

Bachelor Project



**Czech
Technical
University
in Prague**

F3

**Faculty of Electrical Engineering
Department of Electric Drives and Traction**

Modelling of Electric Drive and Vehicle Dynamics for Hardware-in-the-Loop Testing System

Vojtěch Štěřba

Supervisor: Ing. Tomáš Haubert

**Field of study: Electrical Engineering, Power Engineering and
Management**

Subfield: Applied Electrical Engineering

May 2018

I. OSOBNÍ A STUDIJNÍ ÚDAJE

Příjmení: **Štěrba** Jméno: **Vojtěch** Osobní číslo: **457076**
Fakulta/ústav: **Fakulta elektrotechnická**
Zadávací katedra/ústav: **Katedra elektrických pohonů a trakce**
Studijní program: **Elektrotechnika, energetika a management**
Studijní obor: **Aplikovaná elektrotechnika**

II. ÚDAJE K BAKALÁŘSKÉ PRÁCI

Název bakalářské práce:

Model elektrického pohonu a dynamiky vozidla pro HIL testovací systém

Název bakalářské práce anglicky:

Modelling of Electric Drive and Vehicle Dynamics for Hardware-in-the-Loop Testing System

Pokyny pro vypracování:

1. To analyze current status of vehicle dynamics model in MATLAB/Simulink and to design the new model for all-wheel-drive vehicle
2. Create a battery model in MATLAB/Simulink of battery electric vehicle and check the functionality
3. Connect all models for using in real time simulation platform provided by ETAS
4. Update GUI (Graphical User Interface) in ETAS LabCar development environment with the new design

Seznam doporučené literatury:

- [1] MOHAN, Ned.: Advanced electric drives: analysis, control, and modeling using MATLAB/Simulink. Hoboken: Wiley, 2014
- [2] JAZAR, Reza N.: Vehicle dynamics: theory and application. 2nd ed. New York: Springer, 2014
- [3] Pera, M.-C., Hissel, D., and Gualous, H.: Electrochemical Components. Somerset, NJ, USA: John Wiley & Sons, 2013.

Jméno a pracoviště vedoucí(ho) bakalářské práce:

Ing. Tomáš Haubert, katedra elektrických pohonů a trakce FEL

Jméno a pracoviště druhé(ho) vedoucí(ho) nebo konzultanta(ky) bakalářské práce:

Datum zadání bakalářské práce: **26.04.2018**

Termín odevzdání bakalářské práce: **25.05.2018**

Platnost zadání bakalářské práce: **30.09.2019**

Ing. Tomáš Haubert
podpis vedoucí(ho) práce

podpis vedoucí(ho) ústavu/katedry

prof. Ing. Pavel Ripka, CSc.
podpis děkana(ky)

III. PŘEVZETÍ ZADÁNÍ

Student bere na vědomí, že je povinen vypracovat bakalářskou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v bakalářské práci.

Datum převzetí zadání

Podpis studenta

Acknowledgements

I would like to express my gratitude to my supervisor Ing. Tomáš Haubert for a great support during the studies and opportunity to work on the topic of this thesis. I also thank company Porsche Engineering Services company, which was the main supporter of this work.

I would like to also thank my family for moral and material assistance since the beginning of my studies. Without them, I would never got as far. The last acknowledgement goes to my girlfriend Peťa for never-ending love, patience and brewed coffees needed to complete this thesis.

“ Physics is like sex: sure, it may give some practical results, but that’s not why we do it.” Richard P. Feynman

Declaration

I hereby declare that this thesis is the result of my own work and all the sources I used are in the list of references, in accordance with the Methodological Instructions of Ethical Principle in the Preparation of University Thesis

In Prague, 14. May 2018

Abstract

This bachelor thesis is focused on problematic of vehicle dynamics mathematical modelling, battery system modelling and testing of embedded control units in Hardware-in-the-Loop connection. The test-bench for power inverter control unit is described. In the next part of the thesis, vehicle dynamics two-wheel drive model is analysed and the model is extended to all-wheel drive model. New battery model and intermediate circuit was developed for simulation too. The simulation results are compared to data measured in real vehicle. In the last part of the thesis, connection of hardware components with mathematical models is shown and new graphical interface is presented.

Keywords: Mathematical modelling, Hardware-in-the-Loop, Electric vehicles, Vehicle dynamics, Etas, Labcar Operator, Experiment Environment, Battery model

Supervisor: Ing. Tomáš Haubert
České vysoké učení technické v Praze,
fakulta elektrotechnická
Technická 1902/2
Praha 6, 166 27

Abstrakt

Tato práce se zabývá problematikou modelování dynamiky vozidel, bateriového systému a testování řídicích jednotek v rámci Hardware-in-the-Loop zapojení. V práci je popsáno stanoviště pro testování řídicí jednotky výkonového měniče. Dále se tato bakalářská práce zabývá analýzou modelu dynamiky vozidla s náhonem na zadní nápravě a tento model je rozšířen na model pohonu všech čtyř kol. K modelu dynamiky vozidla byl též vytvořen model baterie a napěťového meziobvodu. Výsledky simulací jsou porovnány s výsledky z reálného vozidla. V poslední části se práce zabývá propojením hardwarových součástí s matematickými modely a nové grafické prostředí je představeno.

Klíčová slova: Matematické modelování, Hardware-in-the-Loop, Elektrická vozidla, Dynamika vozidel, Etas, LabCar Operator, Experiment Environment, Model baterie

Překlad názvu: Model elektrického pohonu a dynamiky vozidla pro HIL testovací systém

Contents

1 Introduction	1
1.1 Motivation	1
1.2 Goals of the bachelor thesis	2
2 State of art	3
2.1 Hardware-in-The-Loop systems	3
2.2 PWR-HiL test bench	3
2.2.1 Hardware equipment	4
2.2.2 Software	7
3 Mathematical models	9
3.1 Two-wheel drive model analysis	9
3.1.1 Model hierarchy	9
3.1.2 Simplifications in two-wheel drive model	10
3.1.3 Input signals for the vehicle dynamic model	11
3.1.4 Gear box	11
3.1.5 Load model	12
3.1.6 Wheel shaft	13
3.1.7 Vehicle acceleration	14
3.1.8 Inaccuracies in two-wheel drive vehicle dynamics model	16
3.2 All-wheel drive vehicle dynamics model	16
3.2.1 Major differences in the PWR-HiL	16
3.2.2 Gear box	17
3.2.3 Load model	18
3.2.4 Load distribution	19
3.3 Battery model	21
3.3.1 Battery pack	22
3.3.2 Open-circuit voltage	23
3.3.3 Intermediate circuit	23
3.4 Simulation results	25
3.4.1 Compare of the real vehicle with the all-wheel drive model	25
3.4.2 Compare of the real vehicle with the two-wheel drive model	26
4 Connection of the models	33
4.1 LabCar Integration Platform	33
4.1.1 MATLAB/Simulink models	34
5 Graphical User Interface	35
5.1 Etas Experiment Environment 3.7	35
5.1.1 Workspace elements window	35
5.1.2 Main workspace	36
5.1.3 Instrumentation tab	36
5.1.4 Updated GUI	37
6 Conclusion	41
6.1 Overview of the results	41
6.2 Fulfilment of the objectives defined in goals	41
6.3 Suggestions for future work	42
6.4 Data confidentiality	42
A Bibliography	43

Figures

1.1 Logo of the Porsche company.	2	4.1 LabCar IP interface.	34
2.1 Electromotor simulation card - ES5340.	5	4.2 Simulink inport and outport blocks for LabCar IP.	34
2.2 Input and output signals of ES5340.	6	5.1 Etas Experiment Environment 3.7	36
2.3 Logo of MATLAB.	8	5.2 Porsche J1 dashboard.	37
3.1 Connection logic.	10	5.3 Developed GUI.	39
3.2 Schematic of vehicle acceleration calculation.	14	5.4 Old GUI version.	40
3.3 Updated logic of vehicle dynamics for all-wheel drive.	17		
3.4 Schematic for PI regulator.	21		
3.5 Battery cell equivalent circuit.	22		
3.6 Open-circuit voltage	24		
3.7 Intermediate circuit - active state.	25		
3.8 Intermediate circuit - active discharging.	26		
3.9 Measured position of throttle and brake pedal	27		
3.10 Vehicle speed.	28		
3.11 SOC.	28		
3.12 Battery current.	29		
3.13 Battery voltage.	29		
3.14 Driving torque on rear PMSM.	30		
3.15 Driving torque on front PMSM.	30		
3.16 Speed difference of front and rear motor	31		
3.17 Vehicle speed - two-wheel drive model and real vehicle	31		

Tables

3.1 Car dynamic model inputs.	11
3.2 Gear ratios	12
3.3 Drag force parameters	12
3.4 Gear ratios	18
3.5 Specific values of battery cell	22
3.6 Time constants of intermediate circuit.	25



Chapter 1

Introduction

The segment of electric vehicle industry has been significantly growing during past few years and it has brought new challenges into the industry. Nowadays some major cities are incorporating restrictions of combustion engines and some states actively support purchase of electric vehicles. Many people also buy these cars for their reliability and low operating costs. As a result, new electric vehicles are being developed and new manufacturers enter the market.

The complexity of the vehicles electronic system has been growing significantly, so it is necessary to test all components and their behaviour in every released software version. Manual testing would be almost impossible these days due to the software complexity. For their simplicity, Hardware-in-the-Loop (HiL) testing systems are developed.



1.1 Motivation

Electric car consists of many different computer systems and their connections. Major task is to provide safety and reliability for the costumers. Every minor system in the car has to be tested and verified in automated test systems, where only new software versions will be uploaded and system will automatically evaluate results. During my studies on CTU FEE I found the problematic around electronic control system, communications and power systems very challenging and interesting.

I was given the opportunity to work on currently developed all-wheel drive electric J1 car. The possibility to work and learn from experienced and inspiring engineers from Porsche Engineering Services company was impossible to refuse. I was glad I could turn the HiL project into a bachelor thesis.



Figure 1.1: Logo of the Porsche company.

1.2 Goals of the bachelor thesis

The main goals of this bachelor thesis are listed below:

- Analyse a MATLAB/Simulink car dynamics model of two-wheel drive vehicle
- Extend a two-wheel drive vehicle dynamics model to the all-wheel drive model.
- Create and verify a battery model.
- Connect models in Labcar Operator software.
- Create of new GUI with current J1 design.
- Verify all mentioned models.

Chapter 2

State of art

2.1 Hardware-in-The-Loop systems

The Hardware-in-The-Loop (HiL) is a real time operating system of multiple units for testing embedded control units in environmental models. The system consists of the unit under the test (UUT), dynamical models and signals for the simulation of needed environment. The system is operating in real time to provide the results as close to reality as possible.

According to the best scenario all embedded systems would be tested in real environment, but usage of HiL system can reduce the costs of testing. Moreover it's also possible to run tests, that would be hardly feasible in real world. For example crash reactions or using the systems beyond the range of certain parameters.

The HiL testing is a last development stage before the UUT is released. This testing should provide an assurance that all systems operate correctly and the final requirements are fulfilled. [1]

2.2 PWR-HiL test bench

This section provides information about the test-bench structure. Hardware components together with software equipment of the PWR-HiL system are presented.

PWR-HiL test bench was built by ETAS GmbH for Porsche Engineering Services GmbH internal testing of power inverters control units on signal level. Test solution is built on ETAS ES5340 card for simulation of IGBT powerstage and simulation of permanent magnetic synchronous machine (PMSM).

Moreover, the currently developed all-wheel drive J1 car is equipped with

two PMSM and two power inverters. According to that, the PWR-HiL system is equipped with two ETAS ES5340 cards and also two power inverters.

■ 2.2.1 Hardware equipment

■ Control computer

The entire system is operated by host external computer connected by Ethernet cable. On this computer ETAS LABCAR software must be installed altogether with any other software for environmental model generation and integration. When the simulation is started, compiled models are uploaded from control computer to real-time pc and test sequences can be applied. All data for the simulation and simulation results are stored in the control computer.

Moreover, this computer is also connected to Porsche Engineering Services internal network, so it can be controlled remotely. [1]

■ Real-time computer

The main component of the PWR-HiL is a real-time computer running LABCAR-RTPC software on Linux based system. This computer provides a real time simulation of mathematical models with time cycles under 0.1 ms, so even highly dynamical processes can be simulated. ETAS RTPC technology uses standard commercial components for computers. Because of that, system can be easily updated to a newer hardware with higher computing power. [2]

ETAS ES5340 simulation cards are connected to real-time computer in PCIe slots. In addition some minor systems for PWR-HiL are also connected to real-time computer

■ Electromotor simulation cards - ES5340

The ETAS ES5340 PCIe are internal computer cards developed specially for simulation of electrical motors in automotive industry.

The ETAS ES5340 PCIe simulation boards are connected to the control computer motherboard by PCI slots. These cards can be used to simulate the behaviour of electric motors, combustions engines, IGBT stages and electrified power-trains. That means various motors can be parametrized and simulated.

Simulation cards are connected to PWM gate control signals generated in the tested power inverters. IGBT stage with PMSM is simulated.

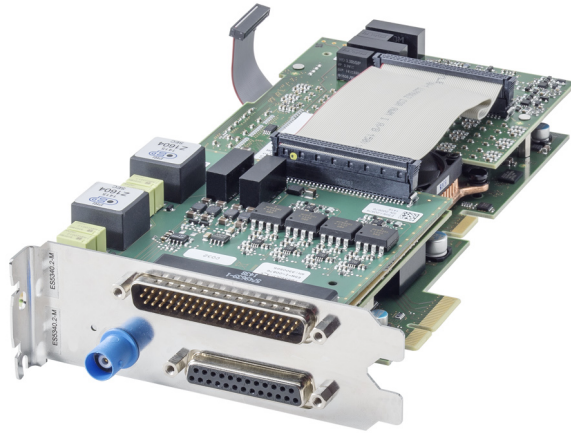


Figure 2.1: Electromotor simulation card - ES5340.

Internal signals generated in Etas ES5340 during the simulation are pre-processed and then sent to the RTPC simulation. [3]

According to [3], the main benefits of the ES5340 are followings:

- Calculations are carried with a step size of 850 ns.
- Phase current prediction.
- Various sensors can be configured on each output.
- Software models (LABCAR-RTPC) are synchronized with the PWM period by means of a task trigger.

Because the HiL system is mainly build for testing and evaluating power inverters behaviour in all-wheel drive equipped with front and rear PMSM, two simulation cards are connected to the RTPC.

Output and input signals are schematically shown on figure 2.2. Signals U_Batt0 and *load torque* can be changed during the simulation.

■ Power inverters

Power inverters used in HiL system are the UUT. Inverters are connected to the system without the high voltage power system module, only the signals for IGBT gates are generated. The gate signals are rerouted to the electro-motor

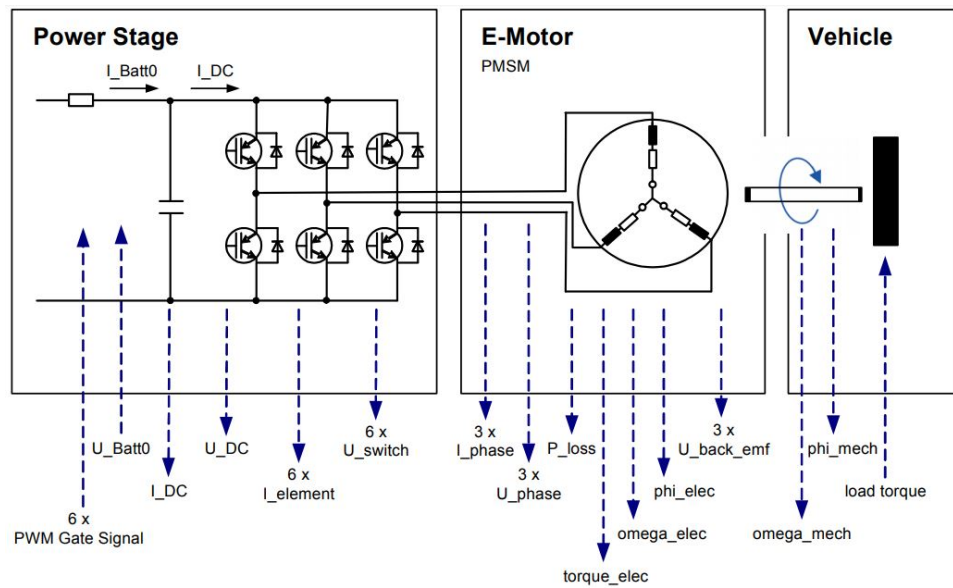


Figure 2.2: Input and output signals of ES5340.

simulation cards ES5340, where the IGBT stage and PMSM are simulated. Virtual simulation of the PMSM provides possibility to test the system even on critical or dangerous states.

Power inverter internal signals are controlled by software INCA also provided by ETAS GmbH.

■ Other hardware

There are various hardware systems connected to the PWR-HiL, but for the purpose of this thesis, they are not described in details. Additional PWR-HiL hardware is mentioned in list below.

- ETAS ES4400 fault insertion unit (FIU), where short circuit can be tested
- Oscilloscope carrier
- Internal power supply
- Break-Out panel
- Can/FlexRay/Lin buses and connectors
- Ethernet connectors
- etc.

■ 2.2.2 Software

The PWR-HiL was delivered together with software portfolio provided by ETAS GmbH, which is important for correct adjustment of the system. Some additional software can be installed based on the customer wishes. This subsection provides information about software used on PWR-HiL.

Software provided by ETAS for PWR-HiL is listed below. LABCAR OPERATOR is summary name for Integration Platform and Experiment Environment.

- LABCAR-OPERATOR Integration Platform
- LABCAR-OPERATOR Experiment Environment
- RTPC
- INCA

There are more programs installed on PWR-HiL (Exam, DiagRa, etc.), but only the important software equipment for purposes of this thesis is described in details.

■ LabCar Integration Platform

Labcar Integration platform is interactive user interface for configuration of HiL systems. Integration platform provides user interface for implementation and connection of environmental models with other devices, models or buses. [4]

Connection manager is described in details in chapter 4. Integration Platform also provides user-space to compile and upload models to real-time pc.

■ Labcar Experiment Environment

The LABCAR Experiment Environment (EE) allows users to create their personalized interface for test settings and evaluation. It also offers a possibility to watch internal values in environmental models and to change internal variables in models during the simulation. In addition EE provides access to all signals in implemented models, hardware, or communication's buses. [5]

Labcar Experiment Environment is used to create the GUI and is described in details in chapter 5

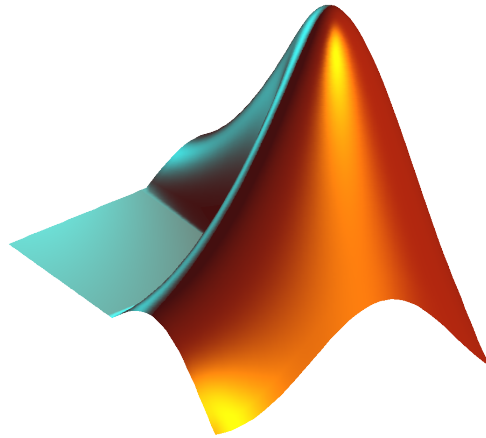


Figure 2.3: Logo of MATLAB.

■ MATLAB/Simulink

The Matrix Laboratory (MATLAB) is software developed by The MathWorks Inc. MATLAB is specialized software for mathematical analysis and numerical computing widely used in industry or academia. In addition to mathematical functions, MATLAB provides possibility to interact with programs written in other programming languages.

There are various MATLABs extension to increase options of the basic product. Extension used in PWR-HiL system for environmental modelling is Simulink.

Simulink is MATLAB extension providing interactive graphical block programming environment for simulation of dynamic systems. Various mathematical functions are preprogrammed in libraries and can be used with drag-and-drop mouse operation.

It also is possible to compile Simulink to C source code for a real time implementation system. [1]

■ INCA

Integrated Calibration and Acquisition System (INCA) is software developed by ETAS GmbH for calibration, diagnosis, and validation of embedded systems.

Inca provides possibility to show and record internal variables of the ECU. It is also possible to change internal variables while the system is running.

To enable access to internal signals and variables, special mapping files of the control unit must be uploaded. [6]

Chapter 3

Mathematical models

Mathematical models required for testing are described in this chapter. Two-wheel drive vehicle dynamic model is analysed. The vehicle dynamic model is extended to all-wheel drive model. This chapter also provides information about the battery model created for the PWR-HiL simulation. In the end simulation results are presented and compared to results from real J1 all-wheel drive car.

3.1 Two-wheel drive model analysis

This section consists of analysis of the two-wheel drive Simulink model used for the HiL testing and simulations in previous developing versions. Structure of this section is similar to model hierarchy used in Simulink. Equations in the model are presented as well

Two-wheel drive vehicle dynamics model was developed for testing of power inverters in previous versions of PWR-HiL with only one power inverter and a ETAS ES5340 card. This model is programmed in Simulink and is still used for testing, even though the model is not accurate.

Because the model was developed in Germany, it originally uses German terminology in all variables and expression. Moreover, for the meaning of this thesis I use English translations and nomenclature.

3.1.1 Model hierarchy

The overall structure of models and hardware used in PWR-HiL system important for this thesis is shown in figure 3.1. There are more models needed to ensure correct behaviour of power inverters e.g. simulation of sensors, but for the purposes of this thesis, they are not described in details.

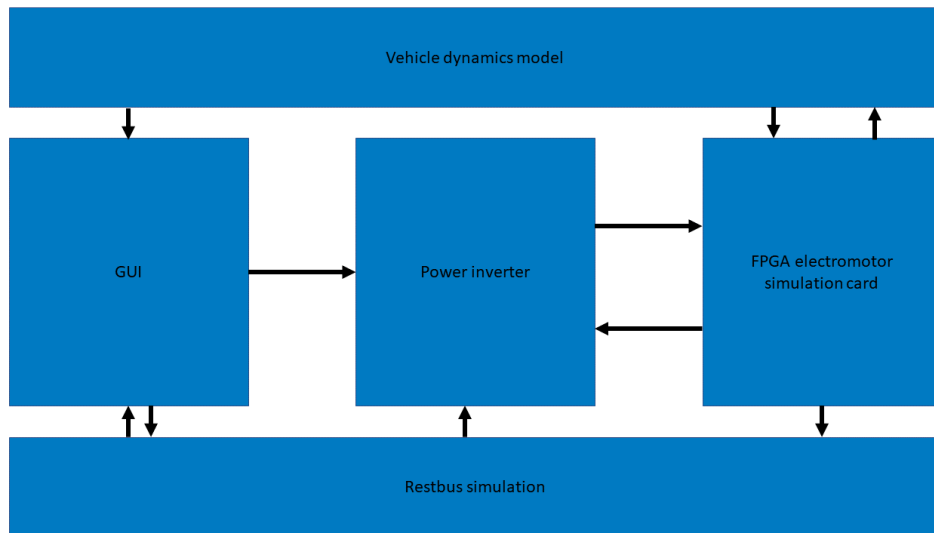


Figure 3.1: Connection logic.

Main task of the vehicle dynamics model is to provide load torque for simulated PMSM. Moreover additional values are calculated and presented (vehicle speed, acceleration, etc.)

Calculated values are shown in created GUI in Etas Experiment Environment. Throttle pedal, break pedal, gearbox and other systems can be controlled. GUI is presented in chapter 5

Restbuss simulation is model of supportive systems in the vehicle. E.g battery system, key ignition or intermediate circuit.

■ 3.1.2 Simplifications in two-wheel drive model

The motion of vehicle can be described by various differential equations with a different complexity. There are many simplifications introduced for purposes of PWR-HiL testing. In order to keep the the computing complexity low and also satisfy the precision of simulation, these quantities are taken in context. [1]

- The model is made as a longitudinal. Sideways moving of the vehicle are not calculated. Also moving in vertical axis is ignored because this quantities doesn't significantly affect power electronics.
- The vehicle is considered as ideal rigid.
- The only forces acting on the vehicle are acceleration force, air friction and braking force.
- The resultant force is in the center of gravity.

Name of the input	Translation	Variable name	Signal source
bParkbremese_HIL	Parking brake	/	GUI
Lastmoment_HIL	Load torque	M_{Lgui}	GUI
Omega_mech	Mechanical omega	Ω_{Mech}	ES5340 simulation card
GUI/Zielgang	target gear	/	GUI

Table 3.1: Car dynamic model inputs.

- The rolling resistance wasn't implemented.

As a result of these simplifications, vehicle dynamics is calculated only with scalar numbers. Vector numbers aren't used and equations presented in the thesis are written in scalar form.

■ 3.1.3 Input signals for the vehicle dynamic model

For better insight, input signals and their sources are given in table 3.1. Input names are given in original German nomenclature. However, English translation is mentioned.

■ 3.1.4 Gear box

In order to keep the PMSM in better efficiency areas, there is a two speed gearbox in currently developed J1 two-wheel drive car. Gear box in mathematical model is simulated by equation (3.1)

$$M_{Wheel} = M_{EM} * i_i \quad (3.1)$$

where M_{Wheel} is torque on output shaft, M_{EM} is torque on input shaft from PMSM and i_i is a conversion ratio

$$i_i = \frac{\Omega_{in}}{\Omega_i} \quad (3.2)$$

In this simplified model of a gearbox, efficiency is not implemented.

The gearbox in mathematical model is implemented as a Lookup Table. Gear ratios used in model and real car are shown in following table 3.2. This equation is identical to equation used in [7].

i_1	15.60
i_2	8.12

Table 3.2: Gear ratios

A	$2.3m^2$
C_D	0.3
ρ_{Air}	$1.2kg/m^3$

Table 3.3: Drag force parameters

3.1.5 Load model

There are various forces in real car, which differ in the direction and their magnitude. In this subsection simplified load model of the car is described. The drag force, brake force and acceleration force is used in the calculation. Rolling resistance wasn't implemented. As mentioned in paragraph 3.1.2, vehicle is moving only on longitudinal direction and therefore, gravitational force is not calculated.

Drag force

A drag force is the resultant force of forces acting opposite to the relative motion of any object moving in respect to the surrounding fluid. In the vehicle dynamic model is drag force implemented by following equation (3.3)

$$F_{Air} = \frac{1}{2} * v^2 * A * C_D * \rho_{Air} \quad (3.3)$$

where v is vehicle velocity relative to fluid, A is the cross section area, C_D is a drag coefficient and ρ_{Air} is in this case density of air. This equation is formally identical to [8] as well as values used. Values used in calculation are shown in following table 3.3

Brake pedal

Brake pedal is also simulated vehicle dynamics model for the needs of HiL testing. Input for brake pedal is stimulated in GUI by slide-bar with value range 0 – 100. This value enters the vehicle dynamic model as a load torque. Braking force is then calculated by (3.4)

$$F_{Brake} = \frac{M_{Lgui}}{r_{Wheel}} \quad (3.4)$$

where r_{Wheel} is wheel radius.

■ Parking brake

Simple model of parking brake is implemented in the vehicle dynamics model. Moreover the parking brake is not implemented with correct physical meaning, but just as a signal switch. This switch is connected to ECU and as a result, internal statuses can be checked. When parking brake is activated, input signal Ω_{Mech} is substituted by zero.

■ Load model

The sum of the forces is a resultant load force acting on vehicle and is calculated as a sum of the forces in equations (3.3) (3.4) and (3.8). Author of the model wrongly decided to add to load model torque on wheel shaft, divided by gear ratio.

$$F_{Load} = F_{Air} + F_{Brake} + F_W * \frac{1}{i_i} \quad (3.5)$$

Load torque on vehicle is then calculated as equation 3.6

$$M_{Load} = \frac{F_{Load}}{r_{Wheel}} \quad (3.6)$$

where r_{Wheel} is a wheel radius.

■ 3.1.6 Wheel shaft

Author of the two-wheel drive vehicle dynamic model decided to calculate drive torque from the angular speed of the simulated PMSM. As a result, torque on wheels must be recalculated for the calculation of vehicle acceleration. This is done in wheel shaft block, where the inputs are Ω_{Wheel} from the equation 3.14 and Ω_{EM} geared provided by PMSM. This calculation is schematically shown on figure.

The difference between the angular speed of wheels and geared angular speed of simulated PMSM is calculated in equation (3.7). Equation inputs are schematically shown on figure 3.2.

$$\Delta\Omega = \Omega_{EMgeared} - \Omega_{Wheel} \quad (3.7)$$

Torque on shaft is then calculated with friction element B_r . The equation (3.8) is used.

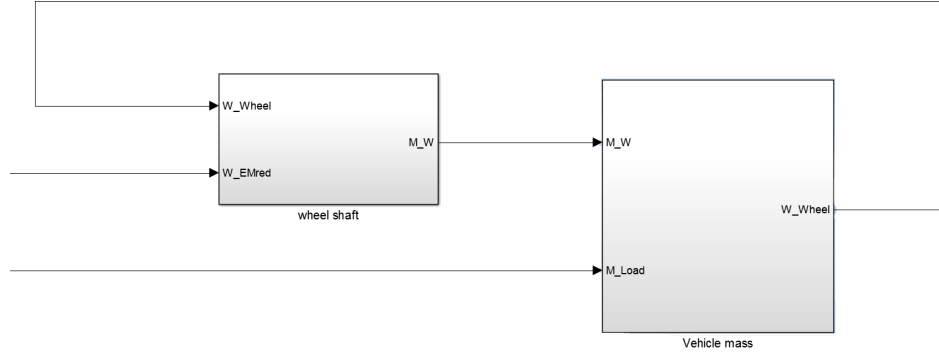


Figure 3.2: Schematic of vehicle acceleration calculation.

$$M_W = \Delta\Omega * B_r \quad (3.8)$$

Load torque on PMSM is calculated from M_W with equation 3.9

$$M_{loadEM} = M_W * \frac{1}{i_i} \quad (3.9)$$

The angle of twist is calculated by equation (3.10) and is compared to critical angle. In case of exceeding allowed values, the M_W torque is set to 0.

$$\int \Delta\Omega dt = \Phi \quad (3.10)$$

■ 3.1.7 Vehicle acceleration

In this part of the car dynamic model the acceleration of the vehicle is calculated. According to D’alemberts principle acceleration torque is generated if there’s imbalance between load torque M_{Load} from equation (3.6) and driving torque on shaft from equation (3.8) M_W . This is described by equation (3.11). Equations are formally identical to equations used in [7]

$$M_W - M_{Load} = M_{Dyn} \quad (3.11)$$

Where M_{Dyn} is dynamic torque. The dynamic torque can be expressed by equation (3.12)

$$M_{Dyn} = J_{Veh} * \epsilon_{Wheel} \quad (3.12)$$

where ϵ_{Wheel} is angular acceleration.

Angular acceleration of the vehicle is then calculated by equation 3.13

$$\frac{M_W - M_{Load}}{J_{Veh}} = \epsilon_{Wheel} \quad (3.13)$$

Angular speed Ω_{Wheel} and the angle of rotation Θ_{Wheel} of the wheels is then calculated by

$$\int \epsilon_{Wheel} dt = \Omega_{Wheel} \quad (3.14)$$

$$\iint \epsilon_{Wheel} dt = \Theta_{Wheel} \quad (3.15)$$

Vehicle speed and vehicle acceleration is obtained with relation 3.16, 3.17

$$v = \Omega_{Wheel} * r_{Wheel} \quad (3.16)$$

$$a = \epsilon_{Wheel} * r_{Wheel} \quad (3.17)$$

■ Rotational inertia

To simplify the acceleration calculation, the longitudinal acceleration of the vehicle is substituted by acceleration of rotating body with the same kinetic energy. This is described by equation 3.18

$$E_K = E_{Krot} \quad (3.18)$$

where E_K is kinetic energy of translation motion and E_{Krot} is kinetic energy of rotating body. These equation can be substituted by known equation from mechanics to 3.19

$$\frac{1}{2} * m * v^2 = \frac{1}{2} * J_{Mass} * \Omega_{Wheel}^2 \quad (3.19)$$

where m is the objects mass, v is vehicle velocity, J_{Mass} is rotational inertia and Ω_{Wheel} is angular speed. Assuming that angular speed can be rewritten as $\Omega_{Wheel} = \frac{v}{r_{Wheel}}$, where r_{Wheel} is the tire radius. Equation (3.19) can be simplified to 3.20

$$J_{Mass} = m * r^2 \quad (3.20)$$

Final rotational inertia is then calculated by with equation 3.21

$$J_{Veh} = J_{Mass} + J_{Tire} \quad (3.21)$$

where J_{Tire} is rotational inertia of one wheel. Author of the model should have used $4 * J_{Tire}$ and this fact is repaired in the new model.

■ 3.1.8 Inaccuracies in two-wheel drive vehicle dynamics model

There are various inaccuracies in two-wheel drive vehicle dynamics model. Some mistakes can be considered cosmetic, but some mistakes are not corresponding with physical reality.

- Vehicle acceleration was calculated as $a = \epsilon * r^2$
- Rotational inertia should be calculated as a $J_{Mass} + 4 * J_{Tire}$
- Load torque on PMSM is wrongly taken from block wheel shaft from equation 3.9
- Driving torque from equation 3.8 doesn't correspond to driving torque from PMSM.
- M_W from equation 3.8 is wrongly taken in context in the load model of vehicle

■ 3.2 All-wheel drive vehicle dynamics model

The major task of this bachelor thesis was to extend the current two-wheel drive vehicle model to the all-wheel drive vehicle dynamics model. This section provides information about changes made in the vehicle dynamics model.

■ 3.2.1 Major differences in the PWR-HiL

There were several updates done in PWR-HiL system and vehicle dynamics model to ensure correct simulation behaviour. Major changes are listed below

- Added second ETAS ES5340 card for simulation of front PMSM to PWR-HiL.

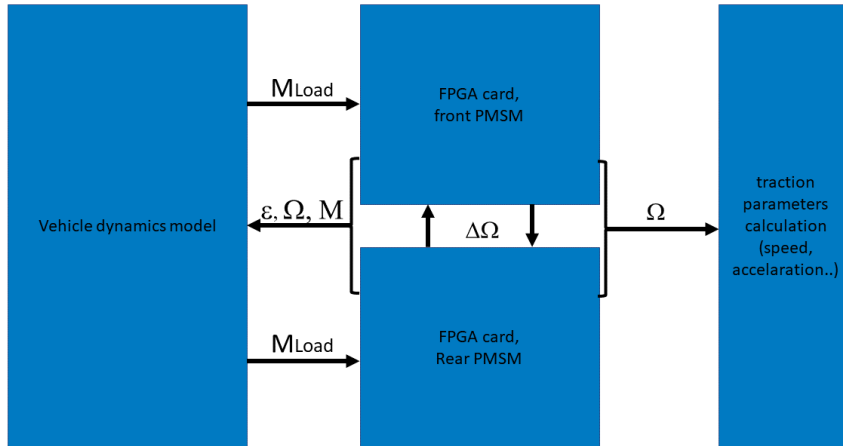


Figure 3.3: Updated logic of vehicle dynamics for all-wheel drive

- Added second power inverter.
- Updated connection manager in LABCAR software.
- Updated GUI in Experiment Environment.
- Basic torque distribution system.

Moreover, different approach was chosen for calculation of the vehicle dynamics model. In previous two-wheel drive model, all values were calculated from the given angular speed of simulated PMSM.

In updated vehicle dynamics model, only load torque on PMSM is calculated and other values (vehicle speed, acceleration, etc) are calculated from the angular speed of PMSM. Updated logic is shown on following picture 3.3. This method is described in [7] as a reduction of forces and weight.

However, model simplifications mentioned in 3.1.2 are the same for the all-wheel drive model.

■ 3.2.2 Gear box

As mentioned in subsection 3.1.4, there is a basic two speed gearbox in currently developed J1 car. This gearbox is installed to keep the PMSM in better efficiency area. In developed all-wheel drive J1, front PMSM is working with fixed transmission ratio. Rear PMSM has the same gearbox as gearbox described in 3.1.4.

Moreover, the hypothetical rotational inertia of the car must be also recalculated, when the gearbox is used. This is described in equation from [7]

i_{1R}	15.6
i_{2R}	8.12
i_{1F}	8.16

Table 3.4: Gear ratios

$$J_{VehG geared} = \frac{J_{Veh}}{i_i^2} \quad (3.22)$$

where $J_{VehG geared}$ is rotational inertia on the side of the PMSM, J_{Veh} is rotational inertial from equation 3.21 and i_i is transmission ratio.

■ 3.2.3 Load model

■ Rolling resistance force

For better simulation results, rolling resistance was added to the load model of the vehicle. According to [9] rolling resistance is force acting in opposite direction of vehicle motion. The magnitude of the force is directly proportional to the normal component of the gravitation force. The equation (3.23) is describing rolling resistance force.

$$F_{RollingRes} = \mu_0 * |F_g| \quad (3.23)$$

where μ_0 is a friction coefficient.

Friction coefficient is strongly affected by many physical aspects and to simulate correct behaviour of friction coefficient car velocity, temperature, materials of the wheels and surface, inflation of the tires and many more physical aspects must be taken in context. Simulation of all the parameters would take a lot of simulation time and as a result, μ_0 is considered to be constant with value of 0.01. This value is provided by [10].

■ Acceleration torque

As mentioned in paragraph 3.1.7, acceleration torque is generated by the imbalance of load torque M_{Load} and $M_{Driving}$ torque on wheel generated by powertrain. The acceleration force is on the side of the load, because of the principle of action and reaction. [9]

$$M_{Acc} = M_{Driving} - M_{Load} \quad (3.24)$$

Vehicle is accelerating, if difference between $M_{Driving} - M_{Load}$ is greater than 0. In case of torque lack $M_{Driving} - M_{Load} < 0$ vehicle is slowing down. When the difference equals zero, vehicle is in steady state and doesn't accelerate.

As described in paragraph 3.1.7, M_{Acc} can be rewritten to form

$$M_{Acc} = J_{Veh} * \frac{1}{i_{iR}} \frac{d\Omega_{EM}}{dt} \quad (3.25)$$

where J_{Veh} is from equation 3.21. In this model of vehicle dynamics, M_{Acc} is calculated as a derivative of output signal Ω_{EM} of the simulated PMSM. Due to the decision to take a rear PMSM as a master unit, signal Ω_{EM} is used for calculation of the M_{Acc} . For the sake of model stability, signal is filtered with discrete FIR filter and filtered derivative is used as well.

It's possible to set directly rotational inertia of the load in internal settings of ES5340 and this value doesn't have to be calculated. Unfortunately it isn't possible to change this value during the evaluation, so this value had to be calculated in vehicle dynamics model.

■ Load model

In the simplified all-wheel drive vehicle dynamics model, final load torque on vehicle is calculated as a sum of rolling resistance force (3.23), air resistance force (3.3), acceleration torque (3.25) and braking torque (3.4). All forces were recalculated to torques.

$$M_{Load} = M_{Air} + M_{Brake} + M_{Acc} + M_{RollingRes} \quad (3.26)$$

This equation can be rewritten as

$$M_{Load} = \frac{1}{2} * v^2 * A * C_D * \rho_{Air} * r_{Wheel} + J_{Veh} * \frac{1}{i_{iR}} * \frac{d\Omega_{EM}}{dt} + \mu_0 * r_{Wheel} * |F_g| + M_{Brake} \quad (3.27)$$

■ 3.2.4 Load distribution

As mentioned before, this vehicle dynamics model is developed for all-wheel drive system with two PMSM. As a consequence, load torque on the vehicle must be split. In real environment, car is equipped with superior system of thrust vectoring and traction control. These systems are not available

on the PWR-HiL, and therefore basic load model distribution model was implemented.

This load distribution model doesn't respect the change of the load on the motors during acceleration or deceleration.

As mentioned in paragraph 3.2.4, all wheels are rotating with the same speed and therefore, power given to the system is based on driving torque on the wheels given by the PMSM.

Proposed torque distribution model is based on following formulas.

$$\frac{M_{WheelR} + M_{WheelF}}{M_{WheelR}} = k \quad (3.28)$$

$$M_{LoadR} = M_{Load} * k * \frac{1}{i_{iR}} \quad (3.29)$$

$$M_{LoadF} = M_{Load} * (1 - k) * \frac{1}{i_{iF}} \quad (3.30)$$

where i_{iR} is transmission ratio of gearbox on rear PMSM. Values are from table 3.2. i_{iF} is fixed transmission ratio on front axis.

■ Balance torque

In real world, all four wheels are rotating with the same speed and the mechanical bonding keeps the angular speed same. In simulated environment of PWR-HiL, this mechanical bonding of the wheels needs to be simulated. This is done with PI regulator wired in following scheme where input to PI regulator is $\Delta\Omega$.

$$\Delta\Omega = \Omega_{WheelR} - \Omega_{WheelF} \quad (3.31)$$

In ideal state $\Delta\Omega$ would be zero all the time. In simulated environment, this is achieved with change of load torque on the motors. This load torque to keep motors in balance is calculated with the PI regulator and is shown on figure 3.4.

In case of lack of speed on front wheels, $M_{balance}$ is accelerating front simulated PMSM and slowing down the motor on rear wheels.

Load torque on PMSMs is sum of load torque from equation (3.30) and balance torque from PI regulator.

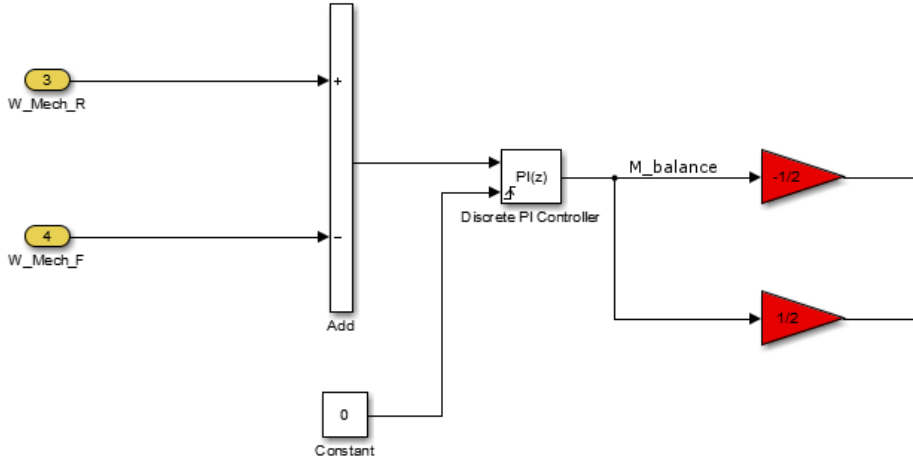


Figure 3.4: Schematic for PI regulator.

$$M_{LoadPMSM_R} = M_{LoadR} - \frac{1}{2}M_{Balance} \quad (3.32)$$

$$M_{LoadPMSM_F} = M_{LoadF} + \frac{1}{2}M_{Balance} \quad (3.33)$$

3.3 Battery model

Nowadays battery system is the most common storage of energy for automotive industry. Majority of electric cars is using battery system to provide electric power for motors. New types of batteries with bigger capacity and energy density are developed. Price of the battery system is continuously decreasing, but even though, battery is still one of the most expensive parts of an electric car.

There are several mathematical models of batteries with different complexity and accuracy. Electrochemical models can be used to optimize physical aspects of the batteries. However, the system complexity is unnecessarily complicated. [11]

Proposed battery model for PWR-Hil is based on electrical model combining current source and resistor. This battery system was mainly developed to observe the energy flow between the battery and the PMSMs. Another point was to test the power inverter behaviour in connection with battery and not to simulate the battery pack with its full complexity.

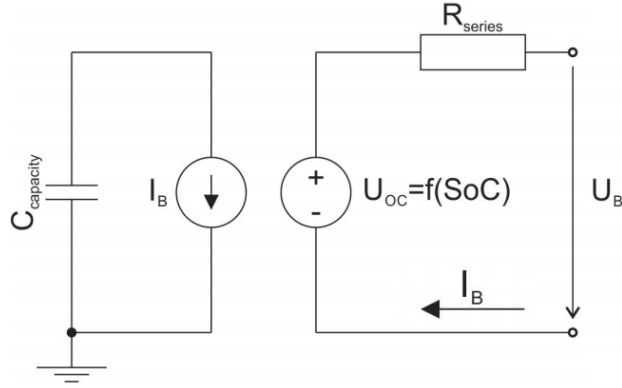


Figure 3.5: Battery cell equivalent circuit.

Property	Value	Units
Nominal Voltage	3.7	V/cell
Charge up voltage	4.2	V/cell
Cut off voltage	2.8	V/cell
Serial Resistance	0.51	mΩ

Table 3.5: Specific values of battery cell

Consequently, battery model with equivalent circuit on figure 3.5 was chosen and following assumptions were made.

- Temperature of the battery cell does not change during the simulation. As a result temperature dependent values are considered to be constant.
- Transient response of battery cell is not taken in account.
- Self discharging and ageing is not implemented.
- Serial battery resistance is SOC non-dependant.

Terminal voltage of one battery cell is calculated with equation 3.34

$$u_B = u_0 - R_{Series} * i_B \quad (3.34)$$

Specific values of battery cell used in simulation are shown in table 3.5

■ 3.3.1 Battery pack

In order to get the correct voltage on electrical machine, battery cells must be organized into a battery pack. Cells are connected in series and final voltage is described by equation 3.35.

$$u_{BP} = u_{Cell} * n_S \quad (3.35)$$

where u_{BP} is terminal voltage of battery pack, u_{Cell} is voltage of one li-ion cell and n_S is number of cells connected in series. To increase the capacity of the battery pack, cells must be organized in parallel. Due to the same resistance, current splits equally between all of them.

$$i_{Cell} = \frac{i_{BP}}{n_P} \quad (3.36)$$

Where i_{BP} is terminal current of battery pack, n_P is number of packs connected in parallel.

In a real battery system, cells are not stressed equally, because the parameters are not the same. To avoid unnecessary ageing, battery is normally equipped with battery management system. [12]

■ 3.3.2 Open-circuit voltage

Open-circuit voltage changes with the state-of-charge (SOC) of the battery cell and there is a non linear relation. As a result, open-circuit voltage is implemented as function of SOC. Battery model all together with car dynamic was programmed in Simulink and therefore this battery property was implemented as a look-up table. [12]

Function $U_0(SOC)$ is shown on figure 3.6. When the battery is fully charged, SOC is equal to 1. When the battery is discharged SOC is equal to 0. Data for this model were internally provided and measured in Porsche Engineering Group.

SOC is function of battery current and can be described by equation 3.37

$$SOC = \frac{1}{Q_C} \int i_B dt \quad (3.37)$$

where Q_C is battery capacity and i_B is a battery current. [12]

■ 3.3.3 Intermediate circuit

Intermediate circuit, which is used in the real power inverter and in the simulation, can be described as intermediate circuit of voltage type. Large capacitor is connected to the battery on one side and to IGBT stage on other

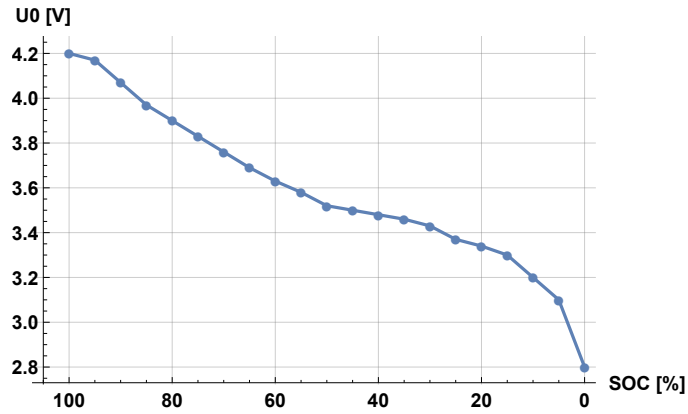


Figure 3.6: Open-circuit voltage

side. This capacitor is installed to stabilize voltage and as a source of peak energy. [13]

Nowadays, most of the power inverters are developed as voltage types in automotive industry.

It is possible to set the capacitor value in IGBT simulated stage in ES5340. However, the active discharging simulation isn't possible to be tested and therefore, new model was developed.

Intermediate circuit is schematically shown on figure 3.7. The u_{out} can be calculated as

$$0 = u_b(t) - \frac{1}{C} \int i_C dt \quad (3.38)$$

$$\frac{1}{C} \int i_C dt = u_{out} \quad (3.39)$$

■ Active Discharging

Various conditions must be fulfilled to start active discharging of the intermediate circuit. These conditions are controlled by the power inverter ECU and the external safety computer. Active discharging must be activated in case of crash or in case of hardware emergency turn off.

Before the active discharging request is sent, battery contacts must be opened and battery must not be connected to the charger. Additional resistor for discharging is then connected to the main capacitor and IGBT transistors are closed. According to internal requirements, intermediate circuit must be discharged under 60V in 5 seconds under any circumstances.

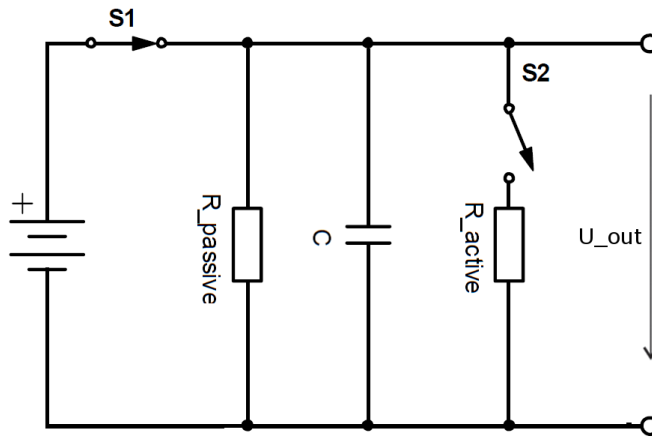


Figure 3.7: Intermediate circuit - active state.

τ_{Active}	0.21s
$\tau_{Passive}$	39.48s

Table 3.6: Time constants of intermediate circuit.

When the hardware is turned off, discharging of the main capacitor is done only by $R_{passive}$ resistor. Time constants of active and passive discharging are shown in table 3.6

Active discharging is schematically shown on figure 3.8 and can be described with equation

$$C * \frac{du_{out}(t)}{dt} = -\frac{u_{out}(t)}{R} \quad (3.40)$$

where R is in case of active discharging calculated as parallel combination of R_{Active} and $R_{Passive}$. In case of passive discharging, the resistor value equals to $R_{Passive}$. $u_{out}(0)$ is voltage on capacitor in the moment of disconnection.

3.4 Simulation results

3.4.1 Compare of the real vehicle with the all-wheel drive model

This section provides simulation results in compare to data measured in real J1 car.

It was possible to obtain data from a real J1 and compare them with simulation results. Data presented in this section were measured during the

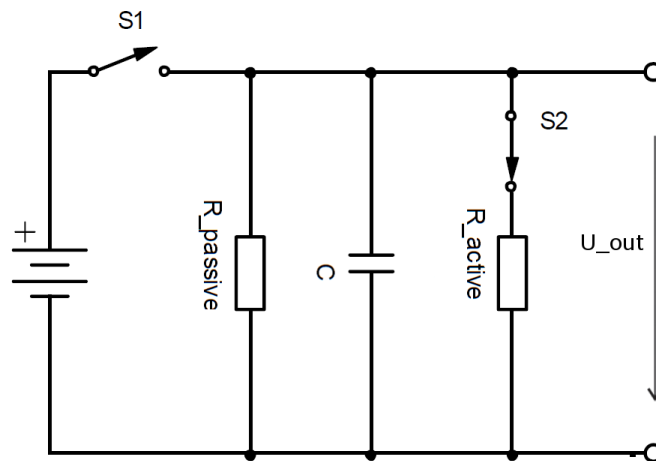


Figure 3.8: Intermediate circuit - active discharging.

test rides on Nordschleife in Germany. During the test rides, all signals and data were stored, so it was possible to reconstruct the behaviour of the driver from the logged positions of throttle pedal and brake pedal. Those signals were used as a input signals in simulation and are shown in figure 3.9.

During the real rides of the J1 vehicle, it's possible to the recuperate energy back to battery. This function is controlled by the position of throttle pedal. Unfortunately, recuperation was not implemented into the HiL and so the results are not exactly accurate. Recuperation can be easily viewed on SOC plot on figure 3.11 or on 3.14, when the negative torque is requested from the PMSM.

Another thing, that was not implemented and might have affected the results, is absence of vehicle vertical movement.

The noise on the voltage and current signal was probably caused by non-implemented transient response of the battery model.

Note: There were several administrative problems with HiL system. To install second ES5340 card into the HiL, there must be a special box made by ETAS. This box is still not present in the HiL, so second machine was simulated directly in the Simulink model.

■ 3.4.2 Compare of the real vehicle with the two-wheel drive model

To provide overall look, the same cycle was done on two-wheel drive vehicle dynamics model. On figure 3.17 is shown the model speed and real vehicle speed. Unfortunately, the battery model wasn't implemented correctly and therefore, only speed test was measured.

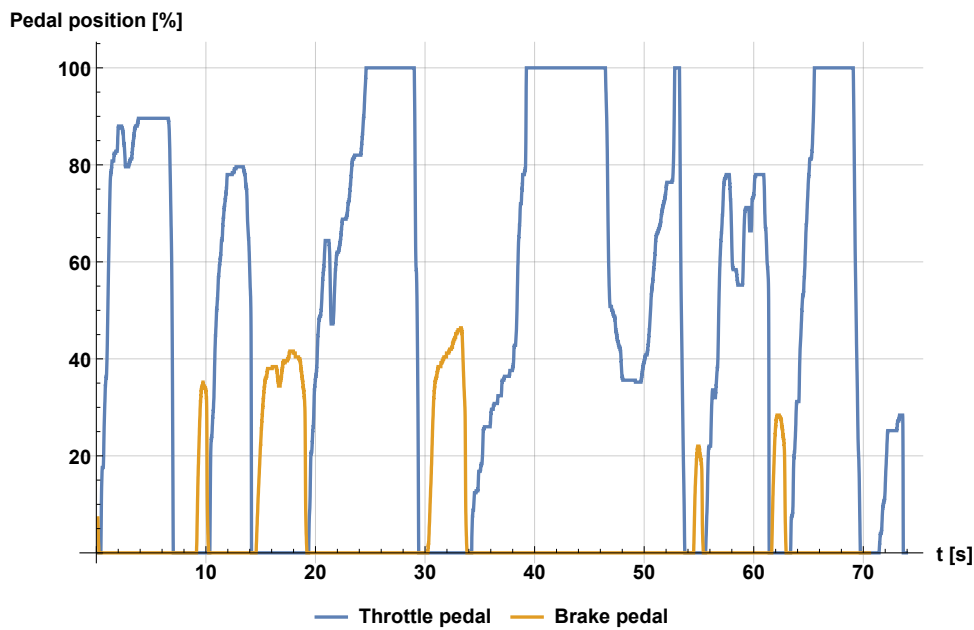


Figure 3.9: Measured position of throttle and brake pedal

Because the model was developed only for one motor, I decided to recalculate requested torque. Requested torque was 1.5 higher than in the all-wheel drive vehicle dynamics.

The difference between the simulation and measured results in a real vehicle might be caused by

- Low value of brake torque on vehicle when breaking
- Wrong value of load torque on PMSM.
- The value of driving torque from PMSM doesn't correspond to driving torque on vehicle.

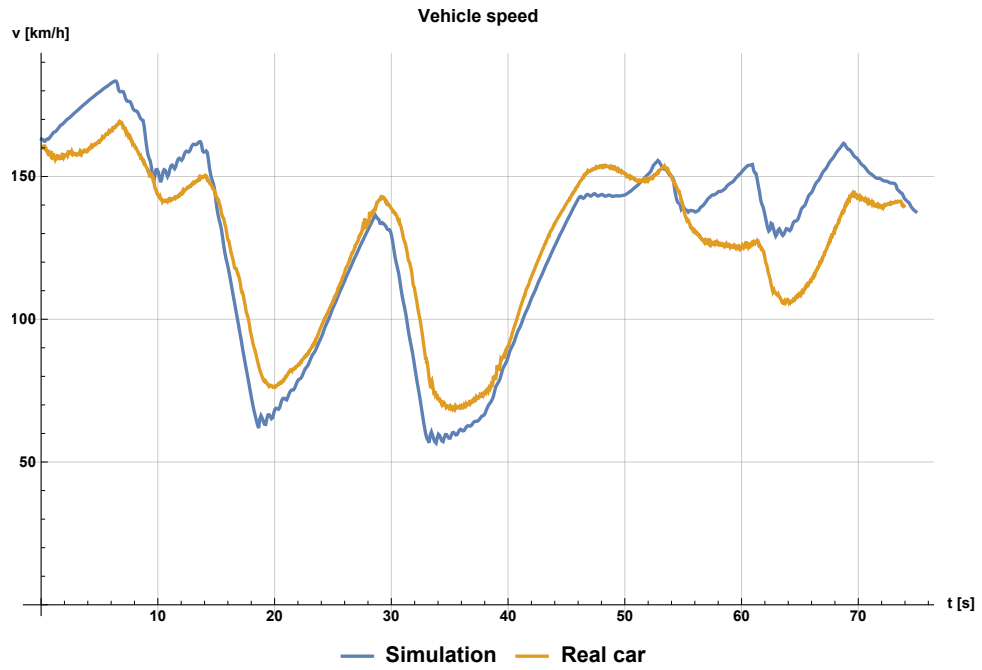


Figure 3.10: Vehicle speed.

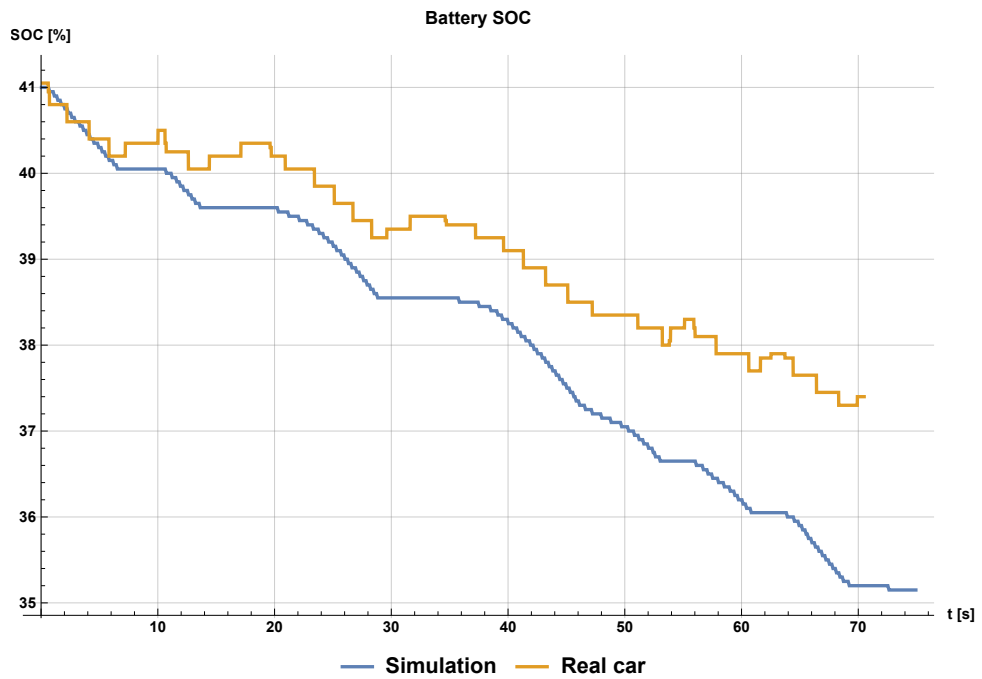


Figure 3.11: SOC.



Figure 3.12: Battery current.



Figure 3.13: Battery voltage.

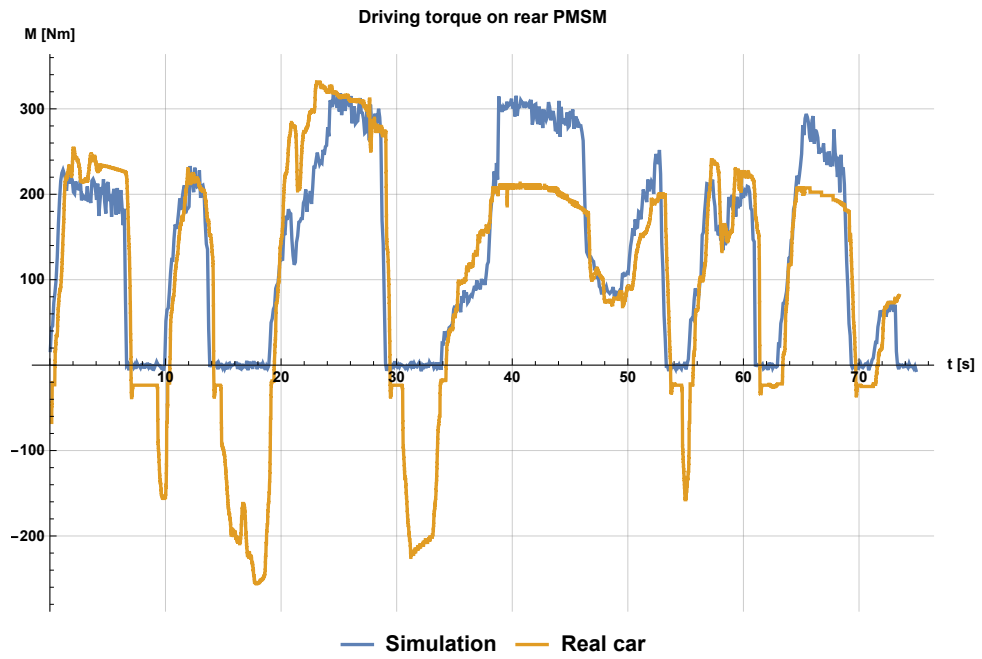


Figure 3.14: Driving torque on rear PMSM.

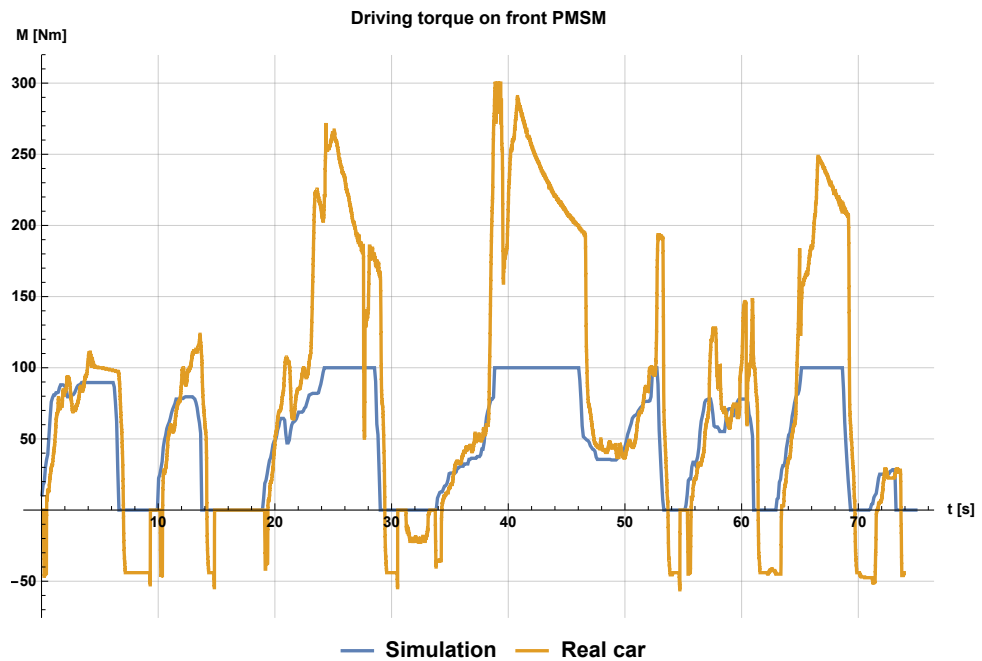


Figure 3.15: Driving torque on front PMSM.

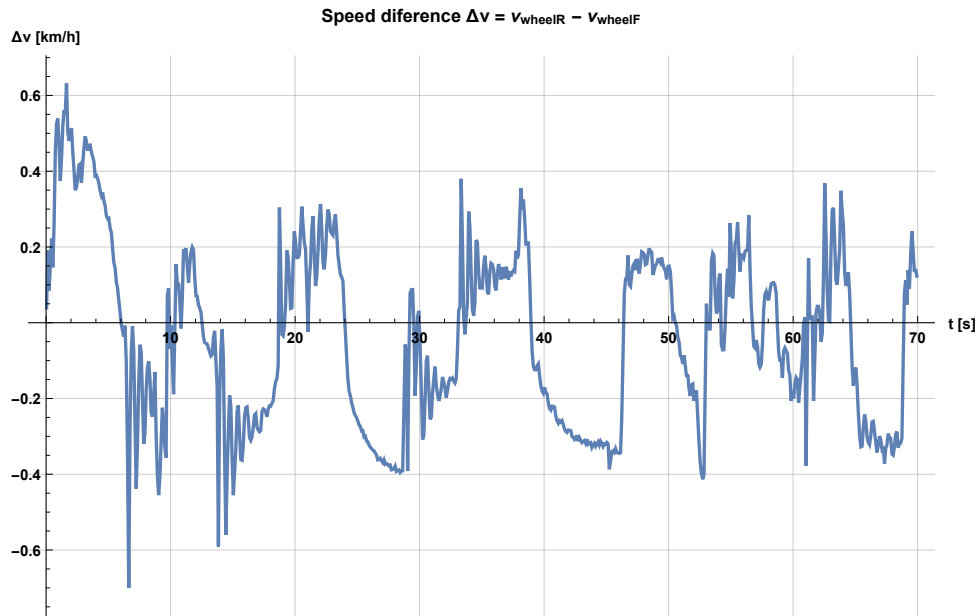


Figure 3.16: Speed difference of front and rear motor

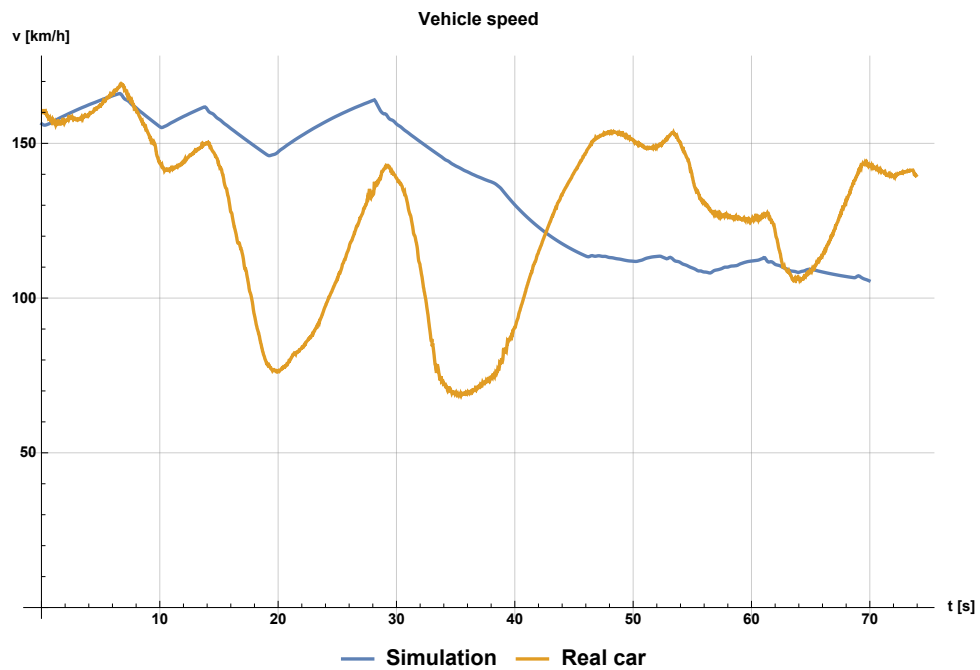


Figure 3.17: Vehicle speed - two-wheel drive model and real vehicle

Chapter 4

Connection of the models

There are various modules implanted in PWR-HiL to ensure correct behavior of the ECU. These models are organized and connected in LabCar Integration Platform.

4.1 LabCar Integration Platform

The integration platform is the user interface through which the HiL system is configured in preparation for ECU testing. It makes it easier to integrate environment models, configure LABCAR hardware, create signal paths between models and hardware, and generate code for the LABCAR simulation target. [4]

According to [4] mathematical models from various sources can be implemented into Labcar Integration Platform and possibilities are mentioned below.

- MATLAB/SIMULINK models
- ASCET modules
- C code modules
- CAN, LIN and FlexRay modules
- I/O hardware modules
- etc.

The main part of LabCar IP GUI is shown on figure 4.1. When the connection between two ports is established, ports turn blue.

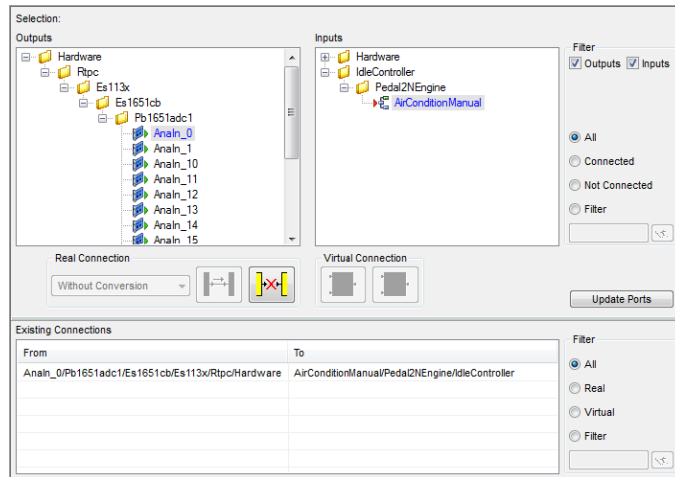


Figure 4.1: LabCar IP interface.



Figure 4.2: Simulink inport and output blocks for LabCar IP.

4.1.1 MATLAB/Simulink models

As already mentioned before, it is possible to implement Simulink models into LabCar IP. However, there are some restrictions to be followed, while implementing the models. [4]

- In case of adding import from another modules, special ports must be used to be recognized by LabCar IP. These blocks are from LabCar Simulink Library and are shown in figure 4.2 .
- Blocks with absolute time shouldn't be used, due to incorrect results on execution.
- There are several blocks for which no parameters and outputs are generated. (e.g. Scope, Floating scope, XY graph, Stop, etc.)
- Only S-functions which contain parameters of the data type double can be processed.
- Only discrete calculation blocks can be used in models.

Chapter 5

Graphical User Interface

5.1 Etas Experiment Environment 3.7

Etas experiment environment is a software for creation of GUI and triggering of the experiments. This program provides user space for experiment settings, real-time values changes, monitoring and test automation. The software tries to provide easy-to-change user space to meet individual customer requirements.

In PWR-HiL Etas Labcar Experiment Environment is used to simulate inputs similar to inputs in the real cars. Porsche main dashboard with throttle and break paddle is imported altogether with signals to change the gears and others. Developed GUI is described and shown later.

When the Experiment Environment is started, imported RTPC models and hardware modules are triggered. This software is running on normal pc and only provides access to values stored in RTPC. [4]

5.1.1 Workspace elements window

This window provides access to all models imported and compiled in LABCAR IP. This tab provides access to model variables, parameters, input signals and output signals of active experiment. Moreover, there is also access to hardware parts and ECU ports.

Different types of modules have different marks to be easily recognized and organized. Also all variables and parameters of the individual modules are shown with different icons depending on type. [4]

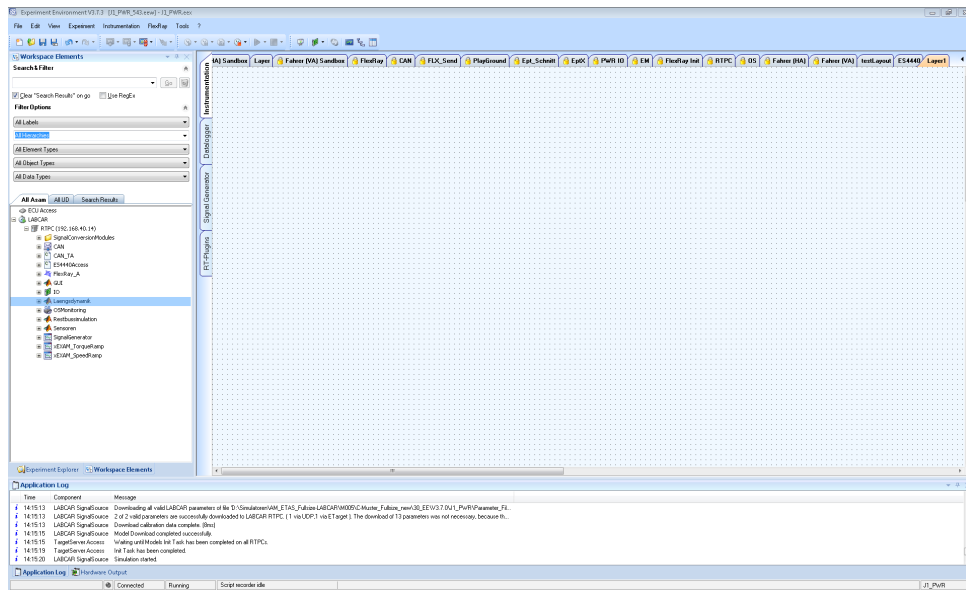


Figure 5.1: Etas Experiment Environment 3.7

5.1.2 Main workspace

Main workspace consists of four tabs for different purposes.

- The instrumentation tab, where the elements are operated and created.
- The datalogger tab, where the datalogger is configured.
- The signal generator, where the signal generators are stored and managed.
- The RT-plugins.

The instrumentation tab is the main tab for GUI project and will be described in details.

5.1.3 Instrumentation tab

The instrumentation tab is the main part of ETAS LabCar EE. In this part of EE multiple layers for different purposes can be created. All properties and instruments are displayed together with input forms for changing the model properties.

An element on the layer can be simply created by drag-and-drop from the workspace elements window and shown/manipulated according to its type.

Output elements can be displayed with various types as well as input elements (edit box, oscilloscope, slider, etc.).



Figure 5.2: Porsche J1 dashboard.

Labels, colors and formatting of the elements can be changed in the properties tab. Different possibilities are available for different types of elements. [4]

■ Instruments

Instruments are special external elements preprogrammed in .NET. They can be implemented to Etas EE and mapped to other signals.

Special instrument for the PWR-HiL and other HiL system was internally developed. This element is Porsche Dashboard and car mode selector with current J1 design show on figure 5.2.

■ 5.1.4 Updated GUI

The new version of user interface provides access to all important monitored values and follows the current J1 dashboard design.

Following elements were implemented.

- Throttle paddle
- Balance throttle paddle
- Break paddle
- Gearbox
- Key Ignition
- Battery values (current, voltage and more)
- etc.

Final version is shown on figure 5.3 together with the old GUI version on figure 5.4, so they can be easily compared.

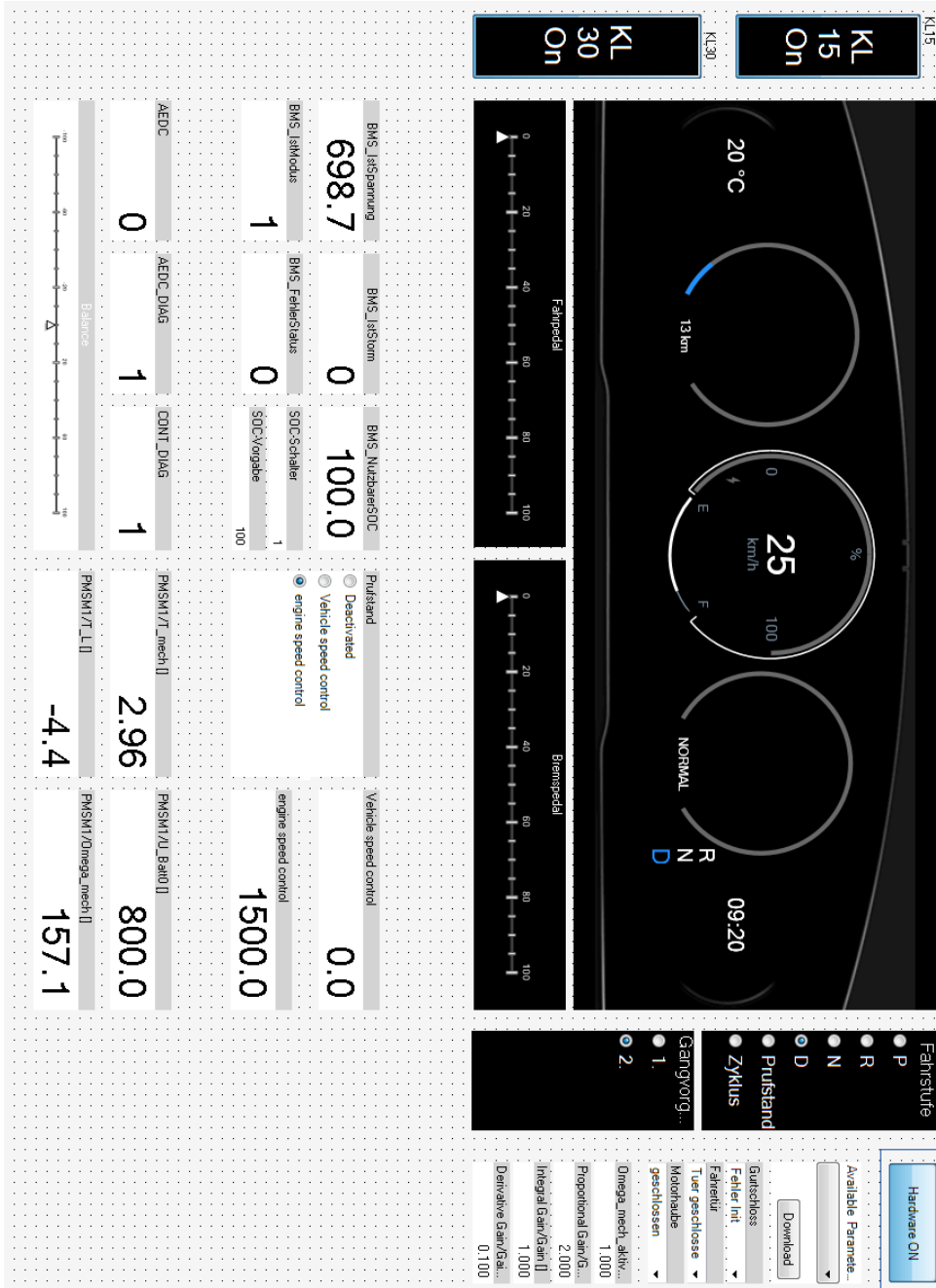


Figure 5.3: Developed GUI.

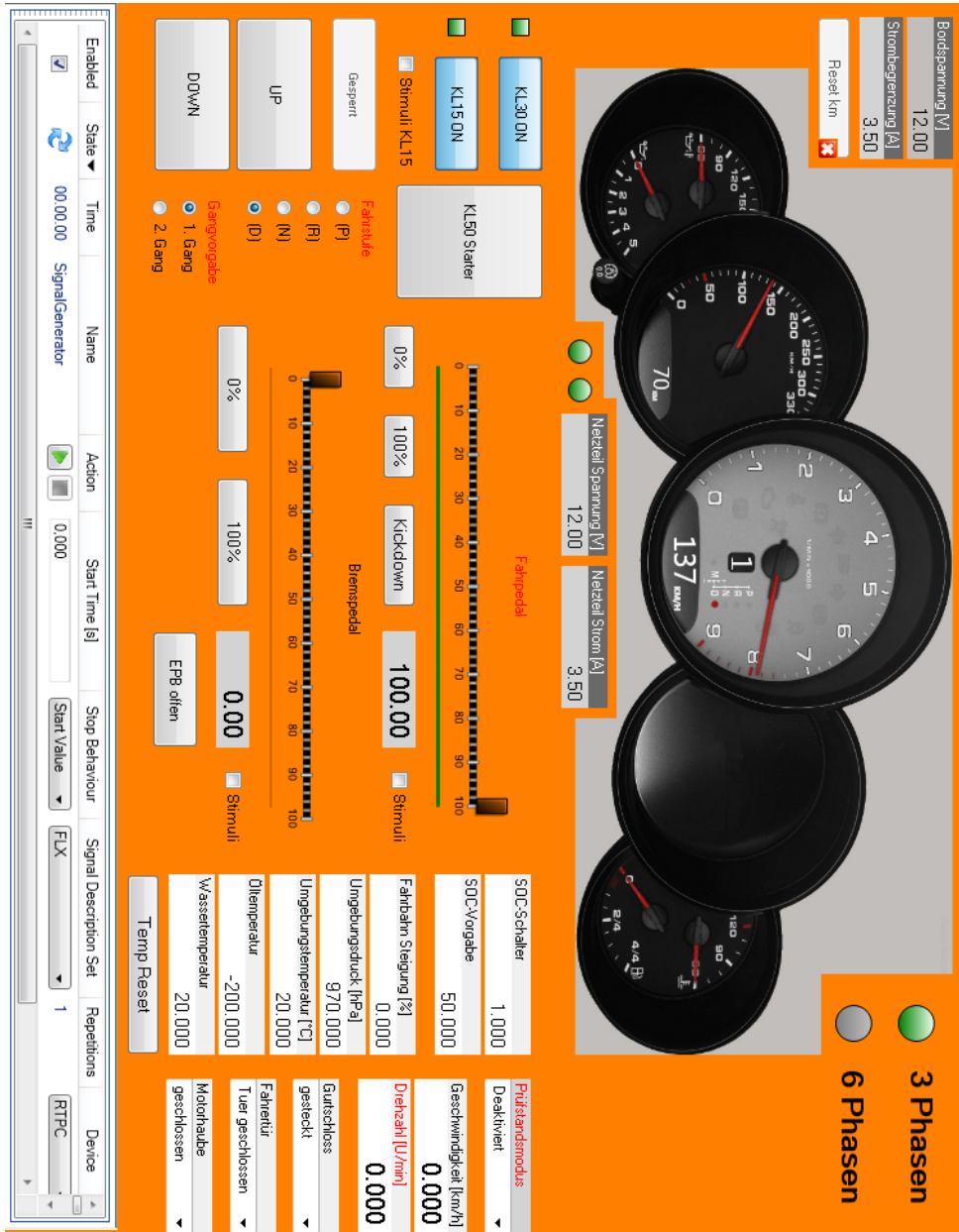


Figure 5.4: Old GUI version.

Chapter 6

Conclusion

The main goal of this thesis was to develop all wheel drive vehicle dynamics models in connection with battery model and new GUI. Models are implemented in PWR-HiL and optimized for it.

6.1 Overview of the results

Chapter 2 provides overall look at HiL system with accent on PWR-HiL system. Hardware structure together with software equipment was presented.

Chapter 3 has 4 main sections.

- The first section presents 2-wheel drive vehicle dynamics Simulink model. Equations used in the model are presented and the model is reviewed.
- The second section deals with the extension of 2-wheel drive vehicle dynamics model to all-wheel drive. New model design was proposed with the synchronization of the motors speed.
- The third section consist of battery model together with intermediate circuit.
- The fourth section finally presents the simulation results in compare to results measured in reality.

Chapter 4 deals with the connection of the models with PWR-HiL system and creation of GUI for all wheel drive model.

6.2 Fulfilment of the objectives defined in goals

I consider all objectives of this thesis to be satisfied.

■ 6.3 Suggestions for future work

The idea of the PWR-HiL is to provide environment for testing of the ECU with new software versions. It means that the system is continuously upgraded and changed.

Important thing in the near future will be to test the model in connection with the second ES5340 card.

Major task for future work might be the implementation of advanced torque control from the vehicle. It would mean also to implement movement in non longitudinal direction. It would also bring challenges with the upgrade of the sensor modus.

Another big task might be to implement recuperation control.

■ 6.4 Data confidentiality

All models mentioned in bachelor thesis were directly developed for Porsche Engineering Services and therefore, all models and measured data can't be enclosed due to the data confidentiality.

Appendix A

Bibliography

- [1] J. Wirsig, “Automatisierte absicherung einer antriebsleistungselektronik für hochleistungsfahrzeuge und deren steuerung mit hilfe eines hardware-in-the-loop-systems,” 2017.
- [2] ETAS, “Etas - labcar-rtpc.” https://www.etas.com/en/products/labcar_rtpc.php, 2018. “[Online; 31.3.2018]”.
- [3] ETAS, “Etas - es5340 – pci express simulation boards.” <https://www.etas.com/en/products/es5340.php>, 2018. “[Online; 31.3.2018]”.
- [4] ETAS, “Labcar-operator v5.4.4 - user’s guide.” <https://www.etas.com/en/downloadcenter/11935-22335.php>, 2018. “[Online; 31.3.2018]”.
- [5] ETAS, “Labcar-operator.” https://www.etas.com/en/products/labcar_operator-details.php, 2018. “[Online; 31.3.2018]”.
- [6] ETAS, “Inca.” https://www.etas.com/en/products/inca_software_products-measurement_calibration_diagnostics.php, 2018. “[Online; 5.4.2018]”.
- [7] P. Koblík, J. Pavelka, and České vysoké učení technické v Praze. Elektrotechnická fakulta, *Elektrické pohony a jejich řízení*. V Praze: České vysoké učení technické, 3. přepracované vydání ed., 2016.
- [8] P. Porteš, “Podélná dynamika vozidel,” Master’s thesis, Vysoké učení v Brně, Fakulta strojního inženýrství, 2015.
- [9] T. Haubert, *Optimal Control Strategy of Hybrid Electric Vehicle*. PhD thesis, CTU, FEE, 2018.
- [10] F. Vlk, *Dynamika motorových vozidel: jízdní odpory : hnací charakteristika : brzdění : odpružení : říditelnost : ovladatelnost : stabilita*. Brno: Nakladatelství a vydavatelství Vlk, 1. vyd. ed., 2000.

- [11] K. Sarrafan, D. Sutanto, and K. M. Muttaqi, “An electric circuit based ev battery model for runtime prediction and state of charge tracking,” in *2017 IEEE Transportation Electrification Conference (ITEC-India)*, pp. 1–6, Dec 2017.
- [12] J. Kacetl, “Mathematical model and validation of powertrain,” Master’s thesis, Czech Technical University in Prague, 2016.
- [13] J. Pavelka, Z. Čeřovský, J. Lettl, and České vysoké učení technické v Praze. Elektrotechnická fakulta, *Výkonová elektronika*. Praha: Nakladatelství ČVUT, vyd. 3. přeprac. ed., 2007.