CHALMERS

xEV Simulator

Virtual Prototyping of Electrified Vehicles Using Real Data

Master of Science Thesis

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

- One way of reducing the emissions in the vehicle industry is to use electrified vehicles. An important method when developing new vehicles is to use simulations. In this thesis the possibility of developing a simulation tool that uses real log data as input, to anticipate the energy consumption of an identical vehicle body as the logged one but with a modeled electric powertrain, is investigated. Logged data of an electric and a conventional vehicle are analyzed to understand which signals are needed and how these signals are either measured or calculated. Further the signals are used to calculate the external forces that acts on the vehicle. The estimated external forces are used as inputs to the simulation tool to enable simulation.
- The results have shown that it is possible to calculate the external forces that acts on a logged vehicle during motion. When comparing the external forces for a specified route, driven with different versions of the same vehicle body but with different powertrains, it shows that the forces are approximately the same, which indicates that the method works.
- The simulation results show that the variations in the results are within 5 % when verifying the log data from an electric vehicle with a simulated electric powertrain consisting of the same powertrain components. The developed simulation tool can be used to simulate an electrical powertrain, with input parameters based on a logged conventional vehicle.

Index Terms: Energy Consumption Modeling, Powertrain Efficiency Simulation, Electric Vehicle, EVs, CAN- signals, Simulation Tool.

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Nomenclature

η	Efficiency
A_f	largest cross-sectional area of vehicle
C_D	Drag coefficient
DOD	Depth of Discharge
F_g	Grading resistance
F_w	Aerodynamic drag resistance
F_{ext}	The summarized external forces
$I_{AC,12V}$	Current drawn by air conditioner, 12 V-system and the immersion heaters
OCV	Open-Circuit Voltage
SOC	State of Charge
T_{ext}	The summarized external forces recalculated into torque
EM	Electric Machine
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
PEV	Pure Electric Vehicle

Contents

Chapter 1

Introduction

1.1 Background

It is assumed that nowadays approximately 90 % of the transportation sector uses oil based fuel for propulsion [1]. At the same time densely populated cities have problems with air pollutions. Thereby to satisfy emission requirements set by different governments there is a need to decrease the greenhouse gas emissions [2].

One way to reduce emissions and the fuel consumption is to use electrified vehicles, including pure electrical and hybrid powertrain setups. Therefore these vehicles are playing an important role for the vehicle industry. When vehicles include both combustion engines and electrical machines the powertrain becomes more complex, which makes it more difficult to analyze newly designed hybrid electric vehicles. Therefore modeling with simulation tools are used to reduce the cost of development of new vehicle models [3].

Most of the simulations nowadays are used with predefined and standardized drive cycles such as NEDC, FTP75, HWFET and US06 [4]. At Volvo Car Corporation there is a simulation tool called VSIM that uses the same idea, where vehicle performance and fuel consumption can be estimated. If real log data, from the test vehicles CAN-system, are used as inputs to simulation models it may give more realistic simulations, and thereby more adapted to the purpose of the simulations. In this thesis the concept behind using real log data is investigated and the simulation results are analyzed.

The basic assumption of this thesis is that when a vehicle is driven, there are external forces acting on the body of the vehicle, which are the same independently of the powertrain. So if these external forces are calculated from a log file then it could together with the velocity be used as an input to a simulation tool. This in order to simulate a different vehicle, with an identical vehicle body but with another powertrain, and thereby forsee the power consumption.

1.2 Purpose

The purpose of this thesis is to investigate the validity of a vehicle simulation tool by studying CAN vehicle signals. An assumption is made that by using the velocity and calculated external forces, of a logged vehicle, it can be used in order to estimate the energy consumption for the same vehicle with another powertrain.

Moreover the purpose is also to investigate what type of log data that is needed to calculate the external forces, acting on the vehicle, and to understand how these are measured or calculated as well as their validity. Further to verify these external forces. The aim is also to investigate whether it is possible to approximately predict the energy consumption with a simulation tool based on this.

1.3 Method

The forces acting on a vehicle in motion are studied. Based on this knowledge and information in log files, methods of calculating these forces are developed. Log files from an electrical vehicle and a conventional vehicle driving a specific route is then used to calculate the external forces for both vehicles. By comparing these forces the methods of calculating them is verified.

A simulation tool is developed where the logged vehicle speed and the estimated external forces acting on the vehicle body are used as inputs. To analyze the accuracy of this tool the simulated energy consumption is compared with the logged data. Discussions around the results are presented and further improvements of the verifications are suggested.

1.4 Limitations

In order to keep the simulation tool simple, all wheels are assumed to have the same speed and the radius does not change for different velocities. The outcomes from the simulations are the efficiency depending on different drivelines and driving patterns, however, no other variables in the environment. The change in external forces due to different masses of the logged vehicle and the simulated vehicle will not be handled in the simulation tool, but the effects are analyzed. It will not be possible to freely choose how to drive the simulated vehicle since it is dependent on the logged vehicle speed profile.

Chapter 2

Technical Background/Theory

2.1 Theory

It is necessary to understand the fundamental physics of vehicle dynamics to be able to calculate the external forces used as inputs to the simulation tool. In the following sections the physics will be explained.

2.1.1 Fundamental physics equations

In this section a description of the fundamental physics behind moving vehicles is introduced. As Guzella and Sciarretta [5] describes it, the propulsion system delivers mechanical power to the vehicle. The power can be seen as momentarily stored in the vehicle's body, in a fictive energy supply as kinetic energy. Further the external forces that act on the body during movement will drain the energy supply, and the net power will be used to propel the vehicle.

As explained in [6] Newton's laws of motion can be used to describe the acceleration of the vehicle. With the second law of acceleration

$$m_{vehicle}\frac{dv_{vehicle}}{dt} = F_{acc} \tag{2.1}$$

the accelerating force, F_{acc}, can be expressed as the mass of the vehicle, $m_{vehicle}$, multiplied with the change in velocity as a function of time, $\frac{dv_{vehicle}}{dt}$. The external forces acting on the vehicle can be divided into tractive forces and resistive forces. Then (2.1) can be rewritten into

$$m_{vehicle}\frac{dv_{vehicle}}{dt} = \sum F_t - \sum F_r \tag{2.2}$$

In (2.2), $\sum F_t$ represents the total tractive forces, and $\sum F_r$ the sum of the total resistive forces. An illustration of the forces are presented in Fig. 2.1.

$$m_{vehicle}\frac{dv_{vehicle}}{dt} = (F_{tf} + F_{tr}) - (F_{rf} + F_{rr} + F_w + F_g) \tag{2.3}$$

Equation (2.3) represents the forces that are presented in Fig. 2.1, where F_{tf} is the tractive force on the front wheels and F_{tr} is the force on the rear wheels. Resulting in $F_{tr} = 0$ for a front-wheel driven vehicle. The subtracted forces are the resistive forces, where F_r is the rolling resistance on the front and rear wheels, F_w is the aerodynamic force and F_g is the grading resistance acting on the vehicle in slopes. Though it could sometimes be more convenient to use torque or power instead of force, which motivates

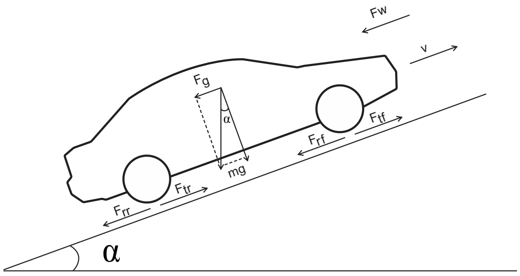

Fig. 2.1 The tractive and resistive forces that acts on a moving vehicle.

the following equations.

$$T = r \times F \tag{2.4}$$
$$P = T\omega = (r \times F)\omega \tag{2.5}$$
$$\omega = \frac{v}{3.6r} \tag{2.6}$$

Transformations between force and torque in (2.4) and from torque to power in (2.5), the radius r refers to the wheel radius. In (2.6) the calculations of the angular velocity of the wheel, in rad/s, is presented when the vehicle speed, v, is given in km/h.

2.1.2 Aerodynamic, rolling and climbing resistances

To be able to calculate the external forces that are acting on the vehicle there are three different equations that can be used [6]. To use these, the environment where the vehicle is driven needs to be known.

$$F_w = \frac{1}{2}\rho A_f C_D (v_{vehicle} + v_w)^2 \tag{2.7}$$
$$F_r = L_n f_r cos(\alpha) \tag{2.8}$$
$$F_g = m_{vehicle} g sin(\alpha) \approx m_{vehicle} g \alpha \tag{2.9}$$

Equation (2.7) describes the aerodynamic force where, ρ is the air density, A_f is the front area of the vehicle, C_D is the aerodynamic drag coefficient and v_w is the component of the wind speed. In (2.8) the force of the rolling resistance is expressed with the normal load that is acting on the centre of the wheel, L_n, and the rolling resistance coefficient, f_r. The force of the rolling resistance should be perpendicular to the surface of the road, which results in an angular term $cos(\alpha)$, where α is the angle of the slope. The last equation, (2.9), describes the climbing or grading resistance. For reasonable values of α, up to 20 %, the approximation presented is valid.

2.2 The topology of different powertrain configurations

In the following sections the most common powertrain configurations are introduced and briefly explained. At first the conventional powertrain is presented, followed by three electrified powertrain setups; the pure electric powertrain, the series hybrid and the parallel hybrid. The purpose is to give the reader a good understanding of the stated configurations and the advantages and disadvantages with electrifications of vehicles.

2.2.1 Conventional internal combustion engine vehicles

The energy used for propulsion of a conventional vehicle is supplied with fuel. The fuel is combusted by the engine which converts the chemically stored energy into kinetic energy. However most of this energy in conventional vehicles is dissipated as heat and a smaller amount of it is used to rotate the crankshaft of the engine. The efficiency of the internal combustion engine (ICE) varies for different speeds and torques, in order to use the engine where it is most effective, a gearbox is mounted between the engine and the wheel axle. A clutch is used for a manual gearbox, and torque converter for automatic gearbox, is needed for smooth transitions between the different gears [7].

2.2.2 Electrified vehicles

Pure electric vehicles

In pure electric vehicles (PEVs) the energy is chemically stored in a battery from where it is delivered to the electric machine (EM) where it is transformed to mechanical energy. The EM has higher efficiency, in comparison with ICEs, in a wider range of speeds resulting in that there is no need of a gearbox. However the torque of the EM needs to be increased when it is delivered to the wheel axle to propel the vehicle, which motivates the use of a final drive. Further the angular velocity of the wheel does not need to be as high as the maximum speed of the EM [6].

As in conventional vehicles there is a need of a differential, in electric powertrains, to allow the wheels, connected to the driveshaft, to rotate at different speeds. However there are electric vehicles built with in-wheel motors that can replace the differential due to that the motors can be operated in different speeds when driving in a curved path. The reduction of the components in the transmission of electric powertrain results in a lighter and a more simplified transmission structure [8].

One of the advantages with electrified powertrains is that the EM can be operated in generator mode, with the possibility to regenerate power back to the battery during decelerations and braking. This advantage results in that the energy efficiency in city-driving and start/stop driving patterns is around 40 % higher for electrified powertrains in comparison with conventional vehicles [9].

PEVs are not as widely commercialized as hybrid electric vehicles. Where the reasons can be stated with the need of larger batteries, which increases the cost and weight of the vehicle, together with a lack of electrified infrastructure for charging of the vehicles. Moreover the relatively short range in comparison to conventional vehicles is a reason for the lower popularity for the PEVs, where the hybrid electric vehicles (HEVs) can compete with the conventional vehicles when focus is on the driving range [6] [8].

Series hybrid electric vehicles - Range extenders

The series hybrid electric vehicle, also called a range extender, consists of two power sources that deliver energy to one power plant. The powerplant is an EM which is used for propulsion of the vehicle. In the most common setups the primary power source is a battery pack and the second one is an ICE connected to a generator to enable generation of energy to either charge the battery or deliver power to the EM as can be seen in Fig. 2.2 [6]. The goal when using a range extender is to give the electrified vehicle the same range as the conventional one. The engine that is used to generate power to the battery is typically smaller for the series hybrid configuration, than for parallel hybrids, due to that the engine only has to deliver average power. However the battery needs to be more powerful for the series hybrid to feed the traction motor during high power consumption [10].

Advantages with the series hybrid are that the battery pack does not need to be as large as for PEVs, and thereby reducing the cost. Moreover the ICE in the powertrain is not mechanically connected to the wheel axle resulting in that the engine can be operated in its most effective region, which improves the fuel economy [9].

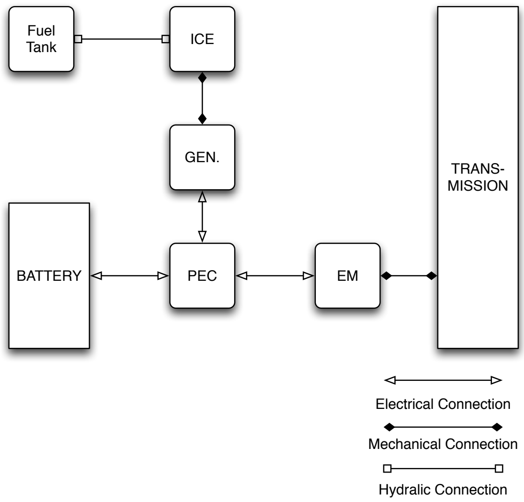

Fig. 2.2 An overview of the powertrain for a series hybrid electric vehicle.

In start/stop driving the series hybrid can be used in its most effective way, when it is possible to regenerate the power during braking. On the other hand highway driving is the most inefficient operation of a range extender. This is due to that the mechanical energy from the ICE is transformed to electrical energy by the generator and then back to mechanical energy, and there are always losses during energy conversion. In [8] it is stated that up to 20 % of the energy from the ICE is lost during this type of operation.

Parallel hybrid electric vehicles

For this configuration the engine and the EM co-operate for the propulsion of the vehicle, where both so-called powerplants are connected to the wheel axles. The parallel hybrids have advantages during highway driving, compared to the series setup. Due to that the ICE can propel the vehicle when driving the efficiency in this case is higher for this type of HEV setup [9]. One type of a parallel hybrid powertrain setup is shown in Fig. 2.3, called separate axle powertrain. It can be seen that it consists of two separate powertrains, one for the rear axle and the other connected to the front axle. It should be mentioned that for this architecture it is not possible to charge the battery pack when the vehicle stands still due to that there is no mechanical connection between the crankshaft of the engine and the EM [6].

2.3 Components in the powertrain

The powertrain consists of different components depending on which powertrain setup that are used. In the following sections the main components of the presented powertrains in Section 2.2, are introduced with the information needed to be able to follow the preceding work in this thesis.

2.3.1 Internal combustion engine

The most common types of ICEs used in motor vehicle applications are spark-ignition gasoline-fueled piston engines [11]. Losses in the ICE is depending on which type of engine that is studied, but at the most efficient regions of torque and engine speed the efficiency of gasoline engines, also called Otto engines, are around 35 % and for diesel engines up to 45 %. However the efficiency of these engines can be as low as 5-10 % in a poor operating point [8]. For ICEs in conventional powertrains only around 15 % of

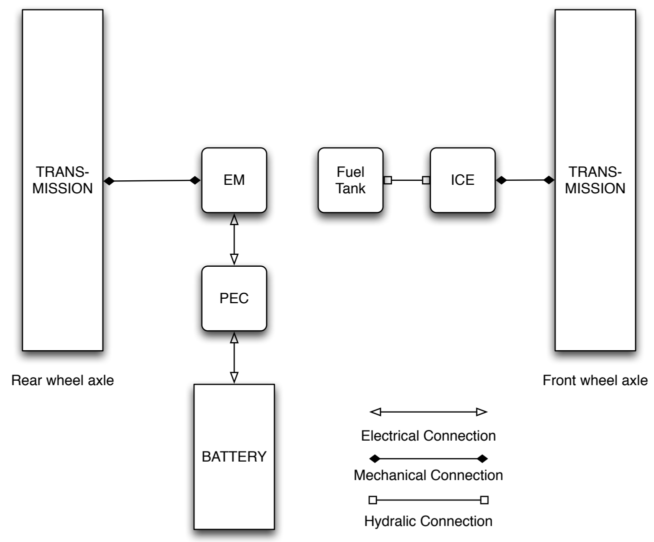

Fig. 2.3 An overview of the powertrain for a parallel hybrid electric vehicle

the energy in the fuel can be used to propel the vehicle [10]. In Fig. 2.4 a typical efficiency map of a spark-ignited engine is presented. The efficiencies depending on the operation points, in the torque-speed plane, are stated in the graph [6].

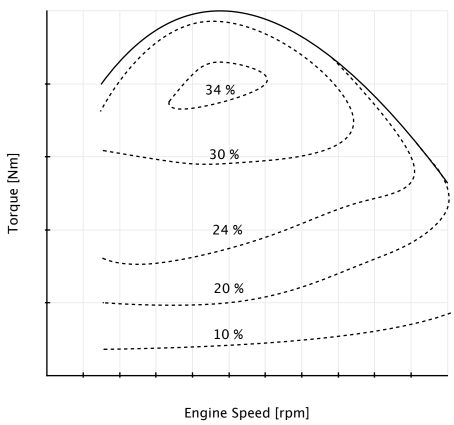

Fig. 2.4 A typical efficiency map of an internal combustion engine. The maximum speed-torque curve and the efficiencies are roughly presented.

2.3.2 Transmission

The functionality of the transmission is to modify the speed and torque of the ICE or EM to better conform to the velocity of the vehicle. Due to that the ICE only can deliver maximum torque at a certain speed and that the torque at low speeds are limited there is a need of changing the power to be kept approximately constant [12]. Moreover the crankshaft of the ICE always rotates in the same direction which makes it necessary to have a gearbox to enable the reversed gear.

When referring to the automotive transmission the clutch and differential is included which results in a total gear ratio from the crankshaft to the wheel axle. In vehicle applications the transmission usually are split up in two different categories; manual and automatic [7].

$$T_{wheel} = T_{ICE} g_{tot.Ratio} \tag{2.10}$$
$$w_{wheel} = \frac{g_{tot.Ratio}}{w_{ICE}} \tag{2.11}$$

The torque and rotational speed of the engine is modified with the transmission as shown in (2.10) and (2.11) with the total gear ratio expressed as $g_{tot.Ratio}$, including the actual gear ratio and the final drive ratio.

Differential

The differential in the transmission has three different main functions; to transfer the power from the crankshaft to the wheel axle, to keep the rotational speed in the gearbox low and to prevent slipping wheels during steering when the inner and outer wheel is rotating in different speeds. The second function is also called the final drive and keeps the losses lower in the gearbox due to lower friction effects. The third function of the differential is not present for the rear wheels in a front-wheel driven vehicle, due to that the rear wheels does not have a fixed connection they spin independently [7] [13].

Clutch

The clutch is used to disconnect the engine side from the wheel side of the transmission. It can basically be seen as two plates that are pressed together and therefore rotates in the same speed. When the driver presses the clutch pedal the pressure between the plates are lowered and they can rotate at different speeds [13].

2.3.3 Electric machine

There are several types of EM but the most common in vehicle applications are permanent magnet synchronous machines. These types of machines are fed with a three phase voltage, modulated with the inverter. During braking the permanent magnets induces a current in the windings which results in a braking torque, in the case of an inverter that can handle regenerative powers.

The torque that can be delivered by a machine is following to the volume of the rotor, for electric vehicles it is desirable with small machines. Therefore low torque and high speed machines are used in order to keep the size of the machines small for a given power level [14]. In comparison with ICEs the EMs can be designed smaller and lighter, as well as up to 6 times more efficient [10].

A way to represent EMs in vehicle simulations are by maximum speed-torque curves and efficiency maps [15]. As can be seen in Fig. 2.5, where the efficiency of a typical EM is presented the efficiency varies with the operating points in the speed-torque plane. The operation of an EM should be designed to be mostly in the most efficient areas [6].

2.3.4 Inverter

To supply the electric machine with proper voltage an inverter is needed. The inverter is also called the controller due to that it controls the operation of the machine. The controller is needed to transform the DC voltage from the battery to the AC voltage required for the EM to operate properly. The requirements by the driver need to be fulfilled, which refers to appropriate torque and speed of the machine. Since EMs are capable of regenerating power from braking the controller should be able to charge the battery with power during these periods [6].

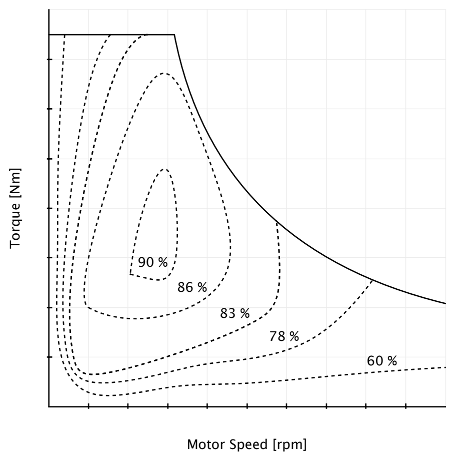

Fig. 2.5 A typical efficiency map of an electric machine. The maximum speed-torque curve and the efficiencies are roughly presented.

2.3.5 Battery

For electric vehicles the energy storage is the most critical part of the powertrain. Usually the manufacturers specify the coulometric capacity of the battery, which is equal to the total ampere-hours. In the specifications, given by the manufacturer, different ampere-hours specified for different current rates are usually stated. If a higher current magnitude is used during discharge then the coulometric capacity is lower. Therefore the current rate needs to be specified together with the ampere-hours, for complete understanding of the battery capacity. In other words it can be explained as the amount of ampere-hours gained when discharging a battery from fully charged until the cut-off voltage is reached.

State of charge (SOC) is another important battery parameter. SOC is defined as the ratio between the actual used battery capacity and the battery capacity of a fully charged battery. SOC is a percentage value between 0 and 100. According to [6] the change of SOC in time can be expressed as

$$\Delta SOC = \frac{idt}{Q(i)}. \tag{2.12}$$

In (2.12), where the charging or discharging current is expressed as i and $Q(i)$ is the coulometric capacity of the battery, given in ampere-hours for the given current rate, i. To calculate the actual SOC-level in the battery the following equation can be used.

$$SOC = SOC_0 - \int \frac{idt}{Q(i)} \tag{2.13}$$

Equation (2.13) where SOC_0 is the initial SOC-level of the battery. The charging or discharging current, i to or from the battery pack should be negative during charging and vice-versa [6]. Moreover the battery power losses can be calculated from known battery current, i_{Batt} and the total resistance, R_{Batt} of the battery as in

$$P_{Batt,loss} = i_{Batt}^2 R_{Batt} \tag{2.14}$$

The open-circuit voltage (OCV) of the battery can be explained as the voltage between the anode and cathode of the battery when it is disconnected from the system. To determine the actual voltage of the battery the OCV needs to be known.

$$V_{OCV} = V_{max} - DOD_{fact}(1 - SOC) \tag{2.15}$$

$$V_{Batt} = R_{Batt} i_{Batt} + V_{OCV} \tag{2.16}$$

In (2.16) the voltage of the battery can be calculated, with the determined open-circuit voltage V_{OCV} from (2.15). Since the OCV is changing, depending on the SOC, the battery voltage in (2.16) needs to be calculated depending on this representation of the battery voltage [16].

Chapter 3

The Simulation Tool

In this chapter the simulation tool is presented. It can be used to simulate how different electric vehicle would perform based on a real log from a vehicle with an identical car body. It should be noticed that the estimated power consumption only is the power consumption of the propulsion system. The first section describes the scripts used to load data to the simulation model. In the next section the driver model and the pure electric vehicle model is discussed with the purpose to give the reader an understanding of the simulation tool, and how it is composed. To estimate the losses in the components of the powertrain loss maps are used. To simulate the performance of the electric machine maximum torque maps are implemented.

3.1 Brief explanation of the script files

The tool is built up by a main script which calls three subscripts before opening the model. The first subscript calculates external forces, based on logs in *.mat* format. These calculations are introduced in Section 2.1.1. There are two versions of this script, one for conventional logs and another for electric logs. The second subscript loads the loss maps and specifications of the components included in the simulated powertrain. The last subscript loads the values for the driver model as well as the physical values of the simulated vehicle, mass and wheel radius. To get further information of the script files and to study the calculations, of the external forces, in detail the reader is referred to Appendix A.1.

3.2 Throttle and brake pedal controller - The driver model

The assumption, that the external forces are the same independently of the powertrain, is mentioned before. This is only valid if the velocity of the simulated vehicle has the same velocity as the logged vehicle. It is thereby important that the error between the reference speed and the simulated speed is small.

To control the velocity of the simulated vehicle a driver model in the the form of a PI- regulator is chosen. The error between the reference velocity and the simulated velocity is used as an input to the regulator, and is expressed in rad/s. This results in a torque response which is represented by a throttle and a brake pedal position. The PI- regulator is tuned to result in a sufficient operation of the simulated vehicle the control parameters can be found in Appendix A.2.

3.3 The pure electric vehicle model

The model representing a pure electric vehicle consists of four parts where the chassis, motor, battery and the transmission are modeled. The vehicle model gives an estimation of the power consumption of the main components in the powertrain. Inputs to the vehicle model are the following signals:

- $throttle\_pos$, Acceleration pedal position
- $brake\_pos$, Brake pedal position
- Trq_ext, Estimated torque, caused by the external forces
- $DCDC\_I$, Current drawn by 12 V system, air conditioner and immersion heater

The different blocks are explained in detail in Appendix A.2. In the following sections brief explanations of the different parts of the model are presented.

Vehicle body

In this block the torques caused by external forces, braking and drag losses are summarized. The drag losses are estimated from a loss map and describe the mechanical losses in the wheel axle. The angular velocity of the wheel is recalculated into vehicle speed.

Electric machine and inverter

In this block the speed of the EM is calculated from the summarized inertias of the components in the system and the torques caused by the EM, external forces, braking and drag losses. The power consumed by, or delivered to, the battery is also calculated here. Further the torque delivered to, or consumed by the motor, as well as losses in the EM and inverter, are determined in this block based on maps.

Battery block

In the battery block the lithium-ion battery is modeled, where the battery voltage, SOC-level and the battery losses are estimated. Based on the equations, presented in Section 2.3.5, appropriate calculations can be done from loss maps. Moreover power limits are calculated to determine if the battery can be charged or discharged with the requested power from the inverter.

Transmission

The transmission in the C30 Electric is relatively simple to model due to that the powertrain has a fixed gear ratio between the electric machine and the wheel axle. There are power losses in the mechanical cogs, which are represented by an estimated efficiency. This is a rough estimation of the losses due to that the losses should be changing with the angular velocity.

Chapter 4

Studied Vehicles and Logged Signals

In the following sections the procedure of calculating the external forces is explained. The first section explains the calculations, followed by a section where the investigated vehicles and the methods of logging are presented. Furthermore the available signals, from the different powertrains, are introduced and how they are handled is explained.

4.1 Calculation of the external forces acting on the vehicle

The method to estimate the external forces, F_{ext} that are acting on the vehicle during motion is presented in this section. It is assumed that the simulated vehicle has identical wheels, rotating with the same angular velocity and having constant wheel radius, which means that it is not changing with the rotational speed. In Section 2.1.1, (2.3) is presented describing the forces that acts on a vehicle during motion, and is rewritten into

$$m_{vehicle}\frac{dv_{vehicle}}{dt} = F_t - F_{ext} \tag{4.1}$$

$$F_{ext} = (F_r + F_w + F_g). \tag{4.2}$$

The external forces, F_{ext}, presented in (4.1), is summarized of the forces shown in (4.2). Since the data from the logged vehicles, that represents propulsion and braking, are representing torque (4.1) is recalculated with (2.4) resulting in

$$T_{ext} = T_t - F_{acc}r_{wheel,log} \tag{4.3}$$

$$T_{ext} = T_{propulsion} - T_{brake} - T_{acc}. \tag{4.4}$$

In (4.3), T_t is representing the tractive torque of the vehicle and including of $T_{propulsion}$ and T_{brake}, as shown in (4.4). It should be noticed that the wheel radius used in (4.3) is the radius of the logged vehicles wheel. To get the torque acting on the wheel axle this radius is used resulting in (4.4).

$$F_{ext} = \frac{T_{ext}}{r_{wheel,log}}. \tag{4.5}$$

It should be possible to freely choose the wheel radius of the simulated vehicle, which makes it necessary to transform the quantity to force acting on the vehicle, as presented in (4.5). The external forces, F_{ext} is recalculated into torque again on the wheel axle in the simulation tool.

4.2 Test vehicles and preparations for testing

In this section the investigated vehicles are presented, with specifications from the manufacturer that are of interest. Further the preparations for testing, during logging, are presented and how the vehicles were driven.

4.2.1 The investigated vehicles

The vehicle models used for logging are two different models of Volvos C30, one with a diesel powertrain while the other is a pure electric one. In Table 4.1 the specifications of the C30 Diesel is presented and in Table 4.2 the specifications of the electric vehicle are shown. The aerodynamic drag coefficient of the C30, presented as C_D in (2.7), is stated to 0.28 and the maximum frontal area, A_f, is $2.18\,\mathrm{m}^2$ [17].

Table 4.1: Specifications of the C30 Diesel [17]

Model	Diesel D2/DRIVe -12
Curb weight	1428 kg
Engine displacement	1560 cm^3
Transmission	Manual (B6 D2)
First Gear	3.727
Second Gear	2.048
Third Gear	1.258
Fourth Gear	0.919
Fifth Gear	0.738
Sixth Gear	0.622
Reversed Gear	3.818
Final Drive	3.611
Fuel Consumption (NEDC)	4.3 l/100km (3.8 l/100km)

Table 4.2: Specifications of the C30 Electric [18]

Model	Electric *Brusa*
Curb weight	1735 kg
Electric Motor Power	82 kW (110 bhp)
Battery Weight	280 kg
Battery Energy (nominal)	24 kWh
Battery Energy (to power the car)	22.7 kWh

4.2.2 Preparations for testing

To be able to compare F_{ext} calculated from electric and conventional logs, test are made. For the tests presented in this report the conventional and the electrical vehicle are driven the same route to be able to verify the methods of calculating the external forces. The route is specified to be driven from Volvo Torslanda to Särö and vice versa, and specified in Appendix B. The reference route is driven with the C30 electric and is traced with the C30 diesel, with vehicle speed during the drive as close as possible to the reference. Since the drives are done on public roads it is impossible to drive the vehicles in the same manner. Therefore two routes are logged in each direction, between Volvo and Särö, with the conventional vehicle.

Before starting the tests, the tire pressure needs to be verified against the specified data from the manufacturer, to have similar conditions. In the case of the C30 electric, the tire pressure is specified to 250 kPa, for all the tires, and the approved tire dimension, that the logged vehicle has is 205/55R16 [19]. In the case of the C30 Diesel the ECO settings were used which was stated to 250 kPa on all the wheels for the tire dimension 195/45R15 [20].

4.3 Available log data for different powertrains

In this section, the signals for the conventional and the electrical powertrain, used in this report are presented. First the conventional powertrain will be handled, followed by the pure electrical one. In the end of this section the logging procedure is explained, presenting the equipment that is used and how the data is handled before the calculations.

4.3.1 Signals of the conventional powertrain

To be able to estimate the external forces that are acting on the vehicle during movement the logging files for the specified vehicle and drive cycle are investigated. For the conventional powertrain the setup and used signals are presented in Fig. 4.1 and listed below.

- Vehicle speed
- Brake pressure
- Propulsion torque
- Fuel consumption
- Clutch position

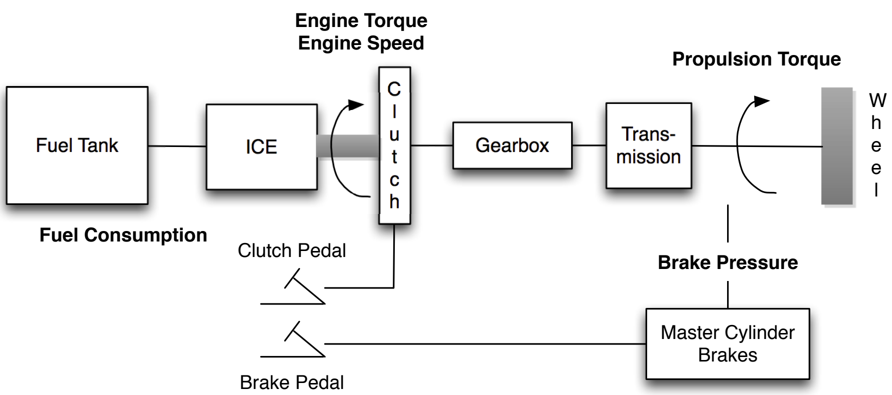

Fig. 4.1 Overview of the conventional powertrain, where the signals are bold

The vehicle speed, $v_{vehicle}$

The vehicle speed is given in km/h and is presented with positive values, resulting in that when the vehicle is driven in reversed direction it can not only be identified from this signal.

Brake pressure signal, P_{brake}

P_{brake} is the the signal of the pressure in the master cylinder of the brakes. To be able to express the braking torque the following equation is used.

$$T_{brake} = P_{brake}c \tag{4.6}$$

In (4.6), c is a constant given from the manufacturer of the brakes and is given in Nm/Bar. When estimating the braking torque it should be noted that it is not compensated for the temperature in the brake discs.

The propulsion torque signal, T_{prop}

The propulsion torque signal is a calculated signal representing the torque that currently is being delivered to the wheel axle. This torque is calculated as

$$T_{propulsion} = T_{crankshaft}g_{act.Ratio} \tag{4.7}$$

$$g_{act.Ratio} = \frac{w_{ICE}}{w_{wheel}}. \tag{4.8}$$

In (4.7), $T_{crankshaft}$ is the estimated delivered torque from the crankshaft of the engine, compensated for the torque needed by the AC and the alternator. The gear ratio, including the final gear and the actual gear ratio, $g_{act.Ratio}$, is estimated with (4.8). Apart from that this is a calculation, there will also be an error during idle operation when the vehicle stands still. There is no information of the clutch pedal in the signal $T_{propulsion}$, resulting in unreasonable values when the clutch is pressed or the gear is in neutral.

The fuel consumption

The fuel consumption signal is a signal representing the momentarily fuel consumption, given in microliters. The value of the signal is integrated for each fuel pulse and is reset to zero at every ignition on. If the total fuel consumption is wanted then the values before each reset should be summarized.

The clutch signal

There is a signal which gives a rough estimation of when the clutch pedal is pressed but it does not contain any information of its position.

4.3.2 Signals of the electric powertrain

In the case of the pure electric vehicle a different set of signals are used. Below the signals are listed, were the first three are used to calculate the external forces, F_{ext}, and the additional ones are used to study the electric model. The vehicle speed and the brake pressure are identical signals with them of the C30 diesel, presented in Section 4.3.1. The electrical powertrain and the stated signals are presented in Fig. 4.2.

- Vehicle speed
- Brake pressure
- Torque of the electric machine
- Speed of the electric machine
- Inverter voltage (DC-side)
- Inverter current (DC-side)

- Converter voltage (HV-side)
- Converter current (HV-side)
- Converter voltage
- Battery current
- Battery voltage
- Depth of Discharge

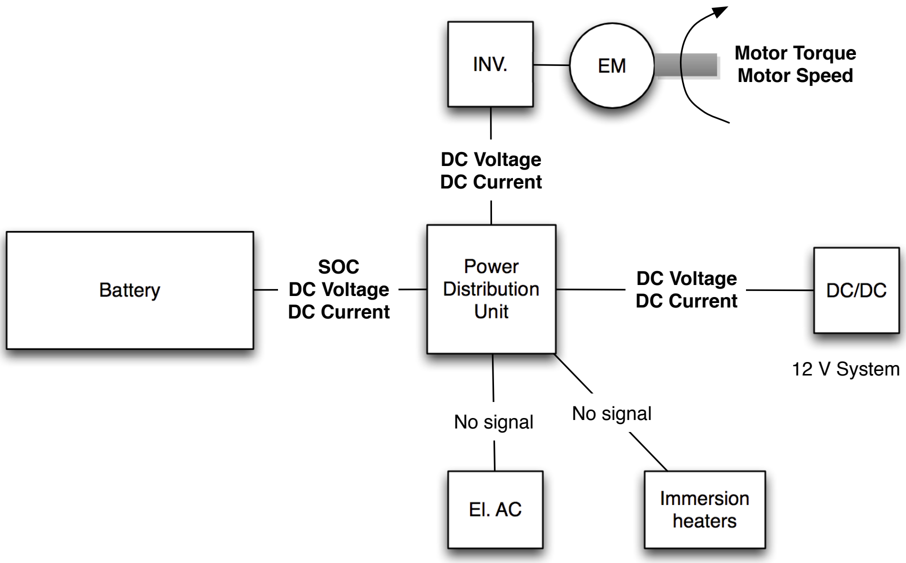

Fig. 4.2 Overview of the electrical powertrain where the signals are bold.

The motor torque signal

When analyzing the propulsion torque of the C30 PEV the motor torque signal is used. The torque representing propulsion is calculated as

$$T_{propulsion,PEV} = T_{motor} g_{fix.Ratio} \eta. \tag{4.9}$$

The constant $g_{fix.Ratio}$ in (4.9) represents the fixed gear ratio of the transmission in the electrical powertrain and is multiplied with the estimated cog efficiency of the transmission η.

4.3.3 Current drawn from battery, not consumed by the motor controller

The power consumed by the 12 V system, electric air conditioner AC, and the immersion heaters shall in the simulations be drawn from the battery pack in order to be able to compare the simulated SOC value with the logged. The current signal from the battery and the current signal to the inverter are used to estimate this current.

$$I_{AC,12V} = I_{Battery} - I_{Inverter} \tag{4.10}$$

The current to the motor controller is stated as $I_{Inverter}$ in (4.10), and is the current on the DC side of the inverter drawn from, or delivered to, the battery pack. When this current is subtracted from the total current from the battery management system, $I_{Battery}$, the result is the estimate of the total current, except the current needed by the electric machine and its controller.

4.3.4 The methods used for logging

The data from the logged vehicles are recorded from the CAN- system of the vehicles. To connect to the vehicles system a computer, with the software *Vector CANalyzer* is used, connected via the hardware *CANcaseXL log*.

When exporting the CAN-signals, analyzed in CANalyzer, there are possibilities to resample the signals. A sample time of 0.1 s is chosen to reduce the size of the exported .mat-files. Resampling of the signals result in the advantage of easier management in Matlab. Moreover a low pass filter of a Butterworth-type is applied to the signals that are filtered. For better simulation performance the vehicle speed is filtered, to reduce the noise of F_{acc}, which is calculated from the vehicle speed, as seen in (2.1). In addition the estimated external forces are filtered for easier analyzes.

Chapter 5

Quality Analysis of Logged Data and Simulation Results

In the following sections, the results from calculations and simulations are shown and analyzed. The first section handles a verification of the external forces, F_{ext}, to confirm that it is possible to estimate the forces from real log data. To verify this, the estimated forces, from both the electrical and the conventional logs are compared and analyzed. In the following sections, the simulation tool is verified, where data from a C30 is used as input and simulated with a pure electrical powertrain, and is compared with the log from the C30 electric.

There are six logs that are investigated. The logs were recorded between Volvo Torslanda and Särö in both directions, the route is presented in Appendix B. The logs recorded with a C30 electric are called log N and S which stands for the direction driven, North and South. A C30 diesel was then driven the same way two times in each direction and those logs are called N1, N2, S1 and S2.

5.1 Verification of the external forces

To enable a verification of the simulation tool, the estimated external forces should be calculated from identical logs from the electric and the conventional vehicle. To be able to verify that the external forces, F_{ext}, estimated from the C30 diesel logs are accurate, the diesel vehicle was driven the same route as the C30 electric. Since it is impossible to drive the vehicles in an identical way, the estimated forces are qualitatively compared, to get an understanding of the simulation results. Moreover the external forces are inputs to the simulation model, which makes it necessary to verify these forces and thereby ensure that they are estimated in the right way.

5.1.1 Comparison between the calculated external forces

The external forces are estimated as explained in Section 4.1. Due to that it is impossible to drive the vehicles in the same manner with identical external forces, the estimated forces need to be qualitatively compared for verification purposes.

In Fig. 5.1 and Fig. 5.2 the external forces for the six different measurements are presented. It can be seen that the forces during the logs with the electric and the conventional vehicles are similar over the distance. If the velocities between the logs are compared it can be seen that they are fairly similar. This is an indication of that the proposed method of estimating the forces of a logged vehicle can be used. If the forces, F_{ext}, are studied during the route, slopes can be identified. Since the vehicles are driven the same

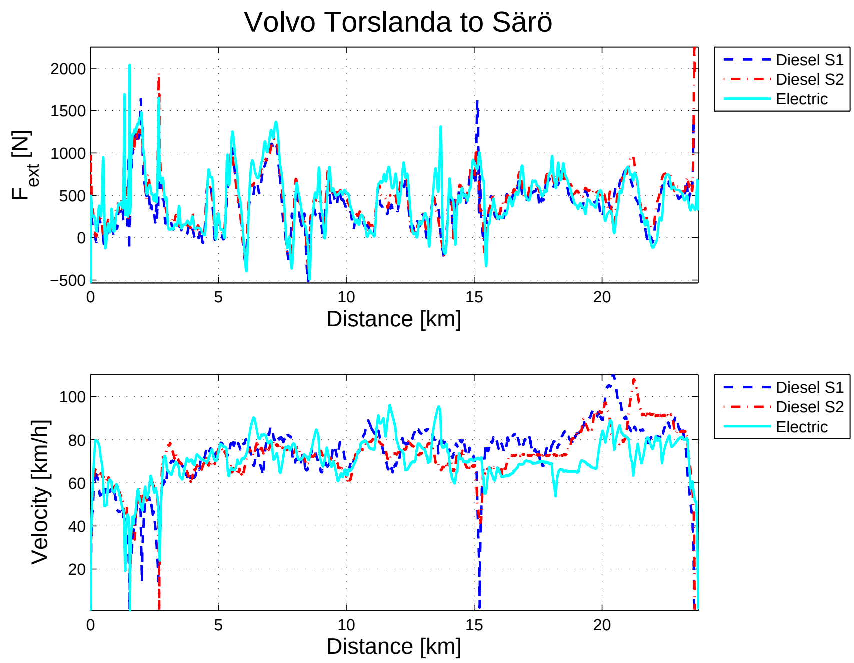

Fig. 5.1 Calculated F_{ext} from three different logs; C30 Electric S, C30 Diesel S1 and S2. The similarities in the external forces can be seen in the upper graph

way with identical vehicle bodies this confirms the stated assumption of approximately equal forces. To analyze and compare the logs, calculated values are presented in detail in Table 5.1 and Table 5.2.

Table 5.1: Comparison between electrical and conventional logs, Volvo Torslanda to Särö

VCC to Särö	Electric C30 S	Diesel C30 S1	Diesel C30 S2
$v_{mean}[km/h]$	67.7	68.3	69.3
$v_{median}[km/h]$	69.6	74.1	72.5
$a_{mean}[m/s^2]$	0.273	0.288	0.234
$F_{ext,mean}[N]$	476.9	407.3	492.0
$F_{ext,median}[N]$	458.4	397.5	489.9
$\sum F_{ext}[MN]$	6.03	5.07	6.04
$E[kWh]$	12.9	10.8	11.9

Table 5.2: Comparison between electrical and conventional logs, Särö to Volvo Torslanda

Särö to VCC	Electric C30 N	Diesel C30 N1	Diesel C30 N2
$v_{mean}[km/h]$	75.3	73.0	70.1
$v_{median}[km/h]$	82.5	76.4	74.0
$a_{mean}[m/s^2]$	0.275	0.242	0.232
$F_{ext,mean}[N]$	548.0	440.3	522
$F_{ext,median}[N]$	545.3	431.2	512.5
$\sum F_{ext}[MN]$	8.42	6.94	8.57
$E[kWh]$	19.7	15.9	17.7

In Table 5.1 and Table 5.2, the presented values of mean and median velocity and forces are calculated during periods when the vehicle is moving. An absolute value of the acceleration and deceleration is

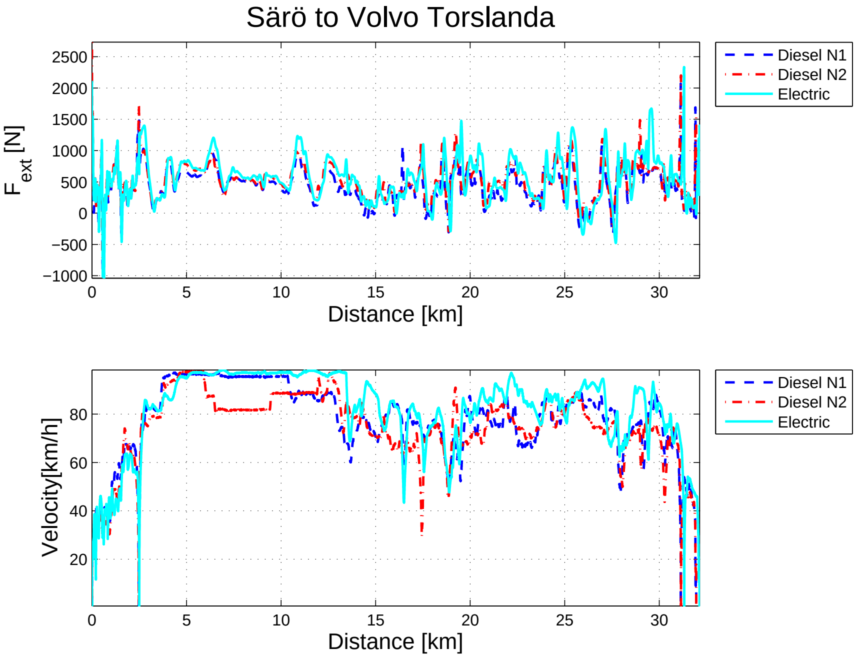

Fig. 5.2 Calculated F_{ext} from three different logs; C30 Electric N, C30 Diesel N1 and N2. The similarities in the external forces can be seen in the upper graph.

indicated with a_{mean}. This gives an indication of how unsteady the velocity is, which is interesting due to the higher energy consumption in accelerations than in constant speeds. The energy needed on the wheels during the routes, E, is estimated from the propulsion torque, with efficiencies of the transmissions. The negative torques are neglected due to that it corresponds to regeneration, which is not possible in the conventional vehicle.

5.1.2 Impact of the change in mass

When simulating different powertrains it results in differences in weight between the vehicles. The inclination during logging is unknown, therefore F_{ext} that is calculated will not be completely valid for a simulated vehicle with a different weight than the logged one. An error is therefore introduced to the simulation tool. To investigate how this affects the results, F_r (2.8) and F_g (2.9), which are needed to overcome the grading and the rolling resistance, are studied.

Grading resistance

The percentual error of F_g will be as large as the percentual difference in mass of the logged and the simulated vehicle. In Fig. 5.3, F_g is presented for different grading angles for C30 electric and C30 diesel. The reason to present angles up to 3.43 degrees, which corresponds to grading of 6 %, is that this is when warning signs are used in Sweden [21]. As can be seen when comparing Fig. 5.3 with F_{mean} in Table 5.1, the contribution of F_g in the external forces can be quite substantial. It can be the dominating term of F_{ext} for steep slopes. It should be noticed that F_g can be both positive and negative depending on the slopes.

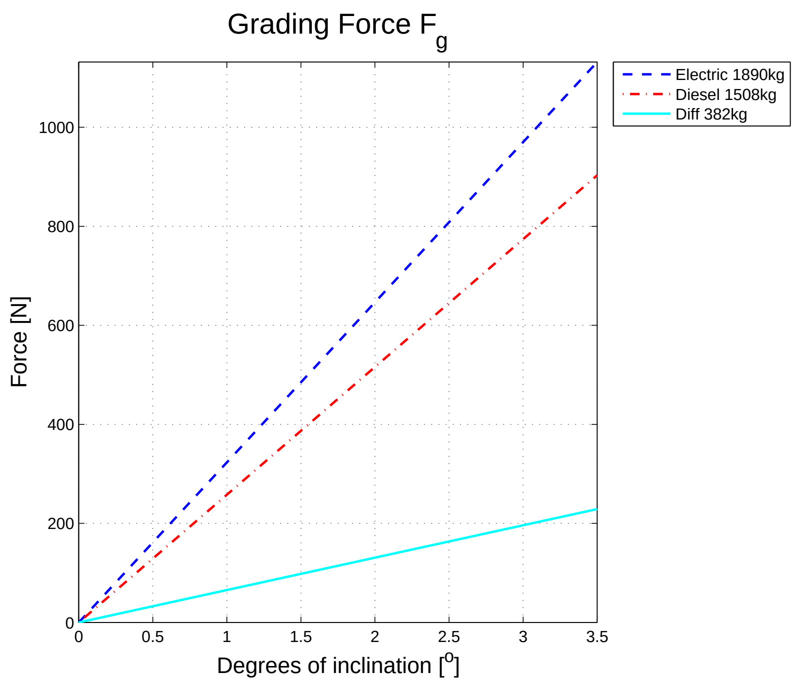

Fig. 5.3 The grading resistance, F_g, for C30 electric and C30 diesel at different grading angles.

Rolling resistance

Another part of F_{ext} is the force that is needed to overcome the rolling resistance F_r, expressed in (2.8). By using this equation it is found that F_r will be around 190 N for the logged C30 diesel and 241 N for the logged C30 electric at a flat surface as the friction constant, f_r , is around 0.013 for asphalt according to [7]. This difference of 49 N will decline to 42 N if driven in a 30 degree slope. As can be seen it does not distinguish notably. So by adding a 45.5 N to $F_{ext,mean}$ for the diesel logs, an estimation is presented in Table 5.3, of how much the weight difference of the two vehicles due to F_r would impact F_{ext}.

Table 5.3: Impact of F_{ext} for weight compensation in F_r for the logged vehicles

	N1	N2	S1	S2
$F_{ext,mean,compensated}[N]$	485.8	567.5	452.8	537.5
Increase of $F_{ext,mean}[\%]$	10.3	8.7	11.1	9.2

5.1.3 Impact of wind speed

When comparing the logs between Volvo Torslanda and Särö it can be assumed that the grading resistance, F_g, and the rolling resistance, F_r, are equal in the case of logging the C30 diesel. Since the logs are recorded with the same vehicle with the same weight in both cases. The component of the external forces that might differ is the aerodynamic force, F_w, which is depending of the vehicle speed and the wind speed, as stated in (2.7).

In Fig. 5.4 the aerodynamic part of the external forces are presented at different vehicle speeds for various wind speeds. From the figure it is possible to see how the vehicle and wind speed affects the aerodynamic drag resistance, F_w.

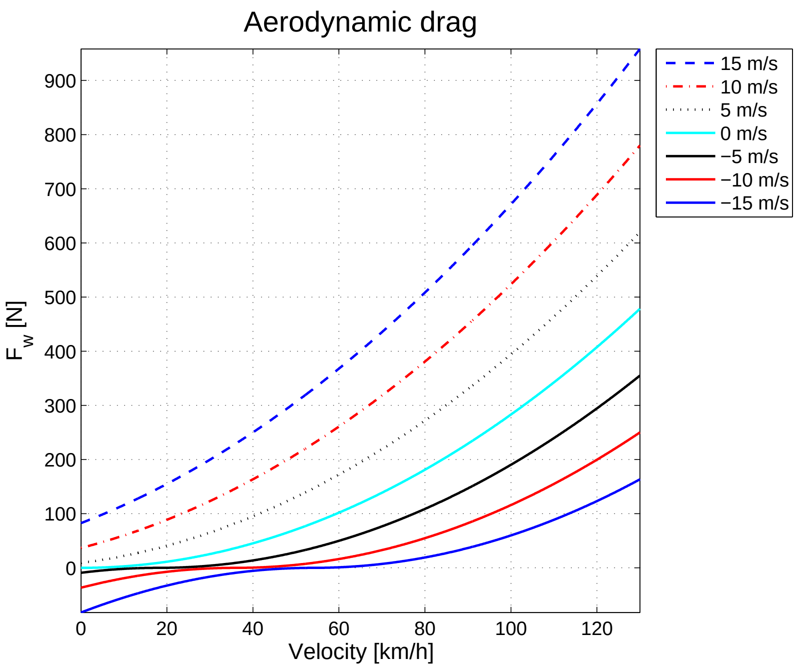

Fig. 5.4 The changes of the aerodynamic force dependent on the vehicle speed at different wind speeds.

When analyzing the external forces for the different vehicles and the different logs the impact of the wind condition can be seen. In Fig. 5.5 a part of the log between Särö and Volvo Torslanda is presented. It can be seen that the forces are approximately the same meanwhile the velocity of the logged vehicles differs.

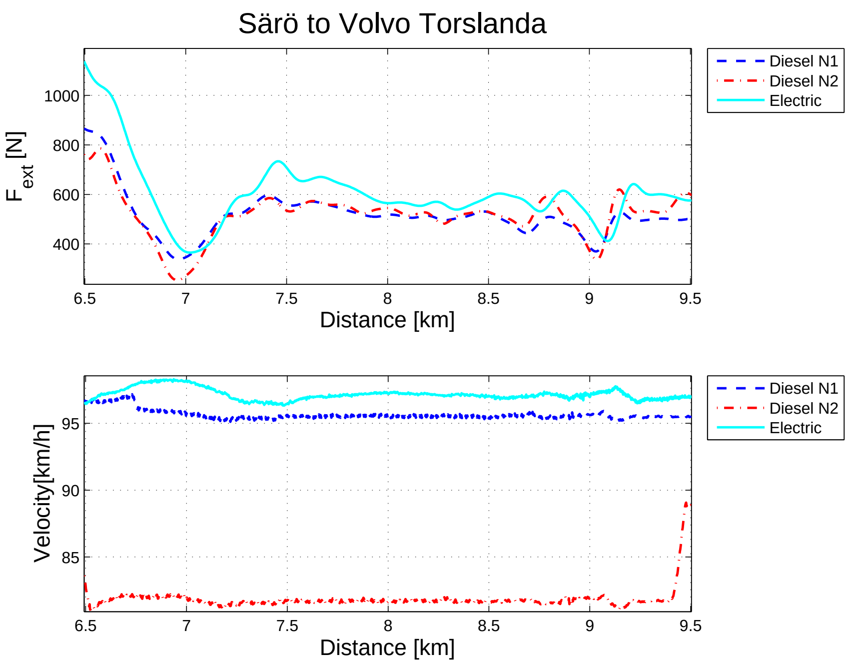

Fig. 5.5 A closer look of the external forces between the electric and diesel logs. It can be seen that the external forces of the Diesel N1 and N2 are approximately the same when the vehicle speed is different.

To investigate if it is possible that the wind conditions could have affected the results weather data from Onsala Observatory is studied [22], and the data is presented in Fig. 5.6 and Fig. 5.7. It shall be noted that weather data is local, which results in uncertainties for the data of the logs, but it gives an indication of the difference in weather conditions between the logs.

The analysis indicates feasible results from the weather conditions, hence it can be said that the changing external conditions affects the different logs, and thereby affect the simulation results. This is not a problem for the use of the simulation tool since the purpose is to compare the real log with the simulation results, but it will affect the validation of the simulation tool.

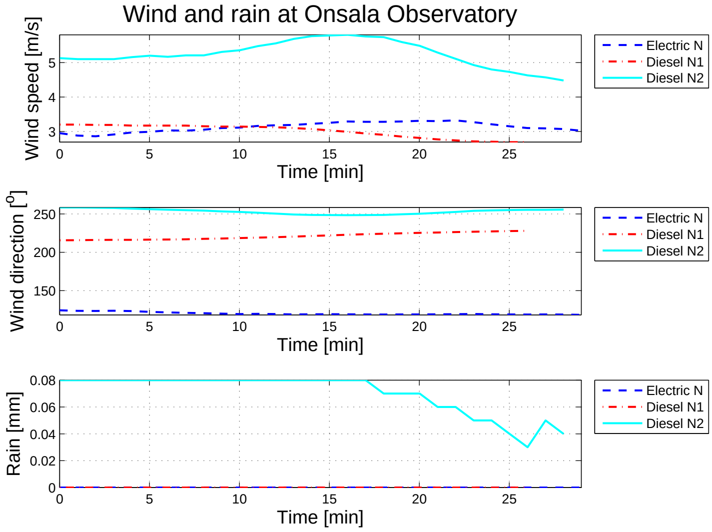

Fig. 5.6 Weather conditions at Onsala Observatory for the time periods of logging between Särö and Volvo Torslanda

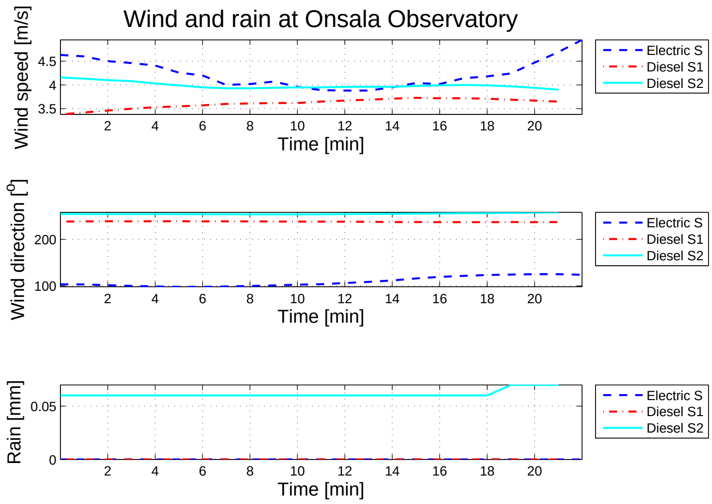

Fig. 5.7 Weather conditions at Onsala Observatory for the time periods of logging between Volvo Torslanda and Särö

5.1.4 Propulsion torque during gear shifting

For the diesel vehicle the propulsion torque indicates incorrect values when the clutch pedal is pressed and when the gear is put in neutral. This is not a problem for the C30 electric since it does not have a gearbox. T_{ext} represents the torque on the wheel axle as a result of the external forces, F_{ext}. By studying the calculated T_{ext} during gear shifting and comparing it with the torque of the C30 electric it should be possible to see if the lack of the propulsion torque signal during gear shifting would lead to any problem.

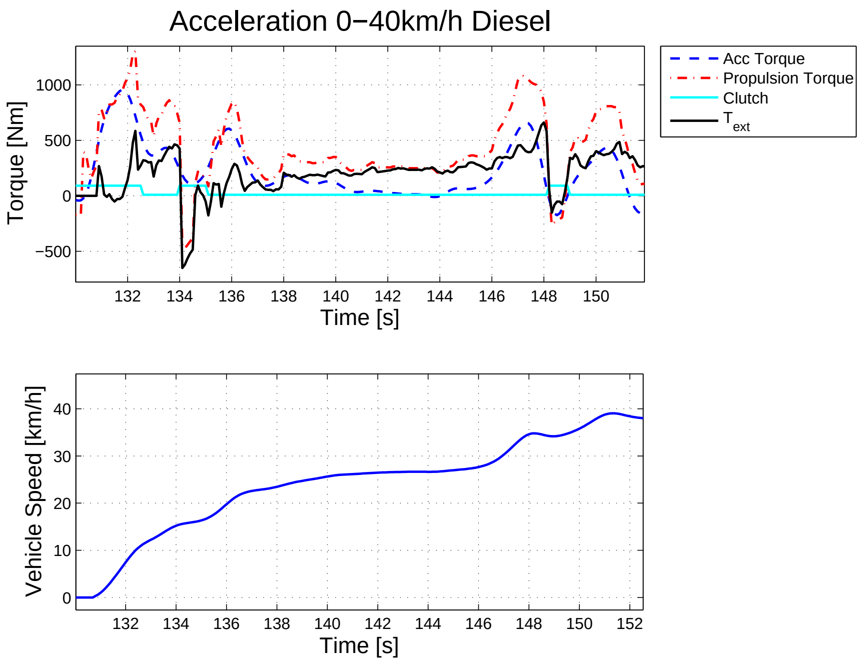

Fig. 5.8 Acceleration from 0 to 40 km/h for a diesel log, notice that the values of propulsion torque is negative when the clutch is pressed.

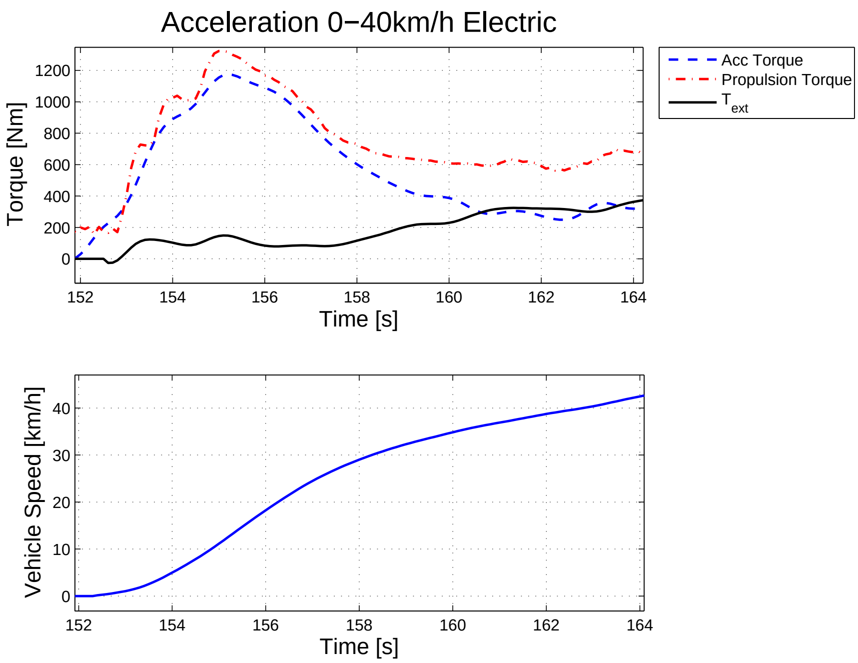

Fig. 5.9 Acceleration from 0 to 40 km/h for a diesel log.

In Fig. 5.8 and Fig. 5.9 the acceleration from standstill to 40 km/h for both C30 electric and C30 diesel is presented. It was performed at the same place but it is not completely comparable since the acceleration is greater for C30 electric. In Fig. 5.9, T_{ext} is as expected low at lower velocities and increases as the velocity increases. But for the C30 diesel, the torque is negative when the clutch is pressed. Moreover the torque is higher than expected right before the clutch is pressed which will even out some of the negative torques that is seen during shifting. A possible explanation to the high values is that the propulsion torque is calculated with a gear ratio based on the engine and wheel speed ratio. This means that when the clutch is not fully pressed and the engine still delivers fairly high torque this torque will be calculated with a too high gear ratio.

5.1.5 Summarized uncertainties of the external forces

The impact of the wind that is discussed will not lead to any uncertainties for the outcome of the tool since this is an external force that will impact vehicles with the same body the same way independently of the power train.

The grading resistance will cause an inaccuracy if the logged and the simulated vehicle differ in weight. This should be taken into consideration when choosing a log for calculation of the external forces, F_{ext}. Since the grading resistance, F_g, can be both positive and negative, a log with only ascent will give greater uncertainties in $F_{ext,mean}$ than a log with both ascent and descent.

The rolling resistance will also cause an inaccuracy in F_{ext} due to weight differences. In some cases it might be a good idea to compensate for this. It would be possible to use (2.8) to calculate the difference in force for the two weights at small inclinations and then add this difference to the calculated F_{ext}.

It should be noticed that a discrepancy in F_{ext}, due to weight differences, will not lead to the same magnitude of discrepancy for the outcome of the simulation tool. Since the mass of the simulated vehicle will be used in the simulation even though it has not been used in F_{ext} calculations.

The inaccuracy in F_{ext} due to poor signals during gear shifting would need more analysis. By studying F_{ext} calculated from the logs of this thesis, the effect of gear shifting seems small but for a log recorded in city traffic this would naturally be a great uncertainty.

5.1.6 Tests in constant speeds

The constant speed tests were done on a flat road, where both the C30 diesel and electric were driven. To reduce the impact of possible inclination and wind conditions the tests were done in both directions. The mean values are calculated and due to that constant speed is kept, the acceleration part of T_{ext} is neglected. The logged propulsion torque of the vehicle during the measurements is used to calculate the power consumption for the specific chassis in constant speeds.

Since the transmission losses are not included in the signal representing the propulsion torque, these losses needs to be estimated. The gearbox losses are estimated from loss maps in various velocities. The needed parameters for the loss map are gear number, engine speed and engine torque. There is no signal indicating the actual gear, which makes it necessary to be estimated with (4.8). The results are presented in Table 5.4, where it can be seen that the gearbox losses are in the range of 2.9 - 3.4 % of the total power delivered by the engine.

Table 5.4: Results from the constant speed tests for the C30 Diesel

Mean Velocity [km/h]	Est. Gearbox Losses [kW]	Mean Power [kW]	Est. fuel consumption [l/10 km]
14.6	0.033	0.967	0.11
30.6	0.065	1.935	0.10
49.5	0.130	4.180	0.14
70.2	0.271	9.200	0.21
86.5	0.424	12.87	0.24

It should be mentioned that the gearbox losses are based on the actual settings in the car during the specific testrun. For example the gear number, the speed and torque of the engine are not optimized for reduced losses. However these results give an approximation of the magnitude of the power losses connected to the gearbox.

The power presented in Fig. 5.10, is the power on the wheel axle for both the electrical and the conventional powertrain, calculated from the engine respectively the EM. It can be seen that the power increases in a square-shaped manner in respect to the vehicle speed, indicating the weight of the aerodynamic drag at higher speeds. However there are uncertainties in the measurements, for example that the driven route was short, resulting in shorter measurements in higher speeds, and thereby greater uncertainties. Furthermore the tests, for appropriate results, should be done on a test track where the conditions are better, in form of less grading resistance.

The efficiency used for the electrical transmission is an estimated value. Since it is a constant value independent of the speed of the EM, it seems that is not completely valid for these constant speed tests. A speculation is that the efficiency represents a valid average value during logs or drive cycles when the EM operates in different speeds during different conditions.

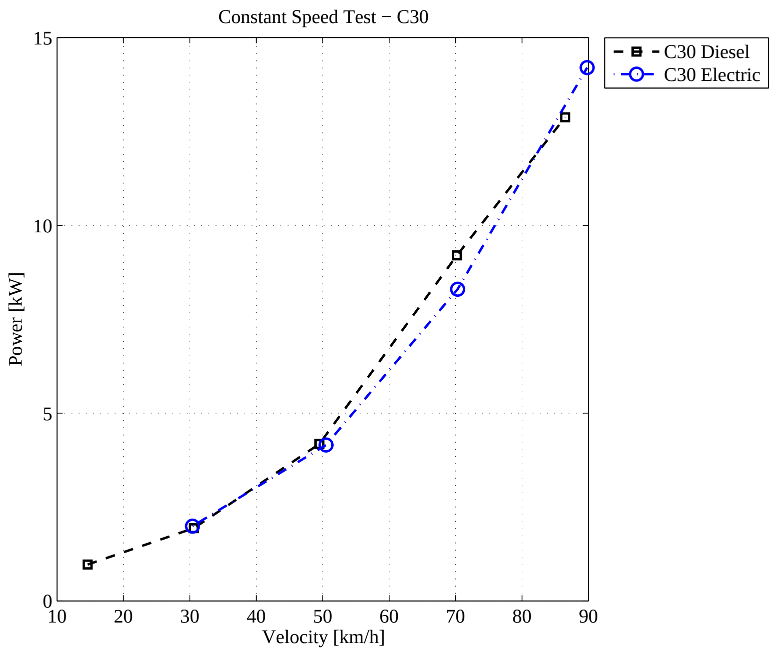

Fig. 5.10 The estimated power on the wheel axle for the C30 diesel and C30 electric during constant speed tests.

5.2 Validation of the simulation tool

In this section the simulation tool will be investigated. First by verifying the pure electric powertrain setup against electric logs. Next a study of the differences between the outcome of the simulation based on the electric and conventional logs, recorded on the same route, is done. This is to clarify the comparability and analyze the differences.

5.2.1 Logged C30 electric compared with simulated C30 electric

To enable a verification of the simulation results, the SOC levels are compared, where the SOC- level of the logged vehicle is calculated from the signals. The calculations to estimate the SOC- level in the simulation tool are presented in Section 2.3.5. The current drawn from the battery during the simulation is estimated with (4.10), presented in Section 4.3.3.

In Fig. 5.11 and 5.12 the results are graphically presented, with detailed values presented in Table 5.5 and Table 5.6. It can be seen when studying the SOC- levels that the simulated vehicle consumes more power than the vehicle consumes according to the logged signals. When studying the drive from Särö to Volvo Torslanda, in Fig. 5.12, it is possible to see that the difference between the logged and simulated SOC- level is growing with the distance. In comparison with Fig. 5.11, where the difference is larger in the beginning of the log, and is increasing in a slower rate. A speculation of the reason to a larger initial error in the log from Volvo Torslanda to Särö is uncertainties in the logged SOC- signal. The discrete signal changes in steps of a minimum 0.32 % and thereby can result in an error in the first value of the signal. If Fig. 5.11 is studied the first 1.3 km, it can be noticed that the SOC- level of the logged vehicle remains on the initial level. A reason to this could possibly be explained with an almost fully charged battery, which could result in a hesitant value. Another reasonable motivation to this, could be explained with an unstable SOC- value, resulting in uncertain indication of the logged state of charge.

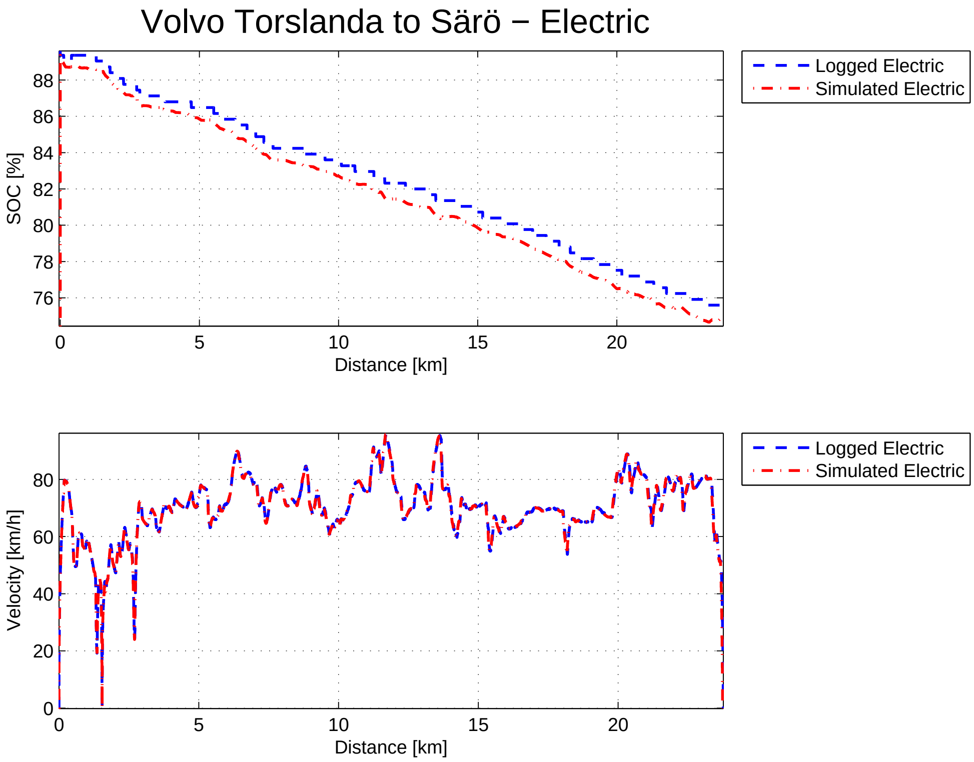

Fig. 5.11 The simulated SOC is compared with the logged SOC. The F_{ext} used for the simulation is calculated from the same CAN recording as the logged SOC, Volvo Torslanda to Särö

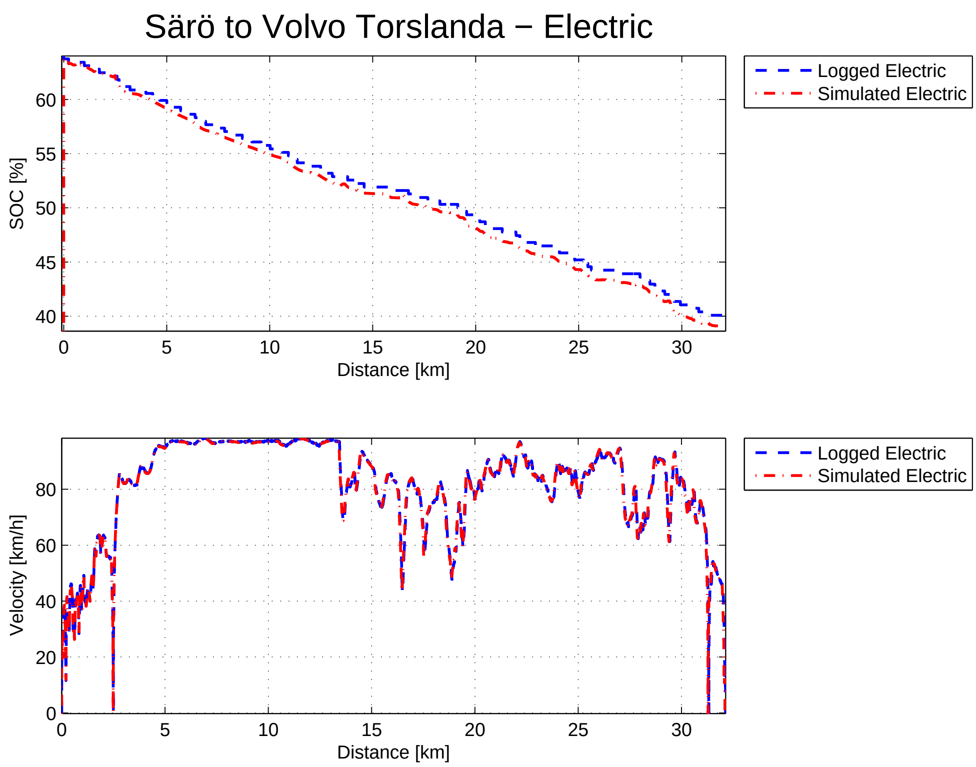

Fig. 5.12 The simulated SOC is compared with the logged SOC. The F_{ext} used for the simulation is calculated from the same CAN recording as the logged SOC, Särö to Volvo Torslanda

In Table 5.5 and Table 5.6 a more detailed presentation of the differences between the logged and simulated SOC- levels are shown. ΔSOC_{log} represents the change, between start and finish, in the logged signal and ΔSOC_{sim} represents the change in the simulated case. The percentage deviation over the entire log is indicated with $\frac{\Delta SOC_{log} - \Delta SOC_{sim}}{\Delta SOC_{log}}$.

Table 5.5: SOC comparison between log signals and simulation, direction: Volvo Torslanda to Särö, where $\Delta SOC_{log} = 13.76\,\%$.

Volvo to Särö	Electric C30 S	Diesel C30 S1	Diesel C30 S2
ΔSOC_{sim}	14.47	12.62	14.40
$\Delta SOC_{log} - \Delta SOC_{sim}$	-0.71	1.14	-0.64
$\frac{\Delta SOC_{log} - \Delta SOC_{sim}}{\Delta SOC_{log}}\,[\%]$	-5.16	8.28	-4.65

Table 5.6: SOC comparison between log signals and simulation, direction: Särö to Volvo Torslanda, where $\Delta SOC_{log} = 23.68\,\%$.

Särö to Volvo	Electric C30 N	Diesel C30 N1	Diesel C30 N2
ΔSOC_{sim}	24.62	19.71	22.55
$\Delta SOC_{log} - \Delta SOC_{sim}$	-0.94	3.97	1.13
$\frac{\Delta SOC_{log} - \Delta SOC_{sim}}{\Delta SOC_{log}}\,[\%]$	-3.97	16.77	4.77

In Fig. 5.13 the difference of the logged and simulated SOC- levels are presented. The consumed power of the inverter and EM, is shown in the second subplot where interesting differences are indicated with ellipses. The circle in the subplot representing the consumed power, indicates large differences in regeneration between the simulated and logged vehicles. In most parts during the simulation the regeneration follows the reference approximately, with minor differences. It should be noticed that during high power consumptions, indicated with the ellipse, the difference between the SOC- values increases. A reasonable explanation of the differences in high power could be that the lookup tables, of the EM and the inverter used in the simulation tool, are uncertain in the operating regions indicated with the ellipse.

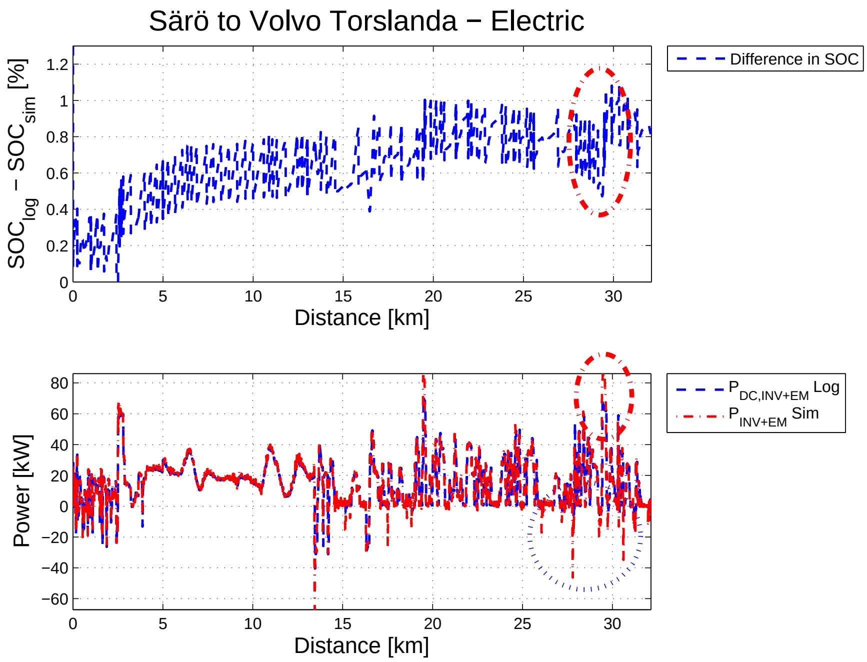

Fig. 5.13 The differences between the SOC- signals is presented together with the power consumed by the inverter and the EM for the logged and simulated vehicle. Notice the differences in regeneration, indicated with the circle, and the higher power consumption, ellipse, leading to a larger error in the SOC- level.

5.2.2 Simulation of electric vehicle based on diesel logs

In Fig. 5.14 and Fig. 5.15 the results of simulations based on diesel logs are compared with the logged SOC signal for the same route. When the graphs are studied it can be seen that Diesel S2 is the only simulated diesel log that consumes more power than the logged, electric one. A possible explanation for this can be found in Table 5.1, since the average and median vehicle speed are higher for the diesel than for the electric log, resulting in a higher power consumption. Based on the discussion in Section 5.1.2 it is natural that simulations with F_{ext} based on diesel logs would result in a lower power consumption because of the weight difference.

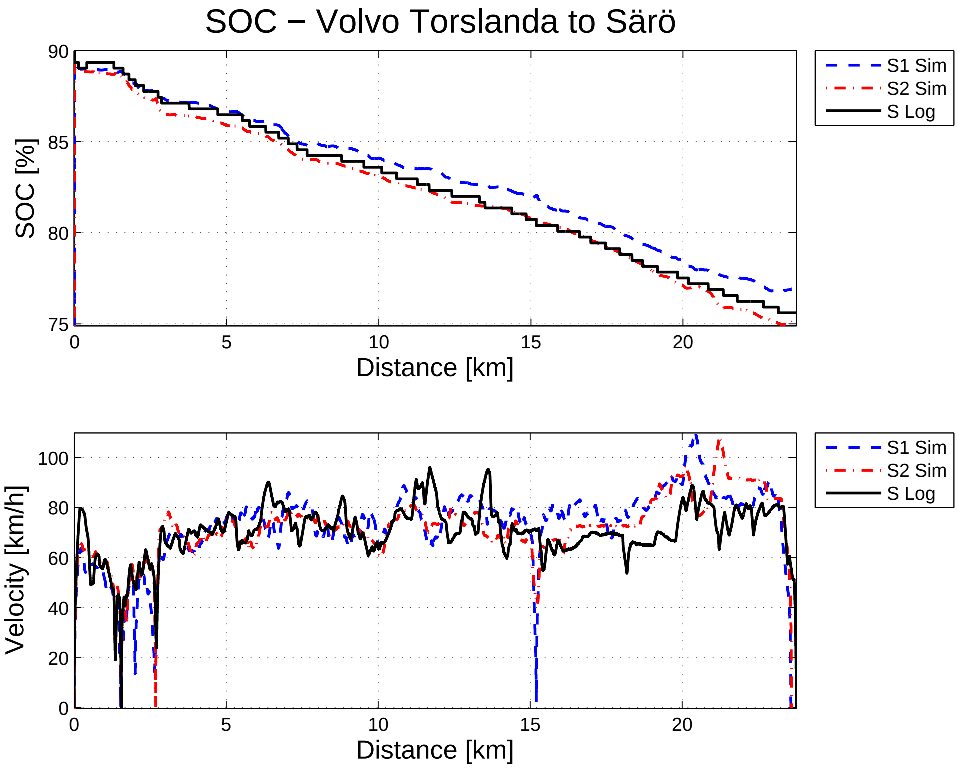

Fig. 5.14 The simulated SOC-levels, based on the routes driven in south direction, are compared with the logged SOC for the electric vehicle, driven the same route.

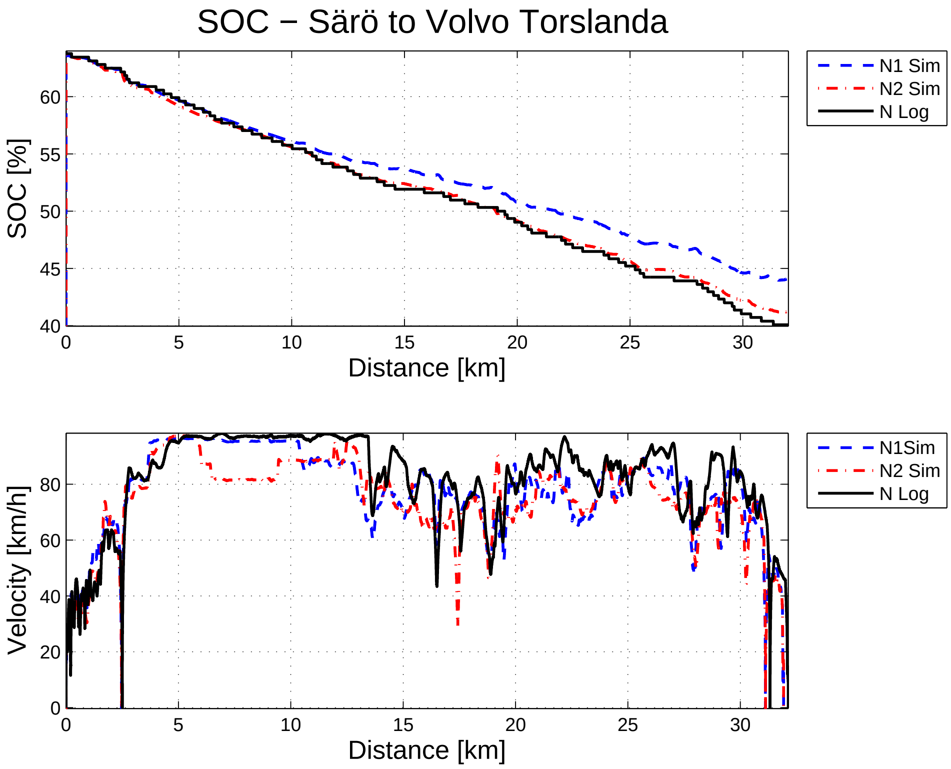

Fig. 5.15 The simulated SOC-levels, based on the routes driven in north direction, are compared with the logged SOC for the electric vehicle, driven the same route.

From the results presented in Fig. 5.14 and Fig. 5.15, and the data in Table 5.5 and Table 5.6, it can be seen that the simulation results are arbitrarily. It should be kept in mind that the estimated external forces between the electric logs and the diesel logs differ. However it is still possible to say that the simulation tool works, when focusing on the logs with corresponding F_{ext} with the electric log.

Compensation of the weight difference

Figures 5.14 and 5.15 are based on diesel logs and there is only one of them that consumes more power than the electric reference vehicle. Based on the discussion in Section 5.1.2, F_{ext} will be too low to represent an electric vehicle when calculated from a diesel log, due to the weight difference. Therefore 45.5 N was added to F_{ext}, based on the calculated difference in rolling resistance for a flat surface. The result of this is presented in Table 5.7 and Table 5.8. It is not possible to confirm that this adjustment of F_{ext} will lead to a better representation of the actual forces, but from the values in Table 5.1 and Table 5.2 this seems to be reasonable. However, by this check it is possible to see how a change of F_{ext} affects the outcome of the simulations.

Table 5.7: SOC comparison between log signals and simulations when F_{ext} is compensated for rolling resistance. The $\Delta SOC_{log} = 13.76\,\%$, where the values from previous simulations are given in brackets.

Volvo to Särö	Electric C30 S	Diesel C30 S1	Diesel C30 S2
ΔSOC_{sim}	14.47	13.70 (12.62)	15.53 (14.40)
$\Delta SOC_{log} - \Delta SOC_{sim}$	-0.71	0.06 (1.14)	-1.77 (-0.64)
$\frac{\Delta SOC_{log} - \Delta SOC_{sim}}{\Delta SOC_{log}}$ [%]	-5.16	0.44 (8.28)	-12.86 (-4.65)

Table 5.8: SOC comparison between log signals and simulations when F_{ext} is compensated for rolling resistance. The $\Delta SOC_{log} = 23.68\,\%$, where the values from previous simulations are given in brackets.

Särö to Volvo	Electric C30 N	Diesel C30 N1	Diesel C30 N2
ΔSOC_{sim}	24.62	21.30 (19.71)	23.19 (22.55)
$\Delta SOC_{log} - \Delta SOC_{sim}$	-0.94	2.38 (3.97)	0.49 (1.13)
$\frac{\Delta SOC_{log} - \Delta SOC_{sim}}{\Delta SOC_{log}}\,[\%]$	-3.97	10.05 (16.77)	2.07 (4.77)

5.2.3 Verification of the simulation tool, comparison of energy usage

A comparison of the energy consumption of the simulated electric vehicles, based on the different logs driven between Volvo Torslanda and Särö is presented in Fig. 5.16 and Fig. 5.17. The energy consumption is estimated, with battery voltage and current in the model. For the simulations, the average $I_{AC,12V}$ is calculated from the electric logs. This current is drawn from the battery during simulations, based on both the diesel and the electric logs, to enable verification. For the logged vehicle the energy consumption is calculated from the signals for battery voltage and current.

According to the energy comparison the discrepancies, between the energy calculated from the logs and the simulated energy, are between 2.1 % respectively 4.6 %.

In Fig. 5.16 it can be seen that the energy consumption of the logged electric vehicle and the simulated vehicle, from the same log, are following closely. This is an indication of that the model is a good representation of the C30 electric and that the simulation results gives appropriate results.

Some of the differences in the simulated diesel logs can be explained by the differences in the external forces. Since the logs are not exactly comparable these differences occurs in the simulation results.

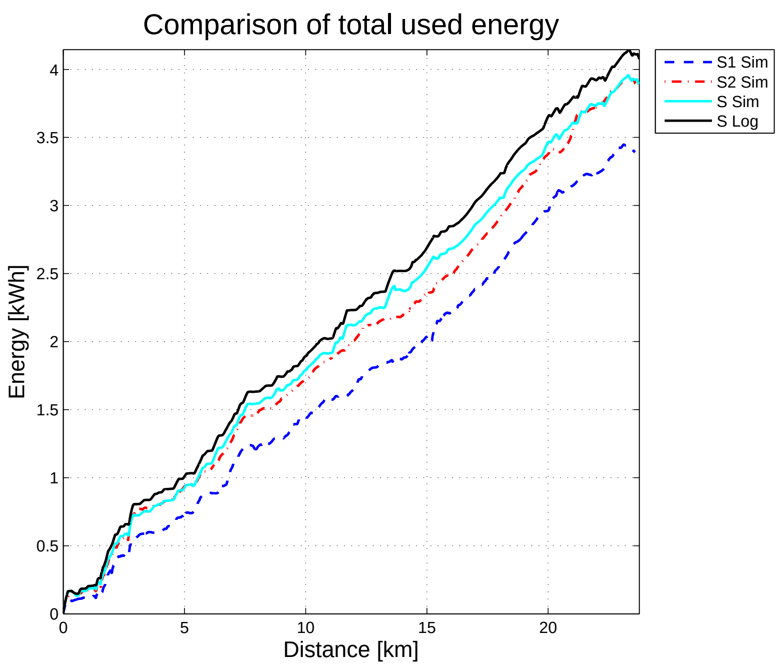

Fig. 5.16 Comparison of the energy usage of the simulated electric powertrains, in south direction. Where Log is the reference calculated from the battery.

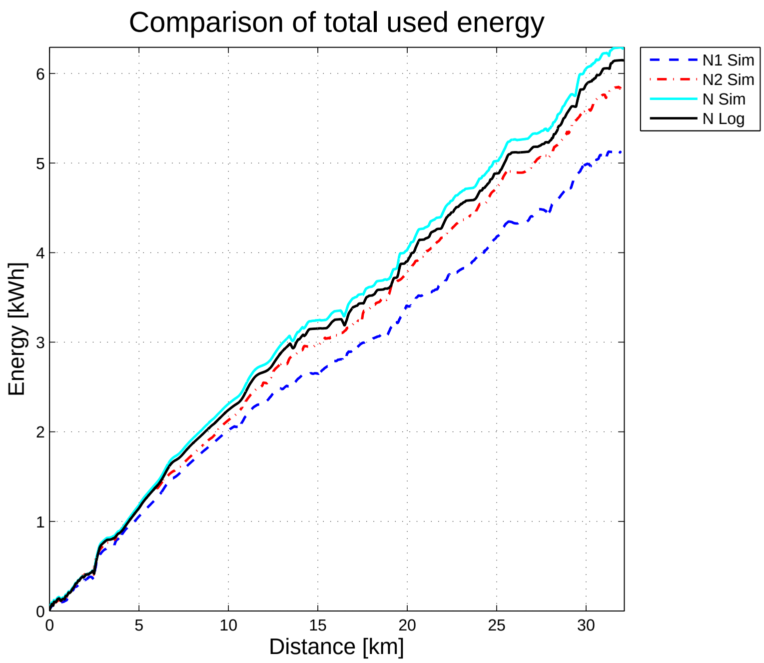

Fig. 5.17 Comparison of the energy usage of the simulated electric powertrains, in north direction. Where Log is the reference calculated from the battery.

5.2.4 Comparison of energy usage for C30 with electric and diesel powertrain

The fuel consumption signal for the diesel log, S2, is used to calculate the amount of diesel that is used. This is then recalculated into energy with a factor of 9.8 kWh/liter [23]. The external forces from the same log, diesel S2, are then used as an input to the simulation tool to estimate the energy taken from the battery. The result of this is presented in Fig. 5.18, where the efficiency of an electrical powertrain, in comparison with the conventional is shown. It can be seen that an electrical powertrain is much more efficient than a conventional powertrain.

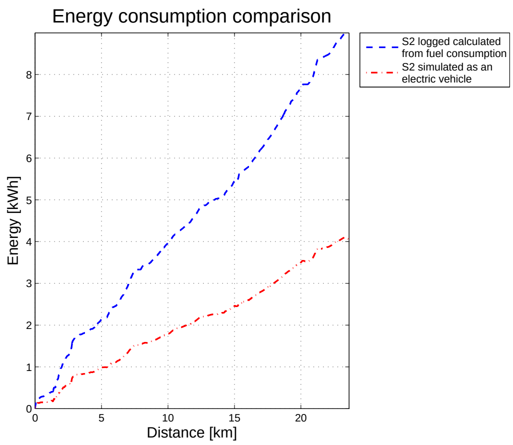

Fig. 5.18 Comparison of the energy consumption of a diesel log and a simulation of an electric powertrain for the same log.

Chapter 6

Conclusions

6.1 Results from present work

One of the sub targets of this thesis is to analyze the possibilities of estimating the external forces from real log data. The results have shown that it is possible to calculate these forces from logs of a C30 diesel and a C30 electric. This can be seen by comparing F_{ext} calculated from both electric and diesel logs for the same route. It can be seen that the estimated external forces, for different logs and same route, are approximately the same.

To estimate the external forces that are acting on the vehicle during the driven routes, signals from logs are needed. The data that are required for the calculations are the propulsion torque, the vehicle speed and the braking torque. However this data needs to be calculated from the existing signals of the logged vehicle.

The braking torque is calculated from the brake pressure of the master cylinder, with a given constant from the manufacturer of the brakes. The brake pressure and the vehicle speed are similar signals for both vehicles. Depending on which type of powertrain that is used, the propulsion torque is calculated differently. When focusing on the diesel powertrain there is a signal representing the propulsion torque of the vehicle, with uncertainties due to the lack of transmission losses. For the electrical powertrain, the torque of the electric machine is multiplied with the fixed gear ratio in the transmission, and with an estimated constant of the efficiency.

For the diesel log there are uncertainties for the propulsion torque signal during gear shifting. This is not handled in this work, it does not seem to have a great impact for the simulations for the logs studied, even though it might have been greater if the logs studied would be recorded in city traffic. Moreover the estimated transmission losses introduces an uncertainty due to the rough estimations.

The developed simulation model has the vehicle speed and the calculated forces of the logged vehicle as inputs. By studying the results of the simulations, it can be seen that the concept works. The assumption of same external forces for identical vehicle bodies but with different powertrains is a central part of this thesis. For the assumptions to be applicable, the simulated vehicle needs to have the same velocity as the logged. To verify the simulation results the energy consumption is compared between the simulated vehicle and the logged ones.

When comparing the logged C30 electric with the simulation results of the electrical powertrain to verify the model, the results show that the differences are between 3.97 % and 5.16 %. These results are based on a comparison between the SOC- levels of the battery. According to the energy comparison the discrepancies, between the energy calculated from the logs and the simulated energy, are in the range of 2.1 % to 4.6 %.

6.2 Future work

A limited number of logs have been used in this thesis. To be able to verify the accuracy of the simulation tool more logs needs to be analyzed. More tests of the vehicles should be done to be able to state that the estimations of the external forces are accurate. The electric and conventional vehicles should be driven together at the same time. This minimizes the impact of changes in the external forces and will result in more identical external conditions. Moreover logs from more specific driving patterns should be done eg. highway, city, and a route with many slopes, in order to be able to verify that the tool works for the different types of driving.

Since the SOC signal of the electric vehicle is sometimes questionable, other methods needs to be developed to verify the simulation results. In this thesis discussions and analyzes are done, on a smaller scale, of the power from the battery to calculate the energy consumption. The results show that this is a possible method of verifications, which could be analyzed more for an appropriate understanding of it.

For the conventional powertrain the propulsion torque signal gives unreasonable values during gear shifting and for neutral. Analyzes of the impact of this, for the simulation results needs to be done in a larger scale. This has larger impacts of the results when simulating a log with more start/stop driving patterns when the clutch is frequently used in comparison with e. g highway driving. Methods of working around this problem can be developed to reduce the uncertainties of the simulation results

The differences in weight, of conventional and electric vehicles, and the impact of the rolling resistance are discussed in the report. It indicates that it can be estimated and a suggestion is that it can be implemented in the simulation tool to reduce the impact of the weight differences. This should be verified, with more data and analyzes of the simulation results. Moreover the power deviations between the logged and simulated data shown in Fig. 5.13 is another point for further investigations to mention.

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Appendix A

More detailed explanation of the scripts and simulation models

The different scripts files and the simulation model of the pure electric powertrain will be explained and it will be stated where adjustments can be made in, order to perform different simulations.

A.1 Explanation of the script files

Here the different scripts, *runSimulation_XX_XX*, *ConstantsFile*, *LookUpXX*, *F_ext_calculation_XXX* and *Model_Car_Parameters_XX*, are presented.

A.1.1 *runSimulation*

It is possible to choose between 3 start up scripts called *runSimulation_XX_XX.m*. The different scripts correspond to vehicle models that can be simulated C30 Electric, C30 Range Extender and V60 with the electric powertrain of the C30.

In the first section of this script the needed directories are added to the Matlab path. Unwanted directories are removed from path in order to prevent fault values in the simulation:

```
%------------------------------------------------------------------------
% Close folders that are not used to prevent the use of fault values
%------------------------------------------------------------------------
rmpath xEV_C30_HEV_Range_Extender
rmpath xEV_C30_Diesel
rmpath xEV_V60_EV
rmpath Logfiles\V60
%------------------------------------------------------------------------
% Open folders that are used
%------------------------------------------------------------------------
addpath Logfiles\C30
addpath Constants
addpath F_ext_calculations
addpath xEV_C30_EV
addpath xEV_C30_EV\LookUp
addpath xEV_C30_EV\Models
```

In the following section the constants and look up data are loaded. In order to change the simulated components the line LookUpBrusa can be changed to another filename.

```
%----------------------------------------------------------------------
% loads constants and parameters
%----------------------------------------------------------------------
ConstantsFile %load constants eg. m/s--->km/h
LookUpBrusa %Load the wanted look up data eg. loss maps
Model_Car_Parameters_EV % Loads the parameters for the wanted simulation
%----------------------------------------------------------------------
```

The next section handles the log files. In the case of the C30, the log used can be either recorded with C30 electric or C30 Diesel. Therefore the first choice that has to be made is which type of log file that should be used. (Below an electric log is chosen, which is done by commenting the diesel section). Further the mass of the logged vehicle, and the radius of the logged vehicles tire must be specified. This in order to get the external forces calculated correctly. The name of the wanted log file should be chosen. The line bc_soc_initial refers to the initial value of SOC in the simulation. The last line starts the external forces calculation script:

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Choose the type of C30 log
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%----------------------------------------------------------------------
% Electric
%----------------------------------------------------------------------
m_vehicle_log = 1890; % curb weight = 1735 kg (source: trafikverket.se)
r_wheel_log = 0.3067;

load('N') % Name of the log-file
%load('S') % Name of the log-file

bc_soc_initial = 0.7;% Start value of State Of Charge (0-1) N=0.6376 S=0.8936

F_ext_calculation_C30_ELECTRIC_01

% %----------------------------------------------------------------------
% % Diesel
% %----------------------------------------------------------------------
% m_vehicle_log = 1508; % curb weight = 1428 kg
% r_wheel_log = 0.308;
% WeightDif=0;
%
% %load('N1') % Name of the log-file
% %load('N2') % Name of the log-file
% %load('S1') % Name of the log-file
% load('S2') % Name of the log-file
%
% bc_soc_initial = 0.5;% Start value of State Of Charge (0-1) N=0.6376 S=0.8936
%
```

```
% F_ext_calculation_C30_DIESEL_01
```

Last the model is loaded:

```
%------------------------------------------------------------------------
%Loads the Model
%------------------------------------------------------------------------
CarModel
```

A.1.2 ConstantsFile

In this file conversion factors, used in script and models are stated.

A.1.3 LookUpXX

The specific components for the simulated vehicle is specified in this script. In order to change the EM/inverter or the battery, changes shall be done in this file.

A.1.4 Model_Car_Parameters_XX

The physical parameters for the simulated vehicle is set here. Weight, wheel radius and inertia. The parameters of the PI-controller (driver) is also set here.

A.1.5 F_ext_calculation_XXX

There are three different scripts for calculation of the external forces. The reason for this is that the CAN-signals used differs depending on which vehicle that is logged. The script files are however built up in the same way. The needed signals are loaded filtered and recalculated into an external forces struct.

A.2 Explanation of the pure electric model and the included subsystems

The pure electric powertrain consists of a *Chassis*, *Motor*, *Battery* and a *Transmission*- block. In Fig. A.1 an overview of the PEV model is presented where the inputs, subsystems and outputs can be seen.

The Motor

The motor block is divided into five subsystems named; *MotorTrq*, *EM/INV losses*, *Motor Speed*, *Power Calculations* and *Regeneration limits*. In the *MotorTrq*-block the torque on the motor shaft is calculated depending on the throttle and brake position signal. Two lookup tables are used which outputs are regenerative and tractive maximum torque depending on the motor speed and the battery voltage. The maximum torque, which can be delivered by the machine at the moment is multiplied with the throttle position which in turn is compared with a limitation signal to ensure that the motor do not use more power than the battery is able to deliver.

In the case of regeneration the regenerative torque is multiplied with a regeneration factor which is dependent of SOC and the brake pedal position. With a value of the SOC = 90 %, regeneration is disabled resulting in a regeneration factor of 0. If the brake pedal position has a value between -0.5 and 0 the model only uses regenerative braking, which is scaled depending on the value. Further there is an algorithm implemented in the chassis block where manual braking is used, together with maximum regeneration, if the brake pedal position has a value between -0.5 and -1. The regenerative output is also compared with the battery limit to ensure that the battery is not fed with more power than the manufacturer has specified.

The *EM/INV losses*-block uses two lookup tables to calculate the losses in the motor and the inverter. The inputs are electrical torque, motor speed and battery voltage, though the lookup tables are independent of battery voltage. The losses of the motor and the inverter is given as a power loss and are added together. If the speed of the motor is below the lower saturation limit of 500 rpm there are no losses of the motor and inverter.

In the *Motor Speed*-block the total torque at the motor side of the transmission is divided with the corresponding inertia resulting in the instantaneous speed of the motor and by integrating this the angular velocity of the crankshaft is given. The transmission losses is represented by a lookup table of the efficiency.

In the *power calculation*-block the power to or from the battery is calculated by subtracting the mechanical power from the motor with the power losses of the motor and inverter resulting in the electrical power drawn or fed from the battery.

Chassis block

In this block the speed of the wheel shaft is recalculated to the vehicle speed. Moreover the external forces, F_{ext}, that are acting on the wheel is converted to the corresponding torque on the wheel shaft and summarized with the braking torque and the drag losses. The braking torque is calculated from stated total braking force of the vehicle, with the actual wheel radius and the drag losses are losses depending on the speed of the wheel shaft. The drag losses are depending on temperature but are in this model assumed to be 100 degrees celsius.

Transmission block

In this block the fixed gear ratio of the C30 Electric, FRONT_EM.ratio, is used to recalculate the motor torque and speed to the wheel side of the transmission. Further the inertia of the vehicle is also transformed, to the motor side of the transmission due to that division with the total inertia is done on that side.

The battery block

The block that is representing the battery is mainly composed of two subsystems, one which is representing the li-ion battery and the other to calculate the charging and discharging limits of the battery. In the subsystem where the battery is represented the battery current is the only input. The battery current is calculated by dividing the actual power to or from the battery with the actual battery voltage. The second input, emphDCDC_I is a signal that represents the current drawn from the 12 V load, the air conditioner and the immersion heaters of the vehicle.

For simplicity the cell temperature is set to 25 degrees of celsius inside the li-ion subsystem which is used to give a internal resistance of the battery. The internal resistance per cell is multiplied with the actual number of cells in the battery. To calculate the SOC the actual current is divided with the initial value of ampere-seconds, that the battery contains. This results in a change per second of the coulometric capacity in the battery and by integrating this from the initial SOC level the instantaneous SOC is given. To be able to calculate the OCV of the battery the equation (2.15) is modeled in a subsystem inside the li-ion block. The levels of SOC which are used in the model are set to 90 % as upper limitation and 10 % as lower limitation.

The battery losses is calculated from the total battery resistance multiplied with the battery current in square, as stated in (2.14). The battery losses is then divided with the actual voltage of the battery resulting in the current corresponding to the battery losses, which is subtracted from the current from the electric motor.

In the subsystem where the power limits of the battery is calculated, two lookup tables are representing the main function. Depending on the cell temperature and the SOC level the maximum charging power is determined. In the same way the maximum discharging power is calculated. These values are compared with the actual battery voltage multiplied with the maximum charging respectively discharging currents, where the minimum values are fed forward. The purpose of this is to ensure that the motor does not draw or regenerate more power than the battery is able to withstand.

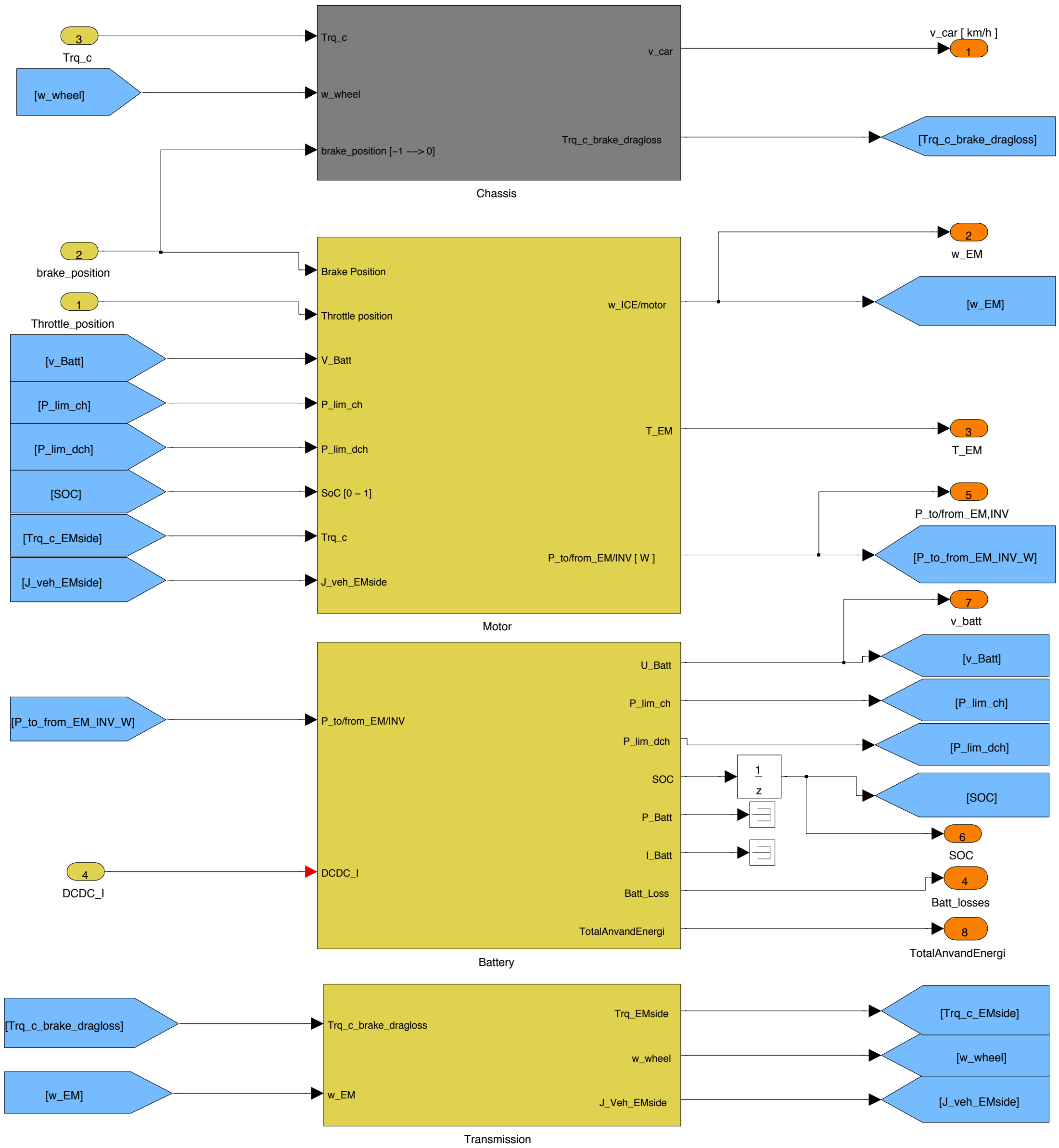

Fig. A.1 An overview of the pure electric vehicle model

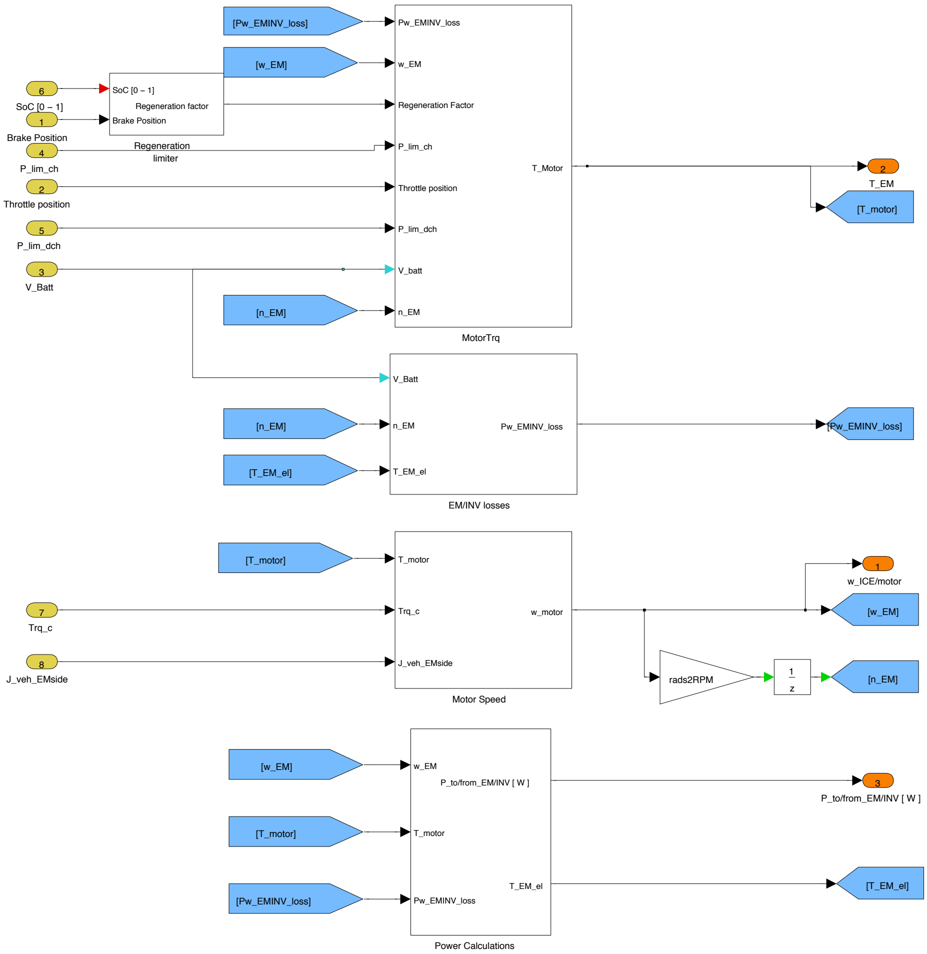

Fig. A.2 The motor block

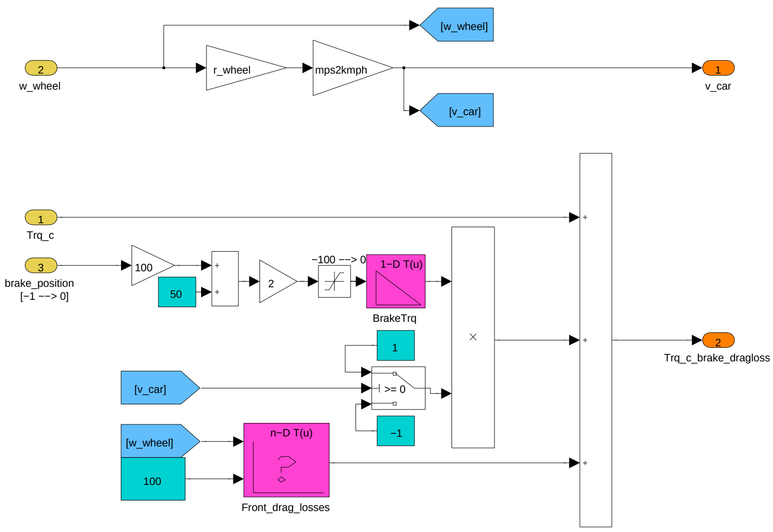

Fig. A.3 The chassis block

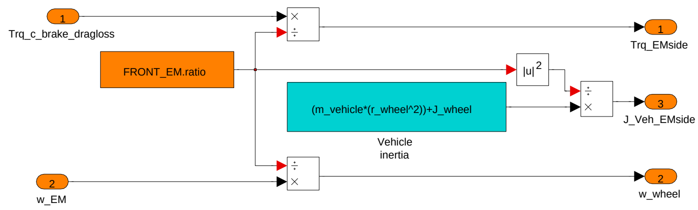

Fig. A.4 The transmission block

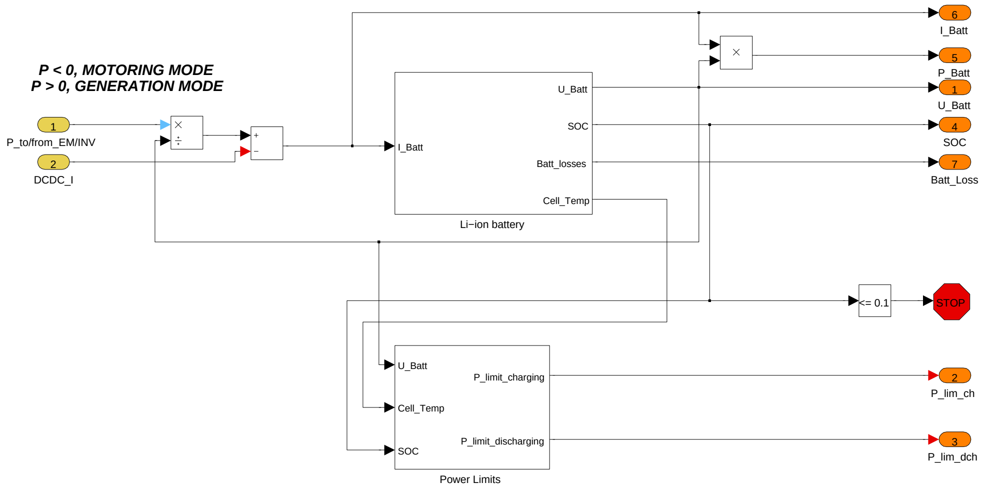

Fig. A.5 The battery- block

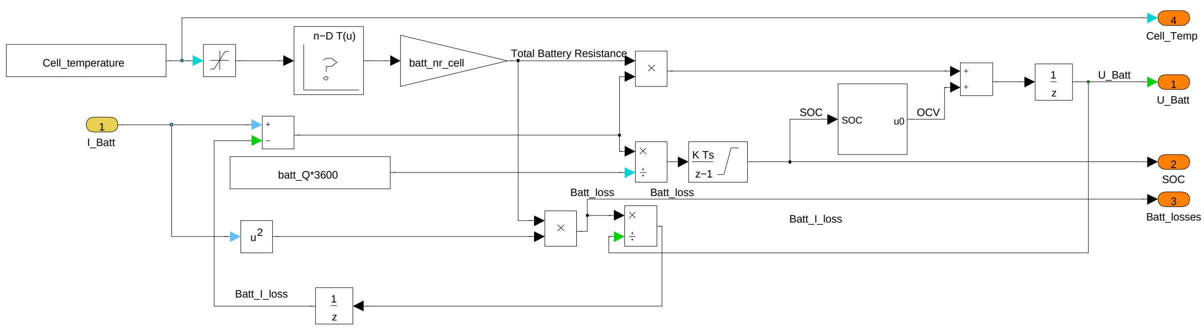

Fig. A.6 Model of the li-ion battery

Appendix B

The route between Volvo Torslanda and Särö

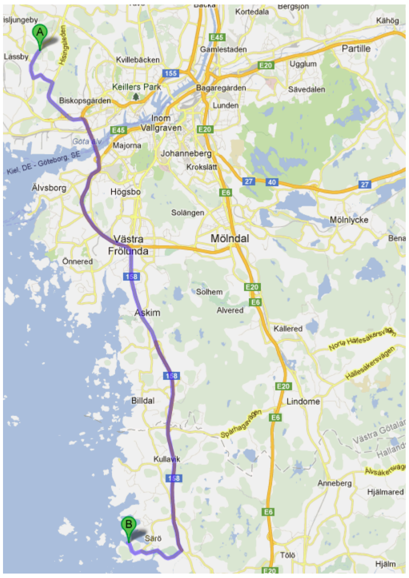

Fig. B.1 The driven route between Volvo Torslanda and Särö. (Source: http://www.maps.google.com)