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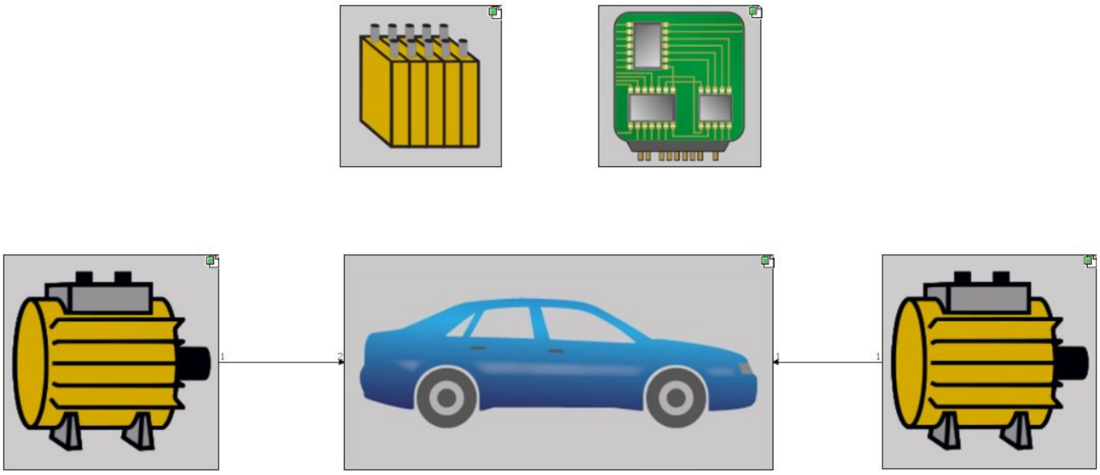

Implementation of vehicle model in GT-Suite for energy efficiency studies

Master’s thesis in Automotive Engineering

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Cover: Vehicle model and its components in the GT-Suite environment

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Abstract

Electric vehicles are comprised of heat-generating components. The operation of the battery, electric motors and their inverters, and the charging components produce heat output that needs to be managed. A battery electric vehicle's thermal management system is responsible for accumulating all the heat from these components, located at different places along with the vehicle, and transferring it to the ambient. In cold conditions, the purpose of the system is reversed, as it needs to maintain and produce the heat required to bring the components up to operational temperature. Thus, the system needs to be adaptable to internal and external parameters and choose the most efficient strategy to fulfil its predetermined goals.

To generate the response of the thermal models, a battery current, motor torque and speed input from a vehicle model are needed. The battery current determines the battery's heat generation during charging or discharging, while the motor's torque and speed the losses or efficiency during its operation. Since the component function and efficiency depends on their respective temperatures, there is a co-dependence or temperature loop between the input and the output of each component. Therefore, a model is created in GT-Suite with VSIM as a baseline and a source for the vehicle's configuration data. Initially, the vehicle model in GT-Suite needs to achieve similar results to the VSIM output. Some deviation is expected due to the different modelling and simulation procedures between the two software. Within Volvo Cars, GT-Suite contains all the thermal models for the electrical driveline components of the vehicle model. Therefore, the integration of the vehicle model to the CVTM satisfies the co-dependence mentioned above, and the complete vehicle simulation with a speed profile being the input can be completed under one software. This increases the accuracy of the simulation and the degrees of freedom regarding the parameter change, like the shutter position, which alters the aerodynamic coefficients during subsequent simulations. In addition to this, the data import and simulation setup and execution can be automated through Python, vastly shortening the workload.

The result of this work is a complete vehicle model, able to reproduce with high accuracy the performance and thermal parameters during a driving cycle and can be used for verification and validation purposes and control development and tuning.

Keywords: Complete vehicle thermal models, vehicle model, co-dependence, heat generation, temperature loop.

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Leonidas Theodorpoulos and Srikar Chithaluri, Gothenburg, June 2022

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BEV	Battery electric vehicle
BMS	Battery management system
CAE	Computer aided engineering
CVTM	Complete vehicle thermal model
EFAD	Electric front axle drive
ERAD	Electric rear axle drive
GT	GT Suite software
HVAC	Heating ventilation and air conditioning
HVCH	High voltage coolant heater
ICE	Internal combustion engine
Li-ion	Lithium-ion
OCV	Open circuit voltage
RC branches	Resistance-capacitance branches
SoC	State of charge
VCC	Volvo cars corporation
WLTC	Worldwide harmonised light vehicle test cycle

Nomenclature

Below is the nomenclature of parameters that have been used throughout this thesis.

Parameters

m_v	Mass of the vehicle
v	Vehicle speed
t	Time
g	Acceleration due to gravity
θ	Road grade
ρ	Density of air
A_f	Frontal area of the vehicle
c_r	Rolling resistance coefficient
R_0	Battery internal resistance
R_1	Thevenin equivalent circuit resistance
C_1	Thevenin equivalent circuit capacitance
F_{trac}	Traction force
F_{drag}	Drag force
F_{roll}	Rolling resistance force
F_{grad}	Gradient force(component of vehicle weight)

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1
Introduction

Striving for a carbon-free society, there is an on-going increase in the demand for battery electric vehicles(BEVs) since electric vehicles have an efficient driveline than internal combustion engine(ICE) vehicles. At the current technology level, the main drawback is the weight of the batteries storing the required energy. Batteries are made from Lithium-ion cells (Li-ion), whose manufacturing is very energy-intensive and produces high amounts of CO_2 [3]. Furthermore, there are concerns over the current battery recycling or re-use infrastructure, as unexploited batteries can become an environmental threat. Large, heavy batteries need to be integrated into the vehicles to secure a good driving range, which greatly increases their weight and reduces overall efficiency. Therefore, the vehicle's systems must operate efficiently to maximize the driving range per energy content in the battery.

An efficient thermal management system is a key factor in the performance of any electric vehicle. With the market leaning toward battery electric vehicles(BEVs), there is a need for an efficient and adaptive system. A BEV's cooling system is constituted by the electric drive and battery cooling circuits, the heating, ventilation and air conditioning circuit and the cooling package. Their coordinated and conditional operation is essential for the overall operating efficiency of the vehicle. The driving range is highly dependent on the operating temperature of the individual electrical components, mainly the battery. Thus, the priority of the control strategy is to preserve that operational temperature, which can impose a heavy energy load. The importance of optimal controls is evident, as they adapt the varying parameters to offer the required cooling or heating with the least energy consumption.

Therefore it is evident that, what constitutes BEVs as a sustainable transport option, is a conglomeration of factors. Firstly, a transformation in the manufacturing of the batteries to a carbon-free process is essential since most of the emissions related to BEVs are attributed to it. Then, the operational efficiency of the vehicle's systems to ensure the optimal usage of the available energy, maximizing the driving range per battery size. Lastly, after the life cycle of the battery, a procedure for recycling or re-using the old batteries will eventually minimize the environmental impact of the BEVs usage as a transport option[4].

1.1 Background

During the product's research and development phase, CAE software plays a vital role in the design process. High-accuracy simulation results offer the opportunity for optimal and detailed controls and, thus, a more efficient thermal management system. To achieve that, the inputs must adequately represent the driving conditions and must be able to test the system's limitations. A complete vehicle model can predict the behavior of the driveline and secure the data that serve as an input for the thermal model of the vehicle's components. The fusion of the two models provides a holistic and more accurate overview of the response of the complete system under different temperatures and loads.

The vehicle model will be created in GT-Suite, which is a 1-D simulation software, and includes the complete driveline, comprised of the electric motors, battery, inverters, joints and shafts, the fixed-gear differential, the axles, and a clutch, the wheels and tires and the chassis. The driveline controls, i.e., torque distribution strategy and the battery management system, are required to achieve the realistic model behavior. The test cycles used will represent highway and city driving and high load performance driving, with various ambient temperatures, to study the system's response, namely the battery current, as well as the motor torque and speed response. The in-house VSIM[1] environment within Simulink will form the basis of the modeling strategy that will be followed.

The integrated model will create a temperature dependence between the driveline components of the vehicle model, and their respective thermal models. The torque request from the motors will impose a current load on the battery, causing a temperature rise in the electrical components. The heat will be dissipated to the coolant, looping throughout the thermal management system. However, the temperature of the battery also defines its performance. Therefore, there is a co-dependence between the requested load and the system's temperature, which eventually creates the temperature loop.

1.2 Aim

At Volvo Cars Corporation(VCC), a complete vehicle thermal model(CVTM)[2] has been developed using GT-Suite software to simulate the thermal management system, climate system, battery and electric drive cooling. Input parameters like the motor speed and torque are fed into the model to run these simulations. These input parameters are obtained from a simulation environment called VSIM, a Matlab-Simulink-based software developed in-house at VCC to run complete vehicle simulations. Since the vehicle configuration data are stored in VSIM, the automation of the data transfer process, from the Simulink environment to GT-Suite and the simulation setup, is conducted through a Python script.This master thesis work aims to create a vehicle model based on VSIM models using GT-Suite software and integrate it with the existing CVTM model to study its advantages and disadvantages.

To study the influence of vehicle parameters on the energy response of the system through an automated, Python-based simulation procedure.

1.3 Limitations

Various departments within VCC use a platform like CVTM. Furthermore, each team is responsible for specific models. Thus, any changes made during the thesis work affect them as well. Therefore the implementation requires collaboration with various stakeholders, and the method needs to be commonly agreed upon, which poses limitations to the progress and practice of the work. Failure of implementation will not affect the other teams, as the current workflow using VSIM and GT-Suite in tandem is already defined and fully functional.

1.4 Problem statement

VSIM models have detailed vehicle models but do not contain extensive thermal models, and similarly, the CVTM in GT-Suite lacks the vehicle model. So to run the CVTM simulation, the VSIM model is to be run before obtaining the inputs to the CVTM, hence increasing the workload. This has given rise to a need to integrate the vehicle model with CVTM and automate the data transfer and simulation procedure with Python to simplify the simulation process and reduce the time needed. Eventually, the complete model will be used to perform energy efficiency studies under various driving conditions.

1.5 Outline

This master's thesis report is separated into the following chapters. Chapter 1 contains the background and the scope of the project. In chapter 2, the necessary theoretical knowledge that forms the method's basis is explained. Moving to chapter 3, the modeling methodology and the method's motivation are thoroughly explained. In chapter 4, the project results, namely comparisons between the GT-Suite and VSIM-based vehicle model and the output comparison of the CVTM when using its respective inputs. In the final chapter of this thesis project, the completed work will be evaluated concerning the results and the concluding outcomes.

2
Theory

The modelling and implementation of the model to CVTM is an iterative process that consists of multiple milestones, as shown below.

1. Creating a vehicle model in GT Suite
2. Vehicle sizing based on VSIM configurations
3. Integrate vehicle model to CVTM
4. Automate the data transfer and simulation procedure with Python
5. Conduct energy efficiency studies

The created vehicle model is based on the already existing vehicle model implemented in VSIM. It includes all the driveline components and its controls, the battery, and the driver model that defines the vehicle driving requirements. It is crucial to identify the modelling depth, as the project's goal is to simulate the vehicle's behavior over a driving cycle, which requires only longitudinal vehicle modelling. Since VSIM and GT-Suite are different environments with different requirements, it is critical to ensure the format of the data taken from VSIM is compatible with GT-Suite inputs.

The integration with the CVTM needs to be non-intrusive, meaning that the existing components should not be changed. This will form the basis of the Python automation, as the script will quickly alter the model parameters, set up the simulation cases, and run different vehicle configurations.

2.1 Modelling environment

The modelling environment is the interface, where all components with mathematical models in the background exist. Those may consist of different levels of modelling, depending on the complexity of the element. An element or object to be functional requires specific inputs and boundary conditions. After the conduction of the object's mathematical procedures, it produces an output. Combining objects whose output can be used as an input results in a complete system model.

2.1.1 GT-Suite/CVTM

GT-Suite is a tool for physical modelling and simulations. It consists of various libraries containing modelled components and environments. Utilization of this software reduces the development time and costs, as it can be used to depict the response of a modelled system accurately and for its virtual verification. This software is the basis of the complete vehicle thermal model(CVTM), as shown in Fig.

2.1. The model handles a 1-D representation of the thermal behaviour of the vehicle. It includes the battery and motor cooling circuits, the heating-ventilation and air-conditioning (HVAC), and the refrigerant circuits. These consist of a combination of pipes, pumps and radiators, with their supervisory controls modulating their operation according to the cooling demands. The general principle is that the produced heat can be redistributed to components that require heating or soaked to the ambient to perform cooling.

The vehicle model that will be integrated into the CVTM will act as a bridge between VSIM and GT-Suite environment, as it utilizes the vehicle configuration data from the VSIM environment to generate the input for the CVTM, effectively eliminating the need to transfer the output of VSIM to GT-Suite to conduct a complete vehicle simulation.

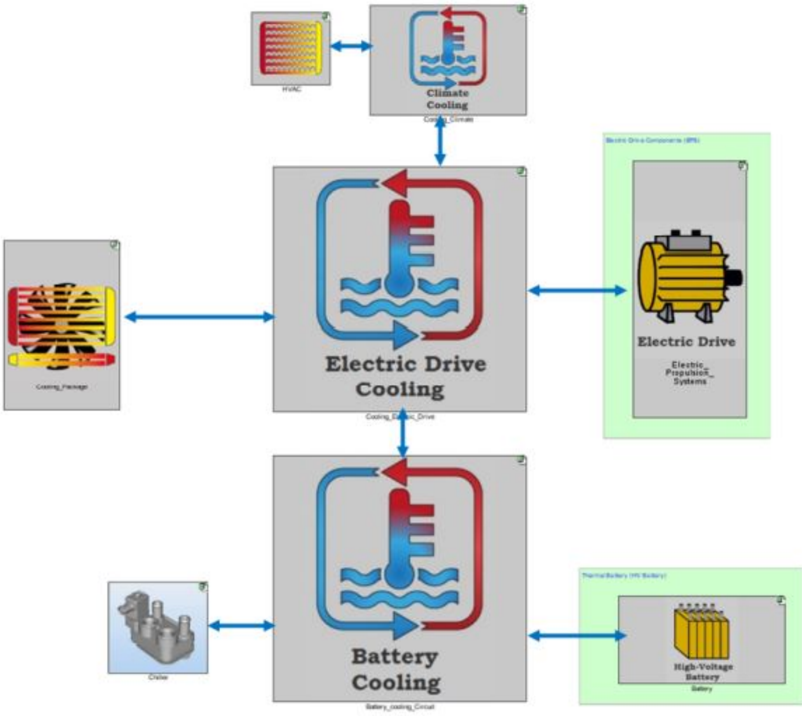

Figure 2.1: GT-Suite Environment

2.1.2 VSIM

VSIM is a Volvo cars in-house Simulink-based software. It consists of various components that depict the behavior of the vehicle. The interface is split into three main counterparts: the driver model, the environment, and the vehicle. In turn, the vehicle counterpart is divided into plants and controllers. The plants include physical modelling of the driveline components such as the electric motors, wheels, tires, brakes, axles and the battery. The controllers have the operating logic of the components mentioned above and their operational limitations. The software is used to reproduce the energy flow and transformation in the vehicle, which is essential for its virtual verification. Having a speed profile, also known as the driving cycle as an input, the model produces the response of each of the components. The output is used to analyze the behaviour of the components, the vehicle's energy efficiency, performance, and the effectiveness of the controls and provide input to the CVTM.

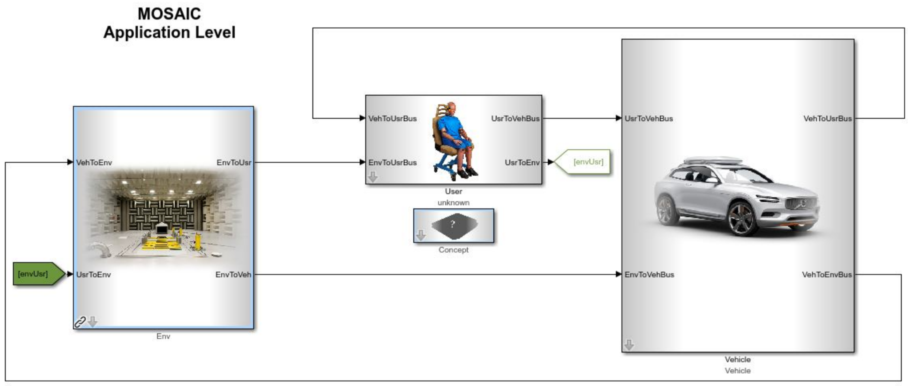

Figure 2.2: VSIM environment[1]

2.2 System model

This project aims to create a vehicle model in GT-Suite and implement it in the complete vehicle thermal models to provide the boundary conditions for the component thermal models. Each of the two systems is modelled using different objects that need to be connected for the complete system to function.

Driving cycle A driving cycle is a speed profile versus time that acts as an input to a model. Based on that, the motoring or braking request is determined, which defines the system's response. The various driving cycles currently used in the industry, ranging from certification driving cycles like the US06 and WLTC and high-demand driving cycles, which consist of steep accelerations and decelerations cycles, to test the limits of the systems. An example of a US06 cycle is shown in Fig.2.3.

2.2.1 Vehicle model

The vehicle model encompasses the vehicle body and its specifications, the driver model that produces the motoring of braking request to the motors, the battery that provides the power and the powertrain controls that distribute motoring of braking request across the axles.

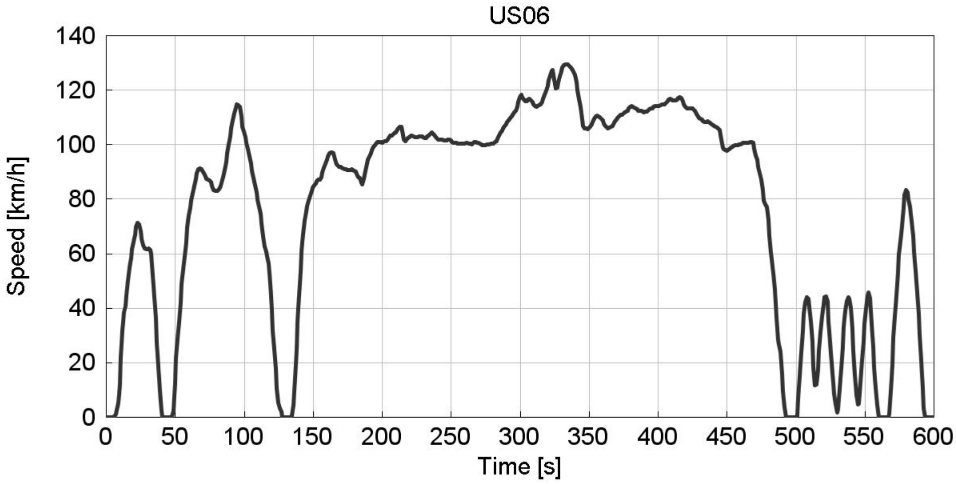

Figure 2.3: US06 driving cycle[1]

2.2.1.1 Vehicle body

The vehicle body includes the chassis, passenger compartment, control units, driveline, joints and shafts, axles, clutches, differentials, wheels, brakes and tyres. All the vehicle body components are responsible for determining the vehicle motion and the normal loads on the axles. The torque demand at the wheels depends on the vehicle's weight, passenger and cargo mass, tire rolling resistance, aerodynamic drag, road grade, and curvature. Other components like the brakes, tires, differentials, shafts and joints, and the losses in power transmission influence vehicles' forward motion.

- **Differentials**
  Generally, a conventional gearbox is not implemented in electric vehicles since the electric motors can satisfy the torque demands. Hence, the efficiency of the differential plays an important role. It depends on torque, speed and operating temperature. The following Fig.2.4 shows the efficiency map of a differential with speed and torque as inputs at a specific temperature.
- **Joints**
  The universal joints are used to connect the differential and the wheels. However, the universal joints are placed at a certain angle since the differential, and the wheels are at different levels, and these angles introduce losses to the drivetrain.
- **Tires**
  Various aspects of the tire like the width, aspect ratio, diameter, rolling resistance factors and traction models are defined.
- **Brakes**
  The friction brakes on the vehicle body operate based on the conditions received from the brake controller if friction brakes have to be engaged or the motor regeneration is sufficient to satisfy the brake demand. Friction brakes are operated on brake pedal actuation, which is determined based on the brake torque demand at the wheels.

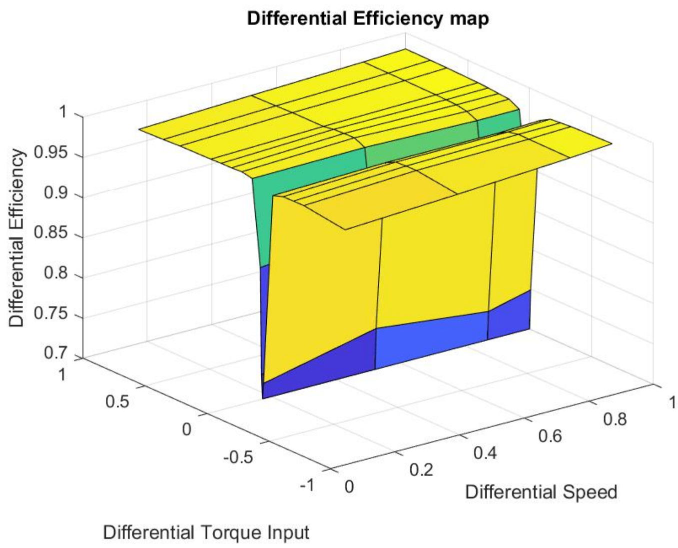

Figure 2.4: Differential efficiency map[1]

2.2.1.2 Electric machine

The electric machine provides the required torque to the wheels to propel the vehicle by converting electrical energy to mechanical energy. The vehicle's battery pack provides this energy. However, its function can also be reversed, as it can brake the vehicle by providing negative torque and converting its kinetic energy to useful electrical energy to the battery. This function is called regenerative braking. The type of the machine defines its operational characteristics and limitations. These limitations depend on the component temperatures, motor speed, torque and voltage.

Starting with the maximum and minimum torque constraints, the machine can provide maximum torque at low motor speeds, with the power increasing linearly until the base speed. At this speed, a control technique called field-weakening takes place, which limits the increase of power, and keeps it at a constant level [7]. This results in a hyperbolic decrease of torque with increasing motor speed. This allows motoring at higher vehicle speeds. The motor's torque output is heavily dependent on its temperature and voltage. The maximum available torque reduces as the temperature rises, while a voltage drop results in a lower torque limit at higher speeds. This constitutes the connection of the vehicle model to the thermal model vital in achieving high simulation accuracy. The characteristic electric motor torque curve is displayed in Fig. 2.5, and it shows how each parameter, temperature and voltage, affect the constraints of the motor.

In general, the major advantage of electric motors is their high efficiency. This is dependent on the combination of torque and speed at which it operates. The losses in an electric motor are the sum of the losses of its components, which depend on their temperature, motor voltage, and input torque and speed. These losses are the copper, teeth, yoke, rotor and air friction losses. Fig.2.6 shows the magnitude of the component losses, with the copper losses having the most significant effect.

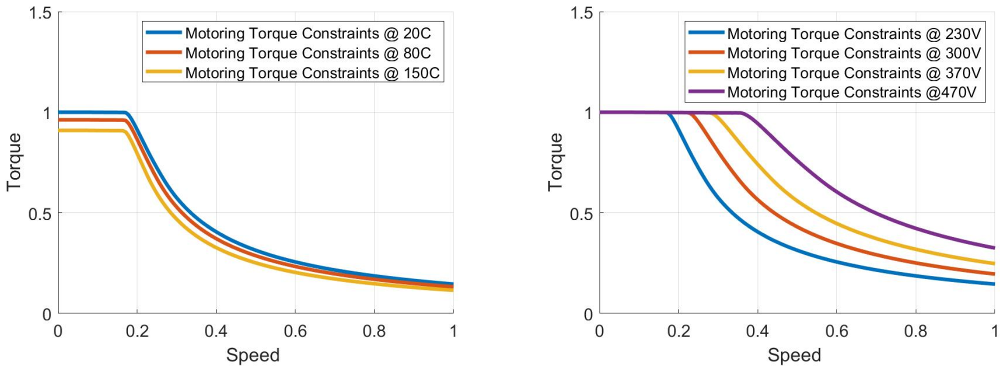

Figure 2.5: Electric machine constraints on temperature and voltage (normalized axes) [1]

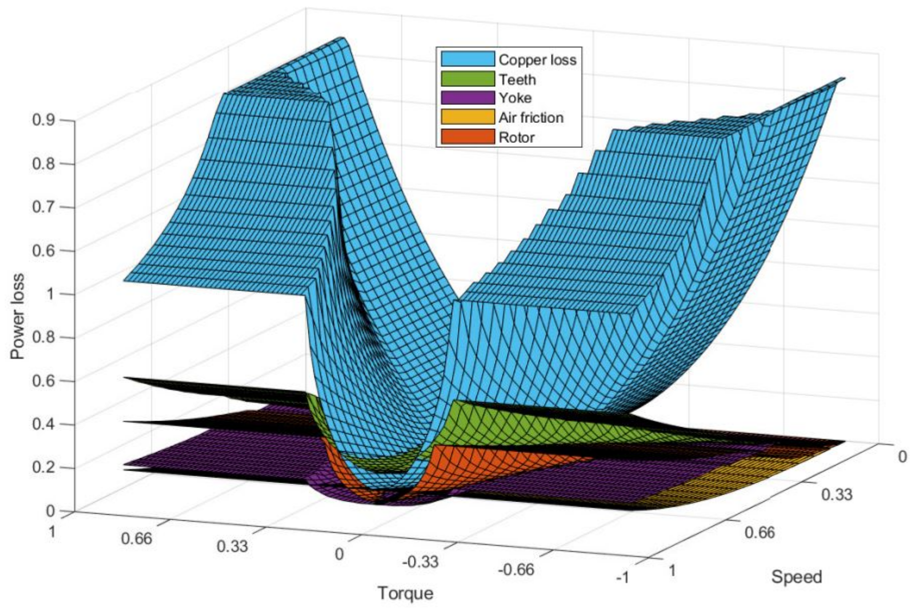

Figure 2.6: Electric motor component losses [6]

Similar to all electrical components, these losses are dependent on temperature and voltage. The general trend is that increasing temperature and voltage leads to increased losses. The combined effects of all the parameters above lead to an efficiency map and are highly dependent on the operating conditions. Such maps for operating temperatures of 20^0C and 150^0C are shown in Fig.2.7. As expected, a higher temperature operation leads to reduced motor efficiency [6].

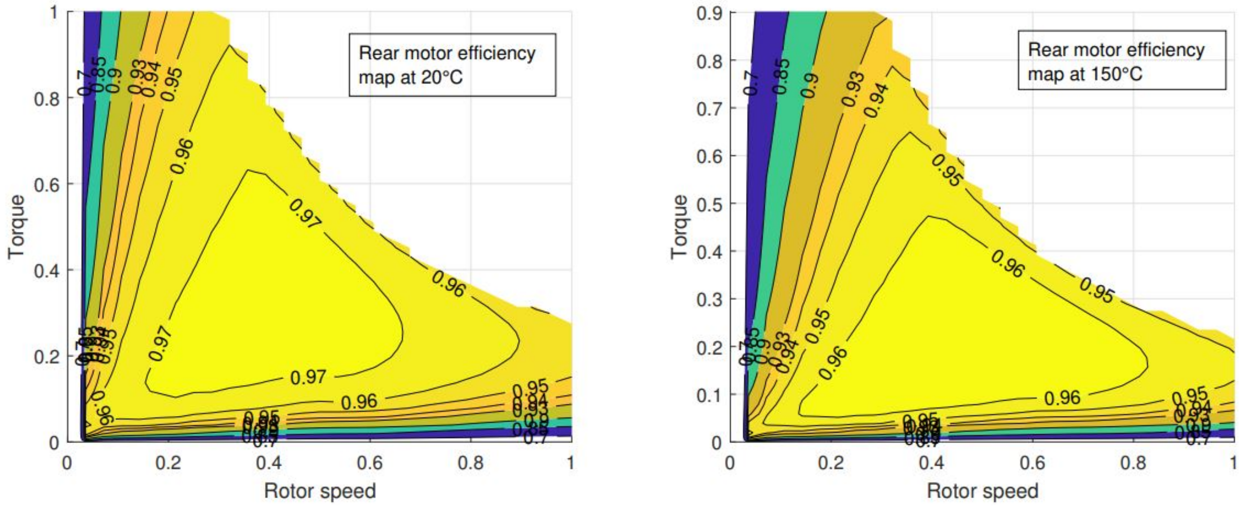

Figure 2.7: Electric machine efficiency map [6]

2.2.1.3 Battery pack

A battery pack is the energy storage component in an electric vehicle, similar to the fuel tank in internal combustion engine (ICE) vehicles. The battery pack converts chemical energy stored into electricity based on the torque demand from the electric motors. Battery packs in BEVs are generally lithium cells similar to mobile phone batteries. But instead, they are arranged in modules, where each module consists of a certain number of cells in series and parallel. Modular batteries have several advantages like structural integrity, a chance for laying better cooling or heating circuits inside the battery pack, and ease of replacement cells in the future if there is any damage to the cells [9]. In Fig.2.8, the layout of an electric vehicle is presented, with the battery pack being placed between the axles and as low as possible, to achieve an optimal weight distribution.

Figure 2.8: Battery pack [5]

Battery parameters: Batteries are characterized by various parameters that define their operational attributes.

- **Battery state of charge(SoC):**
  State of charge(SoC) gives the information about the capacity of battery available, usually denoted in percentage or fraction. A battery is said to be fully charged if the SoC is 100% [10], but for the protection of the battery, the real SoC usually does not exceed 90%.
- **Cell capacity:**
  Cell capacity is defined as the amount of energy that the cell can provide for a certain period of time, and it is measured in Ampere-hr(Ah) [11].
- **C-rating:**
  C-Rate of a cell or battery is defined as the rate at which it can be charged or discharged. For example if the cell capacity is 2Ah and has a C-rating 1 it takes 60 minutes to charge or discharge the cell.
- **Open circuit voltage(OCV):**
  An OCV is defined as the voltage measured across the two terminals of the battery when not connected to any external load and this voltage is also referred to as Thevenin voltage [12].
- **Thevenin equivalent circuit:**
  Any battery can be modeled similar to Thevenin equivalent circuit, having an OCV and an RC branch for electrical dynamics. The following Fig.2.9 shows the Thevenin equivalent circuit of the battery. The Thevenin RC branch is used to reproduce the dynamic characteristics of the battery, with the changes in battery temperature and SoC while charging and discharging [14].

2.2.1.4 Battery management system

The battery management system (BMS) is one of the integral components of an electric vehicle architecture. To ensure safe operation, it computes the upper and lower limits of the voltage and current that the battery receives during charging and discharging. Limits computation is based on various parameters (Soc, temperatures, maximum and minimum current, dynamic voltage drop and current fluctuations) to define the limits and prioritize them since many requirements can overlap. The implementation of the BMS extends the capabilities of the simulation, as at each instant, the acceptable limits are calculated dynamically and applied [8].

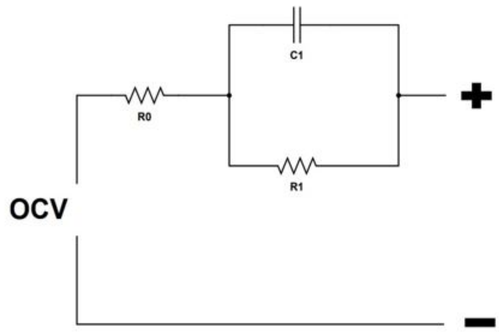

Figure 2.9: Thevenin equivalent circuit with a single RC branches

2.2.1.5 Powertrain controls

As discussed in the section 2.2.1.1 the traction force required to propel the vehicle forward depends on the weight of the car, road conditions and other external factors. In general, any basic powertrain controller uses the driving cycle as input and tries to calculate the traction force required according to the following relation,

$$F_{trac} = F_{inertia} + F_{drag} + F_{roll} + F_{grad} \tag{2.1}$$

The inertia resistance is proportional to the vehicle's weight and the acceleration of the vehicle at each instant and is given by the following relation,

$$F_{inertia} = m_v * \frac{dv}{dt} \tag{2.2}$$

The aerodynamic drag force is proportional to the area of the object and increases with speed squared. The drag force becomes significantly more once the speed crosses $60\frac{km}{h}$ hence giving rise to higher traction demand. The drag force can be calculated using the following relation,

$$F_{drag} = \frac{1}{2}\rho C_d A_f v^2 \tag{2.3}$$

The rolling resistance force is a product of the rolling resistance coefficient(c_r) and the weight of the vehicle and the following equation.

$$F_{roll} = m_v c_r g cos(\theta) \tag{2.4}$$

When the vehicle is on an incline, it has to overcome part of its weight, demanding more traction force to move the vehicle forward. And when going down the incline, this component of its weight aids the vehicle in moving forward, reducing the traction force required.

$$F_{grad} = m_v g sin(\theta) \tag{2.5}$$

Driver model: The driver model in GT-Suite takes the driving cycle as input. Since it has the velocity data every second, the driver model looks for the velocity in the successive second and calculates the acceleration($\frac{dv}{dt}$) in that time step. Next, the driver model calculates the traction force required using the above relations. Furthermore, once the traction force needed is calculated, the torque at the wheels is calculated. Finally, the torque is split to the front and rear motor according to the control discussed in the methodology section.

2.2.2 Thermal model

A BEVs thermal management system is complex and multi-functional. Its purpose is to keep all the components within the operational temperature range and provide climate comfort in the cabin. Therefore, all subsystems are connected, with the controls ensuring the most efficient energy transfer strategies. A general overview of the thermal model is shown in Fig.2.10.

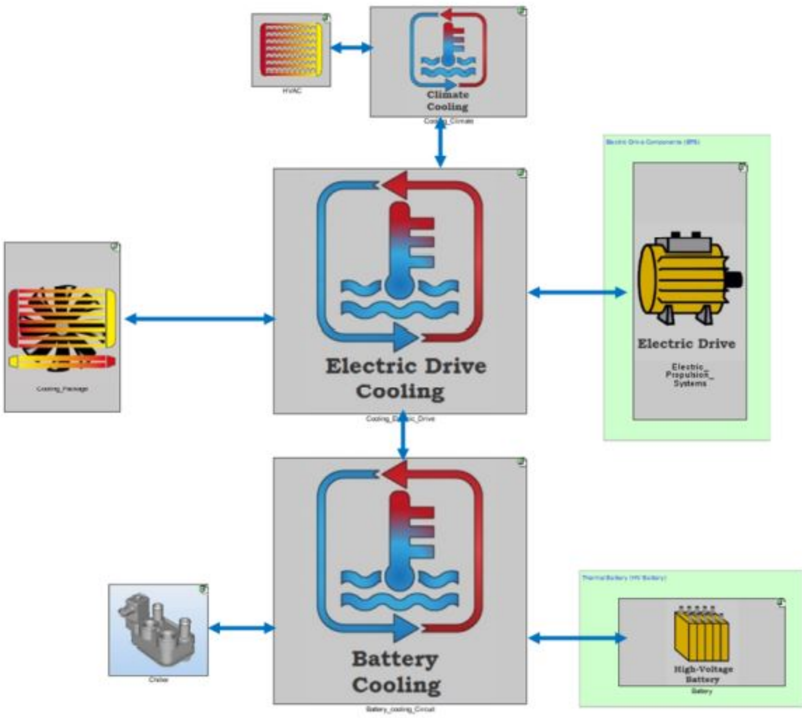

Figure 2.10: Thermal model

The primary heat generators in the system are the battery, electric motors and inverters. The battery circuit includes an individual cell circuit cooling running the whole battery length while the electric motor is cooled through the cooling jacket. This is a surface that surrounds the motor, with coolant circulating in it, where is motor heat is soaked. A typical cooling circuit consists of pipes, radiators and pumps.

Air cooled circuit: Air-cooled circuits consist of pipes connecting the coolant passing through the electrical components to the radiator, where the accumulated heat is dissipated. The coolant is circulated through the system by an electric pump. The circuit is sized according to the thermal load and the number of heat-generating components connected to the circuit [13]. The principal architecture of an air-cooled circuit is presented in Fig.2.11.

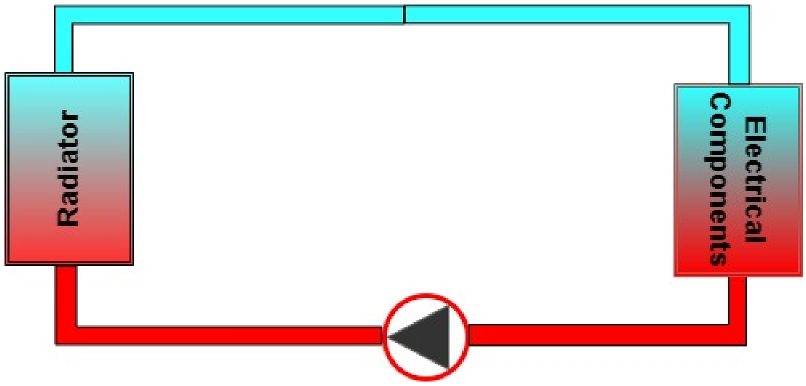

Figure 2.11: Air cooled circuit

Refrigerant circuit: The refrigerant circuit differs from a typical cooling circuit. It consists of a compressor, a condenser and an evaporator. It circulates the refrigerant, whose boiling temperature is lower than water's, ranging from 5 to $10^{o}C$. That adds essential capabilities to the circuit since the refrigerant can either cool a component or heat it by reversing the flow. This reversal is managed by the circuit's compressor, a high-energy consuming part in the circuit. First, the compressor raises the pressure of the refrigerant, thus its temperature, and it passes through the condenser, where it rejects heat. The aforementioned function can be used for heating the battery. Then the saturated fluid passes through the expansion valve, where the temperature and pressure drop. Afterward, it passes through the evaporator, where it absorbs heat. That function can assist the component cooling. The general principle of the refrigerant circuit is shown in Fig.2.12. The refrigerant circuit is also connected to the HVAC system, which defines the cabin conditions [13].

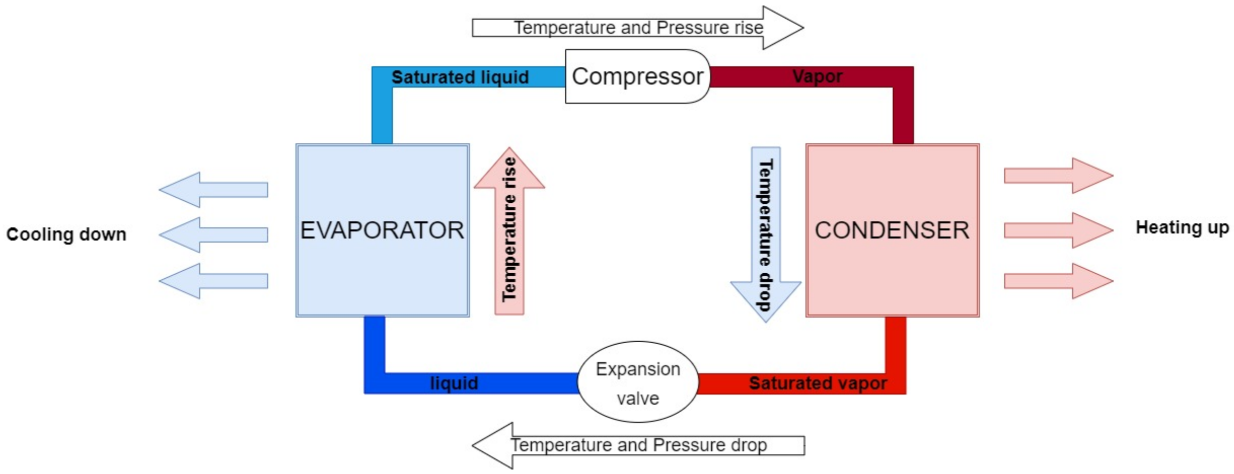

Figure 2.12: Refrigerant circuit

The individual circuits are connected with multiple multi-valve and pump components, whose regulation is determined by the systems controls. Depending on the thermal load, the operating conditions or the targeted function of the vehicle, the demands are categorized and the most important ones prioritized. A typical example is starting driving in cold conditions, where the battery must heat up as fast as possible to reach optimal operating conditions. Smart control of the valves leads to the most efficient strategy, balancing energy efficiency, passenger comfort and performance.

2.2.3 CVTM and vehicle model integration

The functionality of the thermal model and the vehicle model are codependent. For the vehicle model to be accurate, the component temperatures must be accurate. Similarly, the thermal model requires the correct battery current, electric motor torque and speed input for the component heat generation. That creates a temperature loop that enables the correct response of the system to a driving cycle input. This loop is depicted in Fig.2.13.

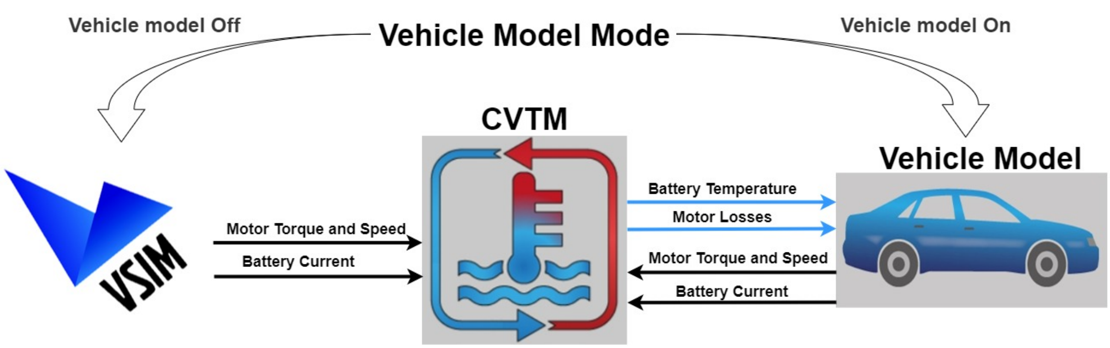

Figure 2.13: Output loop

3
Methods

To create a vehicle model that produces a response to a driving cycle input, the components mentioned in Chapter 2 need to be combined correctly. First, the driver model calculates the torque request to the axle, distributed and sent to the electric motors. Next, the battery provides the necessary power to produce the torque demanded. That, in turn, calculates the current requirement based on the specified battery configuration. Finally, the SoC is calculated based on the remaining battery energy. To create a complete functional model, the created vehicle model in GT-Suite must be integrated into CVTM in a non-intrusive manner, meaning that the thermal models should not be altered. It also needs to be modular, meaning that the switch between VSIM input and vehicle model input should be possible between subsequent simulations.

The vehicle model receives the driving cycle input and produces the battery current and electric motor torques and speeds, used as an input to CVTM. That provides the liberty to run subsequent simulations while altering the vehicle parameters to study the response of the thermal models. Furthermore, since electric vehicles are susceptible to ambient conditions, limited heating-up cases in low temperatures and cooling down in high temperatures can be considered after the integration. Thus, the test cases studied with the integrated model are described below.

Driving cycles at different ambient conditions: The driving cycle's speed profiles are designed to depict certain driving conditions over time. The US06 and WLTP cycles are used for certification and represent everyday driving. The city cycle shows a steady-state driving section in the first half, with a high-demand transient section following. Each of these imposes a different thermal load that the thermal management system needs to control. Combining those cycles with other ambient conditions creates a pragmatic and holistic overview of the various combinations of requirements of thermal management system requirements, which can be used to verify models and system development.

Altering vehicle parameters The thermal management system controls can alter the grille shutter position based on the cooling demand. That, in turn, changes the aerodynamic coefficient of the vehicle, which has an impact on the torque demand. Therefore, it is tested for different drag coefficients to study the component thermal response. In addition to this, sensitivity studies will be conducted to investigate how altering various vehicle parameters can influence the thermal load.

In the following sections, the modelling procedure to create the vehicle model, the integration to the CVTM, and the python automation procedure will be presented.

3.1 Vehicle modelling

The vehicle model consists of the vehicle body, including all the vehicle parameters, the two electric motors driving the axles, the battery pack that provides power to the motor, the auxiliary systems, and the controls that regulate the power distribution and braking. An overview of the model is presented in Fig.3.1, using the GT-Suite internal tutorials as a guideline [16].

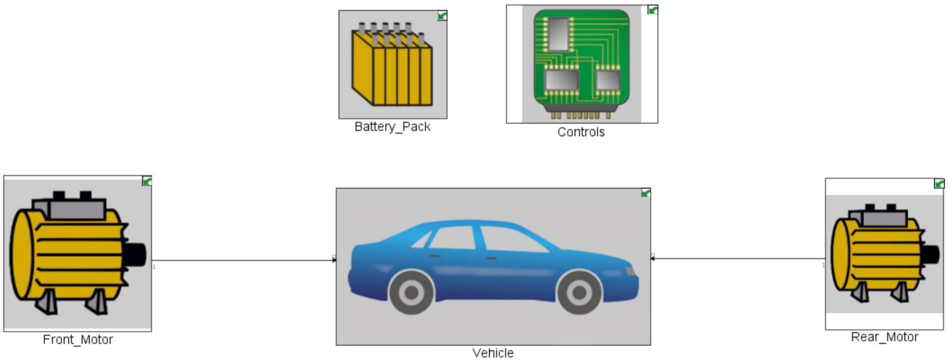

Figure 3.1: GT-Suite vehicle model

3.1.1 Vehicle component

The vehicle model developed in GT-Suite software is modelled to replicate the existing model in VSIM. For the initial setup and simulations, a basic all-wheel-drive vehicle with two traction motors is chosen from the available vehicle configurations in VSIM.
The vehicle component is where all the main inputs of the vehicle are given. Various attributes like the vehicle mass, initial vehicle speed, the vehicle's frontal area, drag coefficient, and vehicle geometry are defined. Besides the vehicle parameters, other components like the motors, battery, differentials, universal joints, axles, brakes and tires are connected. The purpose of these components is explained in Table.3.1.

Fig.3.2 shows how all the components are placed and connected. The motors are connected to the differentials, and the power splits and transfers to the universal joints to the tires with the help of driveshafts. An optional clutch can be implemented for the all-wheel-drive configurations, which disengages the rear motor when it is not in use. Finally, tires and brakes are connected to the axles that contact the road.

Component	Purpose
Vehicle	All vehicle parameters mentioned above are defined
Differential	Splits the power and allow tires to rotate at different speeds
Universal Joint	Power transfer between shafts at different heights
Drive Shaft	Acts as a connection between two universal joints
Clutch	Optional clutch to disengage the rear motor
Axle	To support the wheels and brakes
Brake	To engage in braking action
Tire	Defines traction and rolling resistance characteristics
Environment	Defines ambient conditions
Road	Defines road characteristics

Table 3.1: Components in vehicle chassis

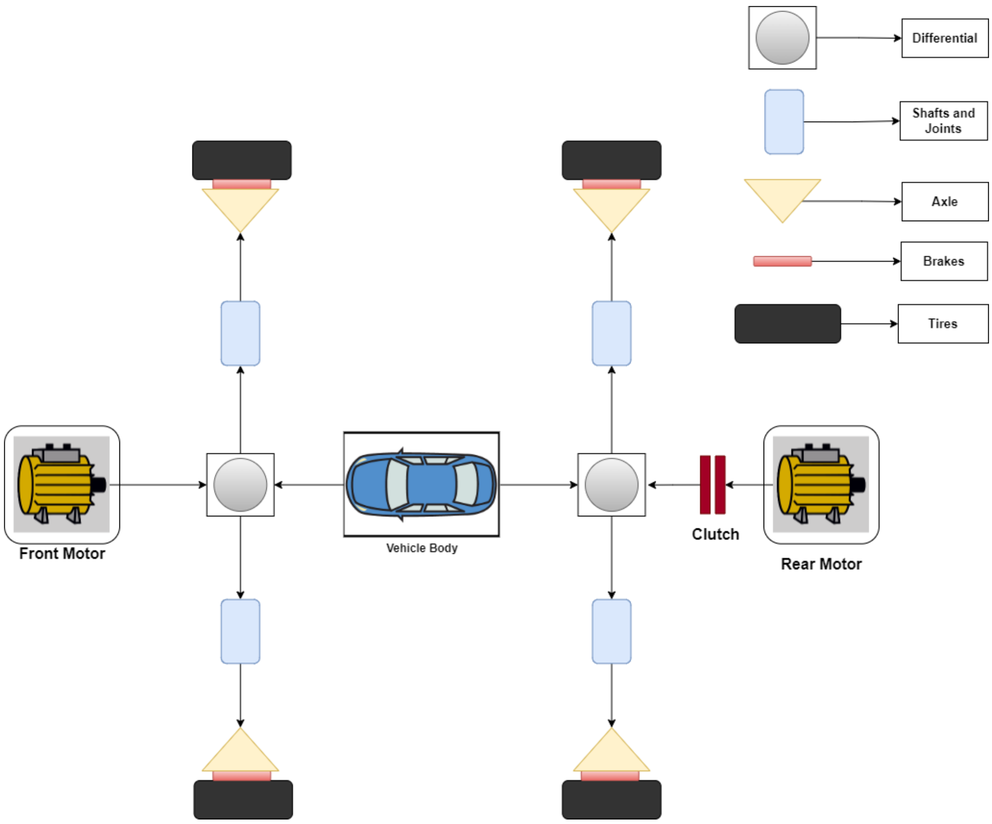

Figure 3.2: All wheel drive vehicle chassis component

3.1.2 Battery

The battery model consists of two main components: the battery, the energy storage, and the battery power limiter that ensures it operates within the allowable limits.

3.1.2.1 Battery

All the attributes in the battery model, like the state of charge (SoC), cell capacity, and the number of cells in series and parallel, are defined. Also, the charge and

discharge maps of circuit parameters like the open circuit voltages (V_{ocv}), internal resistance (R_0) and the Thevenin equivalent circuit parameters like the R_1 and C_1 are defined according to the data taken from VSIM.
The battery provides the required current based on the power demand. This power demand from the traction motors is summed up to input as battery power requests. In addition, the auxiliaries' power requirement is also added.

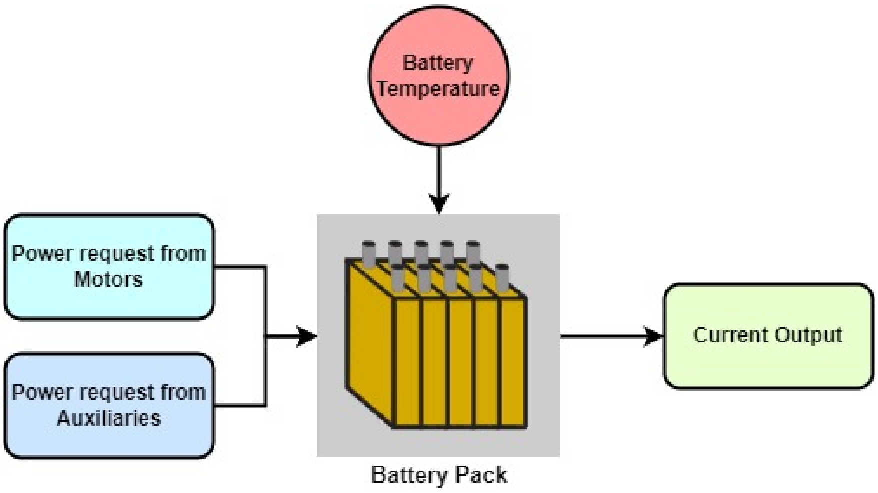

Figure 3.3: Battery

3.1.2.2 Battery power limiter

In the battery power limiter component, main attributes are defined, such as the minimum and maximum discharging and charging voltage limits. Also, a limit on the maximum charge and discharge current is imposed based on the limitations present in VSIM. Since the battery voltage is the product of individual cell voltages and the number of cells in series, the limits on the voltage are imposed using the maximum and minimum cell voltages. Similarly, limitations on charging and discharging currents are set based on current and SoC. The minimum of both the currents is sent as the limits for the battery current.

3.1.3 Controls

The powertrain controls regulate the torque distribution among the axles and brake requests per wheel.

3.1.3.1 Torque request

As discussed in the section 2.2.1.5, the driver model used determines the torque required based on the driver cycle inputs. The torque distribution is performed based on a map, which takes vehicle speed and torque as inputs and gives out the torque distribution ratio for the front and rear motors. The vehicle configuration

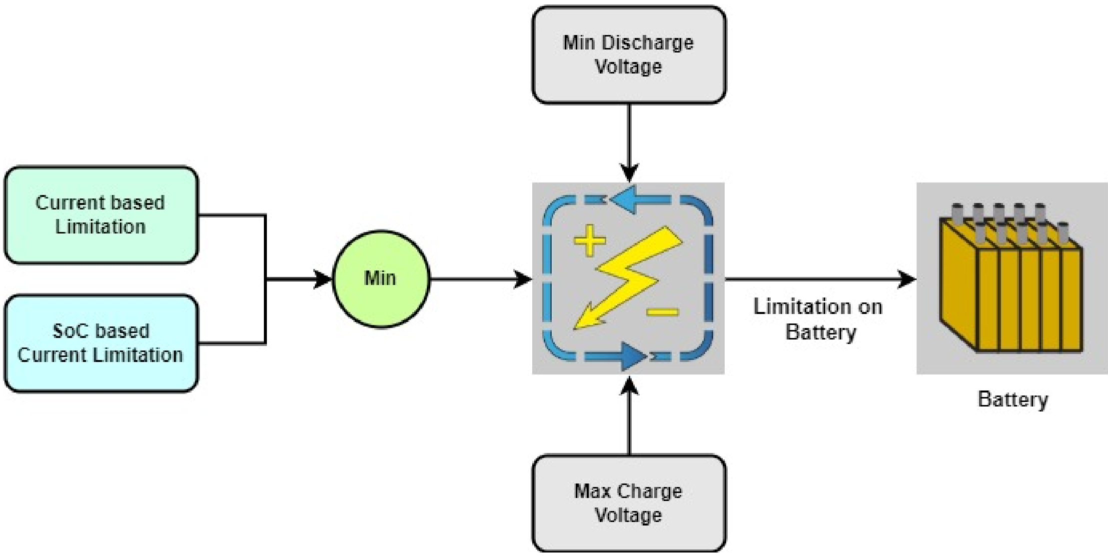

Figure 3.4: Battery power limiter

used utilizes a front distribution strategy that prioritizes the front axle, as seen in Fig.3.5.

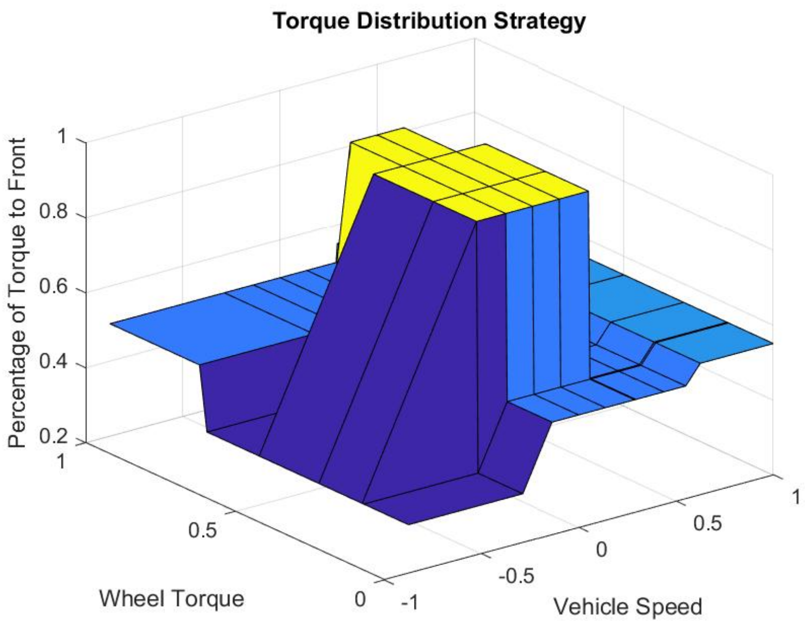

Figure 3.5: Torque distribution strategy

The driver model gives the wheel torque request divided by the differential ratio to obtain the shaft torque request. This shaft torque is distributed to the front and rear motors using the torque distribution map. Since there can also be negative torque demand during braking, this can be utilised for regeneration. Hence, before the torque is sent to the motors, a regeneration limit is imposed on the motor torques safe operation is ensured. Fig.3.6 below shows the general overview of the torque request control.

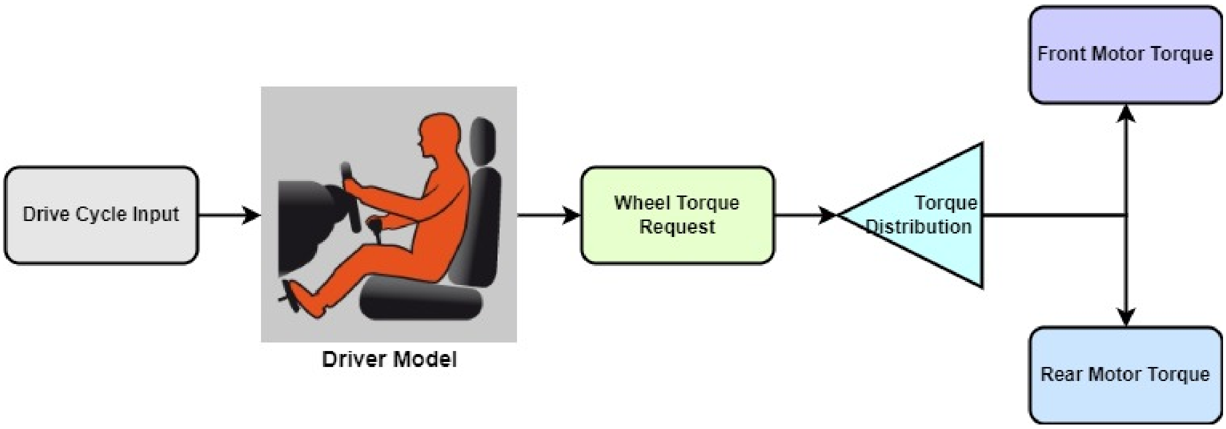

Figure 3.6: Torque control

3.1.3.2 Brake request

A major benefit of electric vehicles is their ability to regenerate energy while braking. Essentially, during regenerative braking, instead of the motor driving the wheels to propel the car, the wheels drive the motor, which imposes a negative or braking torque. That is translated to energy directed back into the battery. Knowing the maximum braking torque allows the controller to define how much the friction brakes need to contribute to the braking to satisfy the demand. It is important to note that the motors usually do not deploy their maximum regeneration capabilities. Therefore, a limiter is imposed to maintain it below the operational levels.
Furthermore, the torque distribution logic defines how much regeneration occurs at each axle. The controller's output is the brake pedal actuation required to satisfy the remaining braking demand. An overview of the brake controller logic is presented in Fig.3.7.

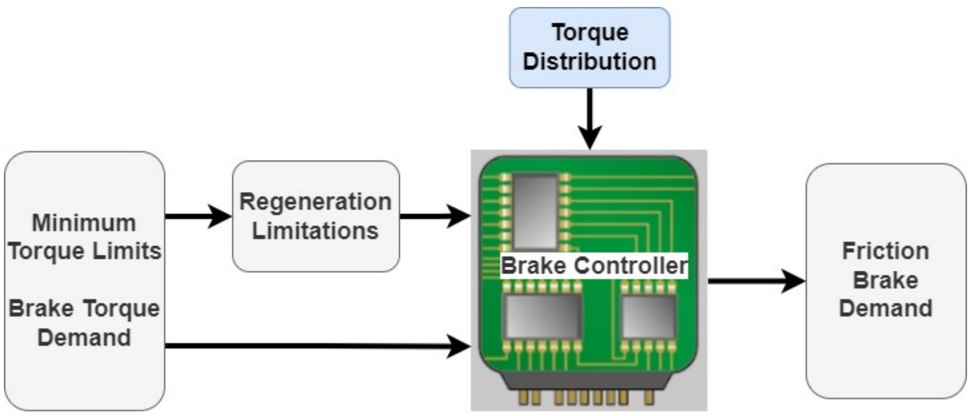

Figure 3.7: Brake controls

3.1.4 Electric motors

The electric motor model receives the torque request and defines the voltage and current required to achieve it. Like any motor, there are losses to be considered to determine the required power. The electric motor component receives the losses from the thermal model, which are dependent on the motor torque and speed, the rotor and winding temperature, and the battery voltage. The inverter losses are introduced following the same methodology as they are transferred from the CVTM. Furthermore, the motor has to comply with the battery limits. Thus, power limits are imposed on the motor, which usually limits the regenerative braking at colder temperatures.
This process results in a torque and speed output used in the CVTM as an input for the motor thermal models.

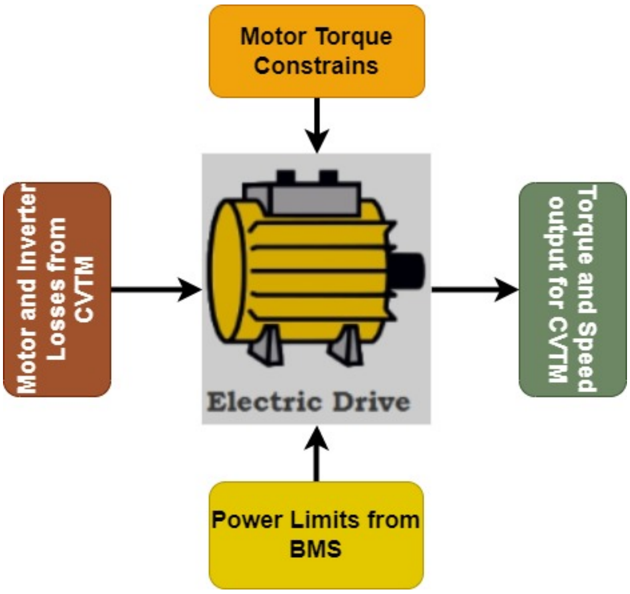

Figure 3.8: GT-Suite electric motor model

3.2 CVTM integration

The vehicle model needs to be implemented in the CVTM in a non-intrusive manner. Modifications are made to the simulation setting components that determine the input source to the CVTM. Therefore, a master parameter is implemented to the model, defining if the input originated from the VSIM output files or the vehicle model, providing ease of use of the model to the user. The logic of the implementation is presented in Fig.3.9.

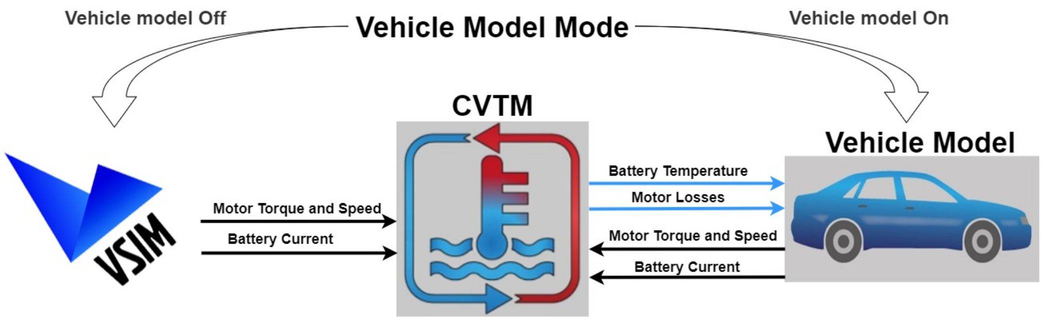

Figure 3.9: CVTM integration

3.3 Python automation

The automation script aims to automate the data transfer, data input, and simulation process. The vehicle configuration data are stored in Matlab files and functions, and the manual transfer of the data is a time-consuming process. The Python script automatically accesses the file where the vehicle configuration is determined, transfers the corresponding component parameters and stores them in variables. Utilizing the GT-Suite capability of importing parameters to components and setting up the simulation setup, the time required to transfer the data and run the simulation is significantly reduced. The process mentioned above is presented in Fig.3.10.

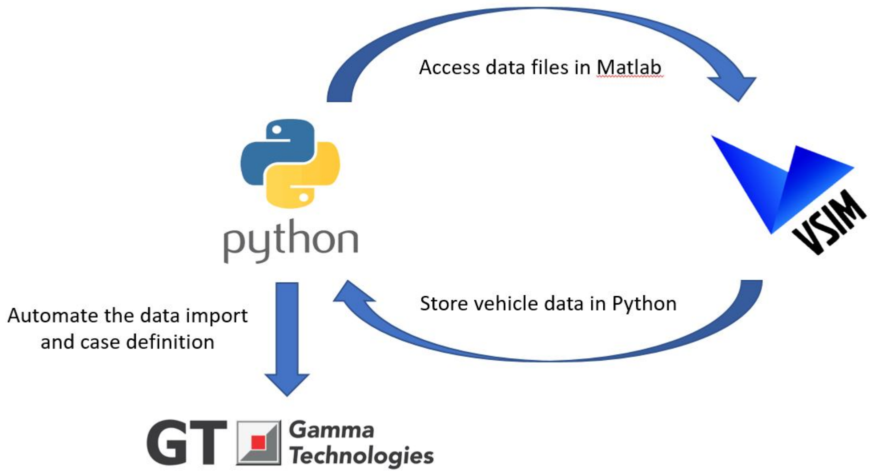

Figure 3.10: Python automation

3.4 Test cases definition

After completing the integration, the complete vehicle model needs to be verified. A combination of driving cycles and ambient temperatures is set to study the difference in the model's response when it utilizes the vehicle model output compared to the VSIM model. It is also vital to ensure that the integration does not influence the behaviour of the default system. The following test cases will be studied.

US06: The US06 cycle represents a usual daily commute test case of everyday driving and smooth accelerations and decelerations. This cycle is appropriate to test the general behaviour of the system since it does not test the limits, as shown in Fig. 2.3.

WLTC: Similar to the US06 cycle, the WLTC cycle, used for certification, represents non-demanding driving conditions. The cycle is shown in Fig.3.11.

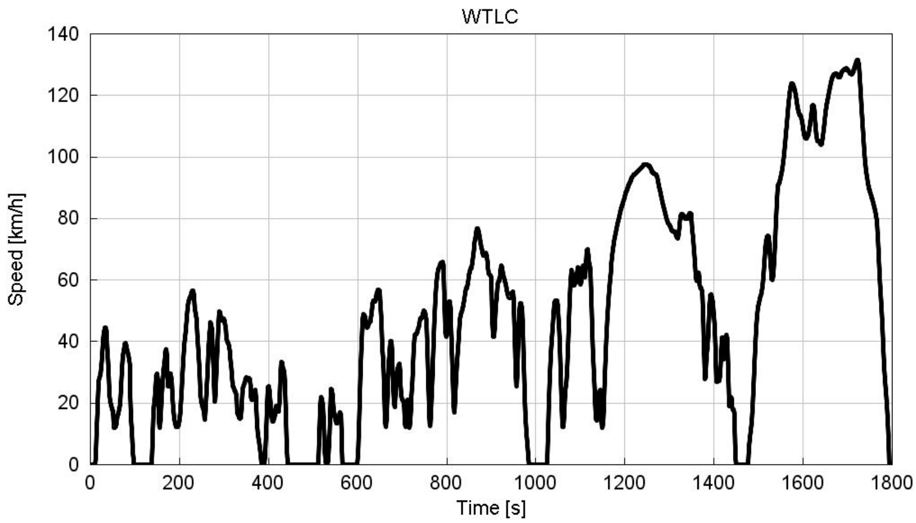

Figure 3.11: WLTC Cycle

City cycle: The city cycle represents an unconventional driving case. It initially consists of a long steady-state medium speed section, followed by rapid acceleration and deceleration sequences. The benefit of this cycle is that it is possible to study the steady-state and transient responses of the system simultaneously and the transition between them. The cycle is shown in Fig. 3.12

Driving cycles at different ambient temperatures: The vehicle's thermal management system controls and regulates its operation based on the component temperature. When the temperature exceeds the allowable operational limits, the valves and pumps' functions change to cool down the components. In contrast, the system heats the components when the temperature is below that threshold. That imposes a different load to the system, especially the battery, that needs to supply the required energy in the heat-up conditions.

In the context of this project, driving cases at -7^0C, 25^0C, 35^0C and 46^0C will be investigated. The effect of the different loads imposed by the driving cycle, combined with the loads due to component temperature, can provide a holistic overview of the system response and be used for control tuning and system validation.

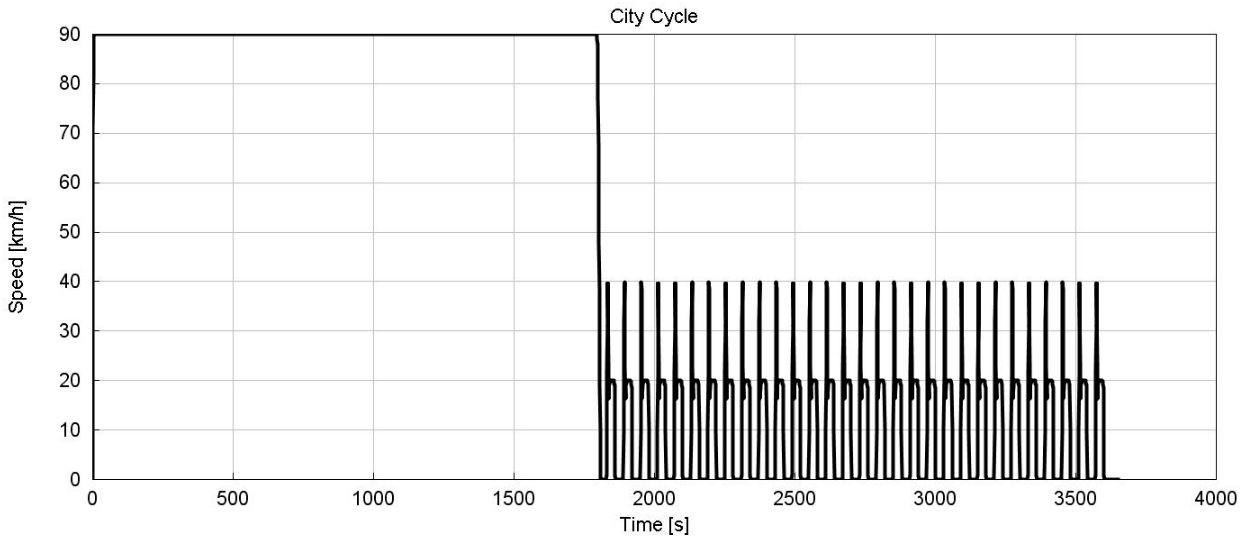

Figure 3.12: City cycle

4

Results

This results chapter is divided into two sections. The first compares the results with VSIM, and the next section with the results from the CVTM integrated model and the energy efficiency studies.

4.1 Comparison between GT vehicle model and VSIM

As described in Chapter 3 the first step is to evaluate how well the created vehicle model in GT Suite behaves as compared to VSIM models, to move forward with integrating the vehicle model with the CVTM. The models are run with different test cycles mentioned in section 3.4, using US06, WLTC and City cycles and the results are discussed in the following sections. The parameters to be compared are the SoC, battery current and motor torques.

A relative error will be used to study the comparisons, as, besides the magnitude of the deviation between the outputs, relative trends are also essential. Thus the following formula will calculate the relative errors, using GT as the reference, with the maximum deviation of 15% being the target.

$$Error\% = \frac{X_{GT} - X_{VSIM}}{X_{GT}} * 100 \tag{4.1}$$

The exact values of the outputs are omitted from all the graphs below, as they are considered confidential by the company.

4.1.1 US06

Here the comparison conducted will be under the ambient temperature of 25^0C. This ambient temperature choice is the battery's operational temperature; thus, any deviations will not be attributed to the change in the battery circuit parameters due to temperature. Fig.4.1 shows the comparison between the SoC, battery current, and front and rear axle torques for the vehicle model and the VSIM model. The vehicle model correctly replicates the VSIM results, which can be observed from the graph below.

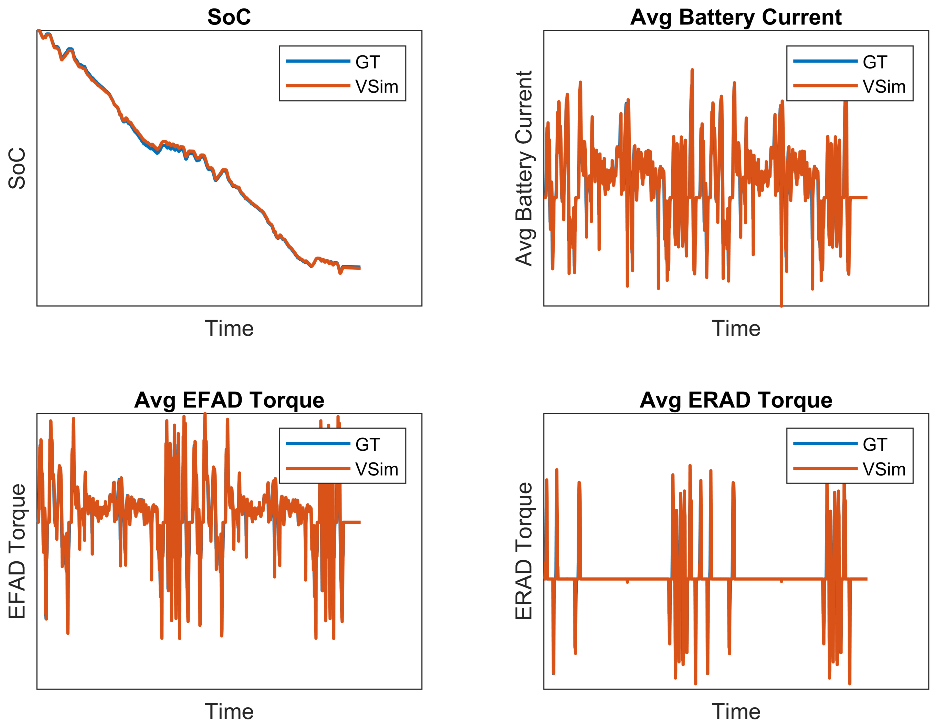

Figure 4.1: Comparison for US06 drive cycle at 25^0C (normalized to GT-Suite)

As seen from the graphs in Fig.4.1 and the relative deviations in Table 4.1, there is a good agreement between the outputs. The SoC provides a good representation of the system's behavior as the overall energy drawn defines it. The deviation in the torques is higher, which can be attributed to the torque peaks, as the more aggressive driver model used in VSIM causes higher torque spikes to achieve the torque request and follow the driving cycle closely. The rear motor is mainly disengaged since the vehicle is primarily front-wheel drive and is activated only when the torque request demands it, causing few peaks throughout the driving cycle. This causes the average torque to be low, resulting in a significant deviation, which can be neglected.
The battery current is the most critical parameter, as the battery is the primary heat source for the cooling system; thus, high accuracy is paramount. The achieved

Average deviation %	
Ambient temperature	25^0C
End SoC	0.03
Front motor torque	-5.38
Positive front motor torque	-3.31
Rear motor torque	-145.11
Positive rear motor torque	36.82
Battery current	-0.32

Table 4.1: US06 cycle deviations

accuracy is 0.32%, which makes the output practically identical.

4.1.2 City cycle

A similar comparison to the US06 cycle is carried out for the City cycle at 25^0C. The City cycle consists of steady-state driving or driving at a constant speed for half of the cycle and a transient driving for the other half consisting of repeated accelerations and braking. From the graphs below in Fig.4.2 and the Table 4.2, it can be seen that the trend in the SoC plot is the same in the steady-state starts to deviate slightly during the transient state. It is the same with the current and motor torques during the steady-state, but the differences can be seen in the transient state. This can be attributed to the different implementation of the torque distribution strategy that GT-Suite utilizes, which enables it to capture the regeneration of the rear axle more accurately. The table below shows the deviation in the positive torque values as low as 0.37% for the front motor and 12.7% for the rear motor, showing that the two models produce the same output under motoring conditions.

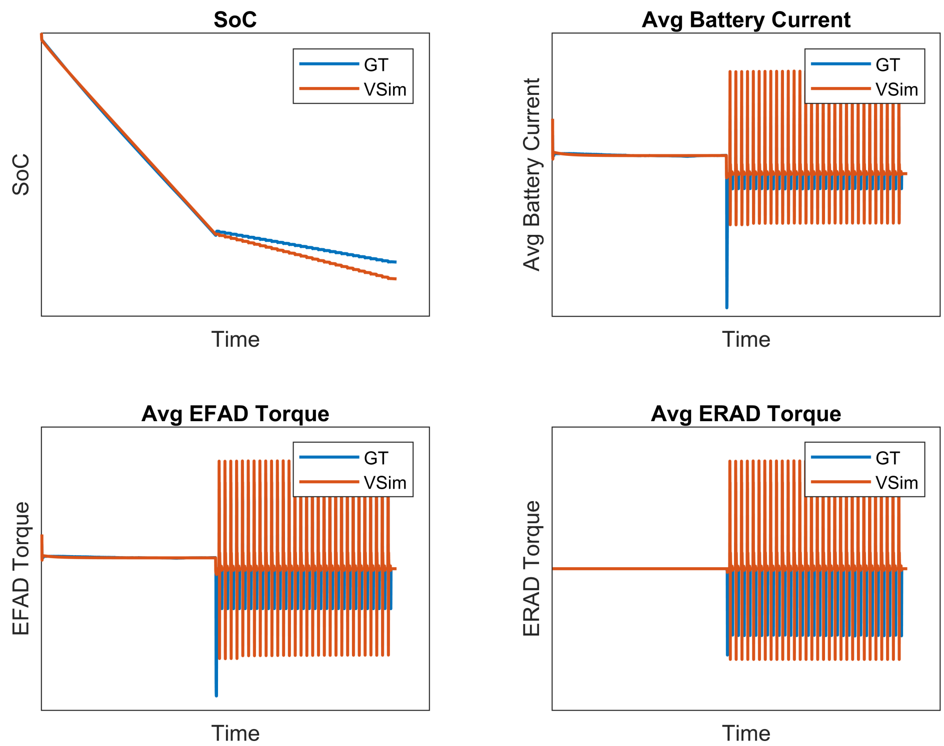

Figure 4.2: Comparison for City cycle at 25^0C (normalized to GT-Suite)

Average deviation %	
Ambient temperature	25^0C
End SoC	0.72
Front motor torque	-16.45
Positive front motor torque	-0.37
Rear motor torque	-201.35
Positive rear motor torque	-12.71
Battery current	-6.91

Table 4.2: City cycle deviations

4.1.3 WLTC drive cycle

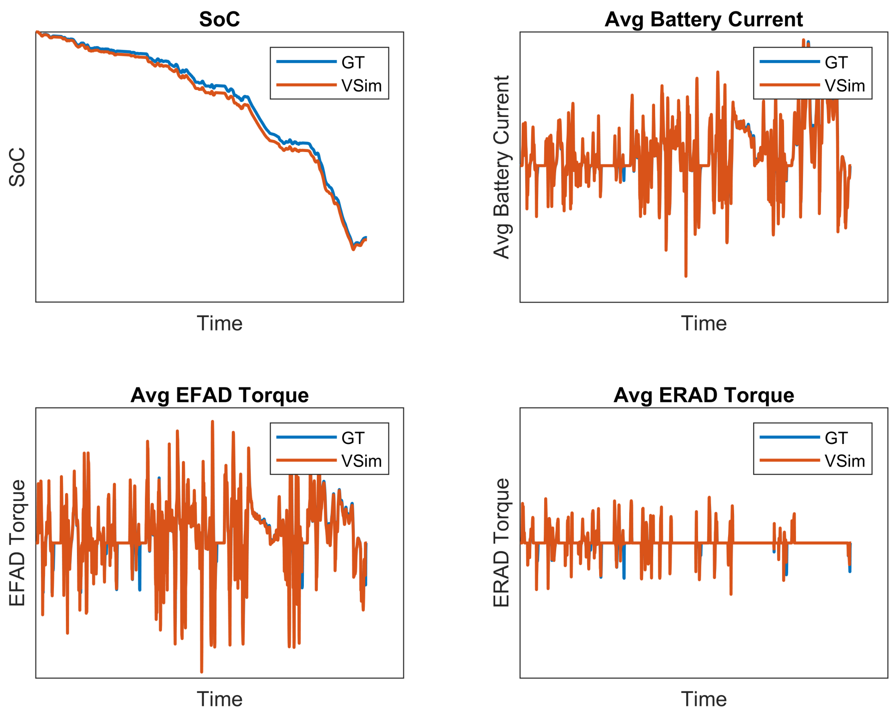

Figure 4.3: Comparison for WLTC drive cycle at 25^0C (normalized to GT-Suite)

Utilizing the WLTC cycle, the outputs are adequately similar. The main differences between VSIM and GT-Suite models lie in regeneration. It can be noticed in Fig.4.3 that the torques for the rear and front motors follow a similar trend and amplitude, with a few exceptions in the negative or regenerative torques, where GT-Suite captures energy during braking while VSIM does not.

Average deviation %	
Ambient temperature	25^0C
End SoC	0.05
Front motor torque	-4.81
Positive front motor torque	-3.20
Rear motor torque	-53.2
Positive rear motor torque	-12.35
Battery current	-0.76

Table 4.3: WLTC deviations

Similarly, the deviations shown in Table 4.3 are below the set accuracy threshold and can be deemed reliable to be used for the CVTM.

4.2 CVTM with vehicle model

After completing the integration of the vehicle model in CVTM, it is run utilizing both inputs, VSIM and vehicle model, for comparison purposes. The target is to investigate the deviations of the outputs for the critical parameters. The variations are expected to be higher than in the previous comparison since the temperature loop is implemented, and the battery temperature and thus its circuit parameters are altered during the simulation.

4.2.1 US06

As discussed in section 3.2, the Vehicle Model is integrated with the CVTM and simulations are performed at 46^0C and -7^0C using VSIM and vehicle model inputs. The following graph compares the SoC plots when the simulation is run with the vehicle model and VSIM as inputs. The temperatures are chosen because the battery performs poorly at very high and very low ambients. Thus, the temperature dependency of the vehicle model will be evident in this comparison.

Fig.4.4 shows the SoC and current comparison between the two inputs at 46^0C. The thermal model in CVTM provides the correct temperature response and cool-down process of the battery, which alters the circuit parameters. Since a battery in the operating temperature has a lower circuit resistance, it has lower losses; thus, the SoC is higher.

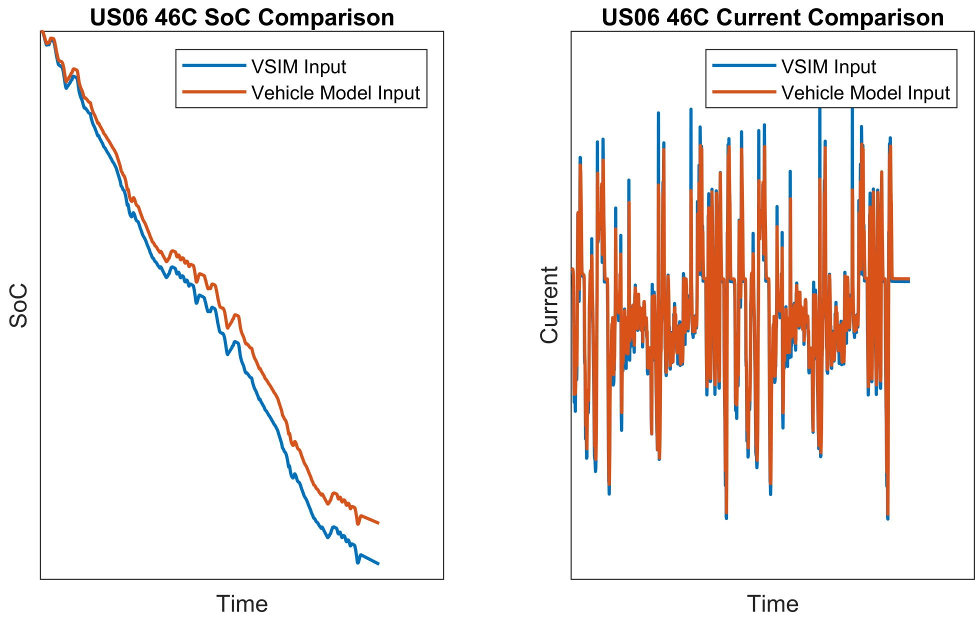

Figure 4.4: Comparison for US06 drive cycle at 46^0C (normalized to GT-Suite)

Similarly, at -7^0C, the battery in CVTM heats up to reach the operating temperature, which lowers the battery losses due to the lower resistance. Fig.4.5 presents the SoCs at cold conditions being lower than the hot driving case due to the energy lost for heating the battery with the HVCH. Therefore, the vehicle model's input causes a higher-end SoC, as the battery operates at its optimal temperature range.

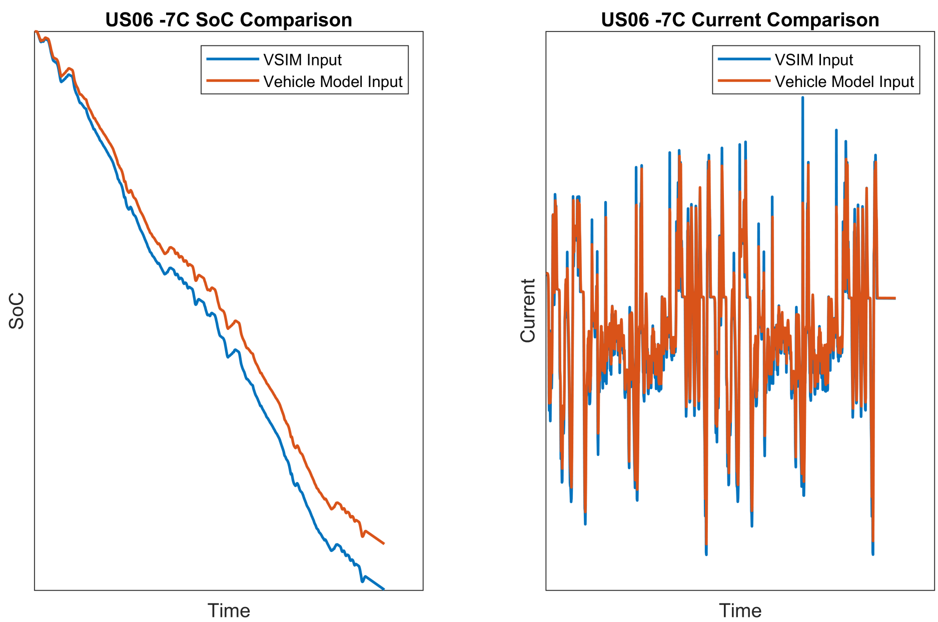

Figure 4.5: Comparison for US06 drive cycle at -7^0C (normalized to GT-Suite)

Average deviation %		
US06 cycle	**46C**	**-7C**
End SoC	0.62	0.9
Front motor torque	6.67	14.3
Positive front motor torque	3.06	4.98
Rear motor torque	80.03	80.36
Positive rear motor torque	-102.8	-102.44
Battery current	5.9	6.8

Table 4.4: US06 cycle deviations (46^0C and -7^0C)

4.2.2 City cycle

The effect of the temperature loop is more evident for the City cycle, especially in the first steady-state section. At 46^0C, the CVTM cools down the battery at the operational range. Thus, as Fig.4.6 and Fig.4.7 show, in the steady-state section, there is an increasing deviation between the two outputs.

Average deviation %		
City cycle	**46C**	**-7C**
End SoC	1.5	1.74
Front motor torque	10.8	16.75
Positive front motor torque	7.8	10.15
Rear motor torque	71.49	71.54
Positive rear motor torque	-1.3	-1.7
Battery current	8.4	7.03

Table 4.5: City cycle deviations (46 and -7C)

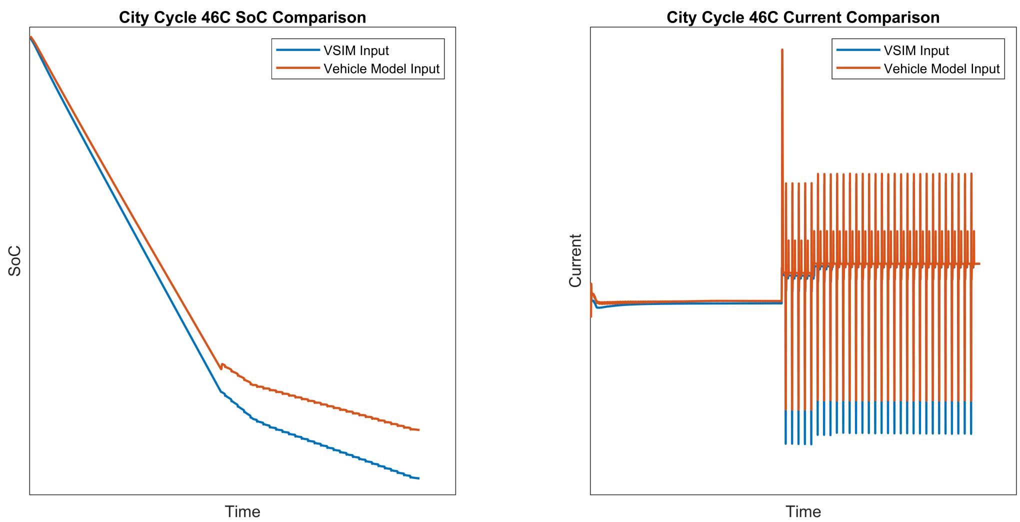

Figure 4.6: City Cycle cycle at 46^0C

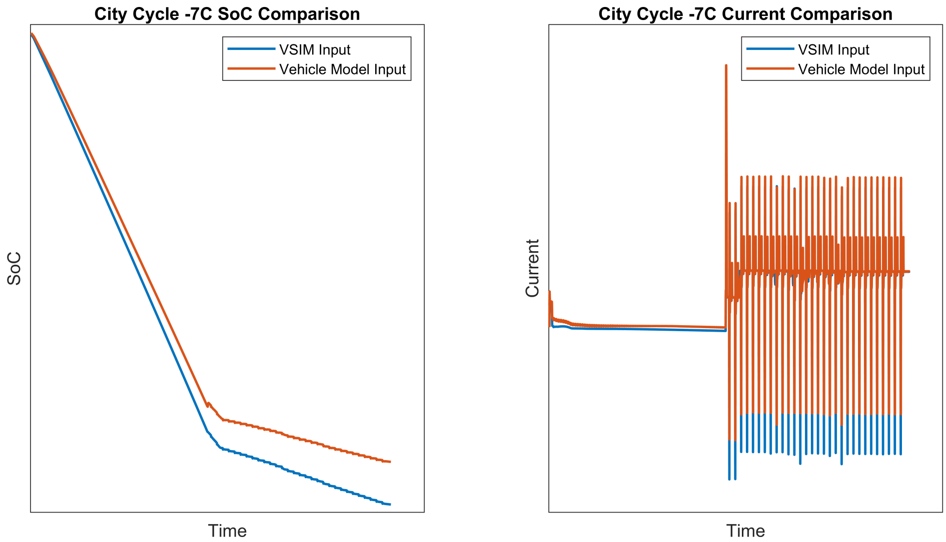

Figure 4.7: City cycle at -7^0C

4.2.3 WLTC

Like the US06 cycle, the WLTC represents a transient driving condition. As the cycle progresses, the deviation grows due to each model's different battery operating temperatures.

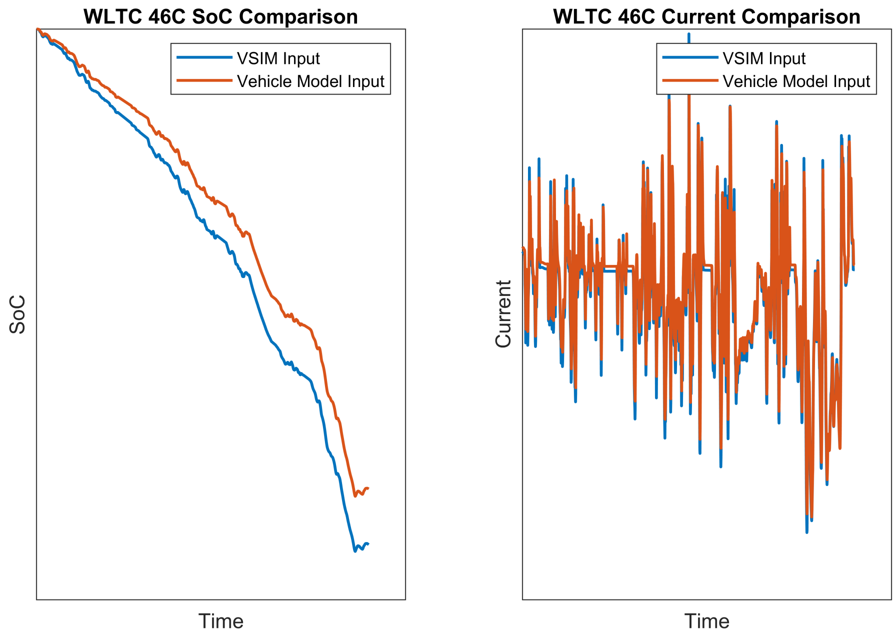

Figure 4.8: WTLC cycle at 46^0C

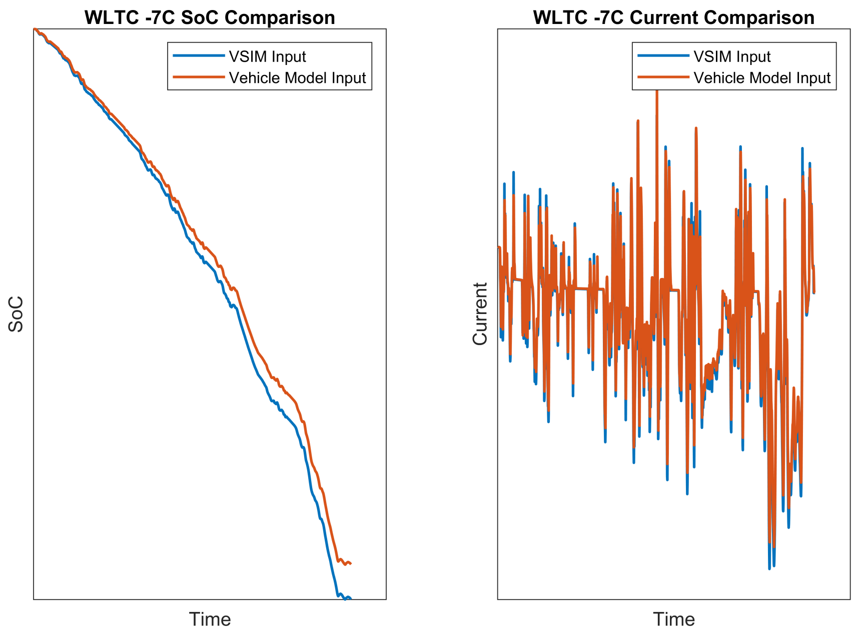

Figure 4.9: WTLC cycle at -7^0C

Average Deviation %		
WLTC	**46C**	**-7C**
End state of charge	0.81	0.68
Front motor torque	6.85	13.25
Positive front motor torque	6.85	4.98
Rear motor torque	47.94	48,34
Positive rear motor torque	-38.47	-39.08
Battery current	10.01	5.58

Table 4.6: WLTC deviations (46 and -7C)

4.3 Energy efficiency studies

The scope of this work is to implement the vehicle model to the CVTM and conduct sensitivity studies by altering the vehicle parameters. The most important parameters are the drag coefficient and the vehicle weight. A correlation can be found between the energy consumed and the vehicle parameters through the studies mentioned above.

4.3.1 Weight sensitivity studies

The use of batteries causes a high weight increase of the battery electric vehicle, influencing its range. The weight difference becomes evident during acceleration segments, as the driveline needs to provide more power to overcome the excess inertia added. To study that effect on the vehicle's performance, simulations are run by varying the mass from the base vehicle mass according to the Table.4.7, with variable intervals, over the WLTC certification cycle at 0^0C. To produce a qualitative representation of the weight effect, the depleted SoC over 1 WLTC cycle is extrapolated over the entire usable battery of 90% SoC to examine the range losses in kilometers and battery energy.

Change in mass(%)	**Range gain/loss(%)**	**SoC gain/loss(%)**
-12	+2.92	+2.94
+6	-1.45	-1.57

Table 4.7: Weight sensitivity

According to the Table.4.7, a set of simulations is run(WLTC) by changing the mass from the base vehicle mass to see its effect on the vehicle's performance. Fig. 4.10 shows the battery energy consumption versus the change in mass of the vehicle, and it can be observed that there is a linear increase in the energy consumption as the mass increases.

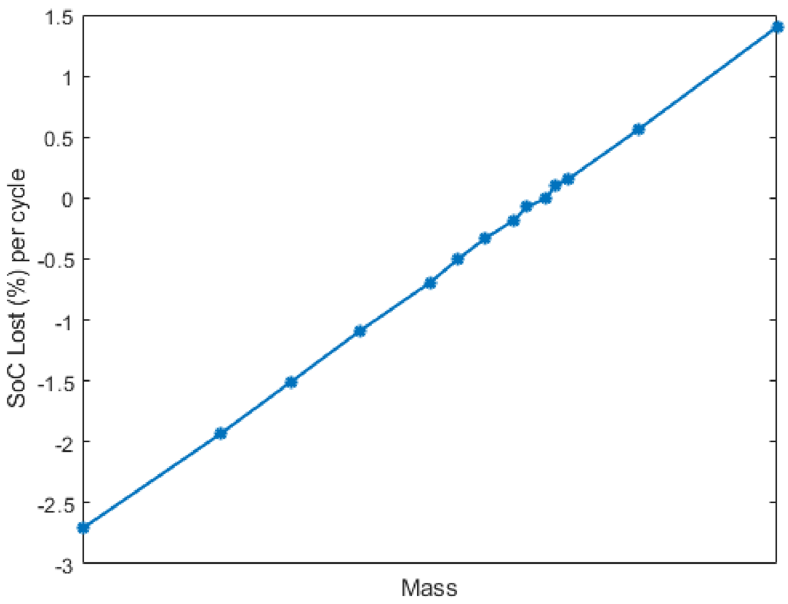

Figure 4.10: Battery energy consumption with variation in mass per WLTC cycle

Similarly, Fig.4.11 shows the comparison between the instantaneous power demand increase concerning the drive cycle run. The comparison is made for a mass change of 300kg. More significant peaks in power demand can be observed with quick changes in the vehicle speed and multiple smaller peaks for shorter accelerations due to the inertia differences.

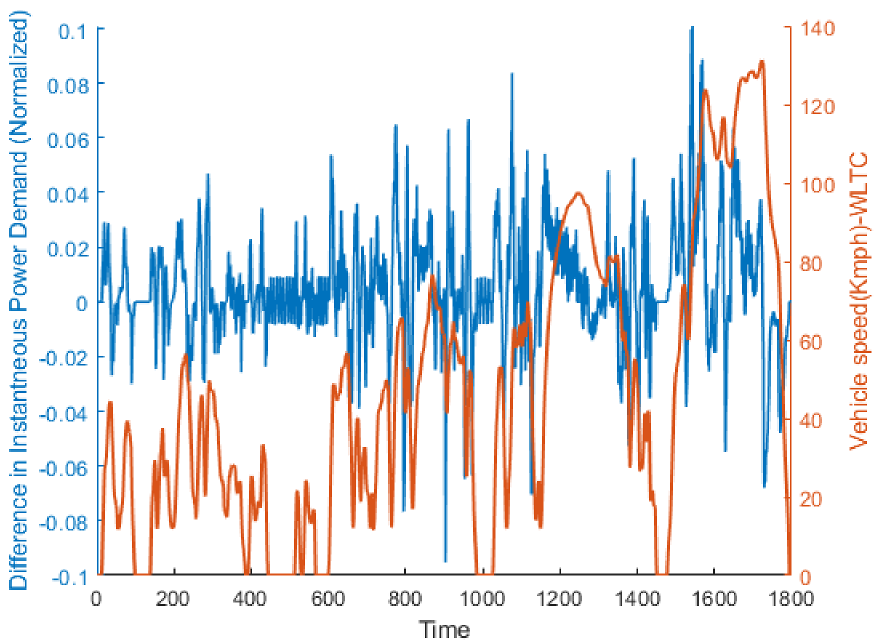

Figure 4.11: Normalized instant power demand for a mass difference of 300kg

4.3.2 Drag coefficient sensitivity studies

Aerodynamic drag is another energy influencing factor that needs to be considered during the design of the vehicle. Its effect is more evident at higher speeds; thus, besides the WLTC cycle, a steady-state simulation of motorway driving for 30 minutes at 120 $\frac{km}{h}$ will be used, during which the vehicle travels up to a distance of 60km.

Since the reduction in Cd has a significant effect on range and energy consumption, similar calculations to mass sensitivity are performed by reducing the Cd by 20%. The range and the SoC gain are around 4% for the WLTC cycle at complete battery capacity expense. In the steady-state simulations, it is observed that with Cd reduction, a range gain of 13.5% and an SoC gain of 12.1% is achieved, as listed in the table below.

Full battery depletion	**WLTC**	**Steady state**
Cd reduction(%)	-20	-20
Range gain(%)	+4	+13.5
SoC gain (%)	+4.1	+12.1

Table 4.8: Cd sensitivity

4.3.3 Vehicle parameter correlation

Having completed the studies mentioned earlier, a correlation between weight and aerodynamic drag can be found. However, since each parameter affects the vehicle range according to the driving cycle, they need to be compared over the same driving scenario. For this comparison, the WLTC cycle will be used. Using the results of 4.3.2 and 4.3.1, the following correlation is calculated

$$1\ \%\ \text{weight reduction} = 1.2167\ \%\ \text{Cd reduction}$$

Thus, it is concluded that over a transient cycle, weight reduction is more effective than lowering the vehicle's aerodynamic drag. The feasibility of each reduction depends on the manufacturer. However, a drag reduction is usually more easily achieved compared to a weight reduction.

4.4 Sankey diagram

The Sankey diagram is used in physics to visualize energy flow through various components. In the context of an electric vehicle, there are multiple energy flows to the different subsystems [15]. In the given test cases, the energy distribution can be examined under the heat-up case of -7^0C ambient and the cool-down case of 35^0C in the WLTC.

In Fig.4.12 the Sankey diagram of the electrical power is displayed. It can be seen that the electric high voltage heater takes more than a third of the power spent during one WLTC cycle at -7^0C. The main power draw is the electric motors, with part of that power returning to the battery due to regeneration.

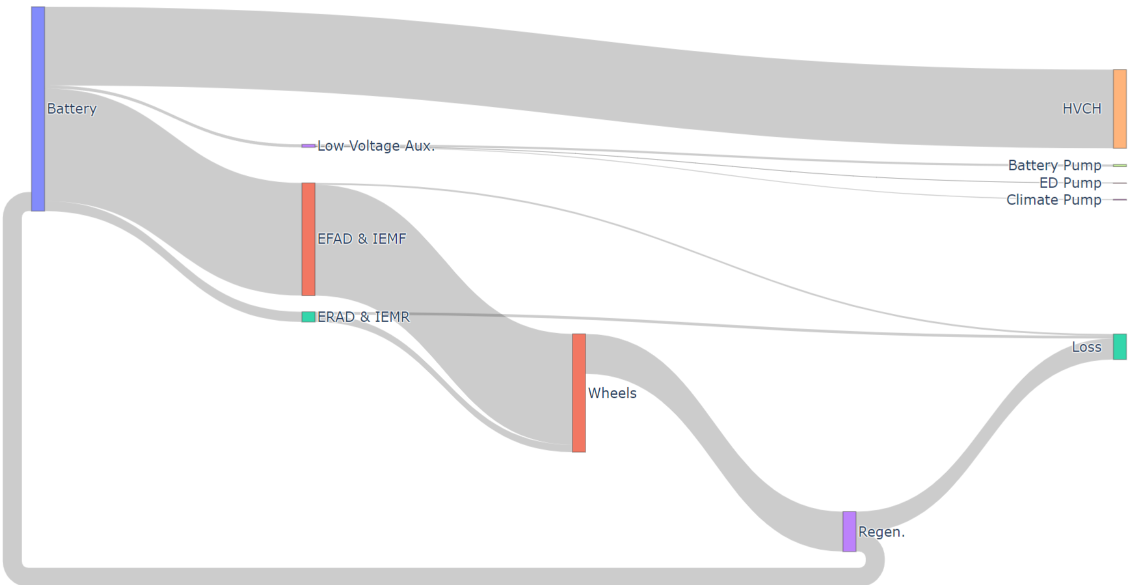

Figure 4.12: Sankey diagram for WLTC at -7^0C

Similarly, in Fig.4.13 for the cooling case, the compressor draws a significant portion of the power spent due to the need to cool down the battery within the operational limits.

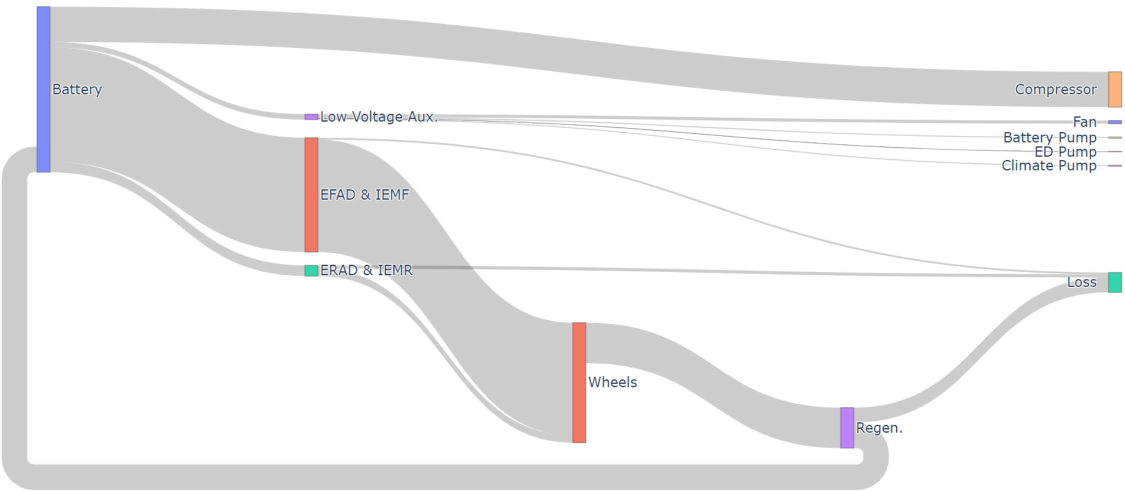

Figure 4.13: Sankey diagram for WLTC at 35^0C

5
Conclusion

The scope of this thesis project included the creation of an electric vehicle model and the coupling with its thermal model. A Simulink-based vehicle model was studied and acted as the basis for the modelling techniques and procedures used in GT-Suite. The motivation of this work was the creation of a thermal loop between the vehicle and its thermal model since the operation of the electrical components is dependent on their operating temperature.

The various components comprising it needed to be modelled and coupled to create this model. Starting with the vehicle's body, the chassis, axles, shafts, clutch, brakes and tires needed to be connected to transmit the power fed by the propulsion system to the road. Following this, the electric drive of each axle was implemented and connected to the losses sourced by its thermal model, as well as its power and torque constrains, to be able to produce the correct response upon a torque request. The power of the motors comes from the battery, where the cell data are inserted, and a battery management system is implemented. The complete driveline requires controls that determine the torque request, the torque distribution between the axles, and the braking power needed.

The created model matches the outputs of VSIM, thus enabling its integration into the complete vehicle thermal model. Conducting simulations with the CVTM while utilizing the inputs from both sources, namely VSIM and vehicle model, for comparison purposes show that the temperature loop in the integrated model produces a more accurate thermal response of the components. The data transfer of the vehicle configuration parameters from VSIM and input to GT-suite is automated via python.

The result of this work is the simplification of a complete vehicle simulation procedure, as the data transfer from VSIM to the GT-Suite step is eliminated. Furthermore, the accuracy of the outputs is increased as the temperature co-dependence is implemented. The final model increases the degrees of freedom between simulations, as the vehicle parameters can be changed, enabling the capability of energy efficiency studies and control tuning.

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