses at all in the energy storage, the control strategy with use of the auxiliary systems when braking will be pointless.

A super capacitor is a good alternative to a battery as energy storage on an electric hybrid bus. In recent years the super capacitors have started to appear in experimental vehicles. Honda showed several hybrid cars (FCX) supplied with a super capacitor and a fuel cell in the power train at the EVS20 exposition in Los Angles, California, 2003 [23].

A super capacitor is good at handling high power exchanges (charging and discharging). The specific power density is higher than in a battery and the specific energy density is less than the batteries, see Table 5-5 [34]. This means that a package with 10 kg of super capacitors can maximally deliver 15 kW for 9.3 seconds. The power density and energy density of a lead acid (PbAc) battery, Exide Maxxima 900, used in the fuel cell hybrid bus is lower than that of the NiMH battery, seeTable 5-5 [14] [39]. The super capacitor system offers more than 30 % higher output power and more than twice the power density compared to the NiMH batteries. However, the super capacitor is not as suitable in handling large amounts of energy. The battery, as opposed to the super capacitor, is better in handling large energy flows, the energy flow is more than 10 times per kg in a battery compared with a super capacitor. The energy efficiency (charge/discharge) for a super capacitor is higher than for a NiMH battery, see Table 5-5 [34]. The energy efficiency decreases as the power rises, both for the super capacitor and for the battery.

Table 5-5 Energy storage alternative.

Energy storage	Energy density [kJ/kg]	Power density [kW/kg]	Energy efficiency [%]
Pb battery	126	0.38	85
NiMH battery	180	0.60	82-93
Super capacitor	14	1.5	90-97

In ADVIS0R it is possible to select a super capacitor and lead acid battery as energy storage. The lead acid battery, Exide Maxxima 900, has an average energy efficiency of (charge/discharge) 83 %. The super capacitor in the simulation program has a charge/discharge average efficiency of 89 %. These values include power electronic power losses.

Table 5-6 shows the simulation results of the fuel consumption improvements from two different hybrid buses with the Control stratege, one with a battery as energy storage and one with super capacitors as energy storage. The simulation results shows clearly that the improvement of the fuel consumption, due to the Control strategy, decreases as the energy storage gets more efficient.

Table 5-6 Fuel improvements compared to the “Reference” hybrid bus.

AC duty cycle	PbAc battery hybrid Control strategy	Super cap. hybrid Control strategy
0 %	0.2 %	- 0.1 %
25 %	1.2 %	0.9 %
75 %	0.8 %	0.6 %
100 %	0 %	0.6 %

The results of Table 5-6 are straightforward to explain. If the electrochemical or electrostatic energy storage has 100 % efficiency then there is no loss in intermediate storing energy there. Thus there is gain in using the same energy “fresh” as it is released in e.g. a deceleration. One to the higher efficiency of the super capacitor the benefits are lower with auxiliary system load control.

5.3 Driving cycle variation

In the Control case there is a more positive influence on cycles with higher speed and more braking energy like the Braunschweig and the FTP75 driving cycles than on the ECE15 and the IDIADA driving cycle, see Appendix D.

In smother cycles like the ECE15 and IDADA driving cycles with less acceleration and braking and more frequent bus stops the “New” case will have more influence on the fuel consumption improvements.

In Table 5-7 the results of the improved fuel consumption for different driving cycles and different bus sets up are presented.

Table 5-7 Fuel improvements on different cycles without AC compared to the "Reference" of hybrid respectively conventional.

Divetrain	System set up	Braunschweig	ECE15	FTP75	IDIADA
Conventional	Control	3.2 %	2.3 %	3.0 %	2.7 %
Conventional	New	5.6 %	7.6 %	4.3 %	9.5 %
Conventional	New+ Control	8.2 %	9.9 %	6.8 %	12.3 %
Hybrid	Control	0.2 %	0.1 %	0.1 %	0.5 %
Hybrid	New	3.4 %	4.6 %	2.5 %	4.8 %
Hybrid	New+ Control	3.5 %	4.7 %	2.6 %	5.0 %

The trend is however the same in all cases and combinations; the "New+Control" case is the most energy saving. It is particularly accentuated in the conventional vehicle.

5.4 Fuel cost calculations

In a city fleet of buses some buses are used for city traffic almost all the time, approximately 18-20 hours a day. These buses are often relatively new and they traffic the inner city. After this period the bus will be used for fewer hours per day, for example during traffic peaks in the morning and afternoon. These different working pattern will influence the average distance a bus travels per day and the average working hours. In Malmö the average total distance for a bus is 65 000-70 000 km per year, calculated for 10 working hours a day. The average speed is about 22 km/h and the fuel consumption is 4.5-5 l diesel equivalent per 10 km [31].

In this thesis, a new bus that works 10 hours respectively 20 hours a day is used in the calculation. The bus will work for 330 days per year. The operation time for one year, calculated in seconds, will be:

$$\begin{aligned} t_{10\ h} &= 1\,\text{year} \approx 330 \cdot 10 \cdot 3600\text{s} \approx 12 \cdot 10^{6}\,s \\ t_{20\ h} &= 1\,\text{year} \approx 330 \cdot 20 \cdot 3600\text{s} \approx 24 \cdot 10^{6}\,s \end{aligned} \tag{5.2}$$

The peak efficiency of the diesel engine is more than 40 %, but most of the time it will not work in a high efficiency operating region [21]. A realistic estimation of the average efficiency of the diesel ICE in a conventional vehicle, with help from the ADVIS0R program, is about 30 %.

$$\eta_{\text{engine}} = 30\ \% \tag{5.3}$$

The diesel fuel is the most common fuel for city buses. The price is of one litre diesel is without Swedish VAT, is 5 SEK/l [42].

$$\left.\begin{array}{l}\rho_{diesel} = 0.82\ \text{kg/l}\\ \text{Q}_{\text{LHV}} = 42\ \text{MJ/kg}\\ \text{Price} = 5\ \text{SEK/l}\end{array}\right\} \tag{5.4}$$

Saving money by improving the fuel consumption

A bus that is driven during 10 hours a day and 70 000 km a year will consume 31500 l diesel. Some extreme buses can travel almost the double distance. The savings per year by improving the fuel consumption one percent of a conventional bus will be:

$$1\ \% \begin{cases}\text{Fuel} = 0.45\ \text{l/km}\\ \text{s}_{10\text{h}} = \ 70000\ \text{km},\ \ Savings = \text{s}_{10\text{h}} \cdot Fuel \cdot \text{Pr}ize \cdot 0.01 = 1\,575\ \text{SEK/year}\\ \text{s}_{20\text{h}} = 130000\ \text{km},\ Savings = \text{s}_{20\text{h}} \cdot Fuel \cdot \text{Pr}ize \cdot 0.01 = 2\,925\ \text{SEK/year}\end{cases} \tag{5.5}$$

For a 5 % reduction the savings will be:

$$5\ \% \begin{cases}10h,\ Savings = 1575 \cdot 5 = 7\,875\ \text{SEK/year}\\ 20\ \text{h},\ Savings = 2\,925 \cdot 5 = 15750\ \text{SEK/year}\end{cases} \tag{5.6}$$

According to the ADVIS0R simulation program the fuel consumption is approximately 20 % lower for the hybrid bus compared to the conventional bus. This means calculating a 1% savings minus 20%. In the 10 hour use the savings will be: 0.8*1 575 SEK/year= 1 260 SEK/year. In the 20 hour use the savings will be: 0.8*2 925 SEK/year= 2 340 SEK/year.

Fuel savings by selecting New technologies

By improving the alternator (generator) efficiency from 55 % (peak) to 88 % for the 24 V system on a conventional bus would save:

$$\left.\begin{aligned} &P_{\text{Input Old alter}} = 4\,100\ \text{W} \\ &P_{\text{Input New alter}} = 2\,600\ \text{W} \\ &\Delta P = 1500\,W \end{aligned}\right\}$$
$$\begin{aligned} &\text{Simulated savings in the convetional bus}: 4\% \\ &t_{10\ h}: 6\,300\,SEK/year \\ &t_{20\ h}: 12\,000\,SEK/year \end{aligned} \tag{5.7}$$

The savings will increase with the electric power consumption of the 24 V system, i.e. AC system power consumption.

By changing the pneumatic doors, suspension, and parking brake to electric or electro-hydraulic systems the savings will be approximately the same for the conventional and hybrid buses. The savings will be:

$$\left.\begin{aligned} &P_{\text{Input Comp}} = 1170\ \text{W} \\ &P_{\text{Input Comp2}} = 260\ \text{W} \\ &P_{\text{New el}} = 75\ \text{W} \\ &\Delta P = 1\,170 - 260 - 75 = 835\ \text{W} \end{aligned}\right\}$$
$$\begin{aligned} &\text{Simulated savings}: 2\% \\ &t_{10\ h}: 3000\ \text{SEK/year} \\ &t_{20\ h}: 5800\ \text{SEK/year} \end{aligned} \tag{5.8}$$

The saving will be equal for the suspension and the doors while the savings for the parking brake will appear as number five among all the savings.

Changing the steering system from open loop to closed loop for the conventional respectively for the hybrid bus will save:

$$\left.\begin{aligned} &\Delta P_{\text{Hybr Steer}} = 470\ \text{W} \\ &\Delta P_{\text{Conv Steer}} = 200\ \text{W} \end{aligned}\right\}$$
$$\begin{aligned} &\text{Simulated savings}: \\ &\text{Conventional}: \quad 0.65\% \qquad \text{Hybrid}: \quad 1.5\% \\ &\text{Conventional}, t_{10\ h}: 1\,000\ \text{SEK/year} \quad \text{Hybrid}, t_{10\ h}: 1900\ \text{SEK/year} \\ &\text{Conventional}, t_{20\ h}: 1900\ \text{SEK/year} \quad \text{Hybrid}, t_{20\ h}: 3500\ \text{SEK/year} \end{aligned} \tag{5.9}$$

The total savings by all the different actions in the auxiliary systems are summarized in Table 5-8. The savings potential for the conventional bus is larger. The reason for this is the Control strategy works much better on a conventional bus than a hybrid bus where most of the regenerated energy is stored in the battery. Also the efficiency of the alternator in the 24 V system of the conventional bus has large impacts on the fuel saving. The DC/DC in the 24 V system of the hybrid bus has high efficiency and rather small improvement potential.

Table 5-8 Savings by the different actions on a conventional bus.

Action	Conventional bus 20 hour use [SEK/year]	Hybrid bus 20 hour use [SEK/year]
New 24 V alternator	12 000	-
Replacing the Pneumatics	5 800	5 800
Close loop steering	1 900	3 500
Control of the systems	9 400	300
Total savings	29 100	9 600

Summary

The payback time for replacing the pneumatic doors and suspension with electrical system will be about one to two years, both for the conventional and hybrid buses. The equipment is all ready on the market and the price will probably decrease as the volume goes up.

The Control is an alternative for the conventional bus but maybe not for the hybrid bus. The Control increases the performance and decreases the fuel consumption. For the conventional bus the pay back time will about than one year. The implementation of the Control is described in Chapter 2.2.

The new 24 V alternator payback time is very difficult to estimate with the present assumptions, see Chapter 4.6, Electrical system. The new alternator including power electronic and additional cooling will have about two years payback time when the component cost has been reduced.

The closed loop steering will not be an alternative for a conventional bus but for a hybrid bus the chances are better. The payback time for a hybrid bus with the closed loop system within three years. The parts and the maintenance in the closed loop steering system are more expensive.

Chapter 6

Conclusions

The Control strategy

The Control strategy functionality is exactly the same for the hybrid bus as for the conventional bus but some of the effects may be different.

The peak shaving, by switching off the auxiliary system when large power is requested by the propulsion system (transmission) has the same effects on the hybrid bus as on the conventional bus. The power source has more power available for propulsion system and consequently the accelerating performance will increase. In the best case the acceleration will increase by more than 8 %.

The use of the auxiliary systems as much as possible when braking reveals one important difference between the hybrid bus and to the conventional bus.

Conventional: The advantages with the Control strategy when braking are highest in a conventional bus, 2 – 6 % of the total fuel consumption, where usually most of the kinetic (brake) energy is converted into heat. The Control also increases the performance of the bus.

Hybrid: The brake energy in the hybrid bus is recovered and stored in the battery (energy storage). The gain by the Control when braking will be the losses in the battery for storing and delivering the power. The charge/discharge energy efficiency of the battery is approximately 85 %. In the hybrid bus the Control strategy will save a maximum of 1 % of the total fuel consumption.

Technology selection

The technology selected for the auxiliary systems is important. The cost for changing the auxiliary systems and the development cost for developing new systems differs a lot. For example: To change the door opening/closing assistance from pneumatic to electric, which is all ready on the market, would improve functionality and lower energy consumption at relatively low cost penalty. To change to a new more efficient alternator for the 24 V system would be a more serious challenge, as this product does yet not exist on the marked why development cost will typical be high. The potential nevertheless, in terms of improved quality and reduced energy consumption, would be great as current heavy duty alternators lack quality and show very low efficiency.

By choosing energy efficient components for the auxiliary systems fuel consumption can be improved by 4 – 10 % in the conventional bus. The improvements for the hybrid bus will be 2.5 - 5 %. The difference is caused by the different use of the auxiliary systems, i.e. number of stops per km, in the different duty cycles.

Total improvements

The total fuel consumption improvements by combining the Control and the new technology selection “New+Control” for the conventional bus is 8 - 12 % and for the hybrid bus 3.5 –5 %. See Figure 78.

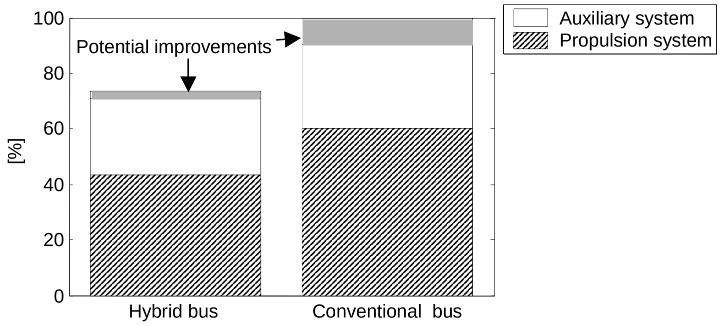

Figure 78: Simulation results for the hybrid and conventional bus. Showing the propulsion system and the auxiliary system energy share related to the conventional bus and the fuel improvement potential of the auxiliary systems when running the Braunschweig duty cycle with AC at full speed.

The difference in the propulsion system between the hybrid bus and the conventional bus in Figure 78 is primarily explained by the regenerative braking in the hybrid bus.

Economic aspects

One-percentage improvements of the fuel consumption when the bus works 20 hours a day is equal to a fuel cost of 3 000 SEK each year. If both the new more energy efficient technology (NEW) and the improved auxiliary system control (Control) for the auxiliary system were implemented on a conventional bus, operated for 20 hours a day, the auxiliary systems improvements would save 29 000 SEK/year For the hybrid bus the new more energy efficient technology (NEW) is the most important, which in the best case saves 10 000 SEK/year. The fuel (diesel) cost calculations are based on 5 SEK/l excluded VAT as the fuel prize is most likely to rise in the future.

The Control is an alternative for the conventional bus but maybe not for the hybrid bus. For the conventional bus the pay back time for the Control will be about one year. The payback time for replacing the pneumatic doors and suspension with electrical system will be about one to two years, both for the conventional and hybrid buses. The new alternator including power electronic and additional cooling will have about two years payback time when the component cost has been reduced. The closed loop hydraulic steering will probably be an alternative hybrid bus. The payback time for the closed loop steering is two to three years.

Future problems

Auxiliary systems are not in focus when it comes to energy consumption optimisation of vehicles. Major reason is that low power is neglected and it has always been that way. Energy consumption optimisation is a matter of improved engine technology and propulsion system technology - auxiliary systems are a necessity for the passenger comfort in a bus or a car. In the future, with very optimised hybrid drivelines, the remaining energy saving potential will be hidden in the auxiliary systems and it must be expected that focus will increase. Having tools available that can display energy consumption of auxiliary systems and be used for auxiliary system optimisation will help moving focus to the auxiliary systems.

As all auxiliary models developed are made compatible with the simulation tool (ADVISOR) used by Scania, it will be used for system optimisation in future projects.

With the advanced electronic circuits in modern commercial vehicles most sensors are either already available or can easily be made available. Major barrier will be to insure the functionality of new systems and control functions that are added.

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Appendix A

Measurements

The tests of the complete vehicle includes duty cycle-, performance, sub system-, rolling-, noise and battery test while the bus was running on the driveline battery. The test location was at IDIADA, Barcelona, Spain. [24]

The bus was tested at the IDIADA proving ground, showed in Figure A.1.

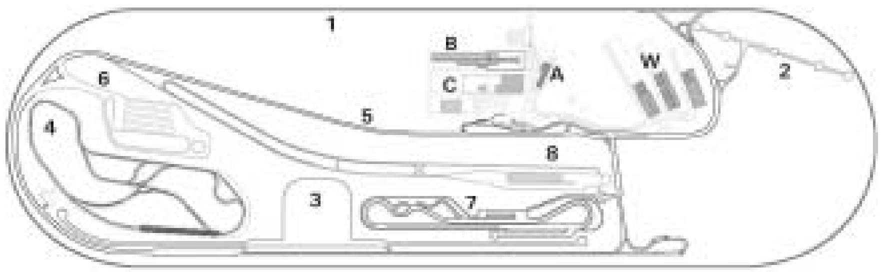


Figure A.1: IDIADA proving ground.

Description:

A. Main building	1. High-Speed Circuit	5. General Road
B. Safety	2. Noise Measurement Track	6. Test Hills
C. Powertrain bench	3. Dynamic Platform	7. Forest Track
W. Workshops	4. Handling Track	8. Straight Surface Braking

A.1 Data Acquisition system

The measurements aimed to map all the energy flows in bus, which are in the forms of chemical, electric, heat and kinetic energy.

All data acquisition system that was used came from Ipetronik.[25] The data was logged as synchronous decentralised data logging with a notebook and SIM-Master unit, see.Figure A.2. The notebook receives the measurement data from the SIM-Measurement Modules via the PCMCIA interface and the SIM CAN BUS. The SIM Master takes over the co-ordination of the SIM Measurement Modules connected to the SIM CAN BUS and provides the clock pulse. Before starting the measuring, the configuration data is transmitted from the notebook to the individual SIM Measurement Modules via the SIM Master. The SIM Master automatically assigns CAN-ID’s. As soon as the SIM Measurement Modules have received the clock pulse from the Master, they convert the analogue or digital sensor signals into a CAN message and transmit this message to the SIM Master via the SIM CAN Bus.

The transfer of the measurement data is synchronised (MASTER MODE). The SIM Master collects and checks the synchronous measurement data and transmits them to the notebook via the SIM CAN BUS.

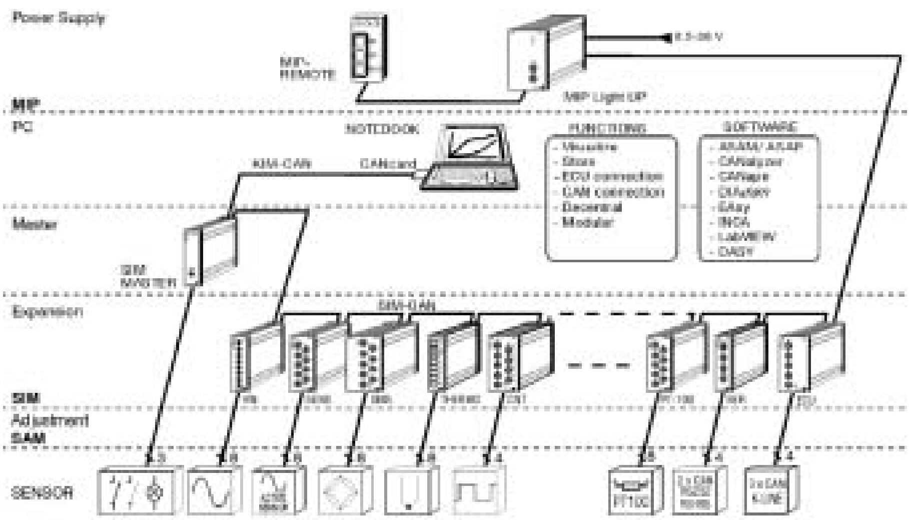


Figure A.2: The on-vehicle data acquisition system.

Technical specification of data acquisition equipment
Voltage supply for all the units is 9 to 36 V.
Sim-Sens: 8 Analogue input, 16 bit A/D converter
2 Digital input, 1 output
8 kHz sample rate
Sensor supply voltage 15, 10, 5 V with maximum 40 mA

Sensors in the system

All the sensors connected to the data acquisition system can be seen in Figure A.3.

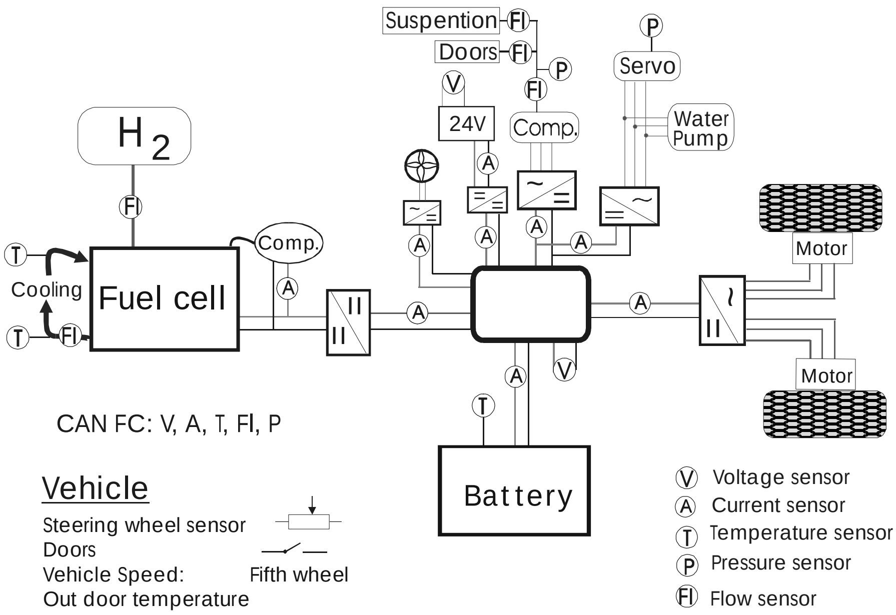


Figure A.3:Overview of the sensors in the data acquisition system.

The data log-file consists of data stored in several columns with the time in seconds from test start in the first column. Data is generally stored and logged five times per second. In Table A.1 the logged variables are listed.

Table A.1: List of variable that were logged.

Time	Clock, 5 Hz	[s]
I24b	Current from 24 V battery	[A]
Ratt	Steering-wheel position in degrees from centre	[degrees]
Fltot	Total air flow in	[l_n/min]
Fldoor	Air-flow to doors	[l_n/min]
Flecas	Air flow to ECAS system (suspension)	[l_n/min]
Door	Digital signal indicating door position 1=open, 0=closed	
Pservo	Pressure in hydraulic power-assisted steering system	[bar]
24 Volt	Voltage of 24 V system	[V]
High volt	Voltage in high voltage system	[V]
Ibat	Current high voltage battery pack	[A]
Imot	Current traction motor system	[A]
Ifc	Current fuel cell system	[A]
I24c	Current (high voltage) to 24 V battery charger	[A]
Icomp	Current compressor (ECAS, brake, doors)	[A]
IsevWat	Current hydraulic pump and water pump	[A]
Speed	Speed of bus	[km/h]
Tbat	Temperature battery (HV)	[°C]
Tout	Temperature outside	[°C]
Pair	Air pressure in the air system	[Bar]

A.2 Current

The current sensors used in the tests were hall effect sensors. The advantage with hall effect sensors are that no break ups in the electric circuits are necessary.

Current transducer HA 200-SB
For current measurements in the driveline (FC, Motors, Battery).

Current transducer HAL 50-S
For current measurements in the output current of 24 Volt battery and the fuel-cell compressor current consumption.

Current transducer LTS 6-NP, see Figure A.4.
For current measurements in the auxiliary system (Servopump, water-pump/compressor, 24 V converters).

Figure A.4: The current sensor for the hydraulic pump, water-pump/air compressor

A.3 Voltage

Voltage transducer LV 25-P, see Figure A.5, used for voltage measurements in the 24 V system and the 600 V system.

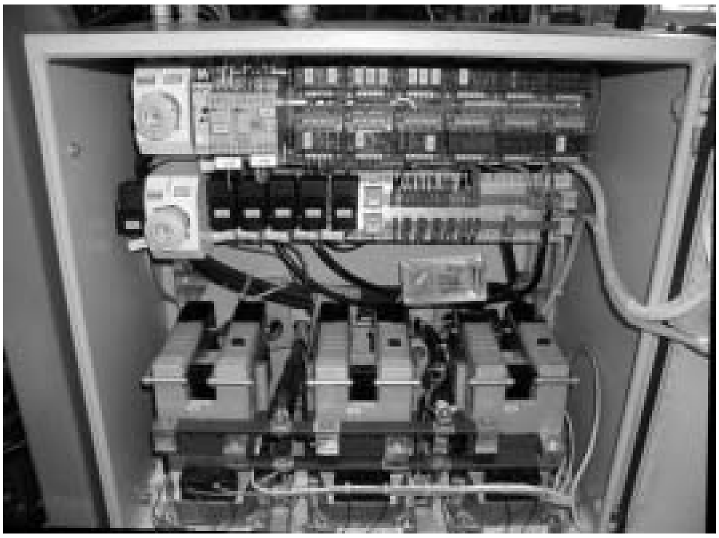


Figure A.5: The current and voltage sensors in the high voltage connection box.

A.4 Airflow

Three air flow transducers, D-6200, are used for the air consumption..
Airflow is measured on following pneumatic circuits:

- Total airflow from compressor to pneumatic system, see Figure A.6
- Airflow to door system
- Airflow to ECAS system.

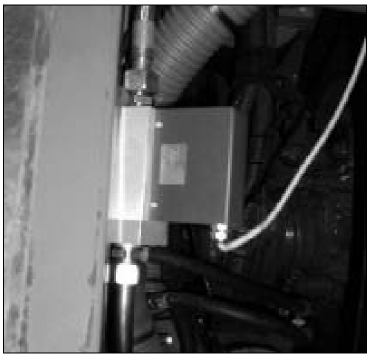


Figure A.6: The airflow sensor.

A.5 Temperature

PT 100 sensors were used for measuring of the temperature in fuel cell system circuits, driveline battery and outside temperature.

Figure A.7: The temperature sensor in the battery.

A.6 Speed sensor

As speed of the vehicle the fifth wheel were used, shown in Figure A.8. It was mounted on rear bumper of the bus.

Figure A.8: The speed sensor, the fifth wheel.

A.7 Other sensors

A Hydraulic Pressure sensor was to measures the pressure in the servo steering system, for calculating the efficiency of the hydraulic pump sub system.

Potentiometer
Steering wheel angel variation of the driver was measured with a potentiometer on the steering axle. The potentiometer was placed under the steering wheel by the driver seat, see Figure A.9.

Figure A.9: The steering angel measurement.

Appendix B

ADVIS0R

The ADVIS0R program is made by The National Renewable Energy Laboratory (NREL). NREL is the U.S. Department of Energy's premier laboratory for renewable energy research, development and deployment. The version 2002 that is used in this application was public, available on Internet until 2004. [1]

B.1 ADVIS0R platform

ADVIS0R provides a backbone for the detailed simulation and analysis of user defined drive train components, a starting point of verified vehicle data and algorithms from which to take full advantage of the modelling flexibility of SIMULINK^{TM} and analytic power of MATLAB^{TM}.

General description of ADVIS0R

The models in ADVIS0R are:

- Mostly empirical, relying on component input/output relationships measured in the laboratory.
- Quasi-static, using data collected in steady state (for example, constant torque and speed) tests and correcting them for transient effects such as the rotational inertia of drive train components.

ADVIS0R was preliminarily written and used in November 1994. Since then, it has been modified as necessary to help manage the US DOE Hybrid Vehicle Propulsion System subcontracts. Since then, over 4500 individuals have downloaded one or more versions of ADVIS0R.

The ADVIS0R user uses Design GUI (GUIDE) in MATLAB^{TM}. A user-friendly environment where the user click on popup menus, push buttons and text boxes to specify the vehicle, see Figure B.1. When the user chooses some element in the popup menu an m-files is selected and run. All the variables that are used during the simulation are set by the m-files and by the user. The simulations are run in SIMULINK^{TM} with the MATLAB^{TM} Workspace variable. Different simulation models are used for different vehicle.

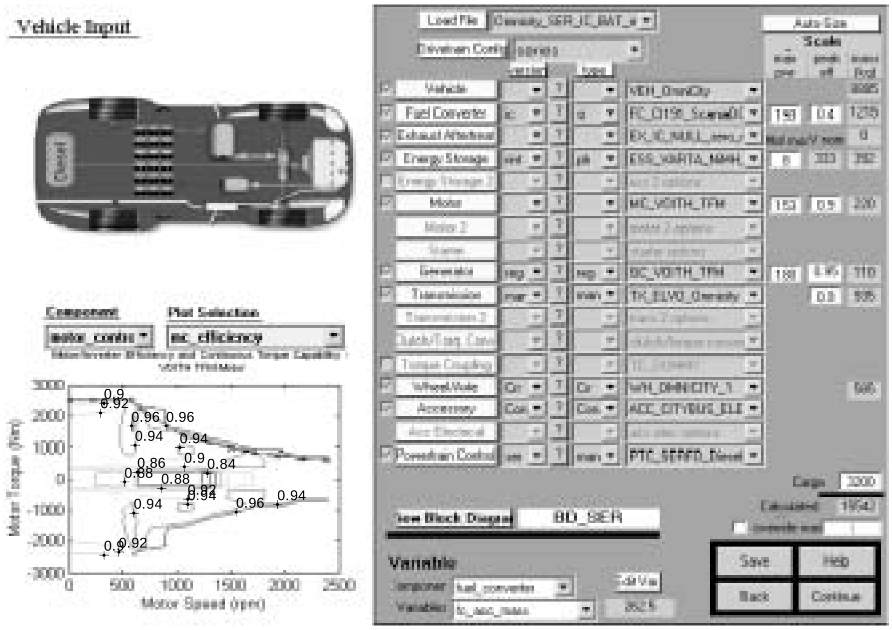


Figure B.1: User interface in ADVIS0R 2002.

When the user is ready he pushes the “Continue” button. The second user specification window will appears, the driving specification window. The user specifies the driving cycle that is going to be used during the simulation

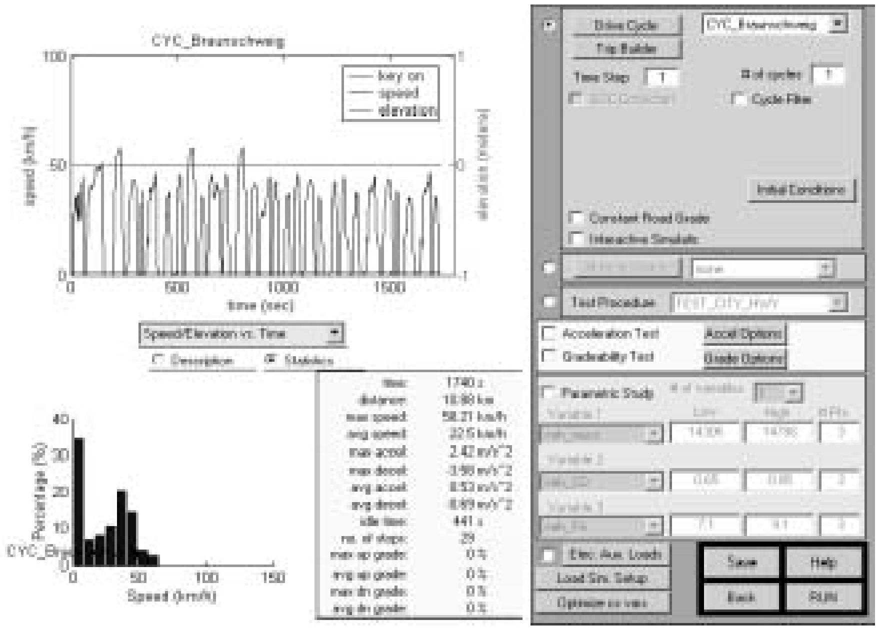


Figure B.2: The second user interface in ADVIS0R 2002.

Figure B.3 presents the summary results (fuel economy, emissions, total distance, etc.) and allows the user to plot series plots by selecting a variable from the popup menu. If the acceleration and gradeability checkboxes were picked in the simulation set-up screen, appropriate results will also be displayed. By clicking the Energy Use Figure button, a new figure is opened showing how energy was used and transferred for the vehicle during the simulation.

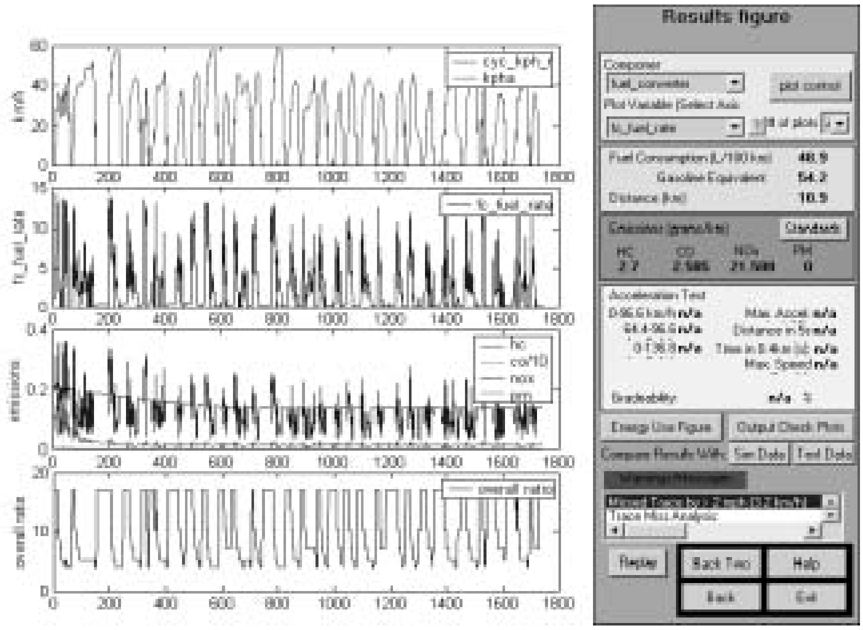


Figure B.3: The result plot in ADVIS0R 2002.

B.2 ADVIS0R m-files

These parameters and variables are used in the simulation model to specify the Auxiliary system.

MATLAB^{TM} parameters for the Auxiliary system of a conventional bus

% AUX control

```
acc_control_onoff=0;
% 0=off 1=on; Controlled power for the AUX systems

acc_ac_onoff=0;
% 0-100% Air Condition duty cycle

acc_tank_init=10;
% [Bar] Initial pressure in air tanks

acc_batt_init=0.90;
% (--) 24 V Battery initial SOC
```

```
acc_door_ecas=1;
% 0=off 1=on; Door and suspension use.

acc_doors=2;
% no of doors [pairs]

acc_cont_high=[0.8 0.6]*max(fc_map_spd.*fc_max_trq);
% (W) Limit for high driveline power use where peak
shaving begins

acc_cont_regen=[1 0.5]*-20000;
% (W) Limit for regenerative propulsion system power
use where AC begins to run
```

% AUX loads

```
acc_mech_pwr=200;
% (W) Mechanical loads like water pump

acc_elec_24V_pwr=70*28;
% (W) 24V grid consumption of 70 amp (excl. AC)
```

% AUX specification

```
acc_cooling_fan_rpm=[0 500 1000 1500 1800 2000 2200];
% (rpm) Cooling fan speed

acc_cooling_fan_pwr=[0 0.16 1.25 4.20 7.3 10
13.3]*1000;% (W) Cooling fan power consumption

acc_cooling_fan_engineratio=1.2;
% (--) Ratio engine speed versus hydraulic system

acc_cooling_fan_displacement=1.35;
% (--) Displasment ratio of hydraulic pump and motor

acc_cooling_fan_slip=2;
% Slip of the pump of the hydraulic cooling system

acc_cooling_fan_eff=0.7;
% (--) Efficiency of the hydraulic motor & pump of the
cooling system

acc_steering_spd=[0 0.2 0.5 4 13 90]/3.6;
% (m/s) Input for the steering, Speed of the vehicle

acc_steering_pwr=[200 520 900 700 200 200];
% (W) Steering power

acc_comp_rpm=[500 1000 1500 2000 2500 3000]/0.91;
% (rpm) speed of the compressor, gear ratio
```

```
acc_comp_airfl=[220 450 650 800 920 1050]/60;
% (l/s) compressor airflow

acc_comp_pwron=[2 4 6.2 9 11 13.5]*1000;
% (W) power consumption of the compressor when
pressurised

acc_comp_pwroff=[0.15 0.2 0.7 1.5 2.5 3.6]*1000;
% (W) power consumption of the compressor when not
pressurised

acc_regen_air_tank=4.5;
% (l) Size of Regeneration Air tank

acc_regen_every=25;
% (l) Regeneration Air tank refill cycle in litres of
compressed air

acc_tank_volume=30;
% (l) Air tank volume

acc_air_limit=[7.5_10];
% (Bar) Limitation of the air-pressure in the tanks

acc_ac_fan_pwr=2600;
% (W) Maxinum power for the AC cooling fans

acc_ac_comp_rpm=[1000 2000 3000 3500]/1.84;
% (rpm) Input speed to the AC compressor and gear
ratio

acc_ac_comp_pwr=[3.75 7.0 9.4 11.25]*2*1000;
% (W) Power consumption of the compressor

acc_ac_pulse=30;
% (s) Length of duty cycle pulse for the AC compressor

acc_gen_rpm=[1100 1500 2000 3000 4000 5000 6000
7000]/3.02;% (rpm) Input speed of the 24 V, 140 A
generator and gear ratio

acc_gen_pwr=[0 4 5.6 6.95 7.95 8.4 9.2 10]*2*1000;
% (W) 24 V, 280 A generator power output

acc_batt_size=220;
% (Ah) Battery size of the 24 V system

acc_batt_nominal=0.90;
% (--) 24 V battery nominal SOC

acc_batt_vari=0.05;
% (--) 24 V battery SOC variation limit up/down
```

```
% LOSS parameters

acc_gen_eff=[0.3  0.49 0.55 0.4996 0.4473 0.4300
0.3957 0.3668];% (--) Efficiency of the 24 V generator

acc_batt_eff=0.9;
% (--) 24V Battery efficiency

acc_mech_eff=0.95;
% (--) efficiency of auxiliary

acc_mech_trq=0;
% (Nm) constant torque load on engine by fan existing
look-up table
```

MATLAB™ parameters for the Auxiliary system of a hybrid bus

```
acc_control_onoff=0;
% 0=off 1=on; Controlled power for the AUX systems

acc_new_system=0;
% 0=Pneumatic Doors & Suspension and open loop
steering. 1=Use of electric doors and suspensions

acc_ac_onoff=0;
% 0-100% Air Condition duty cycle

acc_tank_init=10;
% [Bar] Initial pressure in air tanks

acc_batt_init=0.90;
% (--) 24 V Battery initial SOC

acc_door_ecas=1;
% 0=off 1=on; Door and suspension use.

acc_doors=2;
% no of doors (pairs)

acc_cont_high=[0.8 0.6]*max(mc_map_spd.*mc_max_trq);
% (W) Limit for high propulsion system power use where
peak shaving begins

acc_cont_regen=[1 0.5]*-20000;
% (W) Limit for regenerative propulsion system power
use where AC begins to run

% ACC loads
```

```
acc_elec_water_pump_pwr=200;
% (W) average power for the water pump

acc_elec_cooling_fans_pwr=1500;
% (W) average power for the cooling fan(s)

acc_mech_pwr=acc_elec_water_pump_pwr+acc_elec_cooling_
fans_pwr; % (W) total average power

acc_elec_24v_pwr=70*28;
% (W) 24V grid consumption of 70 amp (excl. AC)

acc_elec_pwr=0;
% (W) standard ADVIS0R variable, not used in the
advanced model
```

% ACC specification

```
acc_steering_spd=[0 0.2 0.5 4 13 90]/3.6;
% (m/s) Input for the steering, Speed of the vehicle

acc_steering_pwr_cl=[0 350 900 600 0 0];
% (W) Steering power with closed loop system

acc_steering_pwr_ol=[500 520 900 700 450 450];
% (W) Steering power with open loop

acc_comp_air=180/60;
% (l/s) Compressor airflow, Hydrovane 502 Electric
motor

acc_comp_el=2600;
% (W) Electric power consumption of the compressor

acc_regen_air_tank=4.5;
% (l) Size of Regeneration Air tank

acc_regen_every=25;
% (l) Regeneration Air tank refill cycle in litres of
compressed air

acc_tank_volume=30;
% (l) Air tank volume

acc_air_limit=[7.5 10];
% (Bar) Limitation of the air-pressure in the tanks

acc_ac_fan_pwr=2600;
% (W) Maxinum power for the AC cooling fans

acc_ac_comp_pwr=14000;
% (W) Power consumption of the AC compressor
```

```
acc_ac_pulse=30;
% (s) Length of duty cycle pulse for the AC compressor

acc_dcdc_pwr=220*26;
% (W) 24V DC/DC maximum power

acc_batt_size=220;
% (Ah) Battery size of the 24 V system

acc_batt_vari=0.05;
% (--) 24 V battery SOC variation limit up/down

% LOSS parameters

acc_elec_eff=1;
% (--) standard ADVIS0R variable, not used in the
advanced model

acc_dcdc_eff=0.91;
% (--) 24V DC/DC efficiency

acc_batt_eff=0.9;
% (--) 24V Battery efficiency

acc_mech_eff=1;
% (--) efficiency of auxiliary

acc_mech_trq=0;
% (Nm) constant torque load on engine
```

Appendix C

Test object

The bus type is a visionary construction from the early 1990s for inner city and airport traffic, called Scania MidiCityBus. The bus is 9.2 m long, 2.5 m wide and 3.2 m high and has capacity for 15 seated and 37 standing passengers, see Table C.1 and Figure C.1. It is a true low floor bus, which means that the passenger compartment has a completely flat and low floor.

During the development of the bus body design, several groups of disabled, elderly people and "normal" passengers were consulted in order to meet all the requirements the passengers could have, so that the bus gives the traffic company the opportunity to offer public transport for everyone. The low floor has been made possible by keeping the wheels and the mechanical gears outside the passenger compartment. In front of the passenger module, the driver's module offers the driver a good place of work.

A diesel-electric series hybrid version of the MidiCityBus was developed by Scania and the German company ZF Friedrichshafen in the midddle 1990s. The bus is partly used as base for the Fuel Cell Bus, see Figure C.1, but it has been fundamentally reconstructed for the new hybrid electric propulsion system involving fuel cell technology.

Table C. 1 General technical description of the bus and the propulsion system.

Bus	Scania MidiCityBus Dim. (LxWxH) Max weight Passenger capacity	 9.2x2.5x3.2 m 13 000 kg 52
Drive line	Series Hybrid with Regenerative Braking	
Fuel Cell System	PEM FC stacks (x2) Power output (gross) Cooling	2x105 cells 0-50 kW Water
Hydrogen Storage	Material Max. pressure Capacity	Stainless steel 200 bar 13.2 kg H_2
Driveline Battery	Lead-acid valve regulated Nominal voltage Energy density Power density Cooling	44x12 V 528 V 35 Wh/kg 380 W/kg Air
Propulsion system	Motors (x2) Power output Cooling	Wheel Hub 2x50 kW Water

Figure C.1: The Scania Hybrid Fuel Cell Concept Bus.

The bus is equipped with an electric series hybrid propulsion system (Figure C.2), which means that the driveline is completely electric and uses energy that is supplied from more than one source. In this configuration, the driveline receives energy from both the fuel cell system and the driveline battery. As the battery serves as a high power energy reservoir, it enables the use of a rather small, and therefore less expensive fuel cell system.

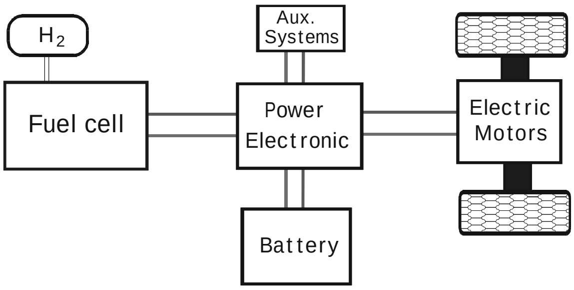


Figure C.2: A series hybrid system.

The fuel cell system has a designed maximum power output of 50 kW. The fuel is compressed hydrogen and the oxygen for the fuel cell is compressed ambient air. An integrated DC/DC converter adjusts the fuel cell output voltage with the voltage of the common power bus (600 V).

C.1 Propulsion system

The propulsion system is located in the rear end of the bus, see Figure C.3. The whole propulsion system, including the fuel cell system, driveline battery, wheel motors and power electronics and auxiliaries can easily be removed from the rest of the bus. This simplifies service and other work on the system.

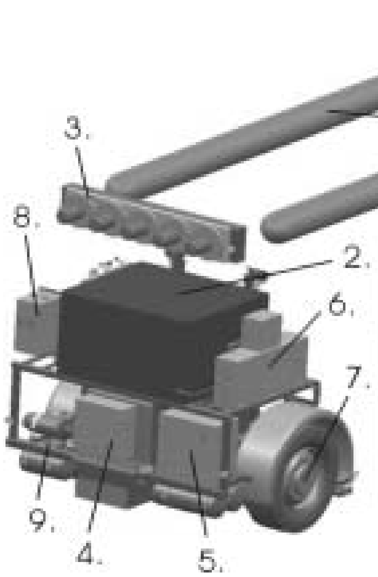


Figure C.3: The propulsion system located in the rear end of the bus.

Description of the propulsion system in Figure C.3: (1) 200 bar hydrogen storage vessels, (2) fuel cell system, (3) radiator and fans for the secondary cooling system, (4) high voltage battery module, (5) power electronics, (6) inverter and control system for wheel hub motors, (7) wheel hub motors, (8) auxiliary system inverters and (9) auxiliary system air compressor and hydraulic pump.

The philosophy of this series hybrid electric driveline is that the driveline battery shall supply the necessary power to fulfil the requirement of speed and acceleration, and it shall also fulfil the requirement of regenerative braking; consequently the fuel cell system is to supply the average energy consumption of the bus keeping the SOC (State Of Charge) of the driveline battery within defined limits.

Driveline supervisor

The supervisor is a microprocessor-based controller, which handles:

- Main part of the human interface via touch screen located at the drivers place.
- Co-ordination of propulsion system initialisation and shutdown (key on/off).
- Information flow in the propulsion system via CAN Bus communication.
- Energy management in the hybrid electric propulsion system.
- Battery management.

The supervisor also gathers information available from the driveline, battery module and fuel cell module making this information available for diagnostics. To the supervisor is attached a touch screen located at the right side of the driver. All information available in the supervisor can be displayed on the touch screen, which is fully programmable.

The fuel cell system

In a fuel cell, the chemical energy in a fuel (*i.e.* hydrogen) is directly, without combustion, converted to electricity in an electrochemical reaction, see Figure C.4. [22] Heat and water are the only by-products. If hydrogen is stored onboard a vehicle, the only emission from the vehicle will be water.

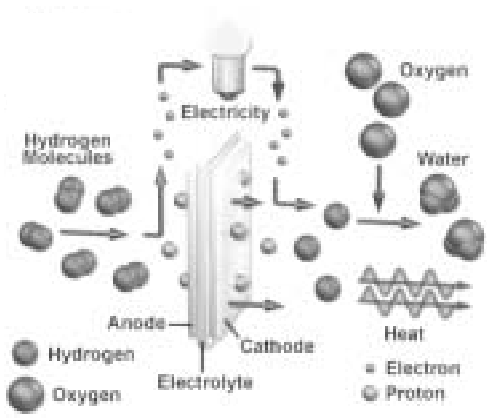


Figure C.4: The fuel cell principle [32].

Hydrogen (H_2) is fed to the anode, see Figure C.4, where the hydrogen molecules split up into their elements: protons (H^+) and electrons (e^-). The polymer electrolyte membrane can only transfer protons (called proton selective) and the electrons must therefore be transferred in an outer electric circuit and electric energy (an electric current) thereby becomes a product. An air is fed to the cathode, where the oxygen (O_2) in the air works as oxidant. The oxygen molecules react with the electrons from the outer electric circuit and protons from the membrane, forming water (H_2O). The driving force for the reaction is the electrochemical potential difference between the anode and the cathode reaction and the reaction is thereby spontaneous. Both reactions have to be catalysed, though, in order to proceed at useful rate.

The cell voltage of a single cell is about 0.6 V to 0.8 V. In order to produce enough energy, several fuel cells are coupled in series in so-called fuel cell stacks. A fuel cell stack can consist of more than a hundred fuel cells.

The fuel cell system (Figure C.6) consists of fuel cell stacks, a hydrogen circuit, an air circuit, a primary and a secondary cooling water loop. The output voltage is harmonised with the high voltage system in the bus, the common power bus voltage, via a DC/DC converter.

The heart of the fuel cell system is the stack module with two PEM fuel cell stacks (Figure C.5). Each stack contains 105 cells. The stack module has a maximum power output of 60 kW in the Scania Fuel Cell Bus configuration. Stack supplier is the Italian company Nuvera Fuel Cells

Europe. The two stacks were integrated into a complete fuel cell system designed and constructed by the French company, Air Liquide.

Figure C.5: Nuvera fuel cell stacks.

The stacks assembly components are metallic. Its dimensions are 58 cm height, 42 cm width and 57 cm length, giving each stack a total volume of 139 litres. This results in a power density of approximately 0.2 kW/litre. It has to be noted that the stack design is from 1997/1998 if compared with today's state of the art stacks where power densities of more than 1.5 kW/litre have been demonstrated. The new generations of stacks that Nuvera works with today have an improved performance, with power densities of over 1 kW/l. With power densities of more than 1 kW/l the stack size and weight is not a key problem in bus applications. More critical problems are the size and weight of the auxiliary systems, the fuel storage system and the driveline battery module.

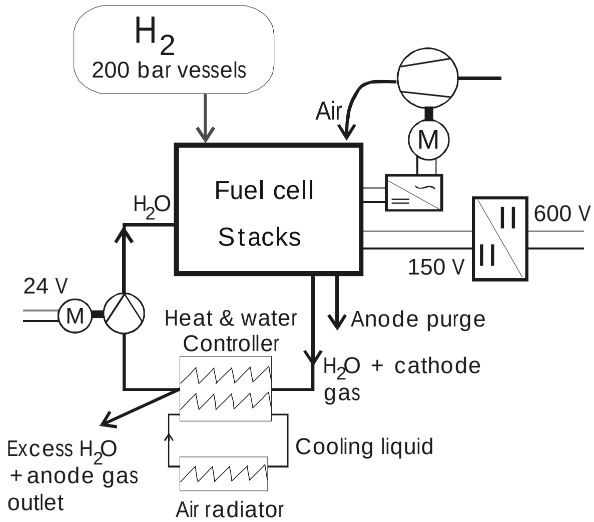


Figure C.6: General view of the fuel cell system.

Excess heat has to be removed from the fuel cell system in order to keep the temperature in the fuel cell stacks within the desired temperature interval, see Figure C.6. Some heat is transferred to the surroundings with the exhaust gases but the major part has to be cooled away. In the design tested, pure water is directly injected to the stack. This, the primary cooling circuit, is heat-exchanged with a secondary cooling circuit integrated with the cooling system of the bus. The secondary cooling system controls the thermal balance of the vehicle by cooling down the fuel cell system, the driveline inverter, and the driveline motors and heating up the bus cabin. Excess heat is removed from the cooling system via a fan assisted radiator system, located on the roof of the bus. Some heat produced in the fuel cell module is also removed through a ventilation system that ventilates the fuel cell module and via heat radiation.

A water management system is integrated with the thermal management system. There is no system for pre-humidification of the reactant gases, which is common in other fuel cell systems. This choice of design reduces the cost, complexity, and size of the whole system. Instead of pre-humidification is pure cooling water directly injected into the stack where it both humidifies the MEA (Membrane Electrode Assembly) and controls the temperature of the stack, *i.e.* cools it down.

Air (*i.e.* oxygen) is supplied to the fuel cell via a twin-screw, oil-free, compressor from Opcon AB.[35] An air filter and silencer system is mounted prior to the compressor. The compressor motor is direct-powered by one of the fuel cell stacks, without conversion via the main DC/DC converter, but via conversion to AC electric power in a separate inverter for the compressor motor.

The fuel, hydrogen, is stored as compressed gas in two stainless steel pressure vessels designed to a maximum pressure of 200 bar, located on the roof of the bus. The total amount of stored hydrogen gas is 875 litres or 13.2 kg. The pressure is lowered in two stages before the gas enters the stacks. It is first lowered to less than 10 bar on the roof, then transferred in a pipe to the fuel cell system module where the pressure is lowered to the working pressure of the fuel cell system stacks, approximately 1.6 bar (abs).

The efficiency of the fuel cell stack, see Figure C.7, is similar to a battery [16]. Major losses in the fuel cell stack are activation losses at low power. It depends on restrictions in the charge transfer at the surface of the electrode. At medium power the ohmic losses dominate. These losses are due to electrical resistance in the electrodes and resistance to ionic flow in the electrolyte. At full power the mass transport and concentration losses are dominating. At very high current densities, the concentration of reactants at the electrode surface may become much lower than that in the bulk.

On small loads (<10 % of the maximum power), the efficiency of the fuel cell system is low due to the screw compressor load, see Figure C.7. The screw compressor supplies the fuel cell with air (oxygen).

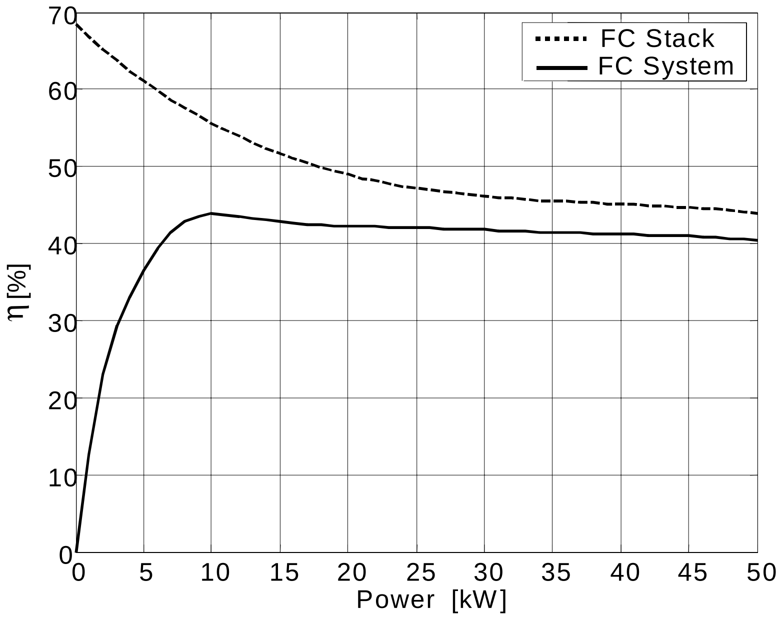


Figure C.7: Fuel cell stack and system efficiency.

Appendix D

Test procedures

The data acquisition system and the sensors used to log all the different physical units like flows, pressures, voltages, currents and temperatures are presented in Appendix A.

D.1 Overview

The testing consisted of stationary test and test-driving with bus stops. The stationary tests were performed to study the single auxiliary system isolated from the other. The stationary tests were made in the workshop where the bus was parked. For example: the door was opened/closed ten times and the airflow, air pressure and the electric power consumption of electric motor driving the compressor were measured. The test-driving involves a moving bus and a suitable proving ground. Appendix A describes the test tracks that were used during the test-driving. International duty cycles with many stops and goes were used. At the stop the bus braked, turned into the stop, the parking brake was applied, doors opened and the suspension adjusted the height (down and up), doors were closed, parking brake released and the bus was driven out of the bus stop.

Test driving

Following list describes the tests that were made, purposes and procedure.

BATTERY TEST

Purpose:	Evaluate the energy efficiency for cycling of the driveline batteries.

Description: During the battery tests, the energy consumption was measured during the whole test drive, from the workshop and back again. After the tests, the energy amount charged into the battery was measured.

ROLL OUT

Purpose: Map the vehicle dynamics, *i.e.* aerodynamic drag and rolling resistance.

Description: Speed up to 60 km/h and let the vehicle glide until it stops (0 km/h). The dynamics of the bus was tested. The only important sensor is the speed sensor.

GRADEABILITY

Purpose: To test the gradeabilty performance of the bus at different SOC and to evaluate the efficiency of driveline motors.

Description: Entering the slope at low speed and then trying to accelerate up the slope.

STEERING

Purpose: To get a knowledge about the steering versus speed.

Description: Bus standing still, 1 revolution on steering wheel in each direction
10 km/h, 1 revolution on steering wheel in each direction
20 km/h, ½ revolution on steering wheel in each direction
25 km/h, ½ revolution on steering wheel in each direction

DUTY CYCLES

Purpose: Map the vehicles performance in simulated regular service and create an evaluation base for comparison with other vehicles.

Speed issues: If a duty cycle contains speeds over the capacity of the concept bus, the bus keeps its electrically limited speed of 80 km/h.

Number of tests: Each duty cycle has to be driven at least once. It is preferable to drive each duty cycle several times to get reliable results.

NOISE
Purpose: Testing of the external and internal noise emissions of the bus.
Description: The bus was tested in accordance to the legal requirements, described in the European regulation Directive EC 70/15, to measure the external noise levels.

Stationary tests

All the stationary tests were made in a work shop where the bus was parked. Purpose of the tests were to and measure all auxiliary loads in the bus. The following list describes the systems that were tested and the test procedure.

24 V SYSTEM
Description: All major 24 V system power consumers were connected (powered up) after one another, while the voltage and current from the 24 V batteries were measured.

PNEUMATIC SYSTEM
SUSPENSION - ECAS
Description: Provoke the compressor to start and then wait until it stops and the air system is full. This is the “zero level”. Lower and raise the bus approximately ten times with some 30-60 s delay. Stop the test when the bus is at normal level and the compressor starts or just has started. Stop logging after the compressor stops.

DOORS
Description: Provoke the compressor to start and then wait until it stops and the air system is full. This is the zero level. Open and close both doors with 15 s delays between the two doors and at least 30 s delay between each “cycle”. Stop the test when the compressor starts or just has started. Stop logging after the compressor stops.

SERVICE BRAKES

Description: Provoke the compressor to start and then wait until it stops and the air system is full. This is the zero level. Push the brake pedal to its end position of full travel and keep it in that position for 15 s before releasing it. The delay between two brakes shall be about 15 s. Stop the test when the compressor starts or just has started. Stop logging after the compressor stops.

PARKING BRAKE

Description: Provoke the compressor to start and then wait until it stops and the air system is full. This is the zero level. Push and release the hand brake with 15 s delay. The delay between two brakes shall be about 15 s. Stop the test when the compressor starts or just has started. Stop logging after the compressor stops.

D.2 Duty cycles

The duty cycles are used for comparing fuel consumptions (energy use) and emissions. Some of the test cycles are only for engines in test benches and others are used for dynamometer or road tests.[13]

The bus has been tested in accordance to several standardised duty cycles in order to evaluate performance of the bus and to record new extended duty cycles including auxiliary systems.[17]

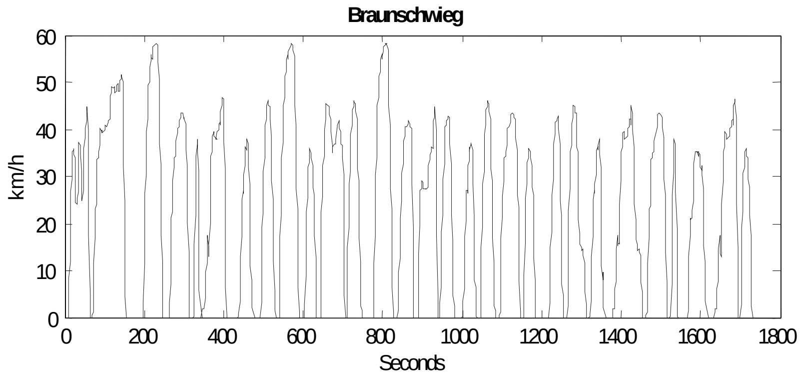
An overview of the duty cycles is shown in Table D. 1. The subjective judgement is based on experiences during the testing. It is mostly correlated to the toughness of accelerations but also to the toughness of braking and the shifts between acceleration and braking.

Table D. 1: Overview of the duty cycles.

Duty Cycle	Dist. [km]	Average Speed [km/h]	Max. Speed [km/h]	Max. Acc [m/s^2]	Stops [#]	Time [s]	Type
Braunschweig	10.9	22.5	58	2.14	29	1740	Urban
ECE15 or EDC	10.5	31.7	90	1.04	13	1191	synthetic urban & rural
FTP75	17.8	33.7	91	1.48	23	1900	Urban (rural)
IDIADA	7.14	20.4	53	1.12	10	1250	Semi synthetic urban

BRAUNSCHWEIG

The Braunschweig duty cycle is a tough urban cycle with high accelerations and many stops. It is often used for bus applications e.g. simulation used by AVL MTC (Motor Test Center) [36][13].



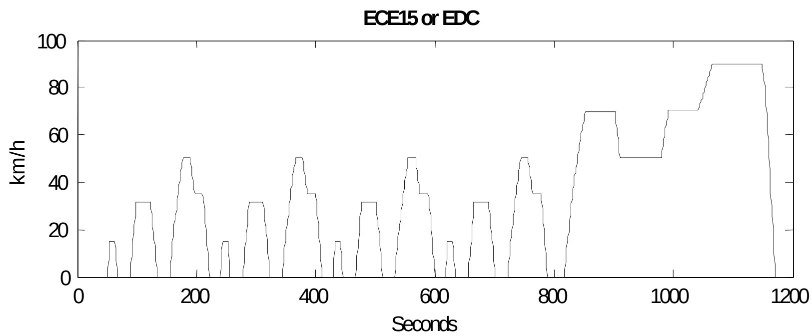
Characteristics

Distance: 10.9 km
Average speed: 22.5 km/h
Max speed: 58 km/h
Max acceleration: 2.14 m/s^2
Number of stops: 29, in 1740 seconds

Figure 79:Braunschweig duty cycle.

ECE 15 OR EDC

ECE 15 or EDC is a European standard duty cycle used for light duty vehicle. The maximum speed is 120 km/h but for slower vehicles, as urban city buses, the speed is limited to 90 km/h. The duty cycle contains no fast accelerations. As the speed of the concept bus is limited to 80 km/h the duty cycle cannot be followed during the last part of the duty cycle [13].



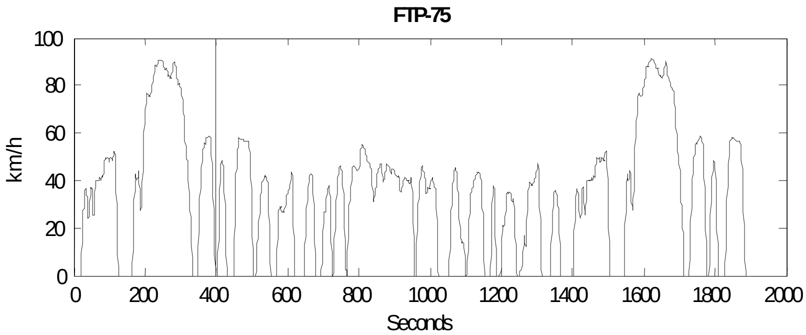
Characteristics

Distance: 10.5 km
Average speed: 31.7 km/h
Max speed: 90 km/h
Max acceleration: 1.04 m/s^2
Number of stops: 13, in 1191 seconds

Figure 80:ECE 15 or EDC duty cycle.

FTP 72, FTP 75

FTP 72 is a recorded American duty cycle from the beginning of the 1970's. It is used for light duty vehicles. The full version is called FTP 75, where the first 500 seconds is added in the end, after a 10 minutes stop. The Swedish government has used this duty cycle for many years, but after the entrance in the European community the use of this duty cycle has been limited. As the speed of the concept bus is limited to 80 km/h the duty cycle cannot be followed during the "high" speed part of the duty cycle [13].



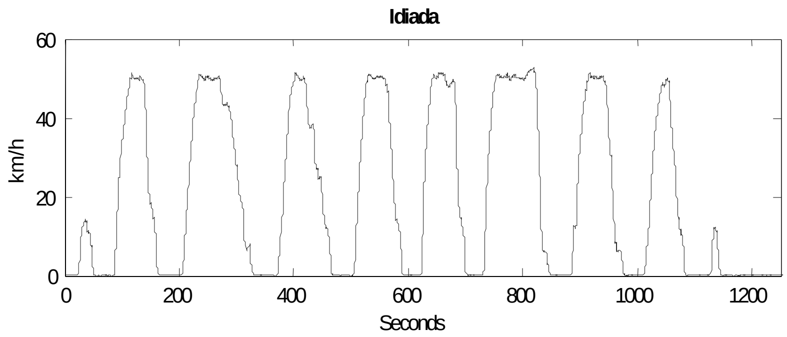
Characteristics

Distance: 17.8 km
Average speed: 33.7 km/h
Max speed: 91 km/h
Max acceleration: 1.48 m/s^2
Number of stops: 23, in 1900 seconds

Figure 81:FTP 75 duty cycle.

IDIADA cycle

The IDIADA cycle was recorded to be able to do bus stops as similar to real stops as possible. The stops in this duty cycle also include activating the steering wheel; the bus turns into a parking place. When the bus has made a stop it turns out on the road again. To perform such a test on IDIADA High Speed Circuit the available parking areas along the circuit is used. The distance between the parking areas and the circuit length defined the duty cycle [24].



Characteristics

Distance: 7.14 km
Average speed: 20.4 km/h
Max speed: 53 km/h
Max acceleration: 1.12 m/s^2
Number of stops: 10 in 1250 s seconds

Figure 82:IDIADA duty cycle.

Speed Reference

Desired speed was displayed to the driver with a laptop computer. The program in the display of the computer showed the Reference speed and a recorded voice indicated the speed. The computer also displayed a graphic overview of the speed profile some seconds ahead. The speed display program was developed in MATLAB™ as a part of my project.

Bus stops and other stops that had a distance definition were marked with assistance of a GPS-system onboard the bus. The distance was displayed on the computer display when the bus was stopped. The distance was also verified with the GPS unit that measured the distance.

Stop definition

A selected number of duty cycles were tested in an extended version with simulated bus stops at specified stops in the cycle. At those stops both doors were opened and the bus was lowered and raised in the front as at real-life bus stop. By experience did it take a minimum of seconds to perform the different procedure when entering and leaving a bus stop. The definition of a bus stop by our experience is when the stop time (0 km/h) is more than 17 seconds.

Appendix E

Nomenclature

Symbols

A	Front Area [m^2]
C_d	Aerodynamic constant in wind tunnel, with no wind variations
C_r	Friction constant, including all frictions (bearings and tire friction)
C_{r1}	First friction constant, including all frictions (bearings and tyres)
C_{r2}	Second friction constant, including all frictions (bearings and tyres)
C_x	Aerodynamic constant in the speed direction, with wind variations
E_{charged}	Energy to the battery [J]
E_{comp}	Energy to the compressor [J]
$E_{\text{discharged}}$	Energy from the battery [J]
$E_{\text{losses bat}}$	Energy from the battery [J]
$E_{\text{regenerated}}$	Regenerated energy to the battery [J]
J	Inertia [kgm^2]

P	Power [W]
ΔP	Power diffrence [W]
$P_{24V\ gen}$	Power of the 24 V generator [W]
$P_{AC+Pneum}$	Power of the AC and the pneumatic systems [W]
P_{aux}	Power of the auxiliary system [W]
$P_{\text{Propulsion}}$	Power of the propulsion system [W]
P_{fan}	Power fan [W]
$P_{friction}$	Power friction [W]
$P_{ICE,\ MAX}$	Maximum ICE power [W]
P_{idle}	Idle power consumption [W]
P_{motor}	Power motor [W]
P_{valve}	Power valve [W]
P_{pump}	Power pump [W]
$\text{P}_{\text{Input Comp}}$	Power input to the compressor [W]
$\text{P}_{\text{Input Old gen}}$	Power input for old generator [W]
$\text{P}_{\text{Input New gen}}$	Power input for new generator [W]
$P_{Out\ gen}$	Electric power generator [W]
ΔP	Power difference [W]
Prize	Diesel prize per litre [SEK/l]
Q_j	Energy of the rotating parts [J]
Q	Energy of the moving mass [J]
Q_{LHV}	Lower heating value for diesel [MJ/kg]

ΔT	Temperature difference [°C]
f	Part load [%]
h	Height [m]
m	Weight of bus [kg]
m_j	Weight of the moving parts [kg]
n	Speed [rad/s]
g	Gravity [9.82 m/s^2]
p	Pressure difference [Pa]
s_{10h}	Distance for a 10 hours use [km]
s_{20h}	Distance for a 20 hours use [km]
$t_{10\ h}$	Time for 10 hours [s]
$t_{20\ h}$	Time for 20 hours [s]
r_r	Gear ratio
s	Distance[km]
v	Speed [m/s]
v_1, v_0	Final and start speed [m/s]
w	Width of the bus [m]
α	Angle [degree, °]
η	Efficiency [%]
$\eta_{battery}$	Efficiency of the battery [%]
$\eta_{storage}$	Efficiency of storing energy in the battery [%]
η_{engine}	Efficiency of the engine [%]
ρ	Density of air [kg/m^3]

τ_{th}	Time constant [s]
ρ_{diesel}	Density of diesel fuel [kg/l]
ϕ_{fan}	Flow though the fan [m^3/s]
ϕ_{pump}	Flow though the pump [m^3/s]
ϕ_{valven}	Flow though the valve [m^3/s]