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Automotive Intelligence for/at Connected Shared Mobility

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Table of contents

1 Executive/ Publishable summary

The document provides an overview of the AI-based EV demonstrator, which is based on a MB EQ5 platform with a custom redesign of some of the powertrain components such as inverter and electric motor. Advanced diagnostic and control features (also AI-based) are introduced and explained. A vehicle simulation model is being set up, to evaluate the longitudinal and thermal behaviour of the system during typical usage as well as the evaluation of an energy-optimized routing algorithm for the vehicle itself.

2 Non publishable information

None

3 Introduction & Scope

3.1 Purpose and target group

The main goal of Supply Chain 2 is the development of an EV5.0 car with AI based fault detection, analysis and mitigation for the powertrain in real time operation, making use of 5G and cloud capabilities and integrating available sensor fusion/perception by utilizing the next generation AURIX platform. The target of this deliverable is to provide an overview of the system design of such vehicle with real-time AI-based fault detection, analysis and mitigation.

With this scope, SC2 redesigned a Mercedes EQC. A new generation of powertrain will be implemented using an 800 V SiC, with real-time diagnostics on the edge provided by the latest AURIX platform. Connectivity and next-gen diagnostics continue with V2C communication gateways and 5G connectivity for real-world testing, and AI modeling will be utilized to enhance BMS

This document provides an overview of the systems, with specifications, scope and relevant preliminary results.

3.2 Contributions of partners

TABLE 1 LIST OF CONTRIBUTIONS BY PARTNER

Chapter	Partner	Contribution
4.8.1.1, 4.8.4	BUT	Integration of the cognitive diagnostic system, required changes comparing to in lab e-drive demonstrator. Inverter control and CAN communication software.
4.1.2	ZF	800V inverter description, with new classical and AI-based diagnostic and control strategies for electric drivetrains
4.1.3	IISB	AI-enhanced battery management system description
4.3.2.1	OTH	Test Drives for Data Collection with an electric vehicle. Data analysis, reasonability and cleaning of the data. Started Building AI-Models.
4.3.2.1	OTH	Conceptual Diagrams of Data Collection Pipeline and Data Processing Pipeline
4.1.1	MBAG	Description of Electric Drivetrain
4.3.1.3	TTTAUTO	Description of the system design and architectural aspects concerning the V2C communication module

4.2	AVL	Comprehensive vehicle model description

3.3 Relation to other activities in the project

Here are now listed the activities connected to other SCs.

- Integration by EDI of 3D and 360° Time of Flight sensing system developed by IFAG, IFAT & IFIN is part of Demonstrator 5 for SC6.
- A cognitive diagnostic system for real-time fault detection from BUT is tested on a lab demonstrator in SC4.
- In order to simplify software integration, the inverter software is largely shared between SC4 and SC2, because both make use of the same control board even though there are differences in the HW.
- TTTAUTO utilized the communication system architecture and connectivity platform used in SC5. Further efforts in SC5 will consider the SC2 demonstrator requirements specifically w.r.t. edge-tocloud connectivity in WP4 and WP5.

4 Demonstrator 1: EV5.0 car

The demonstrator included development and integration in a vehicle using the EQC platform from Mercedes Benz. The activities affected multiple components, such as an electrical machine, inverter, battery and its associated management system (BMS), with the implementation of custom control functions, such as inverter software (4.3.3.2) and an AI-enhanced battery management system (4.1.3). To support and further study the behaviour of the complete system, simulations using a comprehensive vehicle model have been implemented. The defined model covers in detail the specification of the system, inverter, battery, cooling package and cabin specification defining the energy demand to keep the temperatures in operation range, and consequent energy consumption. The physical implementation on the demonstrator vehicle, and its digital representation in the form of a model, are completed with additions in connectivity features as well as targeted algorithms for tasks like fault detection and energy optimized routing.

Together with the development of new hardware components, and its digital-twin counterpart in form of a simulation model, the demonstrator focuses on software functions with multiple purposes. In the scope of the SC2 demonstrator, a new method for real-time fault detection has been developed (4.3.1.1).

4.1 Demonstrator vehicle : HW development

The following paragraphs provide an overview of the components of the demonstrator vehicle that required additional work in terms of redesign or adaptation.

4.1.1 Electrical Machine

Since the modified vehicle will operate on an 800V power net voltage, it was necessary to replace all HV components. Most of these components could be taken over from the 1000kmPLUS project, however, the electric drivetrain consisting of the electric machine, gearbox and drive shafts was not available. MBAG is therefore providing a suitable prototype drivetrain that is tailored to fit the target vehicle and allows for easy connection of the new inverter developed by ZF.

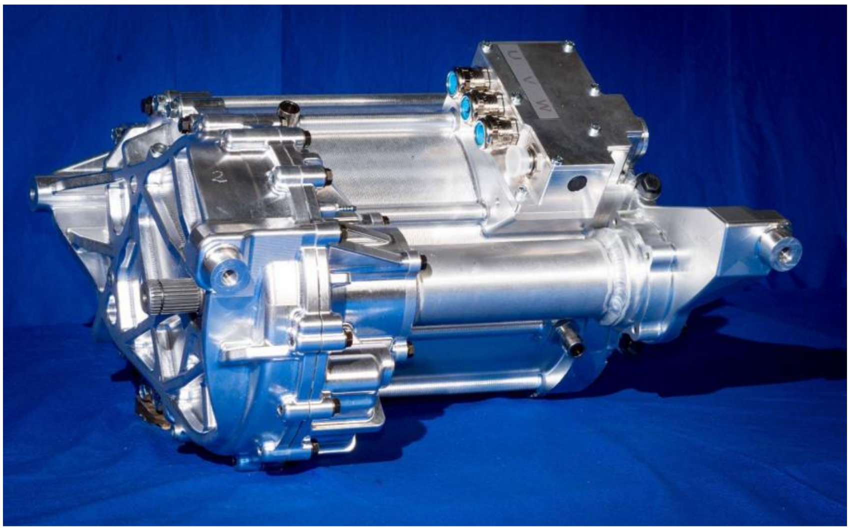

FIGURE 1: ELECTRIC DRIVETRAIN

The drivetrain consists of an electric machine (PSM), a single-gear transmission and a differential. The electric machine provides a peak output torque of 760Nm and a maximum rotational speed of 9000/min. The maximum available short-time peak power is 245kW.

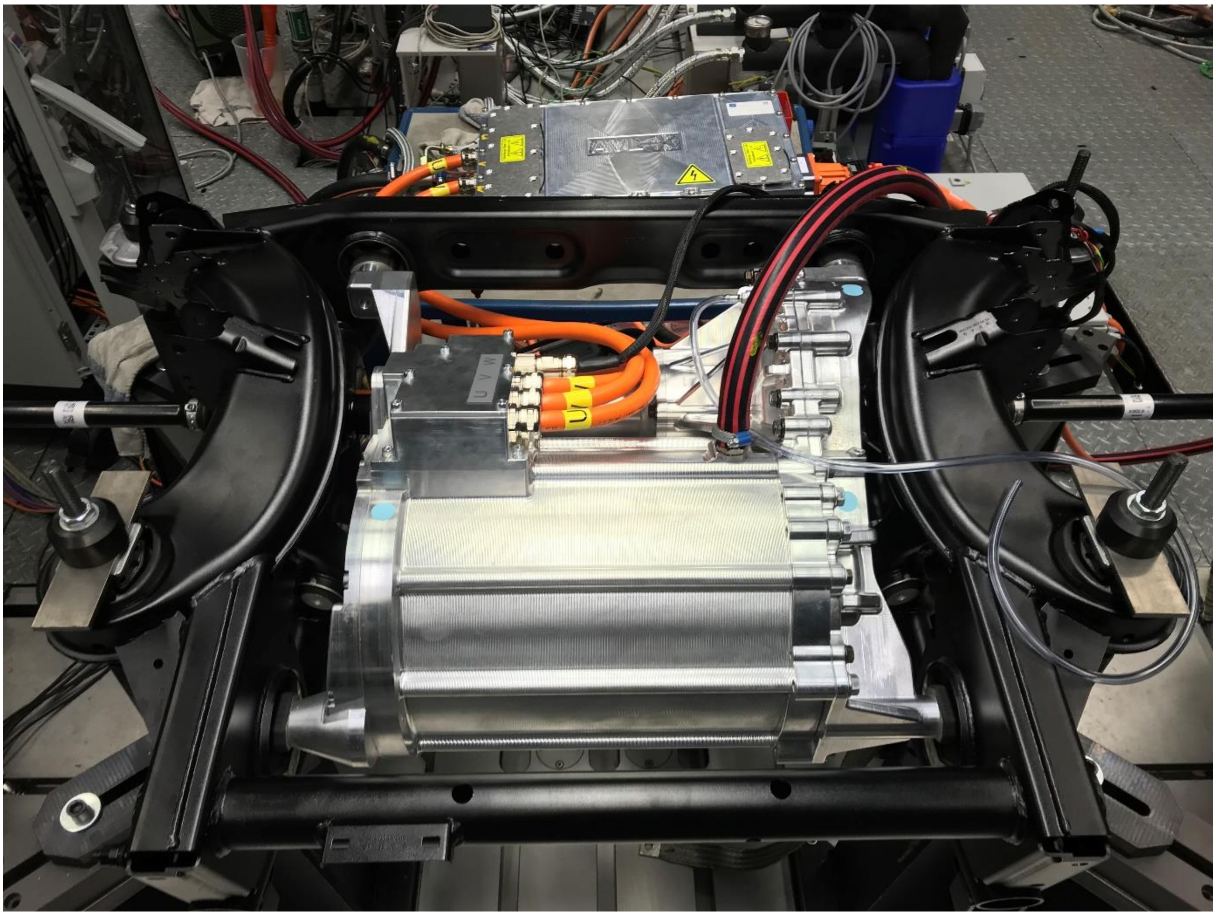

FIGURE 2: ELECTRIC DRIVETRAIN MOUNTED ON TESTBENCH

The electric drive has been validated on a test bench before providing it to the partners to prove functionality and key performance parameters. Figure 3 shows an exemplary testbench run with positive and negative torque.

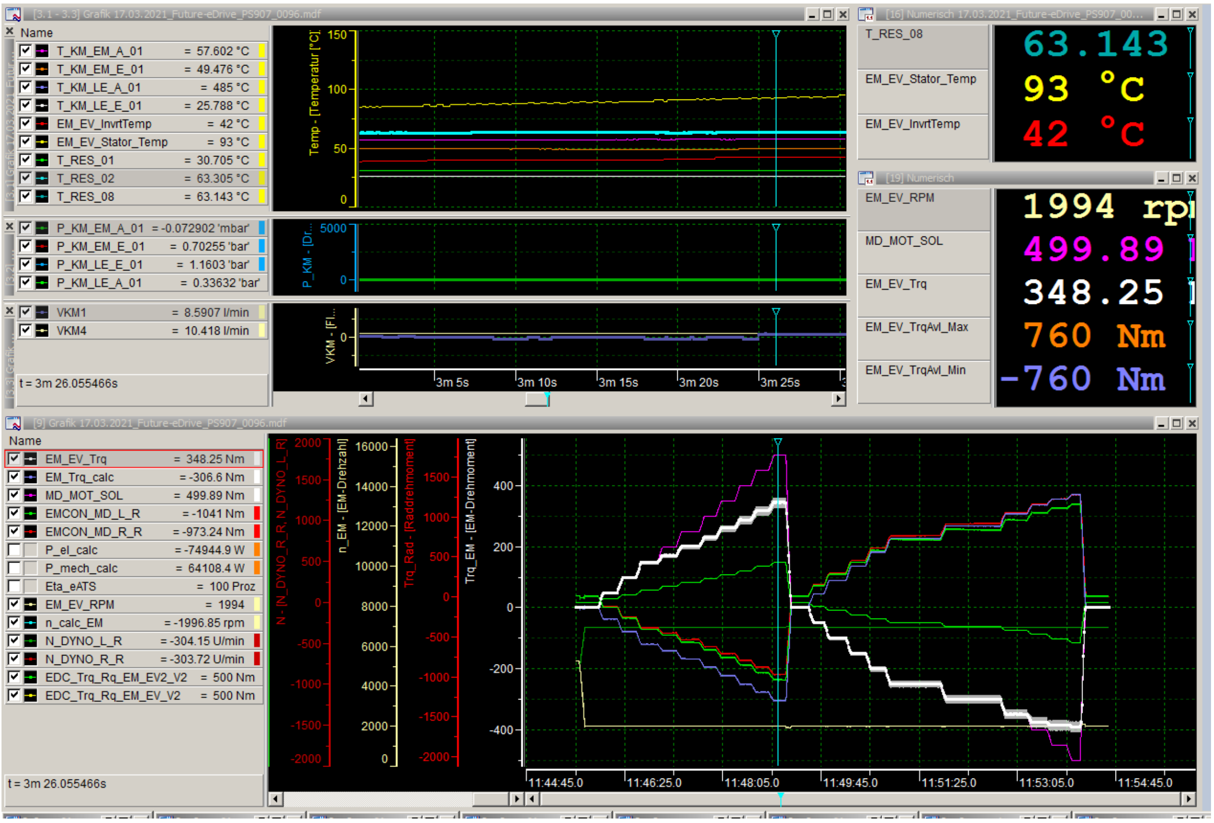

FIGURE 3: ELECTRIC DRIVETRAIN: TESTBENCH MEASUREMENTS

The housing dimensions and mounting points of the drivetrain are designed to fit the integration space in the EQC and allow for a smooth mechanical integration into the demonstrator vehicle.

Further steps will include a specific cooling solution for the drivetrain, since the electric machine is oil-cooled and cannot be directly integrated into the vehicle's cooling circuit. For this purpose, the cooling circuit will be expanded by a heat exchanger, an oil pump and a reservoir. A schematic of the cooling circuits with the proposed adaptions is shown in the following figure.

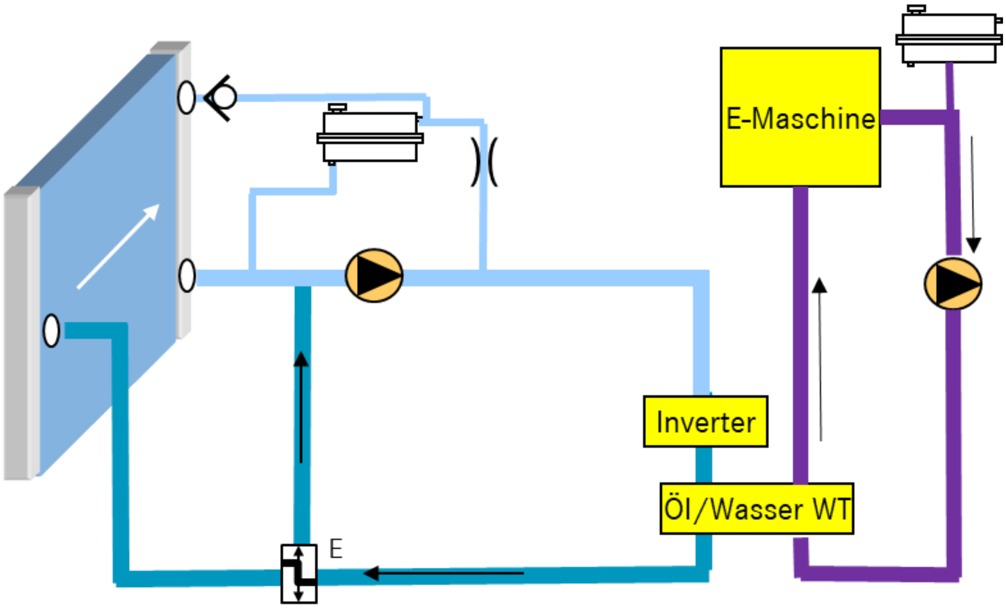

FIGURE 4: PROPOSED ELECTRIC DRIVE COOLANT CIRCUIT

4.1.2 Inverter

ZF provides an available 800V inverter for the demonstration of new classical and artificial-intelligence-based diagnostic and control strategies for electric drivetrains. The main modification to be performed on the inverter is the integration of the new AURIX TC49x microcontroller with PPU from IFAG, which will allow the execution of the previously mentioned diagnostic and control functions.

The provided inverter is shown in Figure 5, as a CAD model. It should be noted that this inverter is different than the one previously introduced in Deliverable D1.2. After internal discussion and review of component availability, it was decided that the new inverter (shown in Figure 1) represents a lower commissioning and integration risk for the project. The main characteristics of this inverter are:

- 800V 6-phase topology based on silicon-carbine (only 3 phases are assembled),
- a maximum current of 900 A, maximum fundamental frequency of 2500 Hz,
- a switching frequency up to 32 kHz,
- total volume of 11 liters with a weight of 6 Kg, and
- a cooling system using a water/glycol solution.

The CAD model of the inverter has been provided to AVL, who performed an evaluation of the integration possibilities into the demonstrator vehicle as shown on the right of Figure 5. It has been decided to integrate the inverter (and the drivetrain overall) into the rear axle of the vehicle. After initial evaluation of integration in the demonstrator vehicle, no mechanical adaptations are needed for the inverter's housing. AVL will design and fabricate a mounting system for integration of the inverter into the rear-axle.

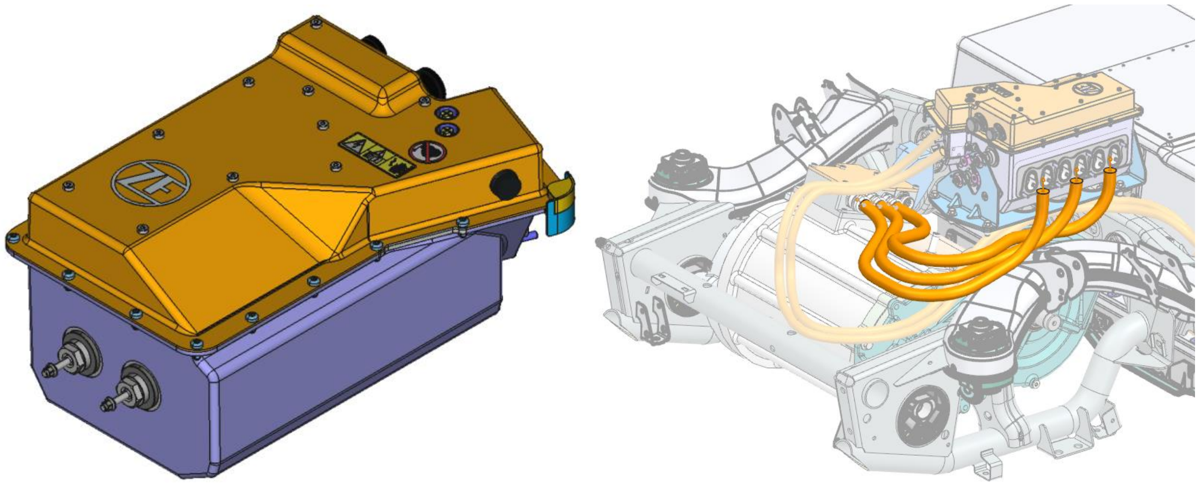

FIGURE 5: ZF 800V SIC INVERTER. LEFT: CAD MODEL: RIGHT, MODEL INTEGRATION INTO VEHICLE

Due to the use of a vehicle demonstrator which is different from the original target vehicle of the 800V SiC inverter, it is necessary to consider the specific needs of the interface between the vehicle and the inverter. Ina summarized form, the vehicle-inverter interface consists of the following signals and signal groups:

- 12V power supply (Clamp 30),
- Turn-on signal (Clamp 15),
- Crash detection signal,
- 2x PT1000 temperature sensor inputs from electric motor,
- 1x resolver signal input group for Tamagawa TS2763N,
- 2x CAN communication busses (one capable of Wake-Up via CAN), and
- Interlock signals at each connector.

It is not planned to redesign or rechose the already available connectors. Instead, the compatibility of the vehicle-inverter interface will be guaranteed by foreseeing the previously mentioned signals in the control electronics design, and by fabricating a new cable harness for use with this inverter.

Although not needed for integration into the vehicle, the interface to the power transistor gate-driver stage is summarized here:

- Three-phase PWM output for two-level inverter
    - Including enable signals and safety logic,
- Analog AC current sensor signals,
- Temperature sensors for current sensor boards,
- Digital HVDC measurement via SPI, and
- SiC NTC temperature measurement via SPI.

These signals play a role mostly at the interface between the control hardware and software; namely, sensor signals of sufficient quality (i.e., accuracy, bandwidth) are required for the needed performance of the control system.

In order to simplify the development process of both the electronic hardware and the software components, which should ideally be compatible with both SC2 and SC4, the control electronics have been designed with a modular approach, divided into three parts. The main Control Board contains the AURIX TC49x microcontroller with integrated PPU, as well as its dedicated power supply. This Control Board is compatible with and will be used in both SC2 and SC4. The adaptation to the needs of both supply chains is done via adapter boards; namely, signals are routed as needed from the microcontroller to the vehicle interface on the one hand, and on the other from the microcontroller to the power transistor gate-driver stage. Figure 6 shows the block diagram of the modular control electronics. In this case, only those components relevant to SC2 are highlighted. Information regarding the interfaces for SC4 will be provided in Deliverable D2.5. Full documentation of the control electronics, their interfaces, and their precise implementation will be provided in Deliverable D4.14 from Work Package 4.

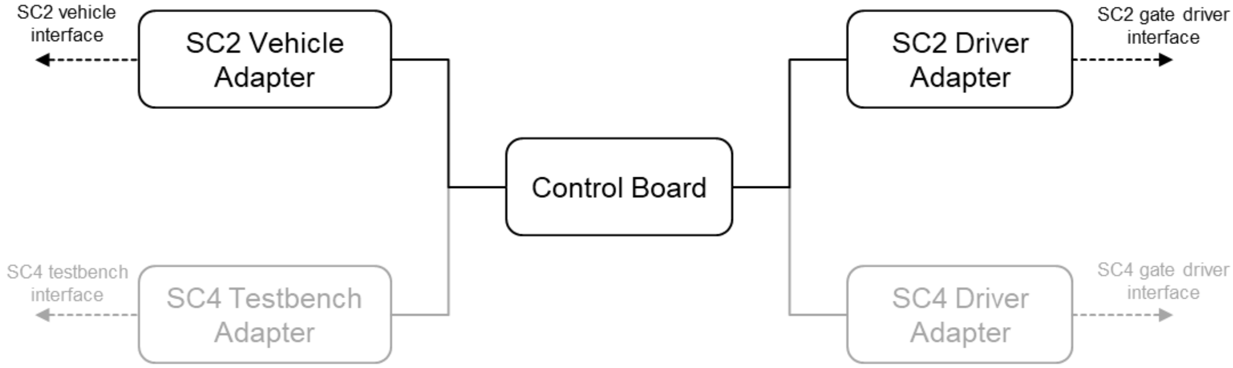

FIGURE 6: MODULAR STRUCTURE OF INVERTER CONTROL BOARD

4.1.3 AI-enhanced BMS

The architecture analysis based on the MBAG inputs to enable the battery management system as a platform for the algorithms to be developed in this project was finalized in task 2.2. The MOXA MC-1121-E2-T[1] was selected as an extension to the foxBMS platform to provide the necessary computational power and memory for the developed algorithms. The MOXA device depicted in Figure 7 s an embedded computer designed for long-lasting, reliable operation in harsh environments. The MOXA device can be integrated into the demonstrator car (1000kmPLUS) by providing a 11.4 to 36 V DC power supply (max. 30 W). The already integrated foxBMS of the demonstrator car (1000kmPLUS) can be extended by the MOXA device via a CAN connection to the foxBMS master board.

[1] https://www.moxa.com/en/products/industrial-computing/x86-computers/mc-1100-series/mc-1121-e2-t

FIGURE 7: MOXA MC-1121-E2-T

Other specification of the MOXA MC-1121-E2-T important for the integration are:

- Power Parameters
  - Input Voltage: 11.4 to 36 VDC
  - Power Connector: Terminal block (for DC models)
  - Power Consumption: 30 W (max.)
- Physical Characteristics
  - Housing: Metal
  - Dimensions: 132 x 122 x 87 mm
  - Weight: 1,340 g
- Environment Limitations
  - Operating Temperature: -40 to 70°C
  - Storage Temperature: -45 to 75°C
  - Ambient Relative Humidity: 5 to 95%

Furthermore, we developed a data preprocessing pipeline where the MOXA device receives the sent raw CAN battery data from the foxBMS in the first step. Afterwards, the data are filtered, decoded, and structured.

FIGURE 8: DATA PROCESSING PIPELINE

During the operation of the demonstrator car, the pipeline depicted in Figure 8 is executed to provide data to the developed algorithms.

4.2 Demonstrator vehicle: Comprehensive vehicle model

The comprehensive vehicle model consists of both the powertrain model and the thermal management model. In particular, the longitudinal vehicle model includes high and low voltage systems, cooling package and cooling circuit model, thermal models of the high voltage battery and of the drivetrain, model of the refrigerant circuit and the passenger cabin. The model is used to evaluate total vehicle energy consumption and particularly how it is influenced by the thermal management system. Figure 9 shows the model's architecture including interfaces between the sub-models.

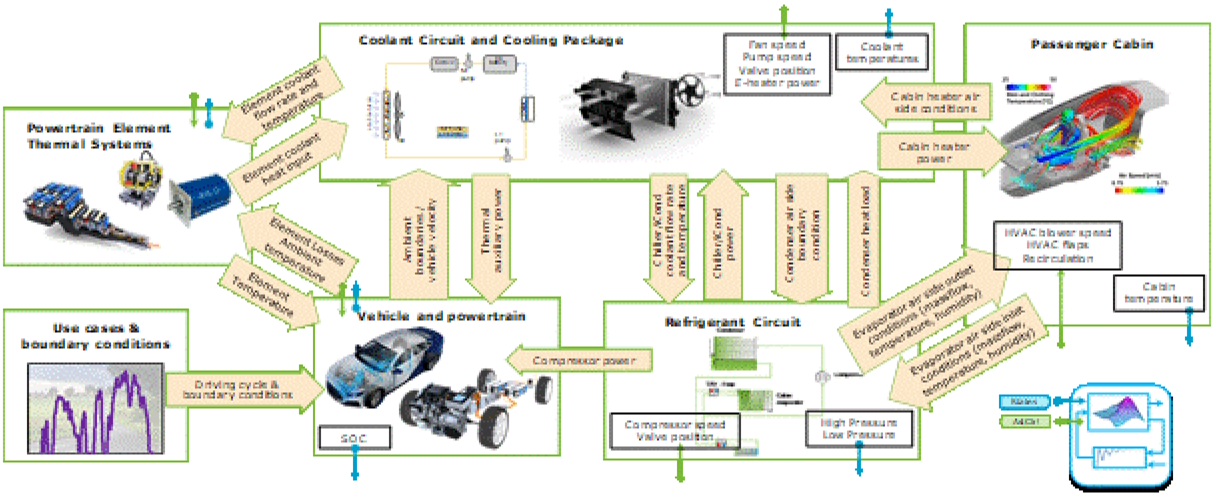

FIGURE 9: COMPREHENSIVE VEHICLE MODEL

4.2.1 Longitudinal Vehicle Model

The longitudinal vehicle model accounts for the main vehicle and powertrain data such as nominal dimensions and masses, battery and e-motor performance, tire properties, aerodynamic resistance, etc. The model is based on Mercedes Benz EQC electric vehicle. The main features of the model can be summarized as follows (Figure 10):

- Definition of driving cycles based on desired velocity profile, definition of charging stations and charging parameters
- The driver model: This model approximates the vehicle velocity to the defined velocity profile of the driving cycle. Thus, it generates control signals for the overall powertrain control. A standard AVL driver model has been parameterized and implemented. Optionally also an external driver model can be used.
- Vehicle longitudinal dynamics and powertrain model. The drivetrain consists of the single-gear transmission, differential, drive axis and wheels, electric motor, battery and brakes.
- Low voltage and high voltage electrical networks, auxiliary components, charger. These components are not modelled in detailbut are considered only as energy sinks or sources.

- Controllers which are necessary to operate the vehicle, e.g. driving strategy, battery charging strategy, halt time.

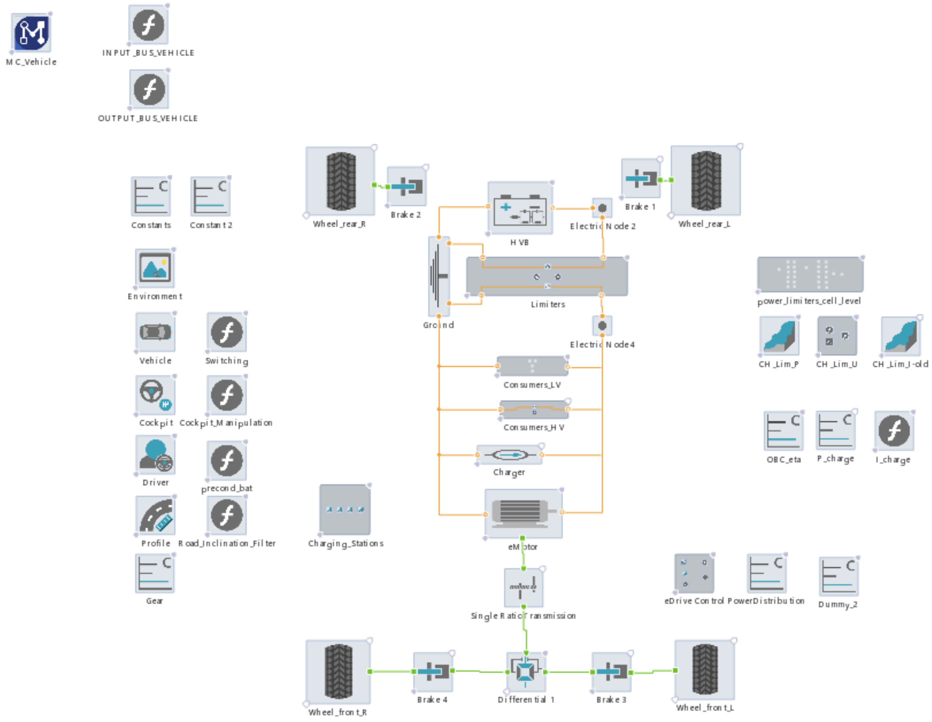

FIGURE 10: LONGITUDINAL VEHICLE MODEL

4.2.2 Vehicle Driving Resistance

Vehicle driving resistance consists of the rolling resistance, aerodynamic drag force and all frictional losses of the driveline. The overall resistance is calibrated based on parameters received from MBAG. The parameters and resulting energy consumption are shown in Table 2.

TABLE 2 VEHICLE DRIVING RESISTANCE CALIBRATION

Name	Unit	Value
Frontal area	m^2	2.67
Drag coefficient	-	0.29
Vehicle weight	kg	2558
Resistance constant part	N	100.9
Resistance linear part	Nh/km	1.13
Resistance quadratic part	Nh^2/km^2	0.03701

Cycle	Energy consumption (kWh/100km)
80 kph	~14.8
100 kph	~18.3
120 kph	~22.9
130 kph	~25.6
WLTC	~18.7
In all cases, assumed energy of all auxiliary components is 500 W, while road inclination 0%.	

4.2.3 Electrical Machine and Inverter

In AVL CruiseM the electrical machine model consists of two components, the inverter and the electric motor. The e-motor can be operated in both the motor and generator modes (motor-mode load map shown in Figure 11). The model provides torque-speed characteristic and power losses at different voltage levels. The losses, calculated based on the efficiency map, are used as heat input for the e-motor thermal model (the thermal model is a separate subsystem as explained in 4.2.6). In a similar way, the efficiency map of the inverter is used to calculate the heat losses, which are sent to the cooling system (inverter efficiency data is currently unavailable to AVL, and therefore assumed).

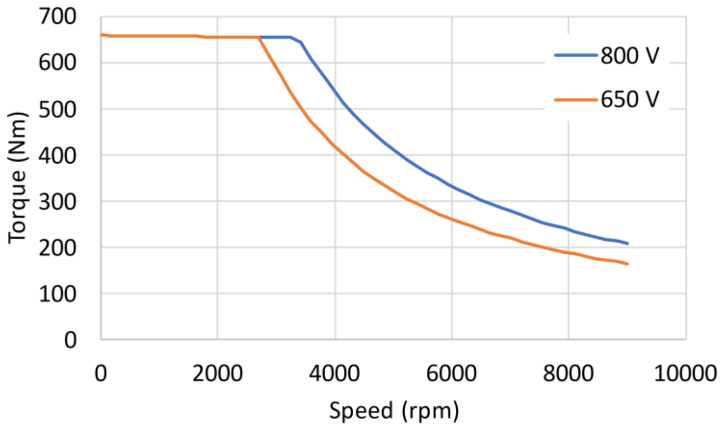

FIGURE 11 ELECTRIC MOTOR LOAD MAP

4.2.4 HV Battery Performance Model and Charging Limits

The battery electrical model is developed as a second order RC model using the maps which were, due to the lack of data, taken from AVL Benchmark for a similar cell and adjusted to fit the cell data provided by Fraunhofer cell (Table 3).

TABLE 3 BATTERY ELECTRICAL DATA

Name	Unit	Value
Cell capacity	Ah	4.2
DC resist. @50% SoC, 1s	mΩ	16
Minimum voltage	V	2.8
Maximum voltage	V	4.25

Name	Unit	Value
Module configuration	-	7s 27p
No. of modules	-	28
Pack nominal voltage	V	721
Pack rated energy	kWh	83

A comparison of the resulting fitted model and cell data provided by Molicel, as well as measurements from Fraunhofer, is shown in Figure 12. As the battery efficiency strongly depends on the cell temperature, the temperature dependence is considered. The cell thermal model is assessed as a separate subsystem as explained in Section 4.2.5. The losses of the battery are used as heat input to the battery thermal model for calculating the cell temperature which is then fed back to the vehicle model as a boundary condition for the battery electrical model.

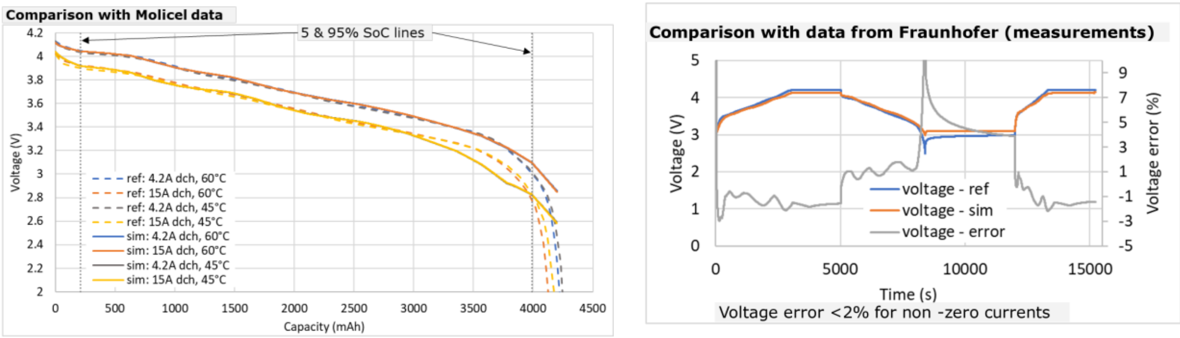

FIGURE 12 CELL ELECTRICAL MODEL - COMPARISON TO REFERENCE

Battery fast charging power is constrained by the cell temperature and State-of-Charge. Therefore, charging power limitation is implemented as a part of the charging strategy. The power limitation curve as a function of the battery temperature is assumed based on AVL experience, while the current limitation as a function of cell SoC is calculated based on preliminary data provided by Fraunhofer (Figure 13).

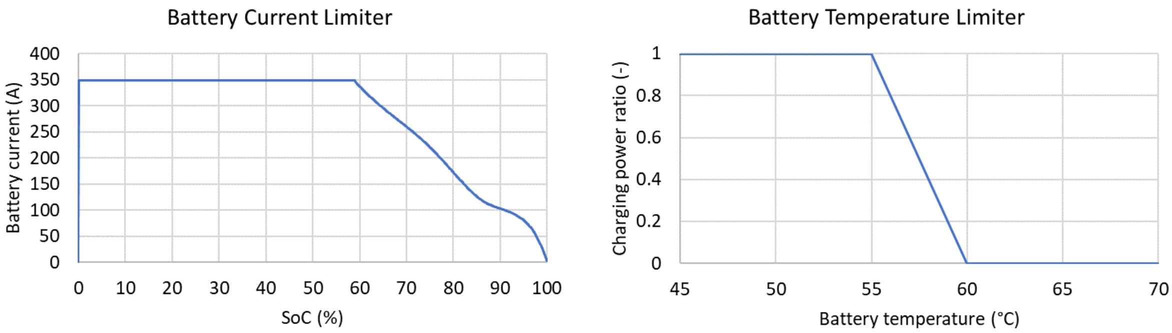

FIGURE 13 BATTERY CHARGING LIMITERS

4.2.5 HV Battery Thermal Model

Due to their mass, HV batteries have a high thermal inertia which dampens the transient thermal behavior of the battery. A 1D lumped mass thermal battery model was built in AVL. Power losses of the battery are calculated in the powertrain subsystem and serve as the input for the thermal model, while the resulting cell temperature is fed back to the electrical model.

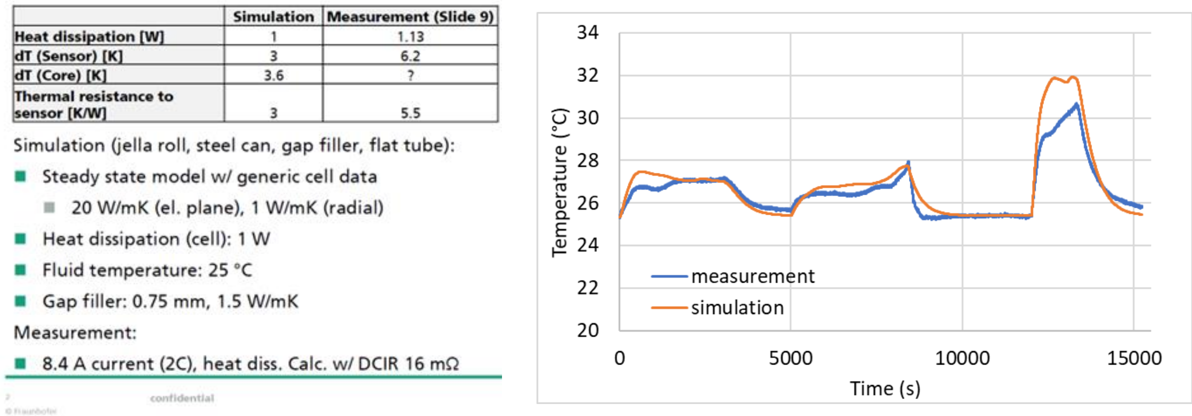

FIGURE 14 CELL THERMAL RESISTANCE

The thermal resistance of the cell and cooling channel is calibrated based on cell measurements provided by Fraunhofer (Figure 14). As can be seen, the simulation overshoots measured temperature which is especially enhanced in the last temperature peak region (current of 2C compared to 1C in the first two regions). The measured cell thermal response might be influenced by cell holders that, visually assessed based on the provided image, have comparably big thermal mass in contrast to the cell itself. The cooling system consists of fourteen parallel cooling pathways with two modules on each (Figure 15). The module is furthermore divided into three parallel cooling channels. The overall thermal resistance of the cooling system to the cell average temperature is 5.4 K/W at 15 lpm battery flow.

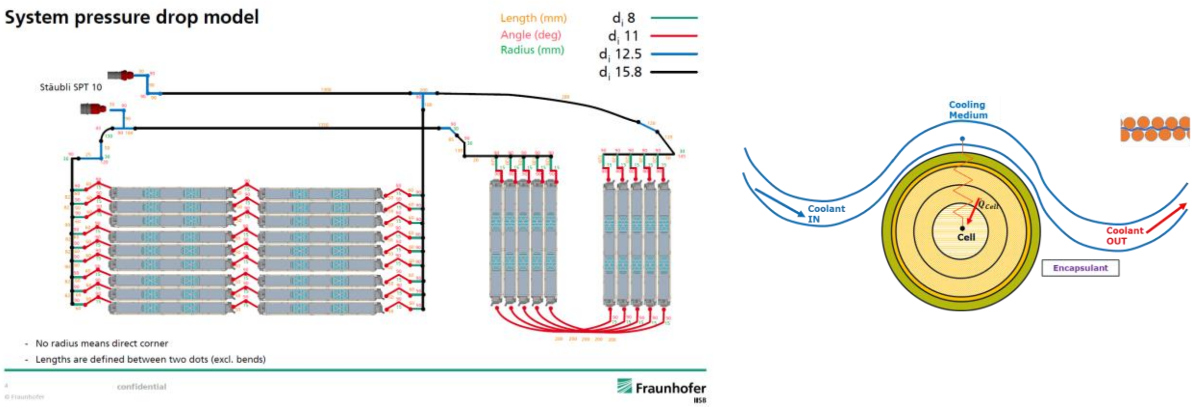

FIGURE 15 BATTERY THERMAL MODEL SCHEME

Cell is discretized into nine masses (Figure 15): three in the radial and three in the longitudinal direction, while a module into five sections along the coolant flow. The model in AVL CruiseM is shown in Figure 16.

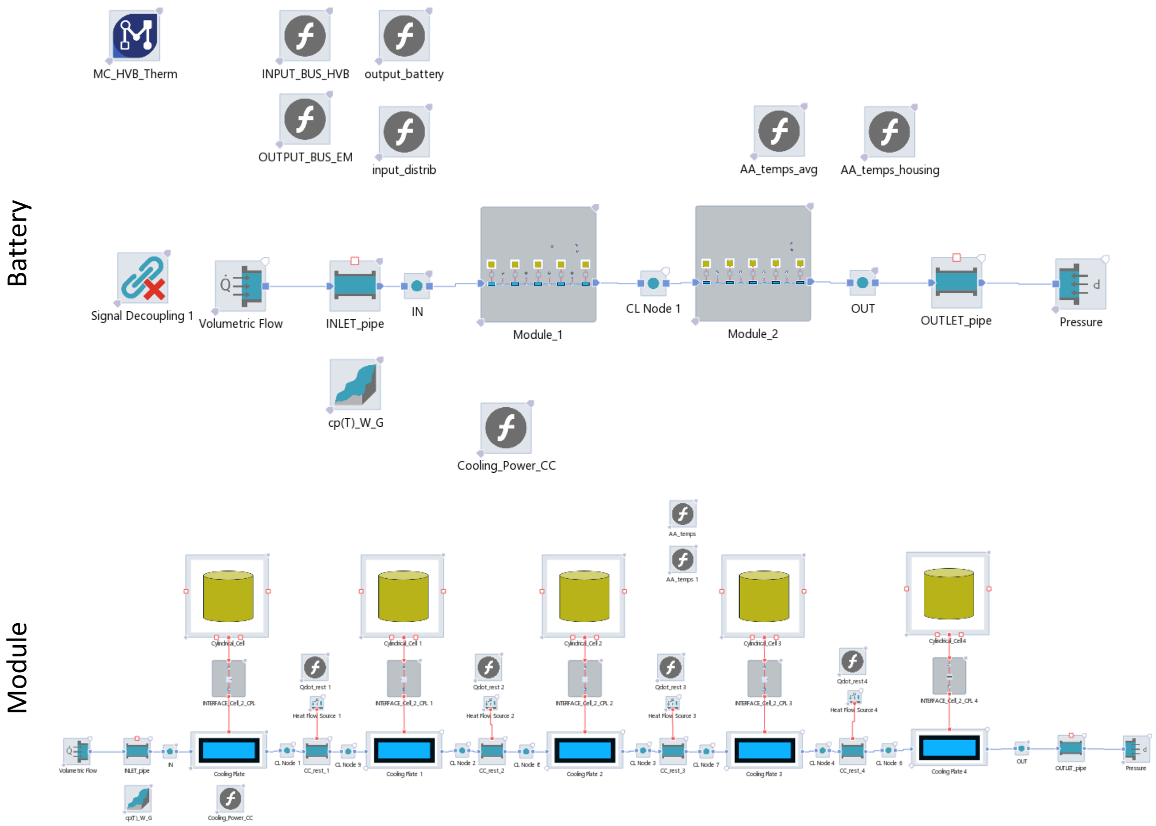

FIGURE 16 BATTERY THERMAL MODEL IN CRUISEM

4.2.6 E-Motor Thermal Model

The thermal model of the e-motor is built in AVL CruiseM by means of a lumped mass model (Figure 17). The thermal inertia of different electric motor parts dampens the thermal response of the system. The e-motor is divided into masses such as rotor, stator, windings, and housing. Thermal behavior (resistance and inertia) is assumed based on the AVL Benchmark for a similar e-drive. The power loss of the e-motor distributes to different masses depending on motor speed and torque.

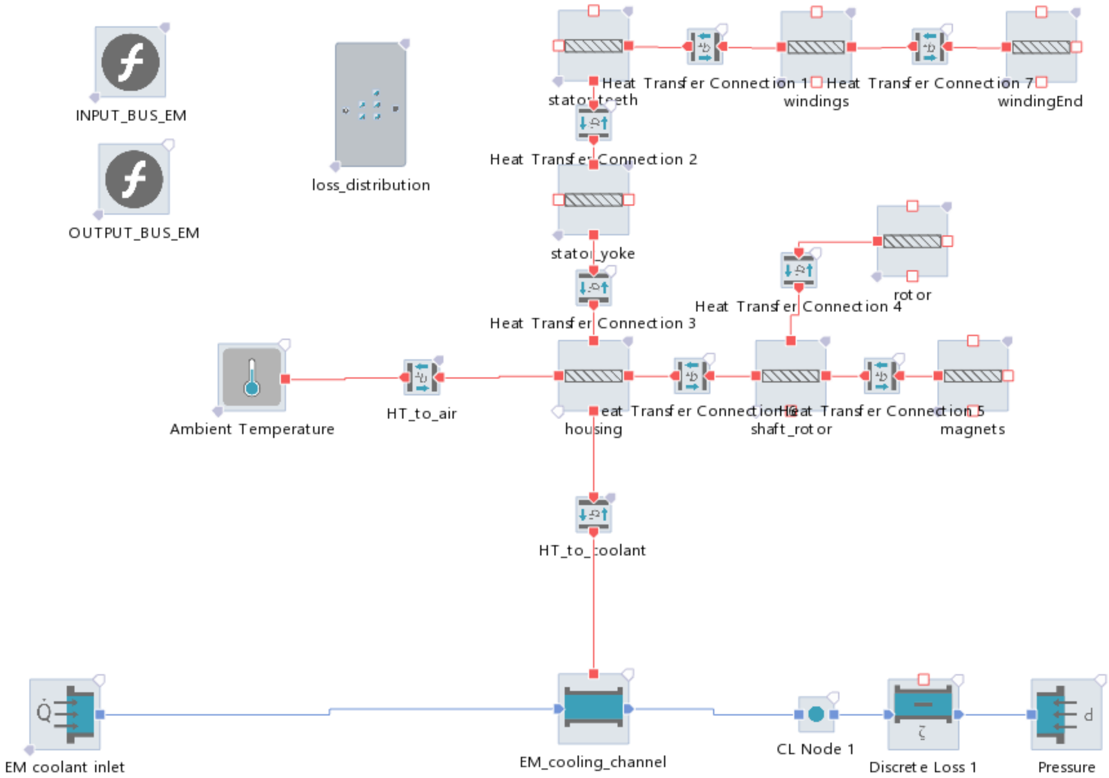

FIGURE 17 E-MOTOR THERMAL MODEL

4.2.7 Cooling Package and Coolant Circuit Model

The cooling package and coolant circuit model is set up according to the original vehicle architecture (Figure 18). It contains both the high and low temperature coolant circuits, as well as the underhood airflow pathway (the refrigerant circuit is explained separately in the following section).

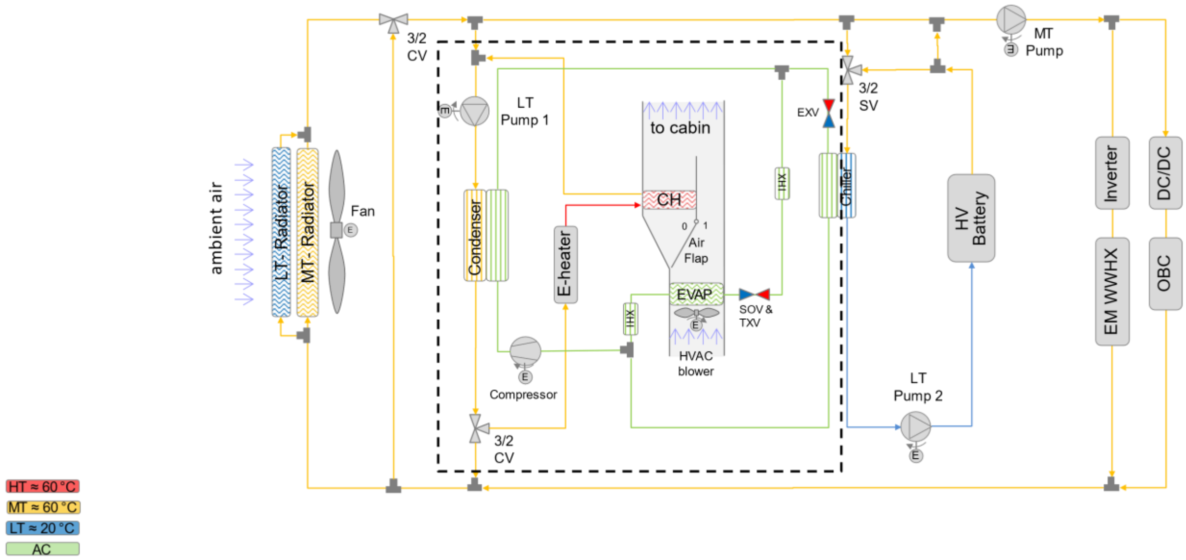

FIGURE 18 COOLING SYSTEM LAYOUT

System components are connected in a thermal network developed in AVL CruiseM (Figure 19). Minor differences to the original vehicle are expected due to changes during the project implementation. Each component is coupled with energy flows across the system boundaries via interfaces. For example, the battery coolant heat rejection is coming from the battery thermal model and acts as a heat source for the battery cooling circuit. On the other hand, the resulting coolant inlet temperature and flow rate are sent back to the battery thermal model to act as a boundary condition for the calculation of the convective heat transfer.

It is important to note that the model contains a mixture of original components of the Mercedes-Benz EQC and new components specific to this project such as e-motor or inverter. Furthermore, it is important to note that information about the existing piping or coolant flow distribution in the circuits has been unknown. Therefore, hydraulic system resistances are adjusted to ensure target flow rates across all components while pumps operate at maximum speed. Therefore, the model will be updated during the project implementation once the data becomes available.

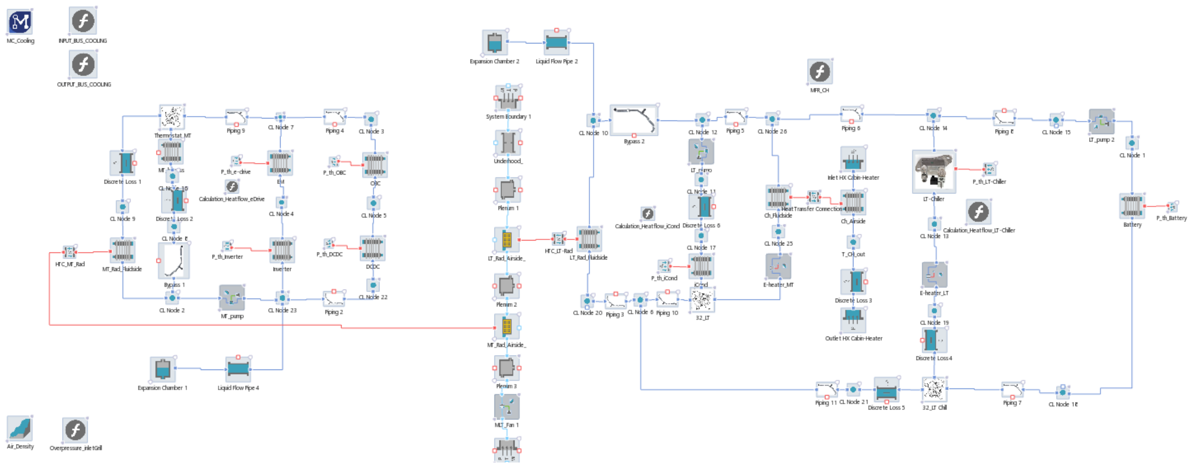

FIGURE 19 COOLANT SYSTEM AND COOLING PACKAGE MODEL

4.2.7.1 Cooling Package

The cooling package consists of a low and a high temperature radiator, additional underhood airflow resistance and a fan. Heat transfer from the coolant to the air side of both heat exchangers is modelled by means of performance maps generated based on data delivered by Mercedes Benz AG. However, no information has been available for understanding the underhood flow limits. Since a common trend in electric vehicle development is a strong focus on optimization of vehicle aerodynamics, it is assumed that the underhood airflow at maximum fan performance is minimized to the value of 0.45 kg/s at 25°C ambient temperature (assumption based on AVL experience).

4.2.7.2 List of Coolant Circuit Components

Assuming that the battery itself is developed for fast charging, the cooling system represents the vehicle side limitation during fast charging. Therefore, a detailed list of currently implemented components can be seen in Table 4.

TABLE 4 COOLANT SYSTEM COMPONENTS

Name	Specification	Source
LT Radiator	636x505x16 mm; 40 kW @ 0.3 kg/s hot, 2.6 kg/s cold, 80/25°C; 23 kPa @ 0.3 kg/s hot; 300 Pa @ 2.6 kg/s cold	Mercedes Benz AG
3/2 Valve (condenser)	6 kPa @ 16.67 lpm @ 20°C	AVL Benchmark
3/2 Valve (chiller)	6 kPa @ 16.67 lpm @ 20°C	AVL Benchmark
LT Pump	8.6 m @ 30 lpm; 12V	Mercedes Benz AG
HV Battery	15 kPa @ 20 lpm @ 45°C	AVL Benchmark
e-Heater	6.2 kPa @ 18 lpm @ 60°C; 10 kW; 800V	AVL
Chiller	17 plates; Coolant: 5.8 kPa @ 10 lpm @ 25°C; Performance: 7.3 kW @ 10 lpm, 40°C, p_{low} 4.25 bar, EXV inlet 11 bar (WG 50/50, R1234yf)	Mercedes Benz AG
Condenser	30 plates; Coolant: 12 kPa @ 19.2 lpm @ 50°C ; Performance : 14.3 kW @ WG 50/50 1500 kg/h, 50°C, and R1234yf 17.5 bar, 330 kg/h	Mercedes Benz AG
MT Radiator	640x502x26 mm; 85 kW @ 3 kg/s hot, 2.6 kg/s cold, 80/25°C; 49 kPa @ 3 kg/s hot; 320 Pa @ 2.6 kg/s cold	Mercedes Benz AG
MT Pump	6.0 m @ 24 lpm; 12V	Mercedes Benz AG
Fan	260 Pa @ 1 m^3/s; 13V	Mercedes Benz AG
e-Motor WWHX	15 kPa @ 10 lpm @ 50°C	Assumption AVL
Inverter (e-Motor)	750 mbar pressure drop (75 kPa) @ 15 lpm @ 70°C	ZF
DCDC (12V)	10 kPa @ 4 lpm	Mercedes Benz AG
OCB	6.3 kPa @ 5 lpm; 11 kW	Mercedes Benz AG
Thermostat	6 kPa @ 16.67 lpm @ 20°C	AVL Benchmark
Evaporator	6.8 kW @ air 360 kg/h, 40°C, 40% RH and R134a 3 bar, TXV inlet 15 bar, 50°C	Mercedes Benz AG
Compressor	33.5 ccm, cooling capacity of 6.7 kW at 7000 rpm, 15/3 bar [abs], SH=10K, SC=0K	Mercedes Benz AG
Cabin Heater	220x152x30 mm; 6.4 kW @ 0.2 kg/s hot, 0.15 kg/s cold, 80/20°C; 4.7 kPa @ 0.2 kg/s hot; 191 Pa @ 0.15 kg/s cold	Mercedes Benz AG

Based on performance parameters and dimensions given in Table 4, performance maps are generated for all heat exchangers.

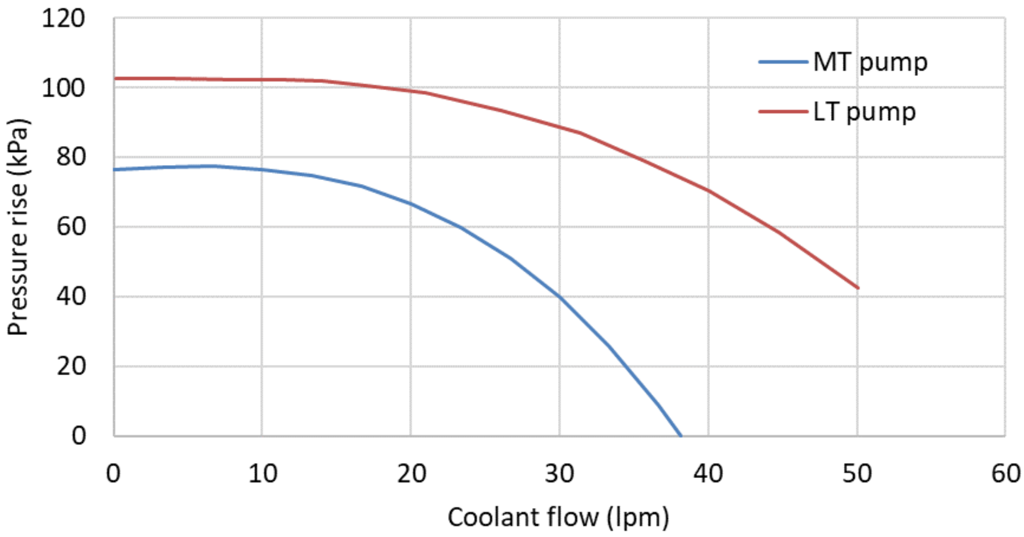

FIGURE 20 PUMP CHARACTERISTICS

Pump characteristics are given in Figure 20 while the fan characteristic is shown in Figure 21.

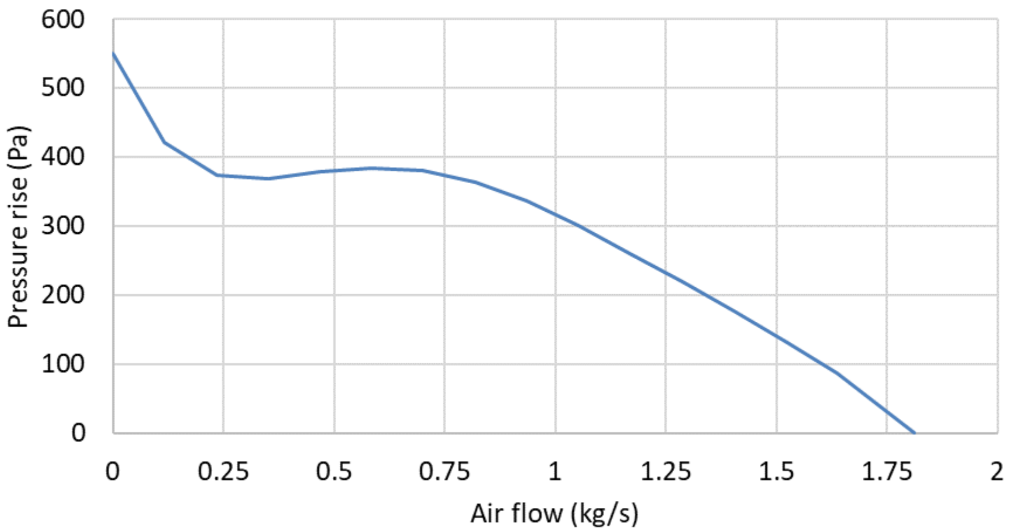

FIGURE 21 FAN CHARACTERISTIC

4.2.7.3 Refrigerant Circuit Model

The refrigerant circuit subsystem is built in GT-Suite. It is modelled in detail in order to be able to accurately access cooling system performance during vehicle operation – especially during the battery fast-charging. The system consists of a compressor, indirect condenser, evaporator, chiller, internal heat exchanger and simplified control. Main system components are calibrated based on available data.

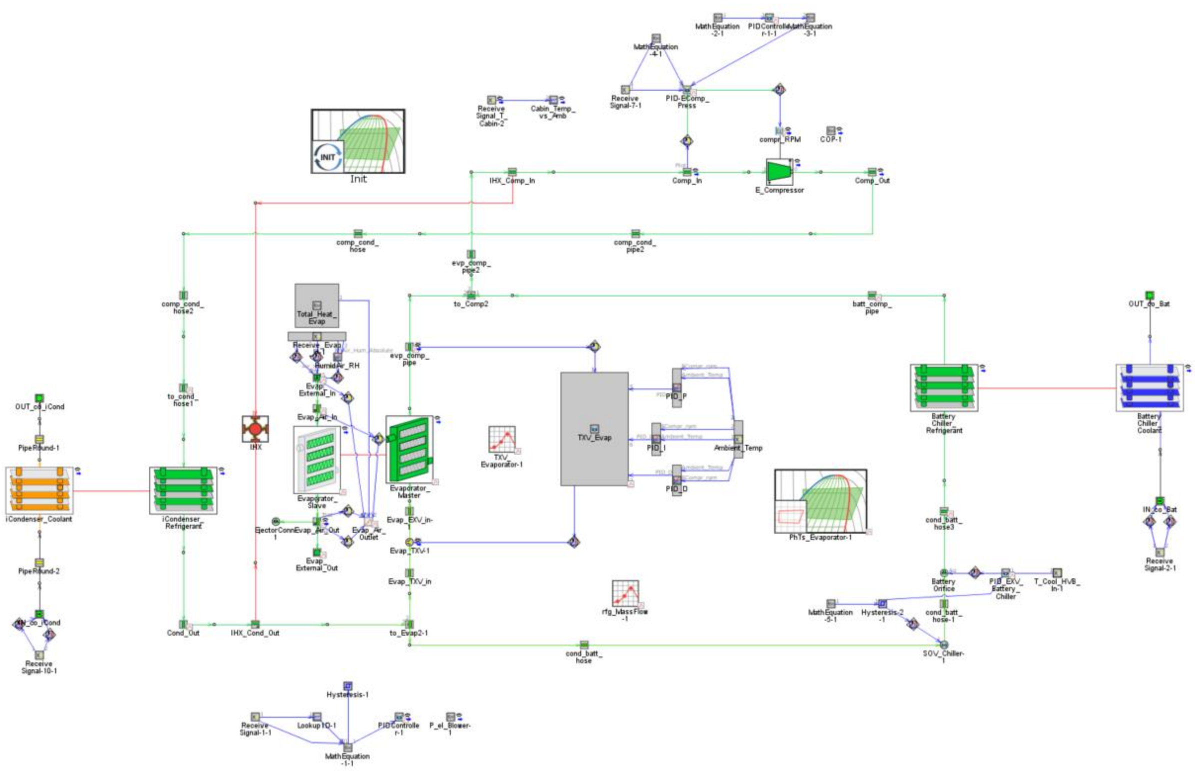

FIGURE 22 REFRIGERANT CIRCUIT MODEL

Condenser performance is calibrated based on data provided by Mercedes Benz AG. The fit after the calibration process is shown in Figure 23. It can be seen that thermal performance fits well at moderate and high loads.

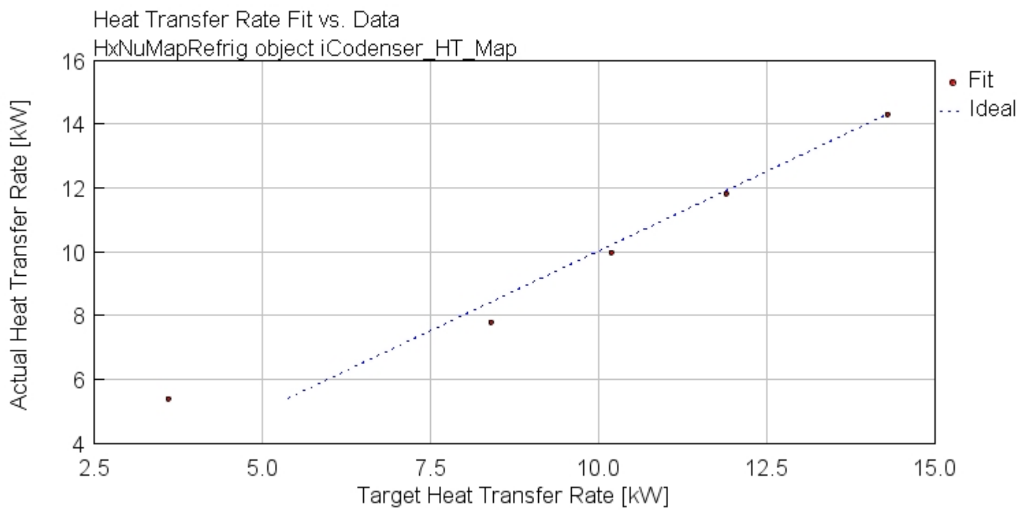

FIGURE 23 CONDENSER - THERMAL PERFORMANCE CALIBRATION

Furthermore, chiller and evaporator performance is calibrated based on data provided by Mercedes Benz AG. Figure 24 and Figure 25 show a very good match between the simulation model and measurement data.

FIGURE 24 CHILLER - THERMAL PERFORMANCE CALIBRATION

The compressor is calibrated based on data provided by Valeo Siemens. The available data is used to calculate isentropic and volumetric efficiency maps of the component given for different pressure ratios and compressor speeds (Table 5).

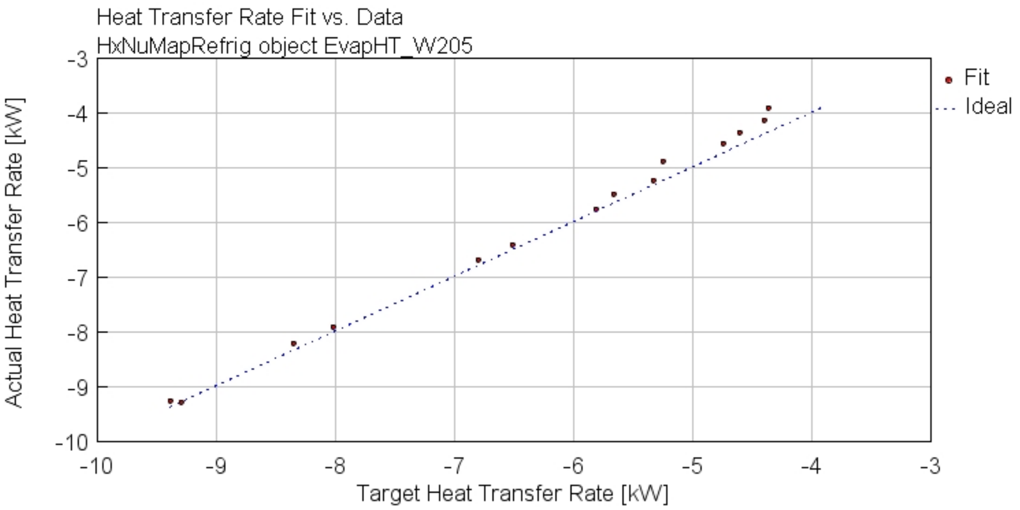

FIGURE 25 EVAPORATOR - THERMAL PERFORMANCE CALIBRATION

eta_isentropic				eta_volumetric			
	2700	5000	7000		2700	5000	7000
5	0. 591061844	0. 61241035	0. 58601552	5	0. 882993333	0. 920399723	0. 95040883
7	0. 486094903	0. 560760754	0. 55823523	7	0. 812527487	0. 870115726	0. 89181270

TABLE 5: COMPRESSOR - PERFORMANCE MAPS

(ROWS: PRESSURE RATIO, COLUMNS: COMPRESSION SPEED)

The geometry of the internal heat exchanger as well as simplified control are implemented based on previous knowledge to ensure stable operation of the model.

4.2.8 Cabin and Cabin Circuit Model

The cabin and cabin circuit model is built in AVL CruiseM. It consists of a cabin compartment and the airflow circuit including the mixing of fresh and recirculated air (Figure 26).

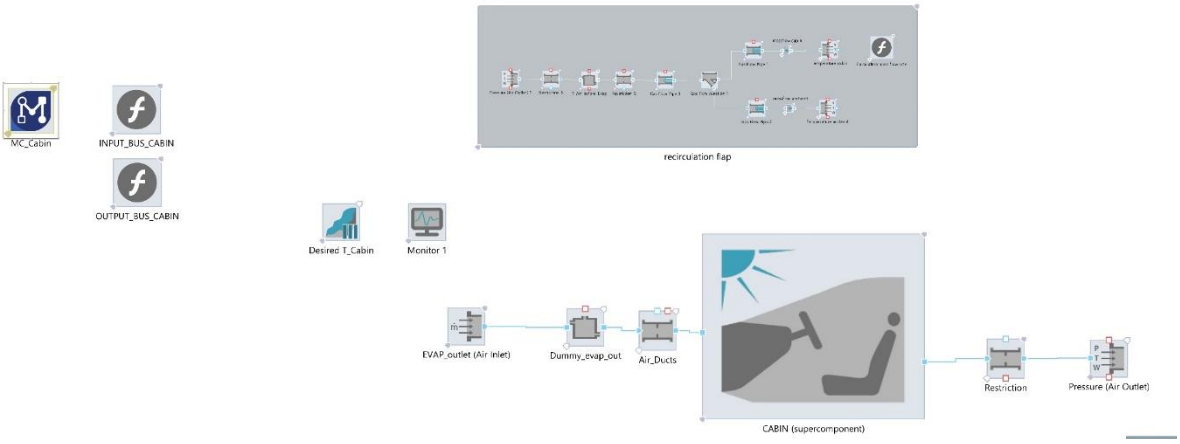

FIGURE 26 CABIN AND CABIN CIRCUIT MODEL

Fresh and cabin outlet air streams are mixed based on the recirculation factor. The defined mixture state is transferred to the refrigerant circuit model as input for the evaporator. The resulting evaporator outlet state is fed back to the cabin model as the boundary condition of the air entering the cabin.

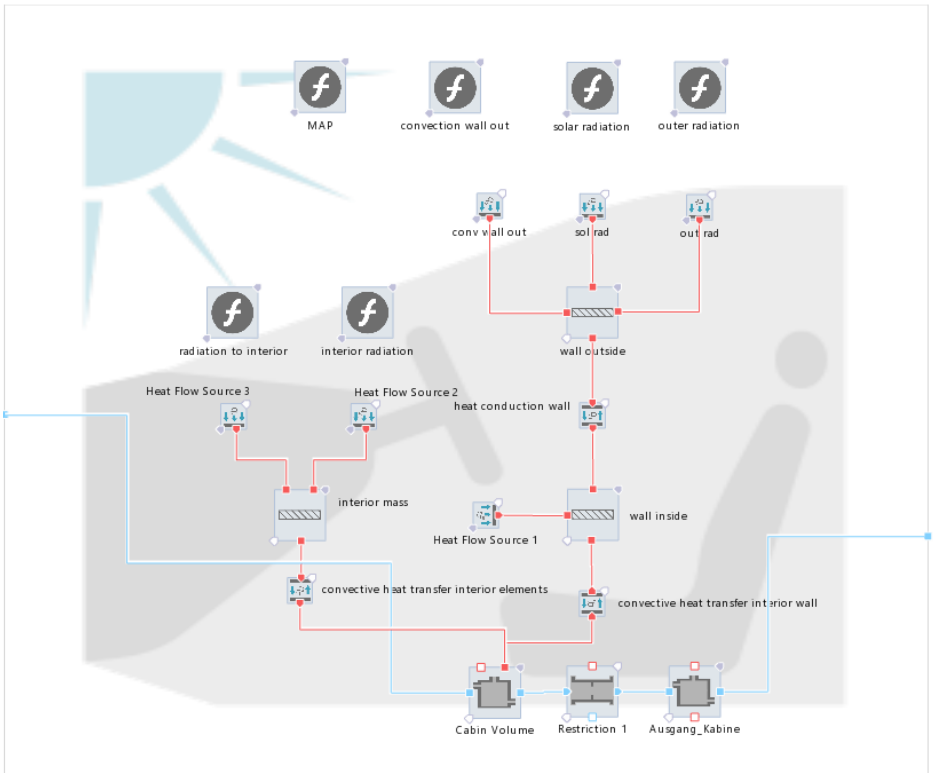

FIGURE 27 1D CABIN MODEL

The cabin model consists of air volume and several lumped masses (Figure 27). Its thermal response is calibrated based on steady-state data provided by Mercedes Benz AG (Table 6), while its dynamic behavior is adjusted based on AVL Benchmark (Figure 28). The cabin model is sensitive to prescribed solar load and cloudiness factor.

TABLE 6 CABIN THERMAL MODEL CALIBRATION DATA (MERCEDES BENZ AG)

Ambient temperature [°C]	Mass flow ducts [kg/min]	Average outlet temperature [°C]	Vehicle velocity [kph]	Cabin temperature [°C]
22	7	4	0	11.7
22	7	10	0	16.2
22	9	4	0	10.5
22	9	10	0	15.2
29	5	4	0	16.8
29	5	10	0	21.0
29	7	4	0	14.4
29	7	10	0	18.9
40	9	4	0	18.7
40	9	10	0	23.5

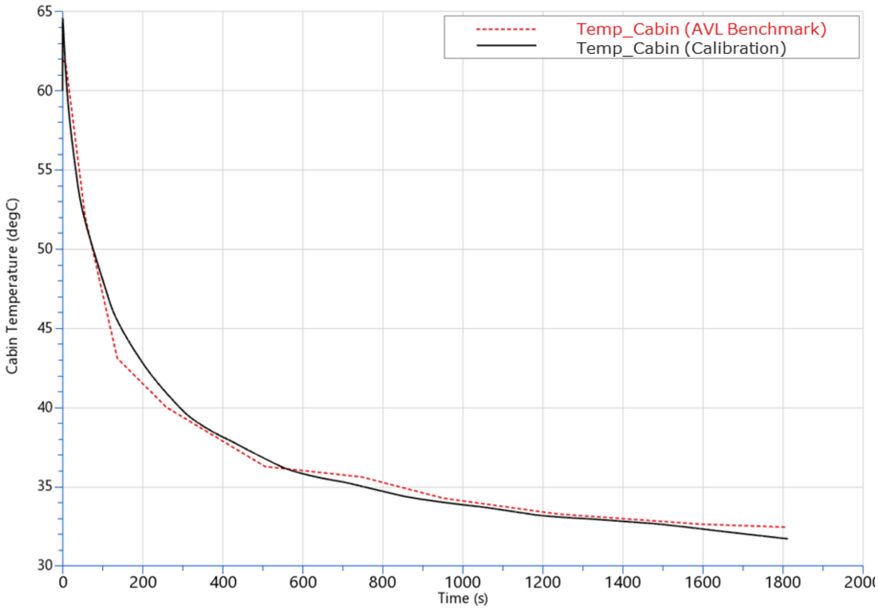

FIGURE 28 CABIN MODEL CALIBRATION

The maximum cool-down performance was evaluated at 40°C ambient temperature and 40% relative humidity for 30 kph constant driving for 60 min.

A/C settings were on max. cooling, max. blower speed, 1000 W/m2 solar load.

Blower speed control as a function of the ambient temperature is implemented to control the cabin temperature (Figure 29).

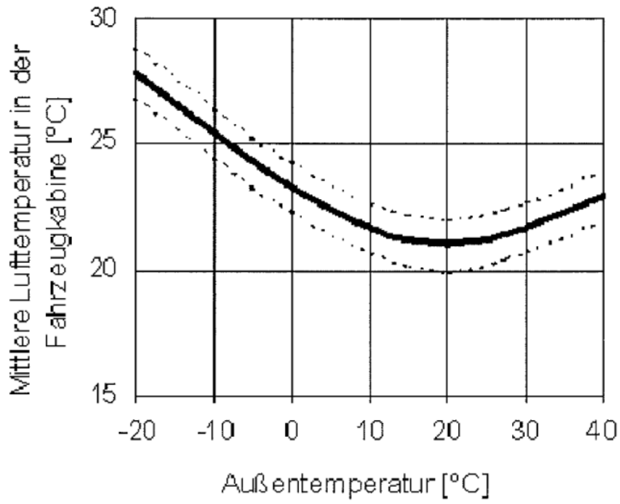

FIGURE 29 CABIN TARGET AS A FUNCTION OF AMBIENT TEMPERATURE (DIN 1946-3 (GERMAN INSTITUTE FOR STANDARDISATION, 2006))

4.3 Demonstrator vehicle: integration, SW and AI development

4.3.1 In-vehicle sensing and connectivity

4.3.1.1 Cognitive diagnostic system for real time fault detection

The cognitive diagnostic system is currently under development in SC4 where a dual three-phase motor is investigated. Since SC2 contains a single three-phase motor, only algorithms prepared to diagnose one of the sub-systems of the dual three-phase motor individually, i.e., without the additional knowledge of the other sub-system will be used. For this reason, the fault detection principles will be based primarily on motor symmetry analysis. Innovative parameter observers based on current and voltage waveform analysis are also suitable for the adaptation for classical three-phase machines. On the other hand, detection principles based on the comparison of both sub-systems together will not be used in SC2.

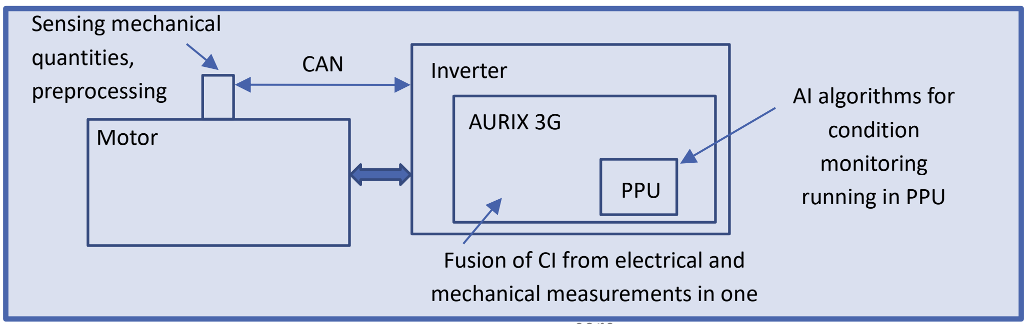

FIGURE 30 BLOCK DIAGRAM OF COGNITIVE DIAGNOSTIC SYSTEM

The block diagram of the cognitive diagnostic system from the perspective of its integration in the car is shown in Figure 30. The sensor of mechanical quantities will be connected to the motor. It will contain a microcontroller for data preprocessing, selected condition indicators computations and CAN communication routines for the connection with the inverter. AI algorithms for fault detection from the measured electrical quantities will be implemented in the parallel processing unit (PPU) of the AURIX 3G microcontroller. The fusion of condition indicators from mechanical quantity measurements and electrical quantity measurements will be integrated into one of the cores of the AURIX microcontroller.

4.3.1.2 Connectivity: Vehicle to Cloud communication module

The architectural analysis of a potential system design for a required V2C communication module was performed and is depicted in Figure 31. The example depicts an up/down-stream data service to provide the necessary data sources for the cloud analysis. In addition, it shows a solution to connect two distinct HPC ECUs - (1) by TTTAUTO and (2) by the novel AURIX™ 4G by IFAG. Both ECUs provide an AUTOSAR software stack, which can be utilized to easily integrate the in-car data communication via e.g. CAN protocol. Both hardware platforms are capable of handling automotive safety requirements up to ASIL-D according to the ISO26262 2018 Standard.

The required training data used by OTH could be gathered via the in-car communication backbone given the decoding information of the OEM. Together with the dedicated software framework, such a platform can be set up as a test environment to benchmark the communication gateway services in the demonstrator.

The majority of technical design and development to provide a proper communication platform for future eMobility is achieved within the activities of SC5. These developments touch the vertical integration across multiple layers in modern automotive E/E architectures to enable a harmonized and latency-optimized execution across the whole system (Figure 31: Platform View – left hand side). TTTAUTO showcases the usage of these improvements of fast, secure and safe communication methods in this output enabler supply chain.

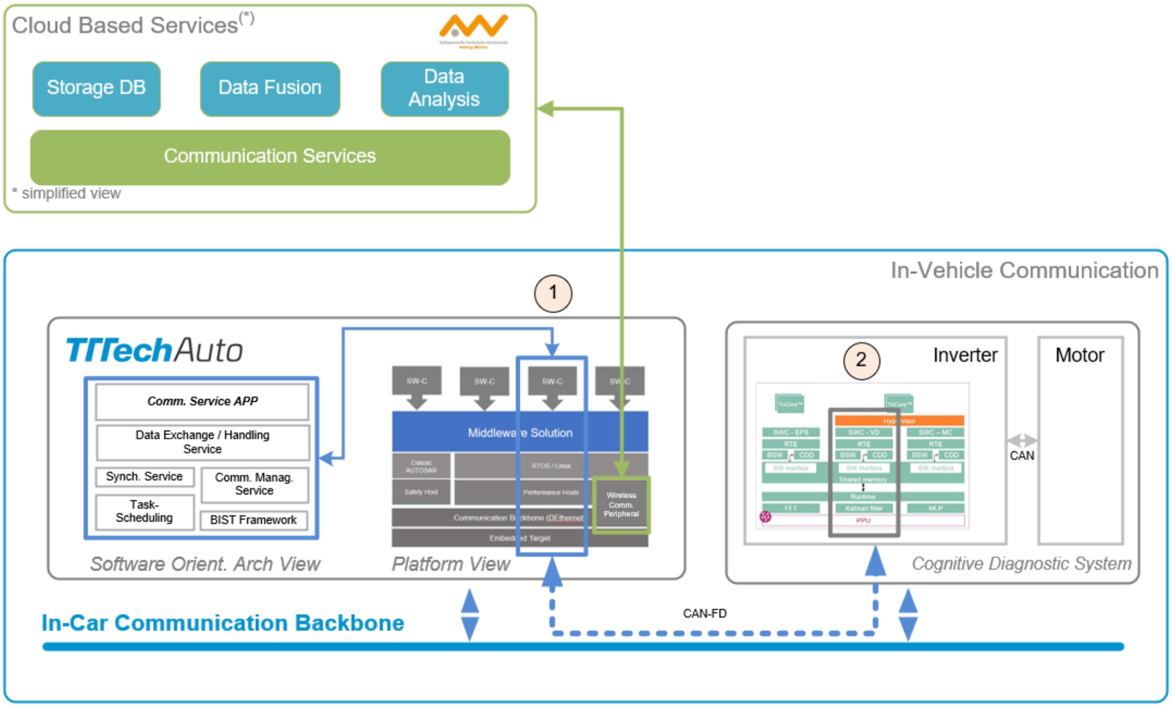

FIGURE 31: ARCHITECTURAL ANALYSIS AND DESIGN OF THE V2C COMMUNICATION MODULE

Within the activities of TTTAUTO in SC2, the following requirements have been tackled and will be tracked further on in the activities of the supply chain:

- Software Integration Framework (AI4CSM_WP1_SCD2.1_25)
- Communication Interfaces (AI4CSM_WP1_SCD2.1_23)

The reminder of the defined requirements of TTTAUTO in SC2 will be pursued in the W5 and WP6.

4.3.1.3 Cloud-based services

Introduction

The project contents for Task 2.2 to be delivered by the OTH were adapted in Version 3.0 of the Technical Annex. The requirements for this data were described in the last report. This section describes the results.

Collecting Data through Test Drives

In order to train AI models a sufficient amount of data has to be collected.

The first step is to find a good data source. That means we had to find an electric vehicle that allows us to gather as much as possible decodable information as possible.

Furthermore, we consider temperature as a fundamental variable because it affects how test drivers drive and how long the battery lasts. Thus, we planned 2 test phases. One in summer (June / July 2022) and one in winter (January / February 2023). The figure below illustrates the process.

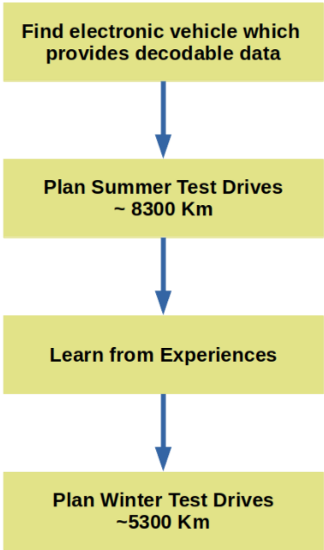

FIGURE 32: PATH FOR FINDING A SUITABLE ELECTRIC CAR AND PLANNING 2 TEST PHASES

The electric vehicle (Tesla 3 performance) was rented for the test drives. It provided 2 data sources. One data source was a well reverse engineered CAN interface, the other was the data aggregated from the official Tesla Account.

Those data sources operate at different frequencies and had to be merged.

In total 16 test drivers drove around 13.000 Km through summer and winter. The test drivers were mixed female and male students and OTH employees, mostly between 18 and 30 years old.

The majority of test drives were planned to take place in one of the following predefined towns: Amberg, Schwandorf, or Regensburg. Most test drives had partially predefined routes. Otherwise, test drivers were free to drive around in the towns. All test drives started at the OTH. So, test drives to Schwandorf contained a fair portion of country roads. Test drives to Regensburg contained a fair portion of Autobahn.

The idea behind predefined routes is that we can analyze the behavior of different drivers at different times. This helps to extract and understand the human dependent driving style component and how this affects the energy consumption of the car.

The idea behind undefined routes is that we want to get a good statistical variation for the test drives so the AI is not trained on biased data.

Data Merging During Test Drives

As already mentioned, there are 2 data sources (Tesla Account and CAN interface) that provide data. We also enrich the data with weather data. Based on the current car coordinates during test drive, temperature and windspeed from the closest available weather station are stored. If the next weather station is too far away, the temperature is linearly interpolated between the closest 2 weather stations. We stored the data of several weather services.

Data Merging After Test Drives

The electric vehicle provides geo-coordinates. It does not provide a list of streets of metadata as traffic lights. So, we had to match the geo-coordinates with a data source that provides such data. That data source is OpenStreetMap. OpenStreetMap is a free and open online map service. The concept of OpenStreetMap is that volunteers create data elements called "nodes" which contain geo-coordinates. Those "nodes" are grouped in linear segments which are called "way_ids". Those way_ids are are usually streets and enriched with a lot of metadata which are important for route planning. This information contains speed limits, road types or traffic lights. The car coordinates must be matched to the corresponding streets. This map-matching process turns geo-coordinates into way_ids and is done after the test drive. The data processing pipeline also optimally stores way_ids, nodes, and metadata such as traffic lights in files. OpenStreetMap relies on volunteers and the data is subject to constant change. So, we have to store all information after a successful map matching process. The whole data pipeline is quite complex and therefore not reported in full detail.

Data Analysis

Data analysis is an iterative process to understand data in a variety of aspects. It's also about cleaning data and preparing, organizing and using this data for modelling. The gathered data is reasonable. For instance, a regression done on the gathered data matches the calculated function.

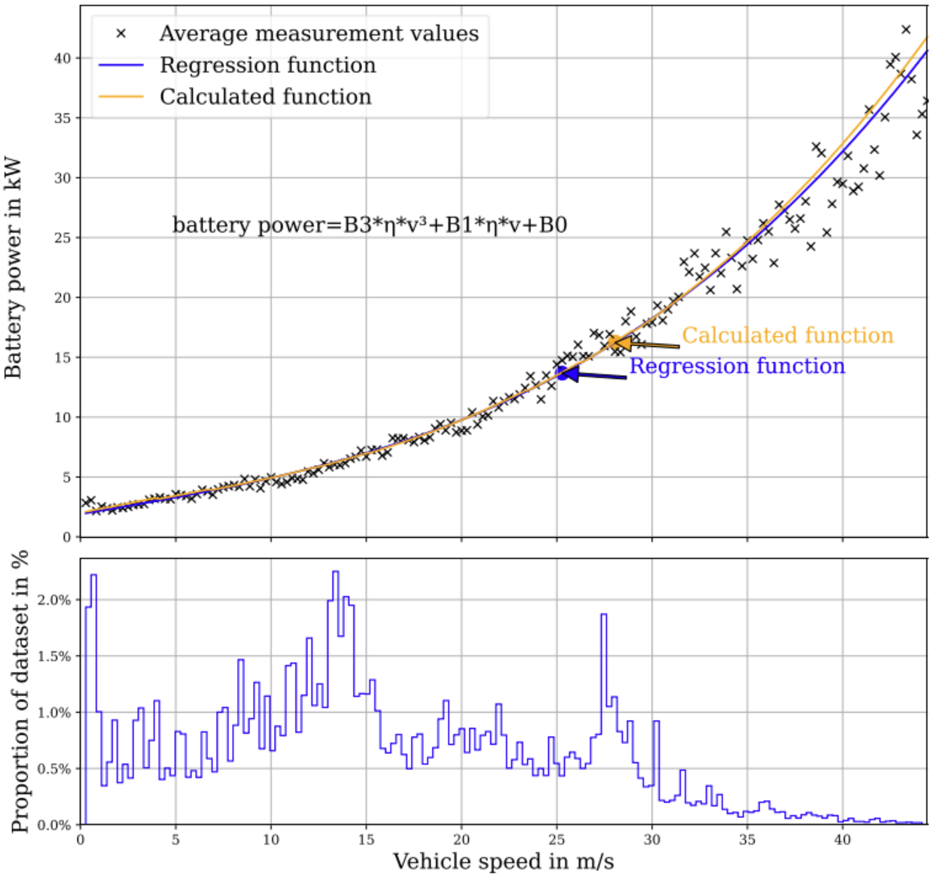

FIGURE 33: THE REGRESSION OF THE DATA FITS THE PHYSICAL EQUATION

The calculated function is a physics-based third order equation:

$$F_T = \underbrace{\frac{dv}{dt} * f * m}_{Accelerating} + \underbrace{m * g * \sin\alpha}_{Grade} + \underbrace{m * g * \cos\alpha * c_{rr}}_{Rolling} + \underbrace{\frac{\rho * A * c_w}{2} * v^2}_{Air}$$

FIGURE 34: THE PHYSICAL EQUATION IS A 3RD ORDER FUNCTION

Another approach is to calculate R^2 (Coefficient of Determination) to find relations inside the gathered data. This helps to find reasonable dependencies and also to find pseudo correlations. Furthermore, pseudo correlations should zero over all test drives. For instance, the “state of charge” decreases during the test drive. A portion of the test drives was performed in the evening when temperatures decrease. Thus, temperatures and state of charge seem to positively correlate. But this is only a pseudo correlation in those data. The situation is different in the morning when temperatures rise. In that case, there is a negative correlation. If test drives were done correctly, the effect over all test drives should be close to 0. And that is what we see.

Another aspect is to analyze data with respect to its completeness and behavioral integrity. For instance, a “state of charge” should decrease during the test drive except for charging phases.

Programming test scripts that run through each data row gives deep insight into how the data behaves and whether or not it can be trusted.

Besides, a playback of the measured data has been programmed. For instance, watching a playback of “battery power” versus “speed” gives a time-related intuition on the data’s expressivity. It’s not only about how data correlate in general, but also when they correlate better and when not. This gives an expectation of what might be achieved with an AI approach.

Next Steps:

The analysis procedure has to be compiled into concrete “learned lessons” to provide data gathering principles when the AI is utilized in other contexts than energy consumption estimation.

Furthermore, AI models are to be trained and to be evaluated.

4.3.2 Software concept description

4.3.2.1 Cloud-based services: data collection pipeline

In the following the data collection pipeline and a simplified data processing pipeline are presented. The “Optimizing Loop 1” and “Optimizing Loop 2” are the main subject of the next project year.

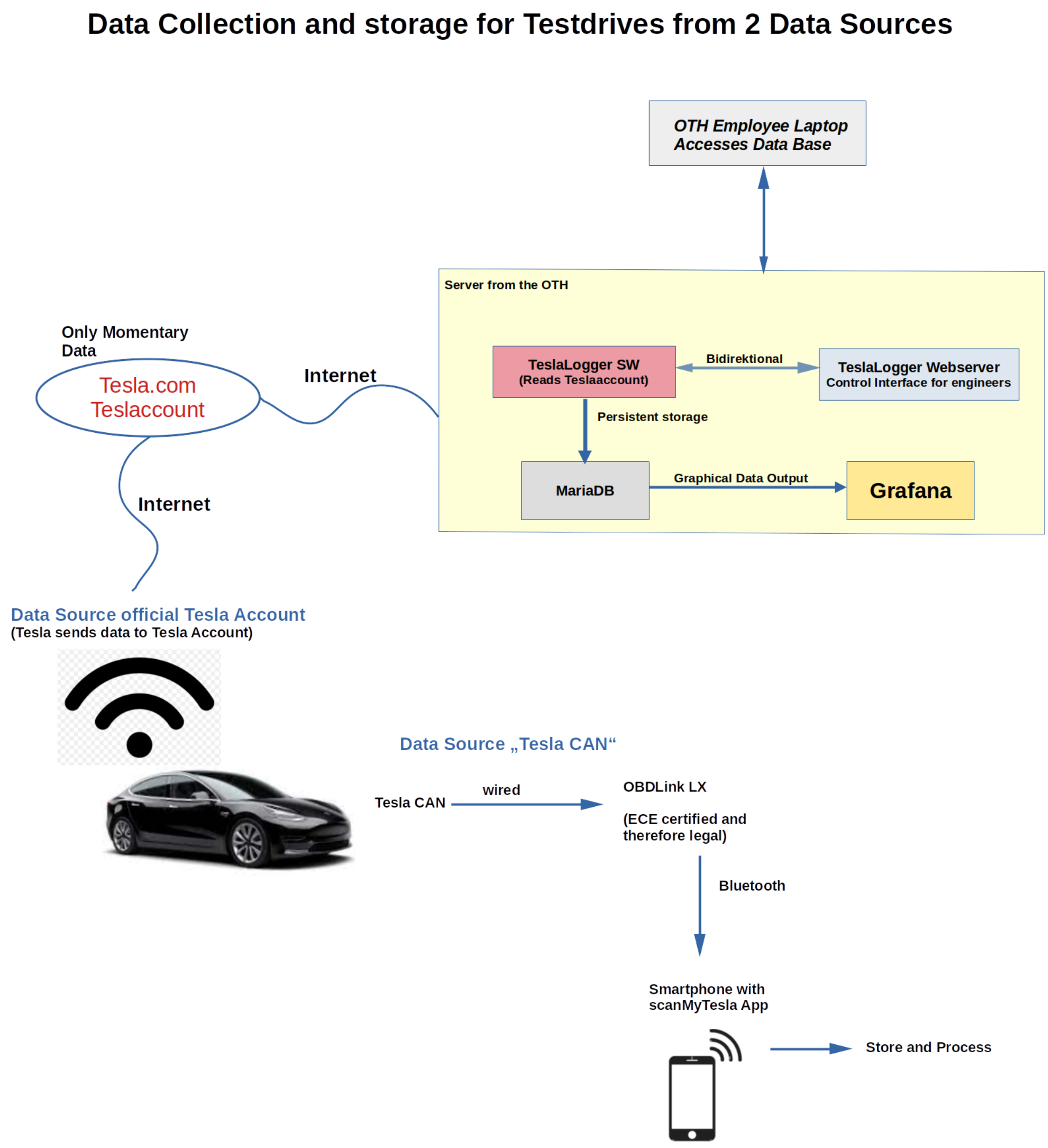

FIGURE 35: DATA COLLECTION PIPELINE

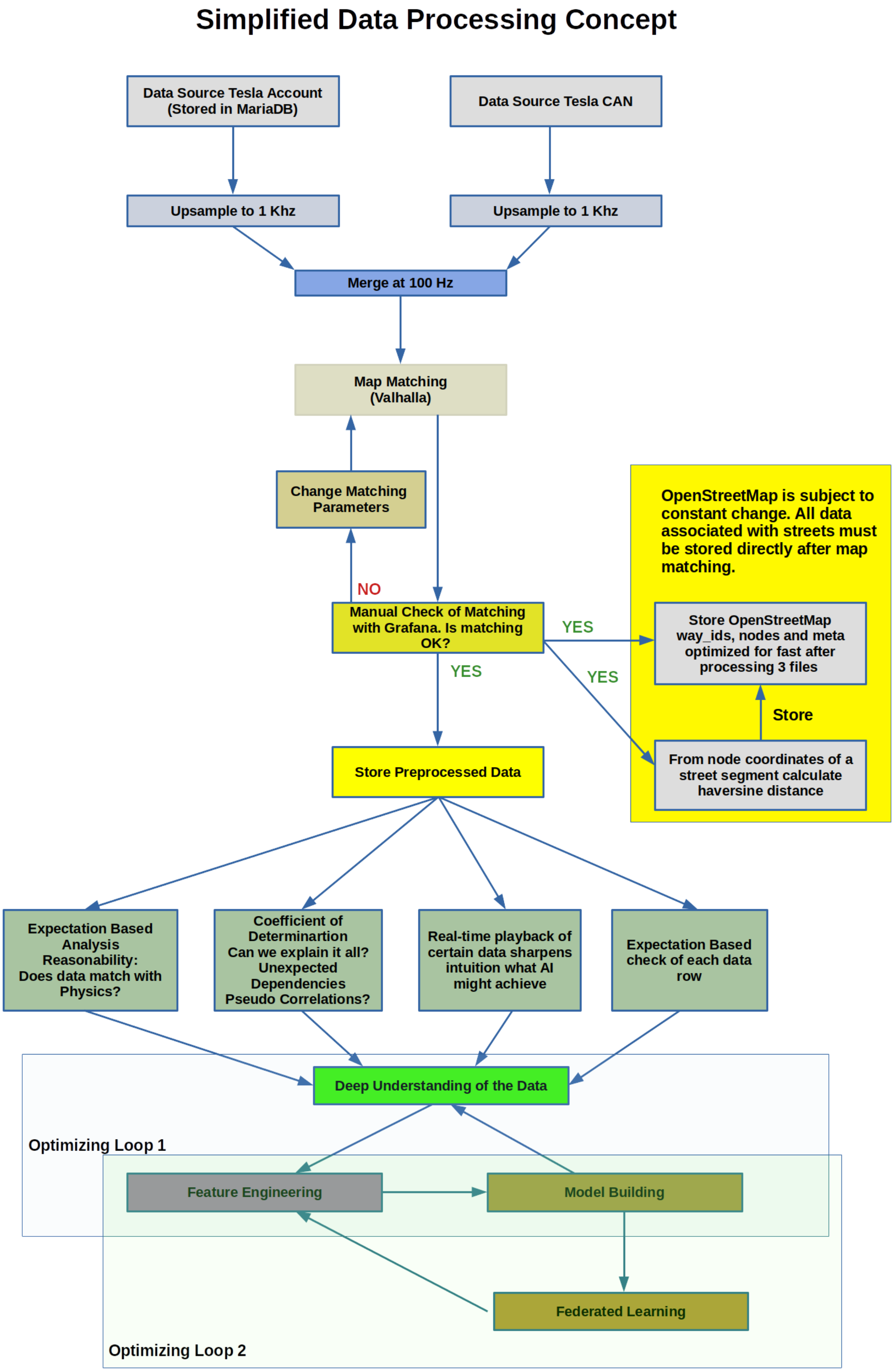

FIGURE 36: SIMPLIFIED DATA PROCESSING PIPELINE

4.3.3 Classical (non-AI) software functions

4.3.3.1 Comprehensive vehicle model simulation

The overall co-simulation of the sub-models is set up in AVL Model.CONNECT™, which is a model integration and co-simulation platform used to link system sub-models into a virtual vehicle. Sub-model of the refrigerant system is set up in Gamma Technologies' GT-Suite (simulation tool with capabilities and libraries aimed at a wide variety of applications and industries), while all other sub-models are set up in AVL CruiseM (a multi-disciplinary vehicle system simulation tool).

4.3.3.2 Inverter software

There are some differences between the demonstration laboratory powertrain (SC4) and a powertrain intended for integration into the vehicle (SC2) from the perspective of motor control and diagnostic software development. The main difference is the different structures of the inverters. Instead of the three-level inverter developed in SC4, the commonly used two-level inverter will be integrated into the vehicle (SC2). The motor used in the demonstrator vehicle will be three-phase in contrast to the dual three-phase motor used to develop the cognitive diagnostic system. Different position sensors also will be used. These differences are being considered in the process of designing the control and diagnosis system. Even though there are differences in the HW configuration of SC4 and SC2 powertrain, it is presumed to reuse most of the SC4 SW parts also in SC2.

To simplify the software integration, both the SC2 and SC4 use of the same control board. Current sensors used for both motors have different ranges; however, the location of the sensors and the frequency bandwidth will be similar. This allows using most of the prepared current monitoring algorithms with only partial modifications.

When using a two-level power inverter, a modification is required in the way PWM signals are generated. Two-level power inverters have more simple methods for PWM generation. On the other hand, fail-operation during a transistor fault cannot be achieved for this configuration. Fail-operational is also not achievable during motor faults because of the used single three-phase structure. Expected redundancy is only in the sensory part of the system. Other faults detected by the cognitive diagnostic system will lead to a shutdown of the powertrain.

4.3.3.3 Inverter CAN communication stack

The Controller Area Network (CAN) communication stack compatible with MBAG EV5.0 vehicle must be integrated into the SC2 inverter SW to demonstrate a working powertrain. CAN communication stack will be partially implemented using MATLAB/Simulink Vehicle Network Toolbox and low-level drivers for CAN will be implemented in C and Infineon Low-Level Drivers (iLLD) drivers. The use of MATLAB/Simulink for CAN communication stack implementation will result in good partitioning of the whole inverter SW, traceability, and easier testing of different submodules (communication, control, diagnostics, safety). CAN database files and CAN inverter control specification will be provided by MBAG with cooperation of ZF. Safety concepts of SC2 inverter integration will come from the cooperation between MBAG, ZF, AVL and BUT. This part will be different from the SC4 inverter SW as only measurement and calibration protocol will be implemented there.

4.3.3.4 CAN bus for measurement and calibration

The SC2 inverter will be also equipped with a separate CAN bus with the measurement and calibration protocol (XCP) implemented. Over this additional communication channel, it will be possible to get more precise results from the diagnostic algorithm and it will be possible to calibrate diagnostic and motor control algorithm parameters.

5 Conclusion

5.1 Relation to the state-of-the-art and progress beyond it

The demonstrator makes use of ad-hoc tailored components and solutions, as described in the previous chapters. In addition, are to be mentioned developments in controls and connectivity, such as diagnostic system (BUT) and fast inter-host communication (TTTAuto). On the control side, the diagnostic system which will be integrated into the car combines the diagnoses from two independent sources which helps to prevent highly unwanted fault positive events and goes beyond the state-of-the-art solutions. The implementation of the inverter control algorithms is on the state-of-the-art level. More profound solution is demonstrated in SC4, where two three phase windings are used in the motor and three level inverter controls the motor. The work related to CAN communication stack implementation and integration will enable to demonstrate functionality of new components in the car and does not go beyond the SOTA. On the connectivity side, the implementation of fast inter-host communication across multiple embedded targets in the modern automotive car architectures is on the state-of-the-art level. The implementation of fast data communication on inter-process communication using multiple zero-copy methods to ensure low-latency goes beyond the state-of-the-art when it targets complex multi-core / multi-host HPC platforms.

5.2 Impacts to other WPs, Tasks and SCs

The activities described in this document are connected with other WPs in the project. The following table summarizes the impact to other tasks and SCs.

Partner/Topic	Description
IISB/ BMS	The integration specification described above will have a direct impact on task 5.2 (WP 5), where the demonstration platform (foxBMS + Moxa) has to be integrated into the demonstration car
BUT	Based on the requirements prepared in WP1, this deliverable provides system level design and the architecture for the further development of algorithms which is being conducted in WP4. The analysis of differences between the work in SC4 and the work presented here, along with the selection of a unified control board, minimizes duplication of efforts. It should also simplify integration in WP5 which will be followed with testing in WP6.
TTTAUTO	The application specific requirements in SC2 will be taken into account in task 4.4 and further on during integration in WP5.

5.3 Contribution to demonstration

Partner/Topic	Description
BUT	BUT will contribute to the car demonstrator by providing algorithms and the software for the inverter. Control algorithms together with low level drivers for the peripherals will be provided. The cognitive diagnostic system mainly realized in SC4 will be conditioned to a single three phase motor and implemented in similar fashion as in the laboratory demonstrator. The inverter algorithms also contain the CAN communication stack with the CPC and enable seamless integration into the vehicle.
AVL	A comprehensive vehicle simulation model which includes the thermal management model is used to determine not only the powertrain energy consumption but also the energy spent on the thermal management of the vehicle. As thermal management plays an important role in the case of BEV performance, the model can be used to study the influence of particular route characteristics on the overall vehicle energy consumption, finally resulting in the achieved range. With the comprehensive vehicle model one can assess the impact of ambient conditions on the optimum route selection, which might be different for hot summer, cold winter or moderate ambient conditions. In the next project phases the model can be used to assess the impact of ambient conditions on the optimum route selection, which might be different for hot summer, cold winter or moderate ambient conditions.
ZF	800V inverter, with associated new classical and AI-based diagnostic and control strategies for electric drivetrains
IISB	AI-enhanced battery management system
MBAG	Electric Drivetrain
TTTAUTO	System design and architectural aspects concerning the V2C communication module

5.4 Other conclusions and lessons learned

No additional conclusions

List of figures

List of tables

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