POLITECNICO DI TORINO

Master of Science in Automotive Engineering

Master Thesis

Development of control strategy for BMW i3 Range Extender

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Abstract

Demands for more efficient vehicles with reduced fuel consumption and low emissions are growing rapidly in these days. Generally, they can create a competition among automakers in the worldwide. In order to satisfy these kind of factors, manufacturing of electrical vehicles (EV) can be regarded as a solution. However, short driving range and charge problems can be considered as disadvantages of the EVs. Currently, a range-extended electrical vehicle (REEV) is being developed to solve this kind of issues.

This study includes the background theories on different types of Hybrid Electrical vehicles (HEVs) together with several types of range extending technologies in HEVs have been discussed and made comparison on according to several criteria including cost, emissions, efficiency, vibration and noise. In addition, the modeling of the subcomponents of the proposed vehicle as well as the formulation of each model are described clearly.

The main goal of the thesis is to develop control strategy for range – extended EVs and to implement in the vehicle model. 2014 BMW i3 Range Extender EV has been selected as a case study. It is a series-type hybrid range extended vehicle which consists of a 0.635L in-line 2-cylinder engine with a 26.6kW generator, 125kW permanent magnet synchronous AC motor, and 18.8kWh lithium-ion battery [1]. Vehicle model with the proposed control strategy and numerical analysis have been performed and analyzed in MATLAB/Simulink software under UDDS driving cycle.

Finally, vehicle model has been validated under selected drive cycle and compared with the experimental test data has been taken from Downloadable Dynamometer Database (D3) testing results, which experimented at Argonne national laboratory. All comparative results and conclusions are given in the thesis.

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1 Introduction

1.1 Introduction

Influences of the environmental pollutions such as global warming and greenhouse effect related to directly fuel consumption and emissions in the automobile industry. One of the main goals of scientists around the world is to save natural oil and gas resources by arranging zero – emission engines. Developing of electrified vehicles have been considered as the best solution for achieving this kind of aims. There are many advantages of electrified vehicles such regenerative braking mechanism for saving fuel consumption. Another advantage of these type of vehicles is that the traction of the electrical vehicles is designed by electric motor, which results to reduce CO_2 emissions and acoustic noises.

However, the rate of market share of electrical vehicles is not increasing quickly because some limitations are exist on charging stations as well as high costs of battery packs and their short term lifetime.

As well as, there are several common architectures for electrified vehicles such as all electric (EV) or battery electric (BEV), hybrid electric (HEV) and plug – in hybrid electric (PHEV). Each selected architecture plays an important role in designing a vehicle, arrangement of components, cost and performances.

An electrified vehicle with all electric architecture (EV) has a battery pack and electric motor instead of an internal combustion engine and a fuel tank. To control of components are simpler than other architectures.

Most of the automobile manufacturers are enlarged hybrid electrical vehicles (HEVs) considering both advantages and disadvantages of BEVs. A hybrid electric vehicle (HEV) is a type of hybrid vehicle and electric vehicle that combines a conventional internal combustion engine (ICE) propulsion system with an electric propulsion system [2]. A hybrid electric vehicle has a smaller battery pack that powers its electric motor by contrasting with plug – in hybrids. It means that, a battery can be charge by internal combustion engine while moving or regenerative braking mechanism when the vehicle is coasting or braking.

A plug – in hybrid electrical vehicles (PHEV) have similar components to common HEVs. The main difference is the size of battery that is bigger in PHEVs allowing increasing the range in EV mode and helping to decrease operating costs. An external electrical source is need to recharge the battery by plugging a charging cable. In today's automobile industry, several kinds of electric vehicles have been developed according to usage of additional source of energy.

However, the main target is that to improve vehicle fuel efficiency and decrease the atmospheric pollution in contrast with conventional vehicles as well as, high battery packs as a source of energy and large electric motors are utilized for vehicle driving in BEVs. In order to find a solution to the problem, it is important to develop appropriate range extenders that will increase the distance covered by the vehicle with single fully charged battery pack.

This thesis can give clear background theories on hybrid vehicle configurations and types of additional sources are used as range extenders. A plug – in hybrid electric vehicle architecture has been modelled and analyzed during the research. In order to model the performance of the vehicle a backward approach has developed at MATLAB/Simulink and calculated energy consumption of the vehicle. A 2014 BMW i3 REX model was selected as a test. Moreover, the most important point is focused on involving the research and developing of control strategies in the proposed system model related to variations of state of charge and vehicle velocity. A test range extender model has been developed to validate the control algorithm of the range extended electric vehicle.

1.2 Problem statement

Hybrid electric vehicles have two energy sources as a battery and an internal combustion engine with one or two electrical machines. In contrast, its control becomes much more difficult than pure electrified powertrain. The control unit is the core of the powertrain in hybrid vehicles and its main function is to manage available power in a efficient way. As the result of developing of energy management algorithms can be achieve best fuel consumption minimization and high efficiency operating points by splitting requested power between different energy sources such the battery and internal combustion engine in range extending electrical vehicle. According to the engineer's perception, a rule - based control strategy is used in the most cases.

1.3 Hybrid electrical vehicle technologies

The term hybrid electric vehicle has two kinds of energy sources which are an internal combustion engine and a battery pack. In this type of electric vehicle, internal combustion engine gets energy from fuel while electric motor takes energy from the battery. Three different types according to degree of hybridization and three types according to powertrain configurations are exist in HEVs. HEVs are classified three categories according to degree of hybridization which are full hybrids, mild hybrids and full plug-in hybrids.

The full hybrid system uses a bigger battery than mild hybrid system also a much bigger electric motor. Hybrid cars can be powered by only electric motors. Not only the fuel saving and less emissions are advantages of the full hybrids but also an internal combustion engine and an electric motor will work together to give the maximum power. The hybrid cars can not be charged, they will charge automatically when the car will break and it will charge by the engine when the car is running. Full hybrid vehicles is more expensive than mild hybrids but provide good fuel economy.

The vehicle is powered with mild hybrid system have an ICE (diesel or petrol), an electric motor in a separate special battery. The main difference in mild hybrid system uses much smaller electric motor and it more likes a starter and also a smaller battery. The electric motor and battery can not be powered the vehicle itself, so without a combustion engine the vehicle will not move in hybrid mild system. However, it uses a battery and an electric motor can allow the engine to switch off when the vehicle stops (such as at traffic lights or in stop and go traffic) in order to save fuel consumption and reduce emissions. Main benefits and purpose of the system are achieving lower emissions and less fuel consumption. More mechanical pieces in the case of failure in the system is considered disadvantages of the vehicle.

The difference between PHEVs and HEVs lies primarily in the size of the battery capacity and the recharging method. A plug - in hybrid electric vehicle (PHEV) has a much bigger battery and it can be charge by plugging a charging equipment, by the ICE or through regenerative braking. During the braking, the electric motor works as a generator, using the energy to charge the battery. The vehicle works on electric mode until the battery nearly depleted, and then the car automatically switches over to use the ICE. The main advantage of plug - in hybrid electric vehicle is an extended all electric range capability. In comparison with conventional vehicle, PHEVs can reduce operating cost and fuel use by using electricity from grid. Plug - in hybrid electrical vehicle have showed low fuel consumption and good performance [3]. Table 1.3.1 demonstrates the classification and features of Hybrid EVs

Table 1.3.1

HEV classification	Start/ Stop	Regenerative Braking	Power assist	Electric drive Capability
Mild HEV	Yes	Yes	Yes	No electric drive
Full HEV	Yes	Yes	Yes	Short electric drive
Plug-in HEV	Yes	Yes	Yes	Extended electric drive
Full Electric	Yes	Yes	No	Full electric drive

Hybrid electrical vehicles are popular for their amplified efficiencies as compared to conventional vehicles. As said earlier, the electric motor and IC engine are mentioned propulsion systems for HEVs. The configurations of the HEV define how the electric motor works in conjunction with the ICE. The components can be connected by different architectures. Generally, three common design options of HEV architecture are exist:

i. Series hybrid electric vehicle
ii. Parallel hybrid electric vehicle
iii. Series – parallel electric vehicle

1.3.1 Series hybrid electric vehicle configuration

The construction of series hybrid electrical vehicle is much simpler compared to other configurations. Series hybrid electrical vehicle is known as electrical coupling. The main components of series HEVs are IC engine, generator, converter, battery pack and an electric motor. The internal combustion engine is connected directly to the generator which the electric power is generated as well as the battery pack and generator connected to the electric motor which is mechanical power can be produced. In series hybrid vehicle, only the electric motor is responsible for vehicle driving. The difference with a pure electric vehicle is that the energy does not come exclusively from a battery recharged by the grid, but also the battery is charged partially or completely by an internal combustion engine.

In this type of the vehicle, the engine is used to generate only the electrical power it provides the engine works at its maximum efficiency. The control strategy is more straightforward when compare with other configurations because there is a mechanical coupling between engine and wheels.

Series hybrids may also be referred to as extended-range electric vehicles (EREVs) or range-extended electric vehicles (REEVs) since the gas engine only generates electricity to be used by the electric motor and never directly drives the wheels. Modern examples include the Cadillac ELR, Chevrolet Volt, BMW i3 and Fisker Karma.

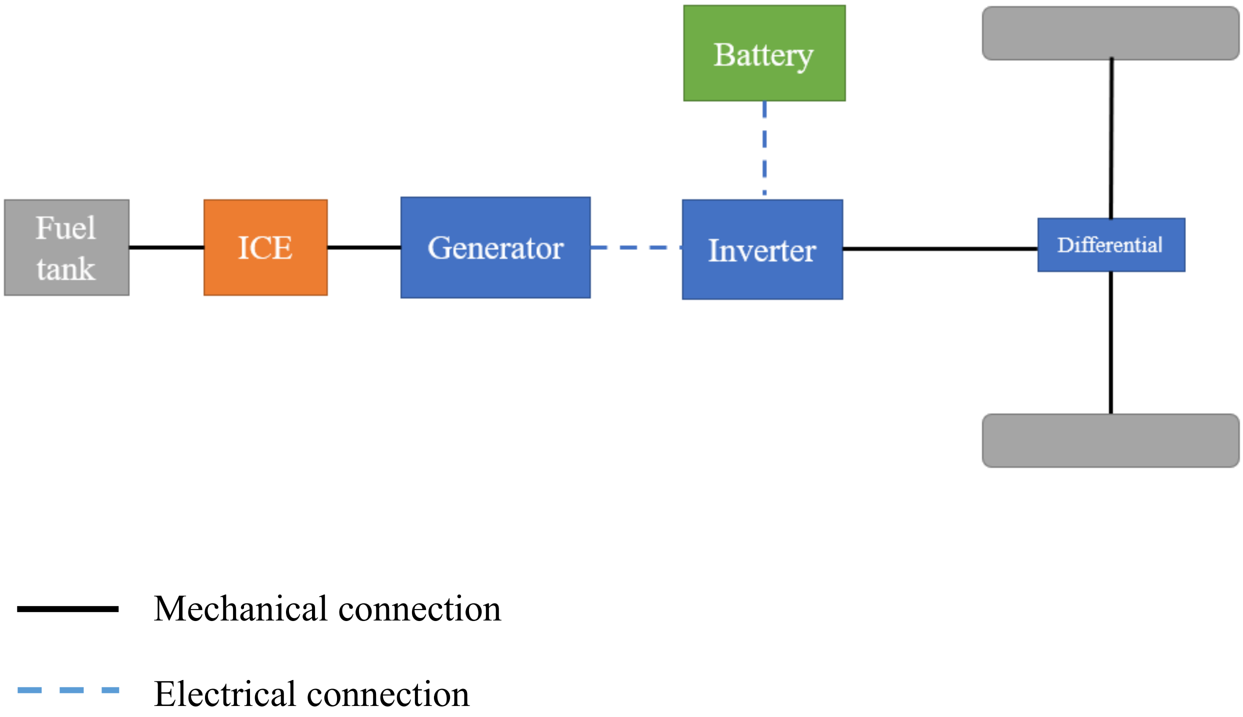

Figure 1. Series hybrid electric vehicle configuration

1.3.2 Parallel hybrid electric vehicle configuration

The hybrid electric vehicle with equipped parallel hybrid configuration can be moved by both an internal combustion engine and an electric motor connected to the wheel as shown in Figure 1.3.2. The powers from electric motor and ICE are merged together with the help of mechanical coupling. The electric motor can be used in low speed condition. Thus, at higher speed, this set up allows the engine to work in its ideal operating range with high efficiency [4]

When the vehicle is propelled only with the EM, the engine can be decoupled, whereas on the other hand, when the ICE is driving the vehicle, the EM is connected and it can be utilized as a generator to charge the battery by regenerative braking or by power provided by the ICE.

The parallel hybrid vehicles can divide into 4 classifications according to the placement of the electric motor in conventional powertrain:

1. Micro hybrids, the EM can be arranged as belt driven or crankshaft before ICE, for this reason, its speed is linked to the engine.

2. Pre-transmission parallel hybrids, the EM can be mounted between the engine and the gearbox.

3. Double-shaft parallel hybrids, the EM can be placed downstream of the gearbox

4. Double drive parallel hybrids, where the ICE can be placed on the other shaft separately from the EM.

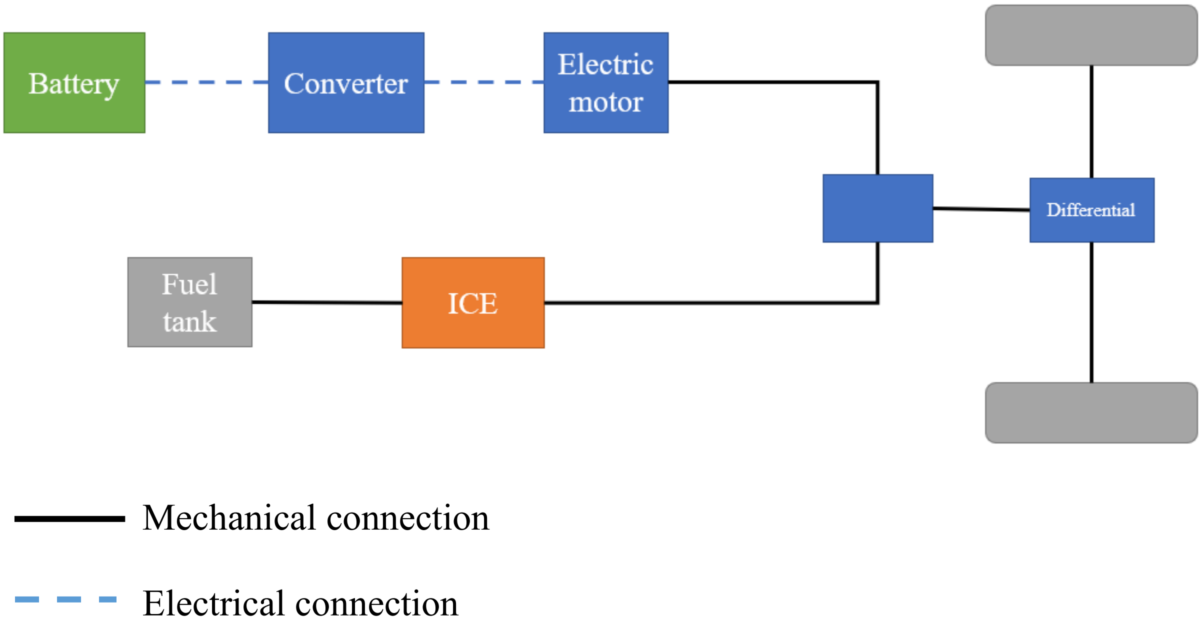

Figure 2. Parallel hybrid configuration

1.3.3 Series - parallel hybrid electric vehicle configuration

Series – parallel hybrid vehicles is also called power – split hybrids are parallel that include power-split devices. It allows for power paths from the ICE to the wheels on the mechanical or electrical way. This configuration combines the best aspects of series and parallel hybrids in order to create an extremely efficient system. In contrast with these technologies, power – split hybrid requires more components and a more complex control algorithm. The power which can be produced by the engine splits to the generator in order to generate electricity, on other hand to the mechanical gear system to propel the vehicle [5]. The architecture of power – split hybrids are shown in Figure 1.3.3

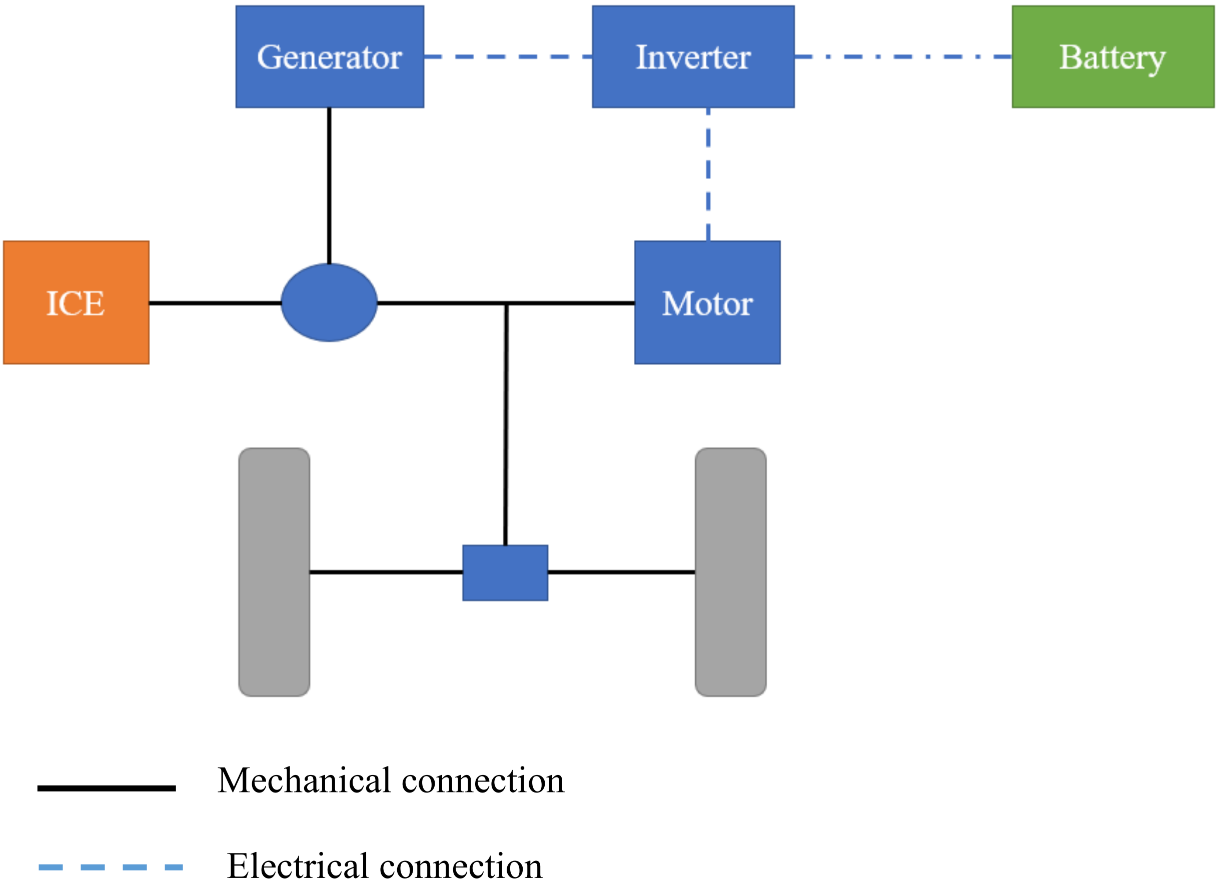

Figure 3. Series – parallel hybrid configuration

This thesis describes more clarified analysis of series hybrid electric vehicle through range extender technology. As a real example of range extender vehicle, 2014 BMW i3 Range Extender was selected for studying. In order to increase the range of the battery electrical vehicle, a range extender is used as an auxiliary power unit (APU) [6].

1.4 Types of range extender hybrid electric vehicle

The main goal of the automakers is to decrease fuel consumption and pollutant emissions in our modern life. Electrical vehicles can be one of the options for achieving these goals [7]. However, they have some disadvantages; for example, it requires much more time to charge the battery, very high price with stronger battery pack and not enough charging stations. In order to solve these kind of issues, range – extended electric vehicles can be proposed for avoiding range anxiety by extended the range.

Range Extender EVs must meet some requirements that the EV cannot use from range extender until the charge of the main battery has been depleted as well as the super ultra-low emission vehicle must be indicated. As below mentioned, series hybrid powertrain architecture are used to design Range Extender EVs.

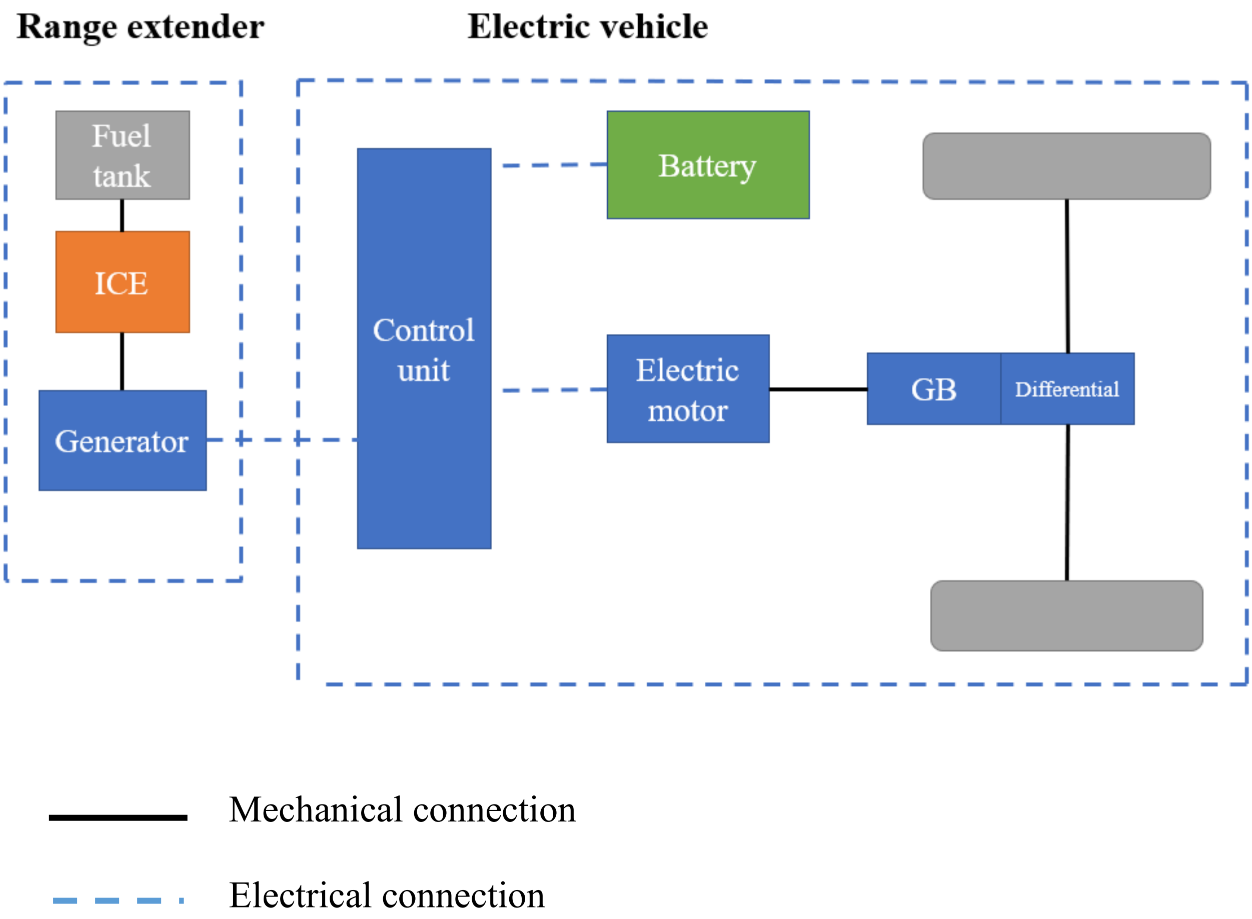

Figure 4. Powertrain configuration of the range extended electric vehicle.

In this section, several types of range extending technologies are discussed and made comparison on according to several criteria including cost, emissions, efficiency, vibration and cost.

1.4.1 ICE as a range extender

The use of the internal combustion engine for propulsion of range extenders for electric vehicles becomes nowadays more and more popular. The main difference between ICE based Range Extender EVs and other HEVs is the engine did not connect to the wheels mechanically. The ICE with coupled generator can delivers electricity to the electric motor when the charge of the battery in depleting mode. In other case, the ICE would charge the battery, when it will be below a certain depleted threshold to avoid damages of battery cell. The Oakridge National Lab performed a study on engine requirements based on degree of electrification and architectural topology [8]. They found that the ICE in an REEV application should be a small engine that can always operate at peak efficiency, since the engine only runs when the battery pack is required to be charged and is otherwise off.

In many northern countries is observed the cold weather with very low temperature for long period of year, the efficiency of the using electrical vehicle is much less in such conditions because more than 40 % of useful energy of the battery will be lost. ICE as range extender can be a reliable energy source for the effective power. Additionally, the battery pack can be developed with the fixed range of the EV and all extra power can be generated by the ICE that can decrease the cost of the battery pack. Moreover, utilizing ICE as range extender system have a significant impact on the lifecycle of the battery by preventing the pack demanding [9]. There are also some disadvantages of using range extending ICE, the vibration and noise would be observed by using ICE as a component of the drivetrain together with high emissions and low efficiency.

1.4.2 Free piston linear generator as a range extender

Free-Piston Linear Generator (FPLG) is an internal combustion engine that does not have a crankshaft. It uses chemical energy from fuel to drive magnets through a stator. In many industrial applications can be used FPLG with its adaptability, high efficiency and light weighted. As well as, it has a noticeable interest to apply range extenders in EV [10]. According to piston assembly, FPLG can be classified into three categories as following:

a. Single piston linear engine generator;
b. Dual piston linear engine generator;

c. Opposed - piston linear engine generator;

The FPLG generally consists of a combustion chamber, linear load converter and a gas spring and they are linked by a connecting road. Its operation by the combustion increasing pressure in the chamber and driving the motion of the piston. The linear load converter is then can convert the piston's motion into electrical energy, which can be used to charge the battery in range extender EVs [11].

There are more potential advantages of using FPLGs compared with conventional internal combustion engines in range extender EVs. One of the main pros is absence of the crankshaft that can allows a variable compression and expansion ratios which can be compatible with different kind of fuels. Furthermore, the FPLGs are cheaper, higher effective, simpler structure and longer service life than conventional ICE [12].

1.4.3 Fuel cell as a range extender

Fuel cells are electrochemical devices similar to the batteries, that converts chemical power to the electricity. Fuel cells divided into five subgroups based on the materials used and working temperature which are alkaline fuel cell, solid oxide fuel cell, phosphoric acid fuel cell, polymer electrolyte fuel cell and molten carbonate fuel cell. The fuel of the fuel cell is stored outside from the fuel cell in the tank, so it is considered the main difference in contrast with battery. The fuel cell does not need to be charged but the fuel tank should be refilled which takes few minutes. The compressed hydrogen gas is used as fuel cell in transportation systems [13]. Fuel cells have not only high efficiency but also they have high power density. However, they are more expensive compared with conventional internal combustion engine and batteries. Another disadvantages of applying fuel cells is the high cost of hydrogen generators. In the fact, fuel cells as range extenders is more feasible than full fuel cell electrical vehicles because of high cost [14].

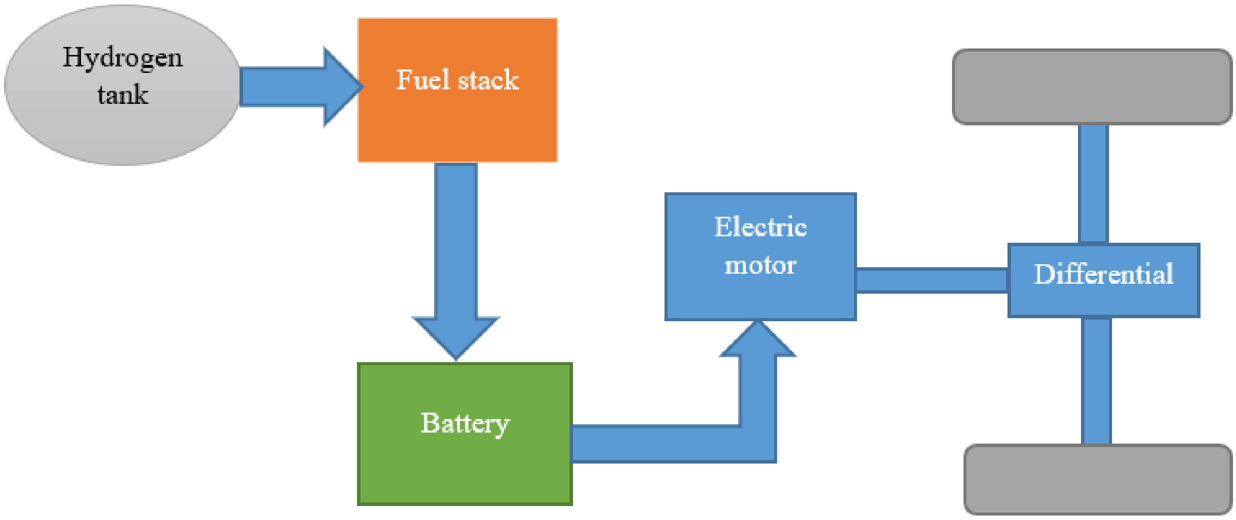

Figure 5. Fuel cell as a range extender configuration

1.4.4 Micro gas turbine as a range extender

A micro gas turbine (MGT) is concerned as a small combustion gas turbine with output power ranging from 30kW to over 200 kW and then also with very high shaft speed [15]. The MGTs are used as one of the options instead of internal combustion engines in range extender electrical vehicles since they can charge the depleted battery. MGTs are generally composed of three main components as an air compressor, a combustor, and turbine [16]. The working principle of MGTs is based on Brayton cycle, where compressed air is mixed with fuel and burned under constant pressure. Afterwards, the combusted mixture expands through a turbine then a shaft rotates and performs generation of electricity.

There are many benefits of using MGTs as range extender in EVs are exits. The MGTs produce significantly decreased exhaust gases in atmosphere as well as an ease operations compared with internal combustion engines. In addition, they have smaller dimensions, which takes a less space in drivetrain configuration. However, some disadvantages are found in applying of MGTs in range extenders that are low fuel to electricity efficiencies, reduced output power, needs of power inverter in order to generate electricity and their high costs [17].

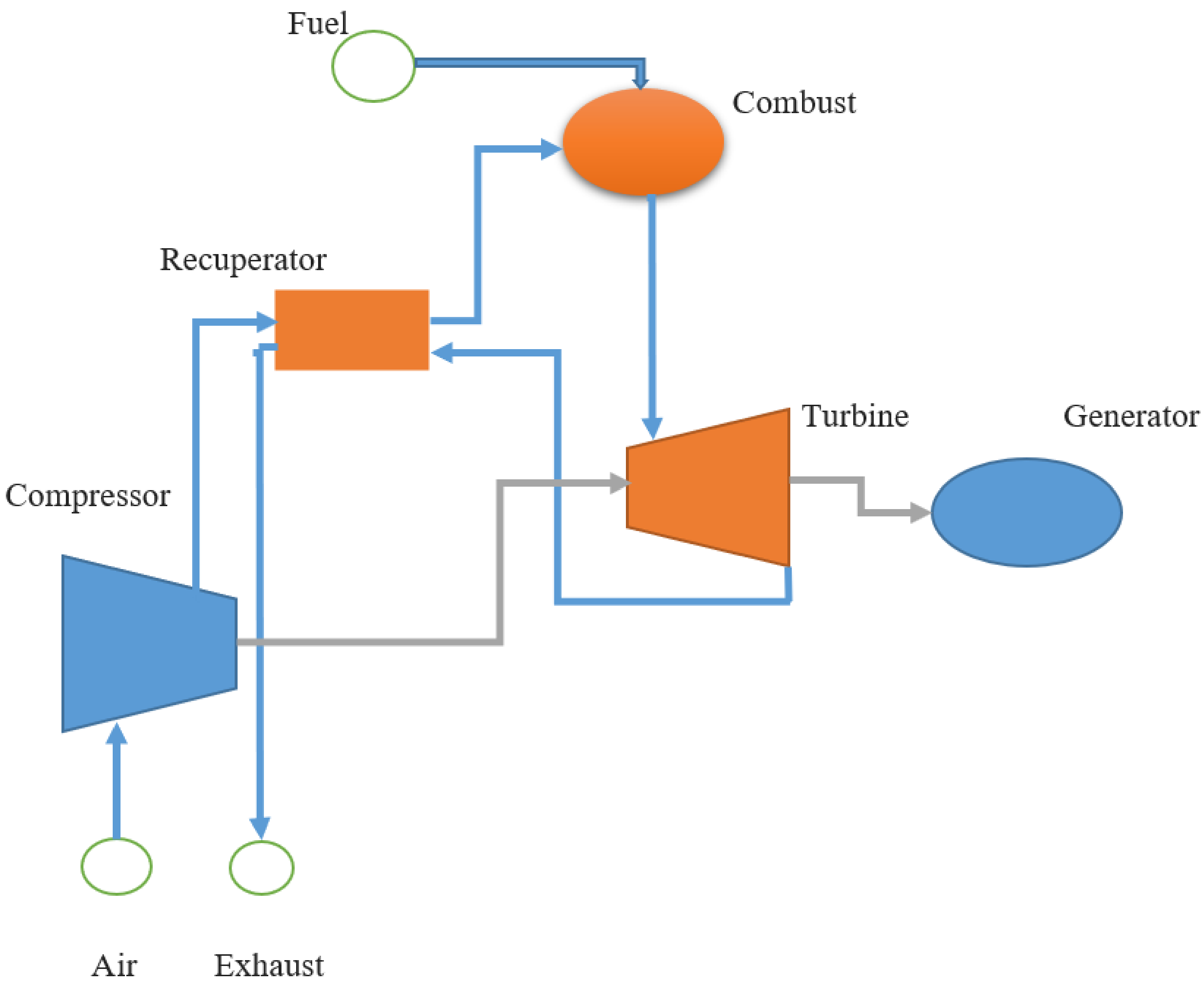

Figure 6. Micro gas turbines as a range extender

2 Modelling of the performance of range extenders

The goal of this section is to construct a model of the Range Extender EVs together with analyzing of modelling approaches. In order to build a full model of the vehicle and to analyze performances of each component, the MATLAB/Simulink has been selected as a simulation software. As well as, EPA UDDS (EPA Urban Dynamometer Driving Schedule) drive cycle has been used for simulation of the model. The 2014 BMW i3 REX is a series type plug – in hybrid range extended vehicle was selected as a real vehicle example.

2.1 Modelling approach

In order to modelling of the HEVs, two kinds of approaches are exist. The first approach is backward also called "quasi static approach" or effect cause method (wheel to engine) and the second approach is forward is called "dynamic approach" or cause – effect method [18].

2.1.1 Forward modelling

Another method is the forward or engine - to – wheel modelling is based on the realization from the cause (force) to the effect (vehicle velocity). The control has to be designed in order to reach the desired velocity, for this reason, this method involves a driver model. The control loop will distribute the energy among powertrain components for vehicle propulsion. Generally, this approach is dedicated to define the control of a system.

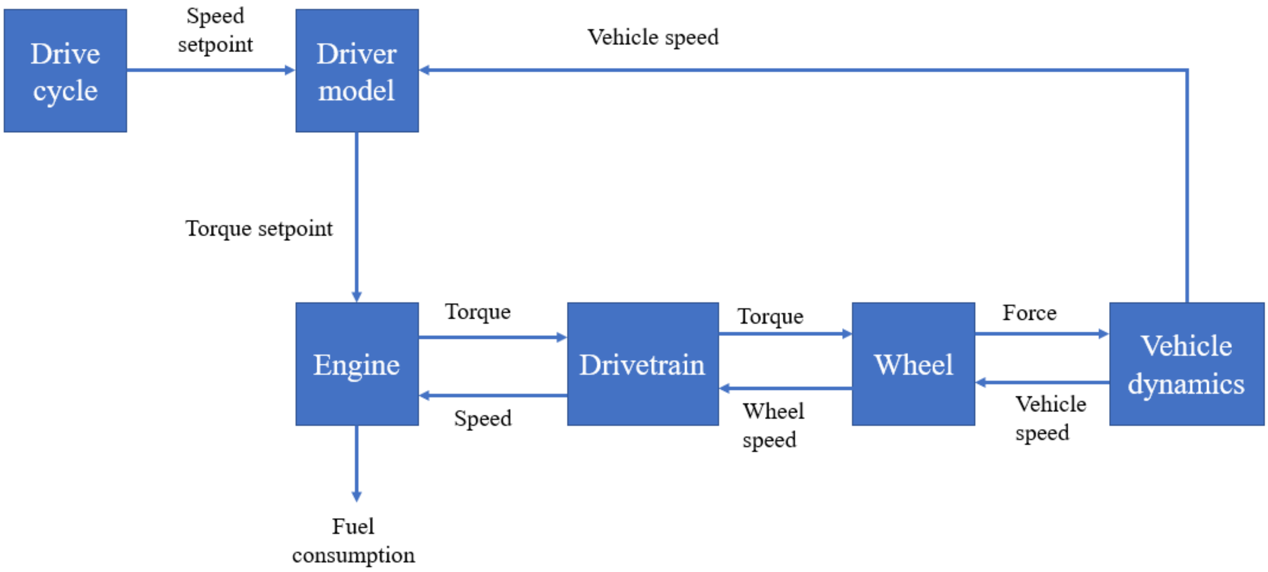

Figure 7. Forward modelling of the conventional vehicle [19]

2.1.2 Backward modelling

The backward approach does not require the model of the behavior of the driver. In order to determine the forces at the wheels, this approach defines the speed profile as an input and then the force is translated to the torque that has to be supplied (by ICE, electric machines …) to deliver the traction [20]. By using of maps for the components of the system, this approach can be faster than forward modelling. Formulation of the backward modelling is given in eq.1.

$$\text{System: } m * \dot{v}_f(t) = F_a(t) - m_f * g * c_r - \frac{1}{2} * \rho_l * c_w * A_f * v_f^2(t) \qquad (1)$$

Cause: force $F_a(t)$

Effect: vehicle speed $v_f(t)$

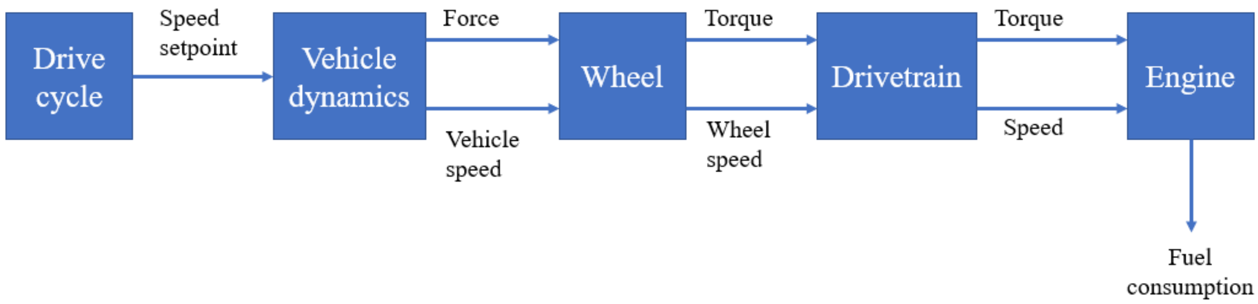

Figure 8. Backward model of the conventional vehicle [19]

2.2 Modelling overview

This section describes the analyzing performances of the vehicle during simulation which is realized from the effect (drive cycle) to the cause (required energy). The model of the 2014 BMW i3 Range Extender is based on backward modelling approach. Figure 1.2.3 demonstrates the full model of the vehicle.

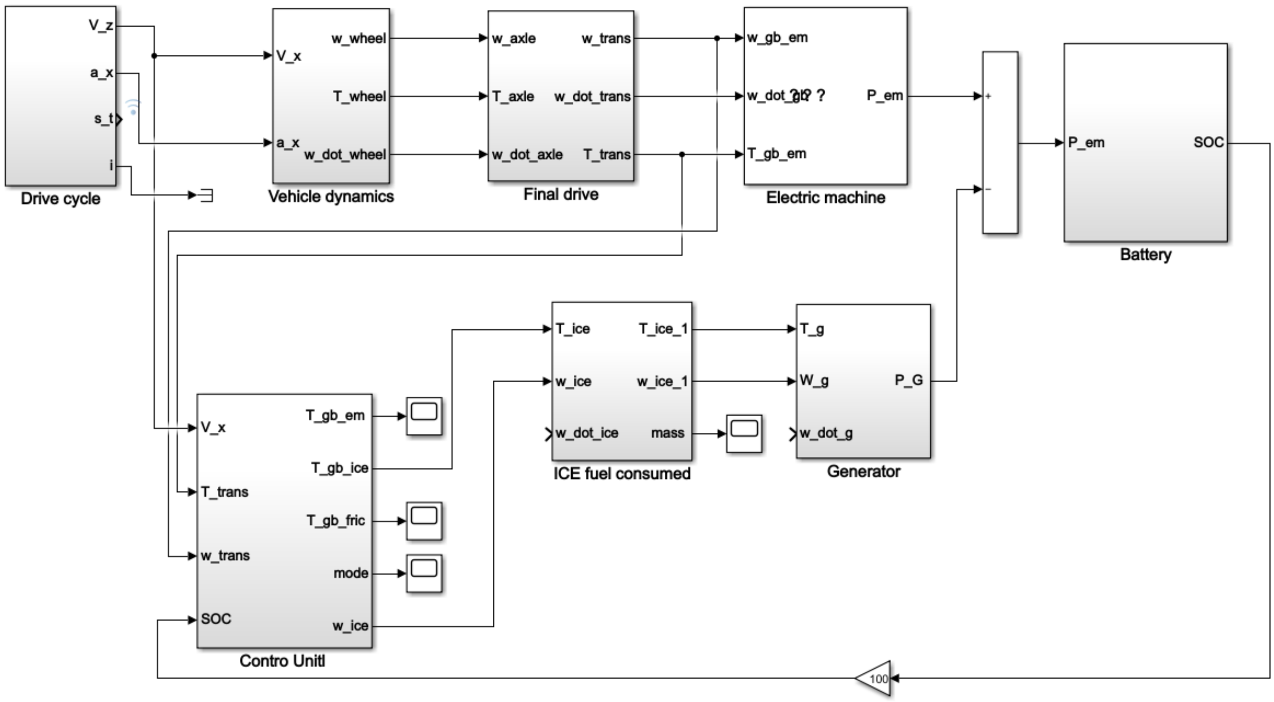

Figure 9. Full vehicle model in MATLAB/Simulink

2.2.1 Drive Cycle

In order to simulate an actual driving behavior, a series of points are needed which represent the vehicle velocity with respect to the time. They can be use in vehicle simulations in order to predict the performance of components of the model. Additionally, drive cycles can be conducted for different purposes such as defining fuel consumption and pollutant emissions. EPA UDDS drive cycle selected as the cycle of the action which has shown in Figure 2.1.1 [21].

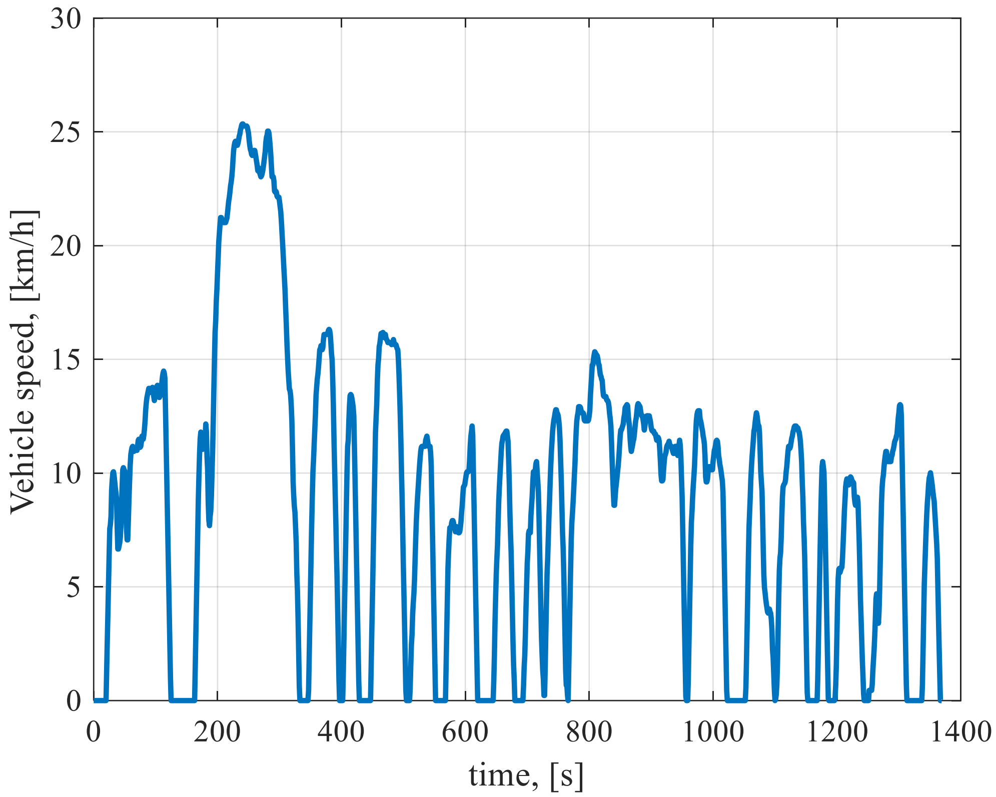

Figure 10. Vehicle speed description in EPA UDDS driving cycle

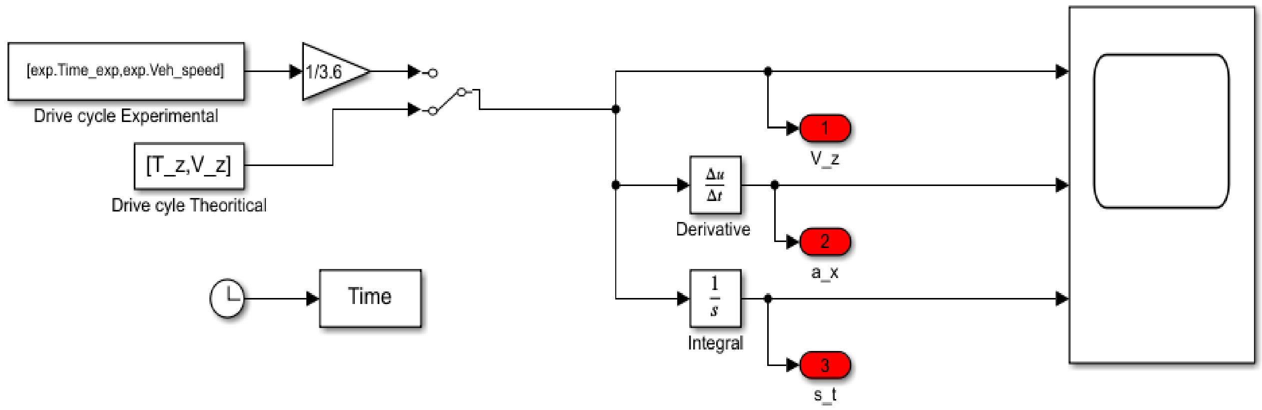

Figure 11. Driving cycle model

The driving cycle can be estimated from the changing velocity of the time. The graph of the change in speed has shown in Figure 10, and the values loaded into the block diagram in Figure 11. In order to get the desired acceleration (eq.1.) and a distance (eq.2.), a derivative and an integral blocks are applied in the model. Both experimental and theoretical data can be loaded into the driving cycle.

$$a_x(t) = dV_x/dt \quad (1)$$

$$S_x(t) = \int V_x dt \quad (2)$$

2.2.2 Vehicle Dynamics

The vehicle dynamics plays an important role in propulsion that involves the vehicle speed and the acceleration as input and generates wheel traction force by considering different forces acting on the vehicle. These forces are transmitted from the electric motor to the wheels by means of a propulsion device to move the vehicle. The motion of a vehicle consists of the following forces that affect it: rolling resistance, aerodynamic drag force and the force generated by linear acceleration. The vehicle has to overcome resistance forces to move.

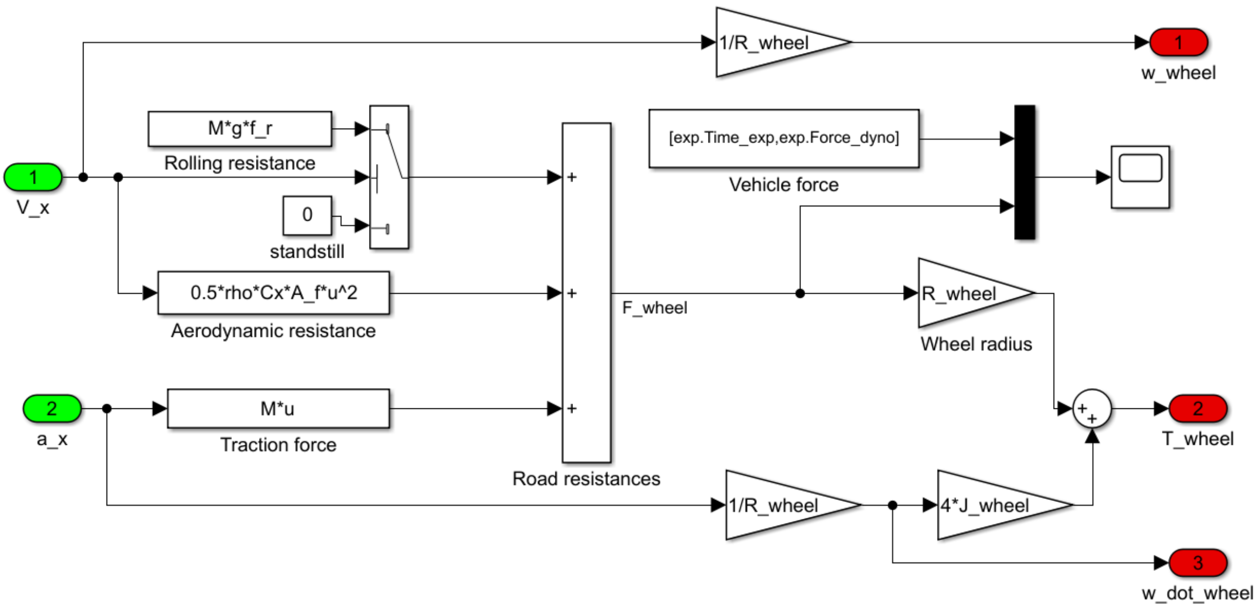

Figure 12. Vehicle dynamics model

Total force (F_t) determined by sum of the rolling resistance force (F_r), aerodynamic resistance force (F_a) and linear acceleration resistance force (F_m) as shown in Figure 2.2.1.

$$F_t = F_{roll} + F_{aero} + F_{tr} \quad (1)$$

$$F_{roll} = M * g * f_r \quad (2)$$

$$F_{aero} = sign(v_x) * (\frac{1}{2} * \rho * C_x * A_f * v_x^2) \quad (3)$$

$$F_{tr} = M * a_x \quad (4)$$

1) Total force

Total force is sum of the all forces effected on the vehicle movement. It includes rolling resistance force, aerodynamic force and traction force as shown in the model.

2) Rolling resistance force

The rolling resistance is indicated as F_{roll} where *M* is the vehicle mass, *g* the gravity acceleration, and f_r the rolling friction coefficient. This coefficient depends on several variables (e.g. vehicle speed, tire pressure...) but in this model it is taken constant.

3) Aerodynamic resistance force

The aerodynamic resistance force acting on the vehicle is F_{aero}. If the vehicle was a prismatic body with a frontal area A_f and an aerodynamic drag coefficient C_x which is taken constant in this model. The air density is ρ and the vehicle velocity is v_x.

3) Traction force

The traction force F_{tr} to propel the vehicle with certain acceleration a_x. Depending on the value of the traction mode vehicle can drive in the following modes:

$F_{tr} > 0$, the powertrain provide the force to the vehicle

$F_{tr} < 0$, the brakes acting dissipating kinetic energy. This energy is stored on the battery and it is called regenerative braking.

$F_{tr} = 0$, the powertrain is disengaged and resistance losses are observed

The output results from this block has shown in Figure 2.2.1 and they are angular velocity (ω_w), angular acceleration (w_dot_w) and torque (T_w) in the wheels. Delivered power (P_w) to wheel can find by using eq.8.

$$\omega_w = \frac{v_x}{R}; \tag{5}$$

$$\omega\_dot_w = \frac{a_x}{R}; \tag{6}$$

$$T_w = F_t * R + \frac{a_x}{R} * 4 * J_w; \tag{7}$$

$$P_w = F_t * v_x; \tag{8}$$

Knowing that the wheel torque (T_w) and mechanical power (P_w) generated by the vehicle's wheels can also be expressed in this block, it is possible to create graphs of them as well. These mechanical results delivered to the next GEARBOX blocks.

Table 2.2.1 shows the vehicle dynamics specifications and wheel parameters of proposed vehicle model.

Table 2.2.1

BMW i3 2014 Range Extender vehicle dynamics specifications	**Values**
Vehicle mass *[kg]* – *M*	1567
Aerodynamic drag coefficient – C_x	0.3
Rolling resistance coefficient – f_r	0.006
Air density [*kg/m³*]– *ρ*	1.21
Frontal area *[m²]* - A_f	2.38
Wheelbase *[cm]*	257
Size *F/R [cm]*	155/70R19|175/60R19
Pressure *F/R [Pa]*	227.5/282.7
Moment of inertia of the one wheel	1.13

2.2.3 Final drive

In the specifications of the BMW i3 REX was mentioned that, it has a single-speed automatic transmission. Two parameters include angular acceleration (w_dot_w) and angular velocity (w_w) of the vehicle should multiply by the single gear ratio (U_f) by passing through gearbox. One of the main functions of the transmission system is the torque between the electric motor and the wheel. The required electric motor torque (T_{em}) can be calculated by considering efficiency of the gearbox (η_{gb}) and gear ratio. As mentioned below, determination of the torque is depended on the direction of the power flow.

It was mentioned that the vehicle has a single-speed automatic transmission

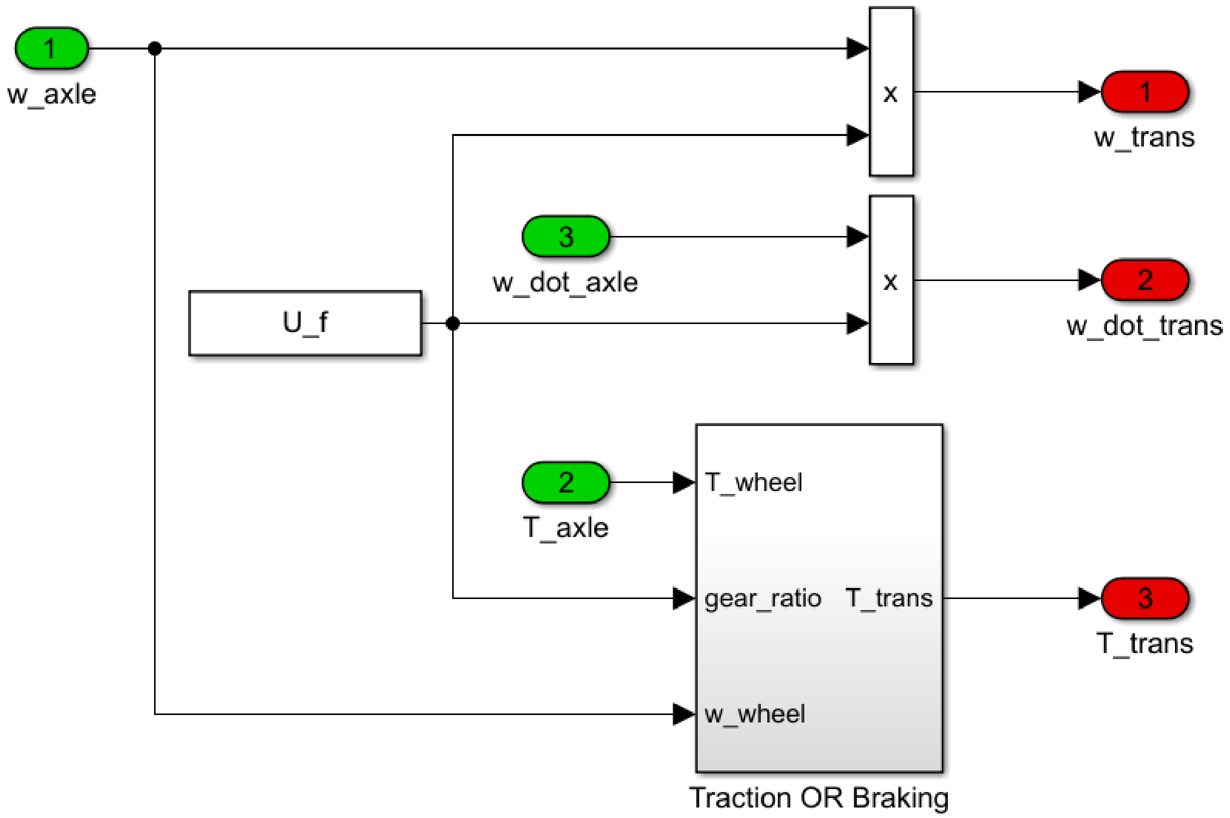

Figure 13. GEARBOX block

The resulting equations are input parameters for the electric motor. It is necessary to determine the direction of power flow and this block is divided into two sub-blocks. The power flow direction is determined through these sub-blocks and these sub-blocks are shown in Figure 14. Depending on the movement of the vehicle, traction or braking mode is activated. The determined parameters are realized by the following equations 1,2 and 3.

$$w_{em} = w_w * U_f ; \quad (1)$$

$$a_{em} = w\_dot_w * U_f; \quad (2)$$

$$T_{em} = \begin{cases} \frac{T_w}{\eta_{gb}*U_f} - \text{Traction mode} \\ \frac{\eta_{gb}*U_f}{T_w} - \text{Braking mode} \end{cases} \quad (3)$$

Where,

w_{em} - angular velocity of electric machine [rad/s]

a_{em} - angular acceleration of electric machine [rad/s^2]

η_{gb} - efficiency of a gearbox [-]

In addition, this transmission model is determined based on the following equation:

$$F_{tr} = \frac{T_{em} * U_f * \eta_{gb}}{R} \quad (4)$$

Where,

F_{tr} – traction force [N].

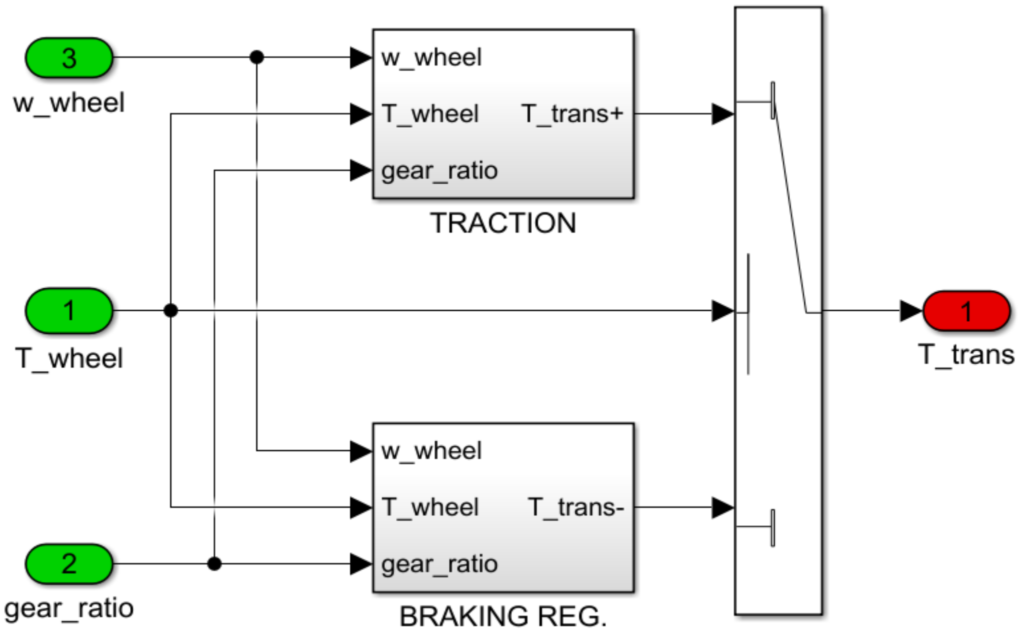

Figure 14. Traction and Braking mode in power flow direction block

Transmission parameters used in modelling of the vehicle are shown in Table 2.3.1.

Table 2.3.1

Transmission Identification	GE1B130H/GE1B131H
Type	Single gear
Single gear ratio	9.7:1

2.2.4 Electric motor

An electric machine (EM) in a HEV is used in two ways, either as a motor or as a generator/alternator. The difference between a generator and an alternator is that the alternator delivers an alternating current, which is rectified, while a generator delivers a direct current. In generator mode the EM converts mechanical energy into electrical energy to charge the battery. In motor mode the EM converts electrical energy, from the battery, into mechanical energy to propel the vehicle.

Generally, the electric power from the battery is delivered to the EM in Backward model. The propulsion of the vehicle is ensured as a result of the transmission through the gearbox to the wheels. In the model of the vehicle, the EM will define necessary energy for the driving. According to the battery state of charge, the EM can use energy from battery or generator which converts fuel energy to the electrical.

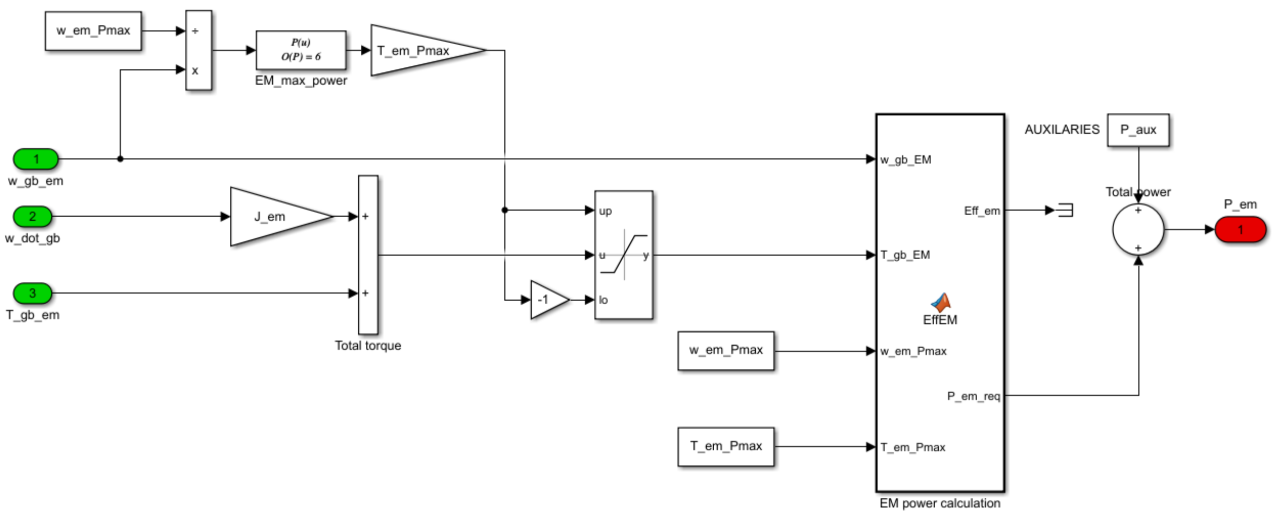

Figure 15. EM model

Using the equations given in the previous block, ω_{gb_em}, ω_{dot_gb} and T_{gb_em} are comes from the gearbox as an input to the EM. These parameters are used to determine the needed electrical power (P_{em}) for the propulsion. There is used a power calculation function block for calculation. Additionally, there is also auxiliary power that need to use extra components (air conditioner, heater and etc.) of the Range Extender electric vehicle. It should be noted that the value of P_{aux} varies depending on driver's needs in the ambient. For example, on a winter day, more power is required as a result of using the heater. So, the total electric power is calculated by using the eq.1. Figure 15 represents the schematic block of the EM in MATLAB/Simulink.

$$P_{em} = w_{em} * T_{em} + P_{aux} \quad (1)$$

In this case, the characteristic limitations of the operation of EM in determining the minimum and maximum torque. For that reason, it can be need to check the transmitted gearbox torque. This torque provided as electric motor torque (T_{em}) which already known. The border of T_{em} is following:

$$T_{\max\_em} < T_{em} < T_{\min\_em} \quad (2)$$

Performance testing and efficiency mapping for the 2014 BMW i3 was conducted at various torques and speeds. From the literature, an efficiency map of the electric motor is made by using Web Plot Digitizer tool [22,23]

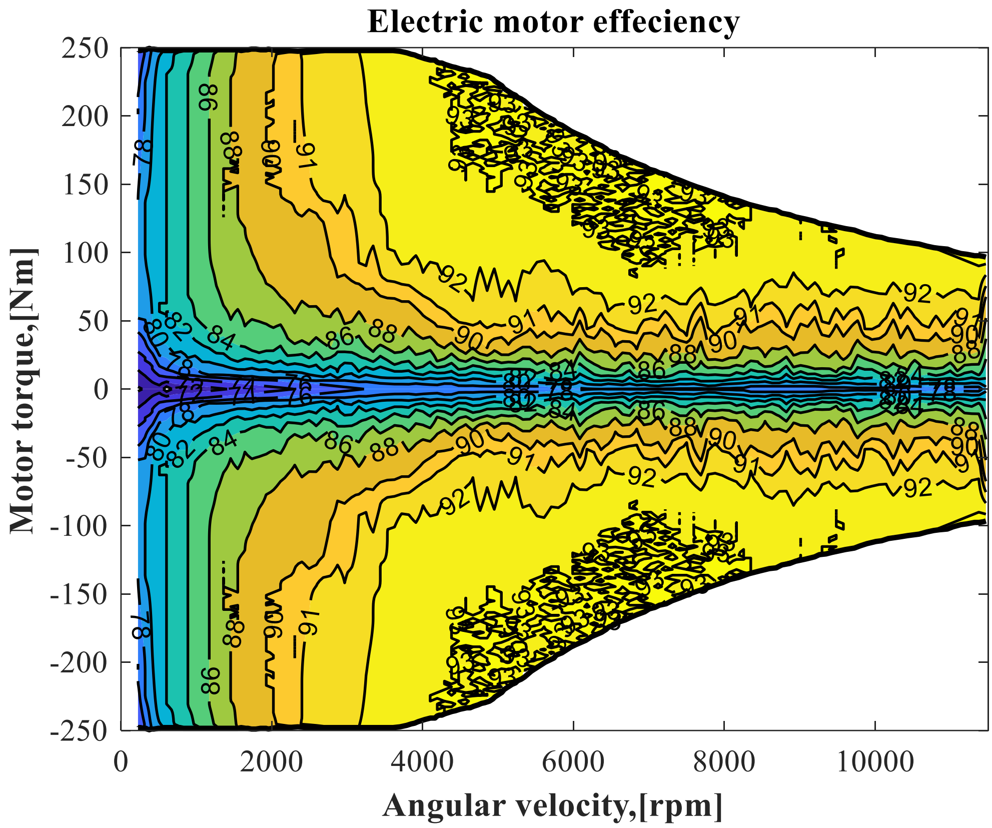

Figure 16. 2014 BMW i3 REX motor efficiency-Electric motor efficiency

The efficiency of the electric motor (η_{em}) is depended on the angular velocity (w_{em}) and torque (T_{tot_em}). It should be following:

$$\eta_{em} = f^*(w_{em}, T_{tot\_em}) \quad (3)$$

$$T_{tot\_em} = T_{em} + \frac{a_t}{R} * J_w; \quad (4)$$

An electric motor parameters of 2014 BMW i3 Range Extender have shown in Table 2.4.1

Table 2.4.1

Type	PM AC Synchronous
Maximum power *[kW]*	125
Maximum torque *[Nm]*	250

2.2.5 Battery

The energy storage systems are considered an important component of the PHEVs, HEVs and pure EVs. Usually, three kinds of batteries are used in EVS including Lithium – ion battery, Nickel – metal hydride battery and Lead – Acid battery. In the most cases, PHEVs use Lithium – ion batteries by considering several advantages. This type of the batteries have the highest energy capacity with small size among other rechargeable batteries (100-265 W/kg) [24]. Lithium – ion batteries always give their last bit of the power and performs at a lower capacity after repeated charge cycles.

Performance and Longevity - Lithium-ion chemistry is highly efficient compared to other types of batteries. In addition, they are capable of delivering voltages up to 3.6 volts, which is three times higher than their nickel alternatives. Due to the very low self-discharge rate (approximately 1.5-2% per month), batteries have a long lifespan [24].

Versatility - Lithium-ion batteries have an ideal level of solution in collecting renewable energy during various motion cycles. The technology can be a great solution for high-powered devices.

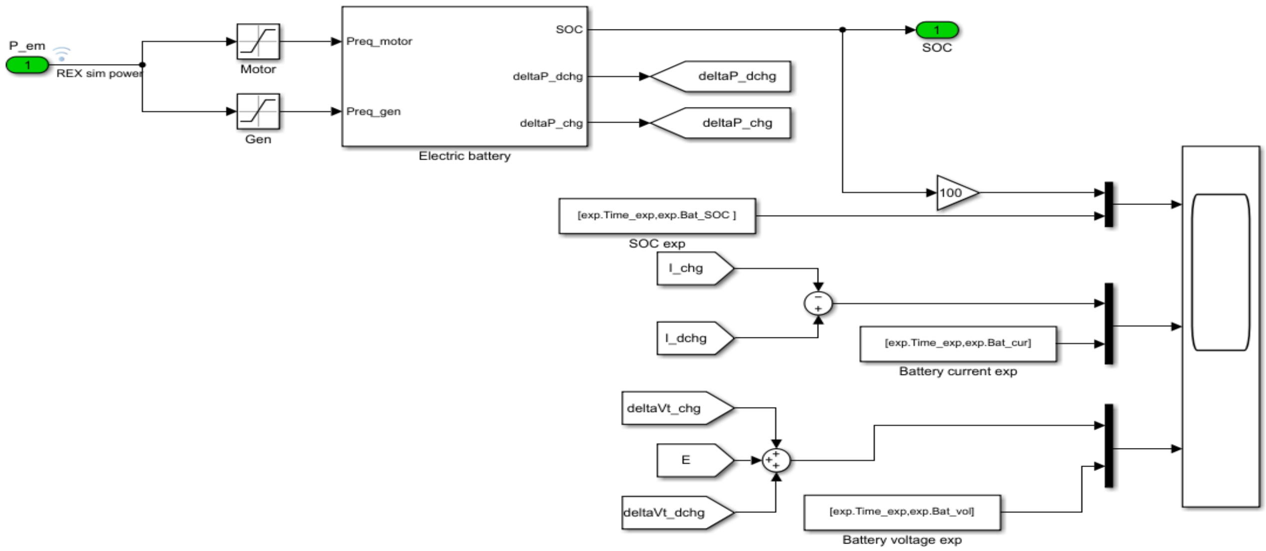

Figure 17. Battery model

In this section, dynamic charging and discharging characteristics of the lithium – ion battery is modelled to determine its operating voltage and SOC with a satisfactory level of accuracy. From the literature, two kinds of methods in battery modelling are exist which are the equivalent circuit network (ECN) and electrochemical approaches [25]. In order to build the model of the battery, ECN modelling technique is used because it can be used in a real time applications. As well as, the battery is modelled using the Thevenin model that is the most popular ECN model as shown in Figure 18.

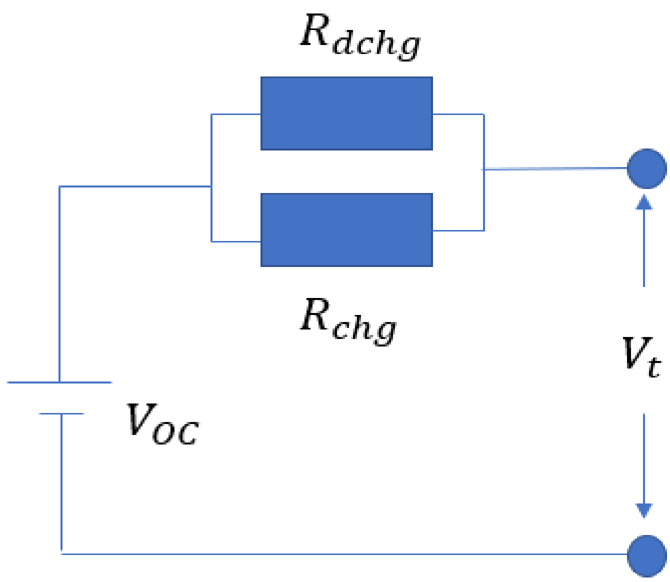

Figure 18. Thevenin model of the battery electrical circuit [26].

Charging resistance (R_{chg}), discharging resistance (R_{dchg}) and open circuit voltage (V_{OC}) are analyzed as function of battery SOC in the Thevenin model. The total demanded power for the vehicle propulsion is the input to the battery. On the other hand, the SOC is the output in the battery model [27].

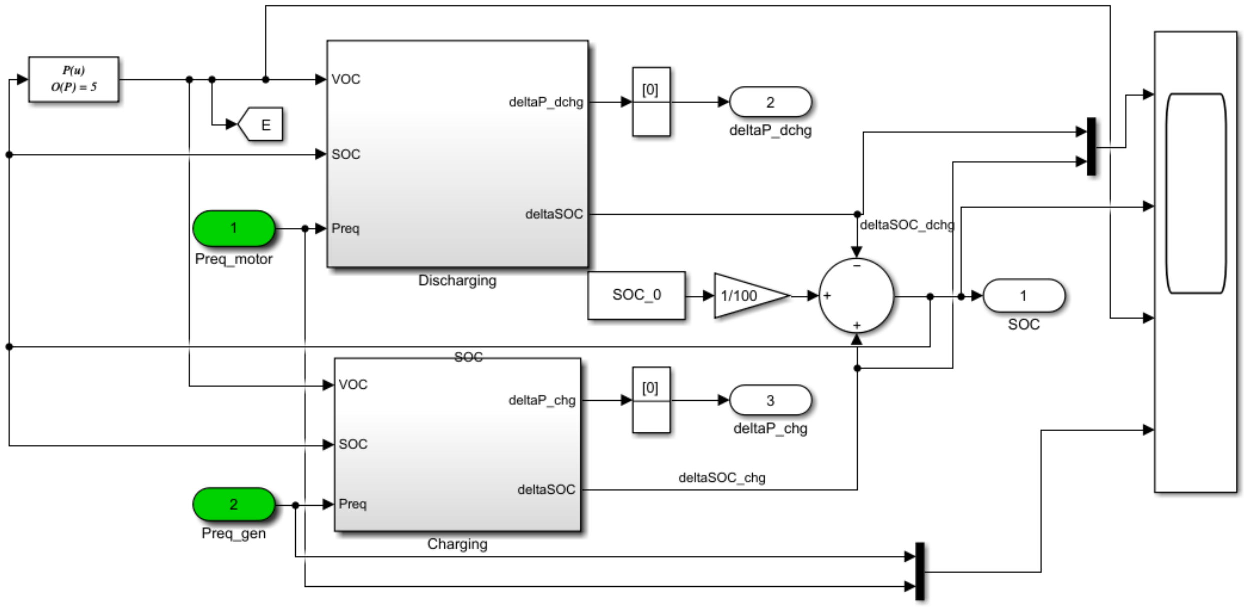

Figure 19. Working principle of charging/discharging of the battery

The SOC of the battery has been calculated in the following equation.

$$SOC = \begin{cases} SOC_i - \dfrac{\int_{t_0}^{t} I_{dchg} dt}{Q_{nom}} - Traction\ mode \\ SOC_i + \dfrac{\int_{t_0}^{t} I_{chg} dt}{Q_{nom}} - Braking\ mode \end{cases} \quad (1)$$

Where,

SOC_i – initial value of state of charge [-]

Q_{nom} – nominal value a battery capacity [C]

I_{dchg} – value of discharging current [A]

I_{chg} – value of charging current [A]

By knowing the value of R_{chg} and R_{dchg} and V_{OC} it should be evaluating the I_{dchg} and I_{chg} by solving the following equations:

$$I_{dchg} = \frac{V_{OC} - \sqrt{V_{OC}^2 - 4 * R_{dchg} P_{bat}}}{2R_{dchg}} \quad (2)$$

$$I_{chg} = \frac{-V_{OC} + \sqrt{V_{OC}{}^2 - 4 * R_{chg} P_{bat}}}{2R_{chg}} \tag{3}$$

From the Thevenin model battery power (P_{bat}) also analysed by using the given components. Power balance equation applied to equivalent circuit.

$$P_{batt} = \begin{cases} I_{dchg} * V_{OC} - I_{dchg}^2 R_{dchg} - Traction\ mode \\ I_{dchg} * V_{OC} + I_{dchg}^2 R_{dchg} - Braking\ mode \end{cases} \tag{4}$$

Analysis of open circuit voltage, charging resistance and discharging resistance by battery SOC in MATLAB/Simulink is shown in Figure 20.

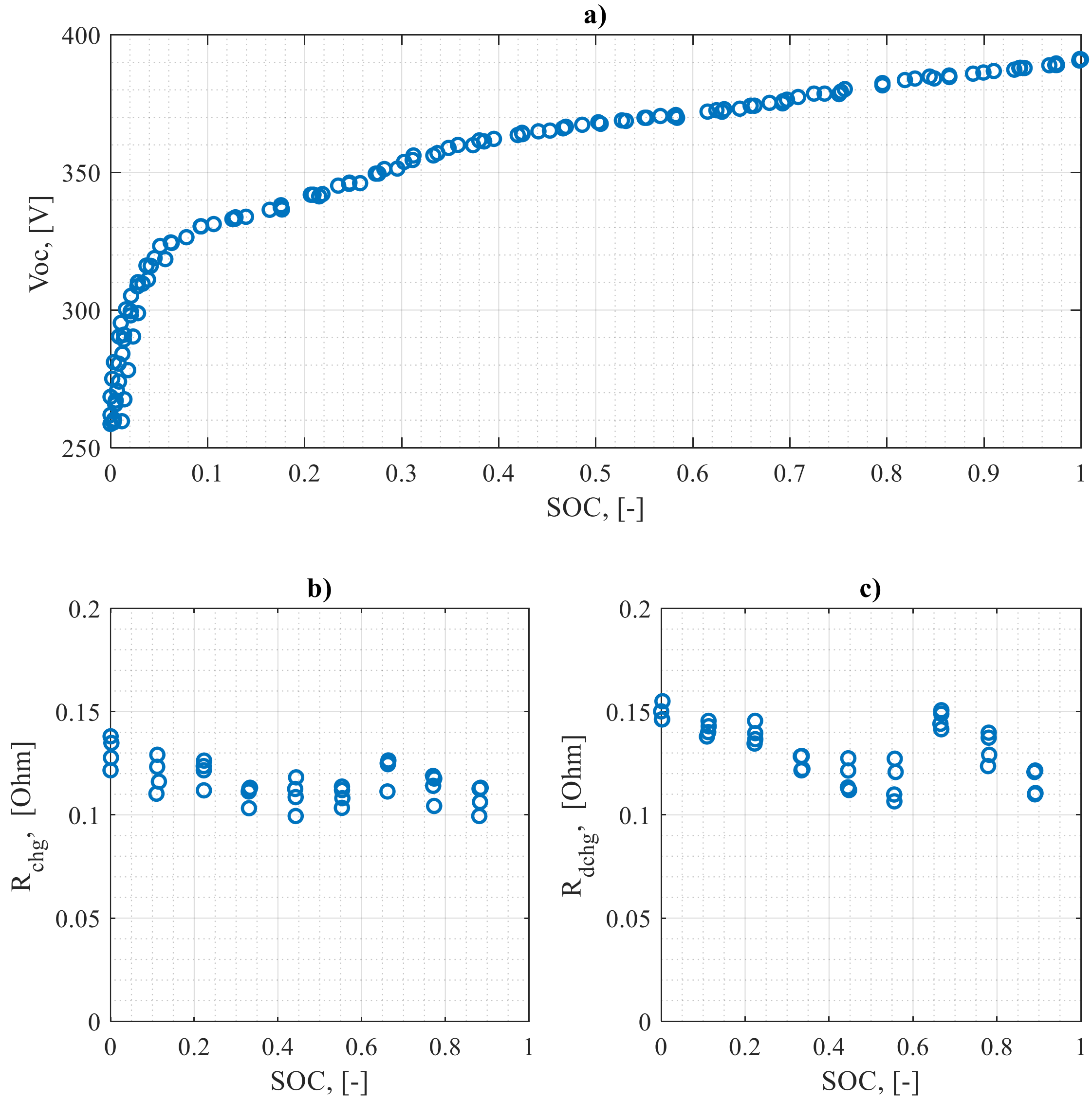

Figure 20. V_{OC} , R_{dchg} and R_{chg} analysis by SOC

Table 2.5.1 shows the specifications of battery which is used in modelling of Range Extender EV.

Table 2.5.1

Manufacturer	Samsung SDI
Type	Lithium-Ion
Cathode material	NCM
Number of cells	96
Cell configuration	8 modules,12Cells per module, Connected in series
Nominal cell voltage *[V]*	3.7
Nominal system voltage *[V]*	355.2
Rated pack capacity *[Ah]*	60
Rated pack energy *[kWh]*	18.8
Weight of pack *[kg]*	235
Pack specific energy *[Wh/kg]*	79.8
Pack Energy density *[Wh/l]*	98.5
Pack location	Underneath vehicle center
Thermal management	Active refrigerant

2.2.6 Internal combustion engine

Generally, the range extender EVs have two energy sources which are a battery pack and an internal combustion engine (ICE). When the vehicle operates as pure electrical or as hybrid electrical modes, we will later discuss in the developing of control strategy section. Now, we will deal with the mathematical modelling of the ICE and its implementation in MATLAB/Simulink. The model of the ICE is quite simple. It involves requested torque by the control unit (T_{req_ice}) and the rotational speed of the crankshaft (w_{ice}). The outputs are delivered torque (T_{del_ice}) and fuel mass flow rate (m_{dot}). In order to find fuel mass flow rate, some mathematical formulas are needed. It is directly connected to the brake specific fuel consumption (BSFC) which is a parameter that indicates the efficiency of the engine which burns the fuel and generates rotational power at the shaft. Generally, BSFC is used evaluating the efficiency of the ICE in automotive engineering. In our case, we have the efficiency map of the engine which gets as the result of tests [28]. Mathematical description of the model as following:

$$\dot{m}_f = BSFC * P_e \tag{1}$$

$$T_e = \frac{n_c * V_d * p_{me}}{2 * pi * n_r} \tag{2}$$

$$P_e = w_e * T_e \tag{3}$$

Replacing (2) and (3), we can rewrite the formula for mass flow rate as the function of the mean effective pressure of the engine:

$$\dot{m}_f = \frac{BSFC * w_e * n_c * V_d * p_{me}}{2 * pi * n_r} \tag{4}$$

In the formula (4), we need define a cylinder displacement V_d which is calculate as below,

$$A_p = \frac{pi * B^2}{4} \tag{5}$$

$$V_d = S * A_p \tag{6}$$

Rewriting the formula (6) by putting (5) in (6), we can get the cylinder displacement V_d:

$$V_d = S * \frac{pi * B^2}{4} \tag{7}$$

Where,

$\dot{m}_f$ – mass flow rate [kg/s];

$BSFC$ – brake fuel consumption rate [kg/J];

P_e - effective engine power [W];

w_e - engine speed [rad/s];

T_e – effective engine torque;

n_c – number of cylinders;

V_d – cylinder displacement [m^3];

p_{me} – mean effective pressure [Pa];

n_r – number of crankshaft rotations for a complete engine cycle;

B – cylinder bore of the engine;

S – stroke of the engine;

The mass flow rate of the engine is calculated by the brake specific fuel consumption map of the engine and provided parameters of the engine of the BMW i3 Range extender in the Table 2.6.1

Table 2.6.1

Internal combustion engine parameters	**Values**
Model	DOHC-8 valve I-2
Maximum output power [kW]	25
Maximum engine torque [Nm]	55
Maximum engine speed [rpm]	4300
Displacement [l]	0.647
Fuel type	Gasoline
Fuel tank capacity [l]	7.2

The break specific fuel consumption of the engine is usually represented as a contour plot with together engine speed and torque.

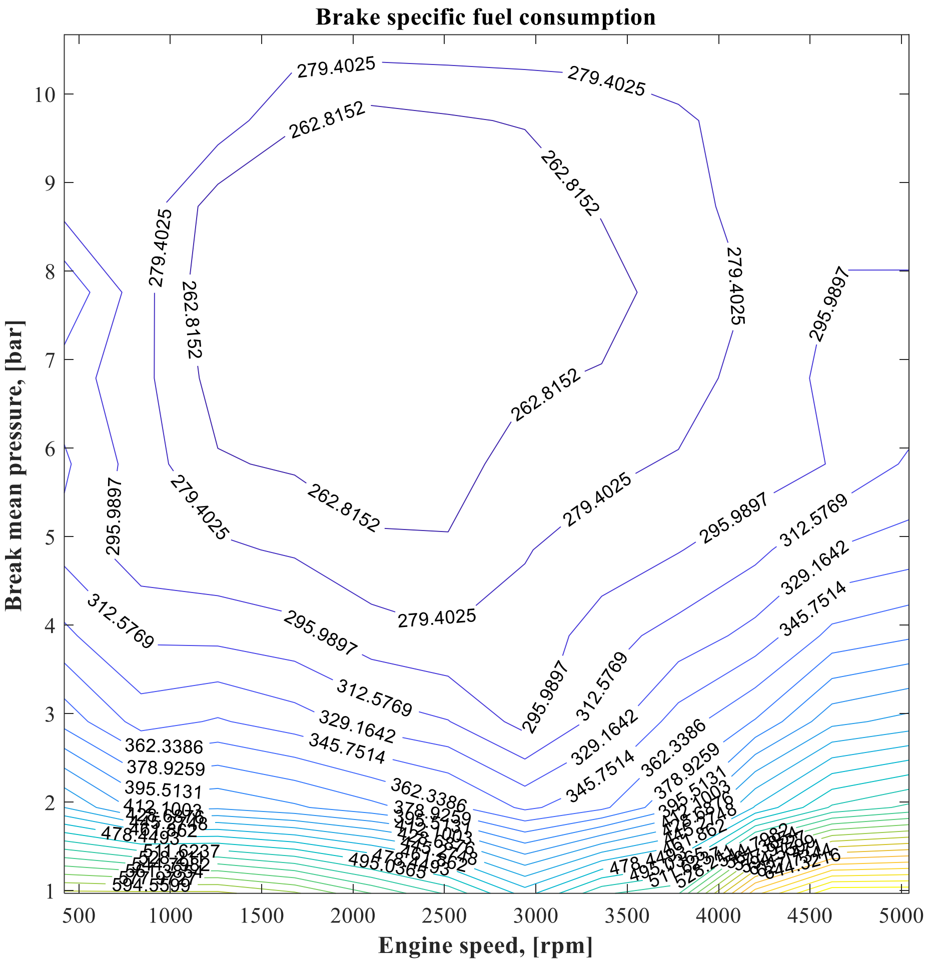

Figure 21. Brake specific fuel consumption map of the engine model [28]

As the result, we obtained the Simulink model is based on the mathematical modeling of the engine. Additionally, the model will measure fuel consumption of the engine in gramms.

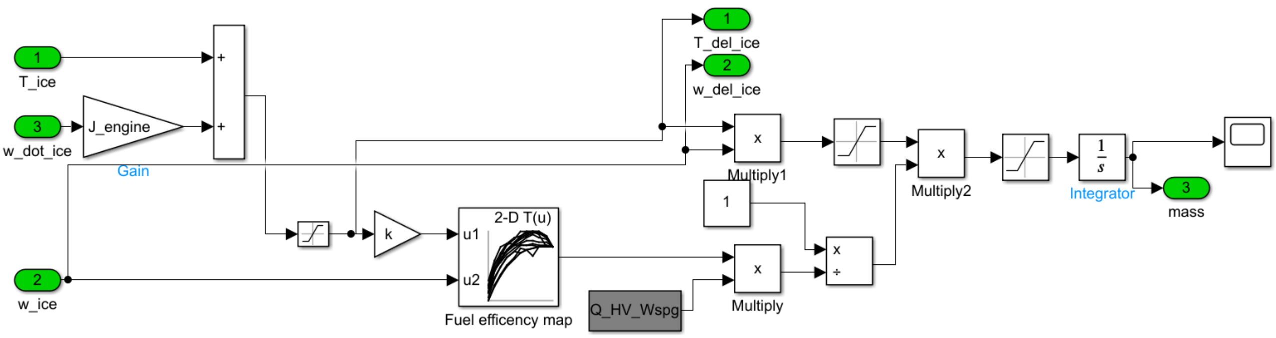

Figure 22. The engine model

2.2.7 Generator

In a Range Extender EVs, a generator is a device that converts mechanical power to electrical power. Source of mechanical power includes an internal combustion engine in our model. The generator model receives an engine torque and angular velocity as inputs and generates electrical power.

The efficiency of the generator (η_{gen}) is formed by the dependence of the angular velocity (w_{gen}) and torque (T_{tot_gen}). It should be following:

$$\eta_{gen} = f\ (w_{gen}, T_{tot\_gen}) \tag{1}$$

$$T_{tot\_gen} = T_{em} + w_{dot\_gen} * J_{gen}; \tag{2}$$

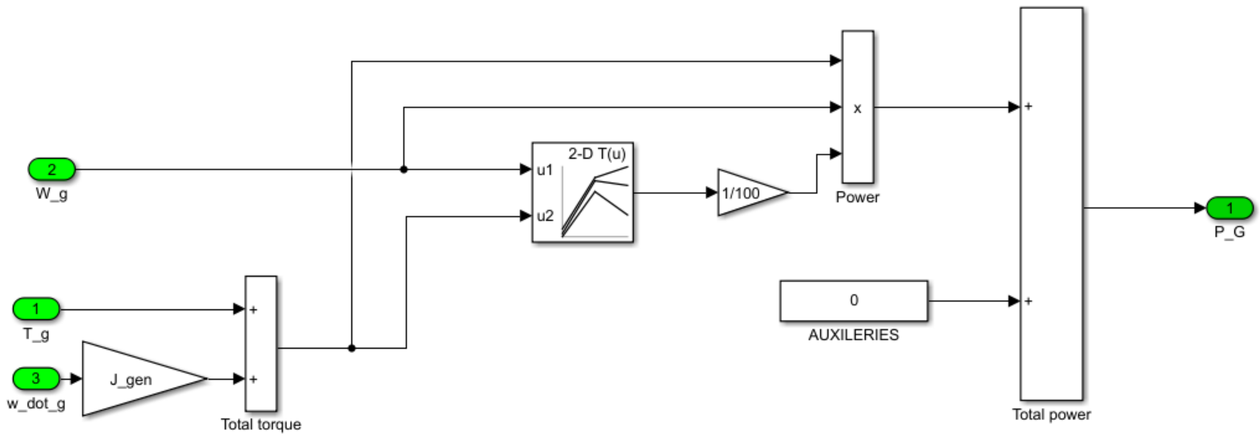

Figure 23. Generator model

Parameters of generator is used in the model have shown in Table 2.7.1.

Table 2.7.1

Maximum torque *[Nm]*	250
Output power *[kW]*	26.6

2.2.8 Control unit

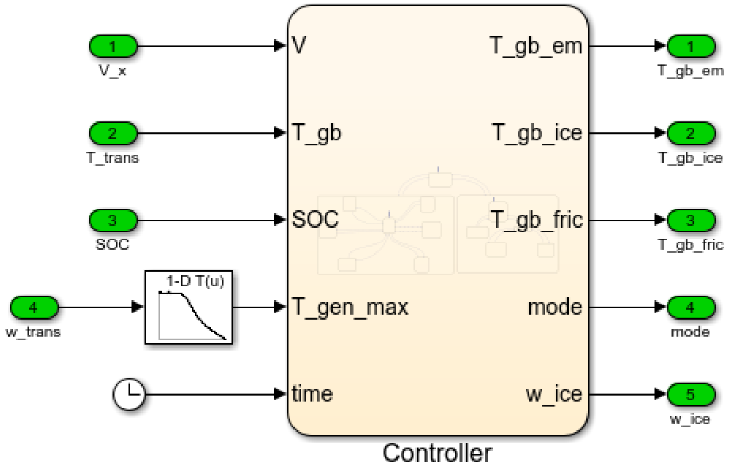

Figure 24. Controller block of EV

Designing of controller block was one of the main goals in this thesis. The vehicle speed, required torque by the gearbox and battery SOC are given through an input port. The limit torque values of the generator is implemented through a 1- D look-up table. There is also given time through clock in order to check control modes.

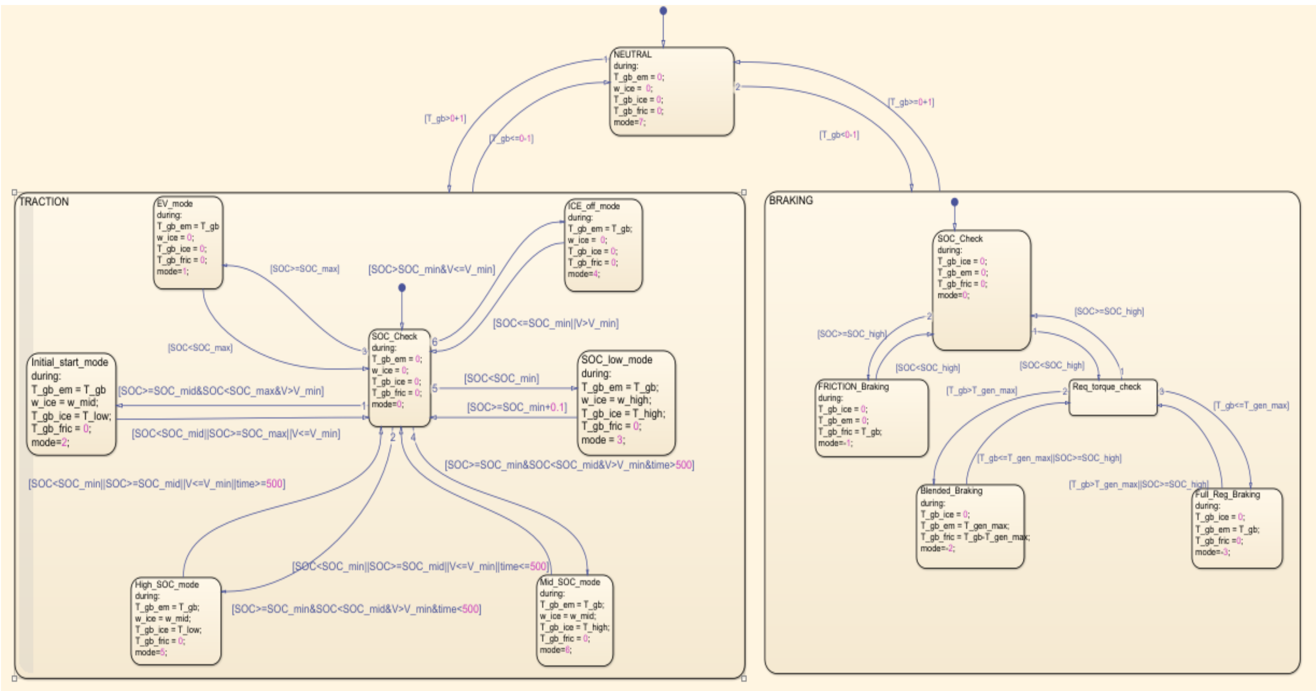

Figure 25. Demonstration of control modes by Stateflow chart

Execution of control modes has shown through Stateflow chart in controller block. Initially, the control should decide to enter TRACTION or BRAKING block depending on value of the torque which requires by driving cycle. The variation of battery SOC, vehicle speed and time defines which the control should execute. More clarified explanations of the controller and operating modes are given in the next chapter.

3 Development of control strategy

3.1 Range extender control strategy

By using of the battery and the internal combustion engine as energy sources in HEV technologies are requested more complicated control algorithms. In a range extended electric vehicle, there are exist charge depleting (CD) and charge sustaining (CS) mode control strategy. The vehicle is driving as pure electric in CD mode. Apart from this, it includes an appropriate control algorithm in a charge depleting mode. Analysis of control strategies are described in the next chapters.

The series hybrid drive systems are requested much simpler control algorithm than parallel or mixed hybrid technologies. As we know, Range extender drive system is based on series hybrid drive. In these days, many control strategies are used in such systems.

One of the such method is that, the battery state of charge (SOC) is divided in two modes. Charge depleting (CD) mode – after a full charge of the battery the vehicle operates as battery electric vehicle (BEV). When the battery is discharged till the certain threshold value of the SOC, the vehicle operates in charge sustaining mode (CS). In this mode, the internal combustion engine is turn on and tries to maintain SOC in proper state [29].

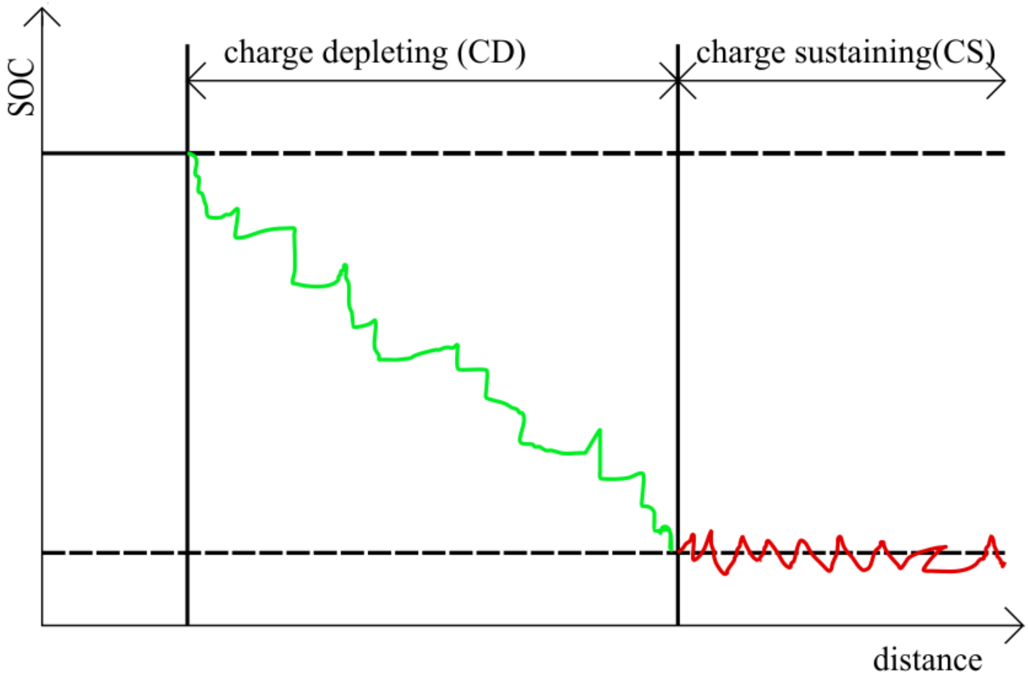

Figure 26. Charge depleting (CD) vs charge sustaining (CS) modes

Controlling the vehicle in CD mode is the same with BEV. An electric motor receives all needed power for the propulsion from the battery pack. However, CS mode requires a more complicated control strategy. By operating of internal combustion engine (ICE), there can be two energy sources and an electric motor can get required power from generator. In addition, the generator supplies power to charge the battery in order to keep its proper state.

In this thesis, control model of BMW i3 REX is designed and analyzed by real vehicle test results.

During modelling of BMW REX drivetrain, of course, we need to design model of the controller in order to get results and compare with experimental values. The controller is designed using of Stateflow in Matlab/Simulink based on control strategy modes that is described above. Every operating mode described by a state. Switching of one state to another is depended on setting conditions given in control modes.

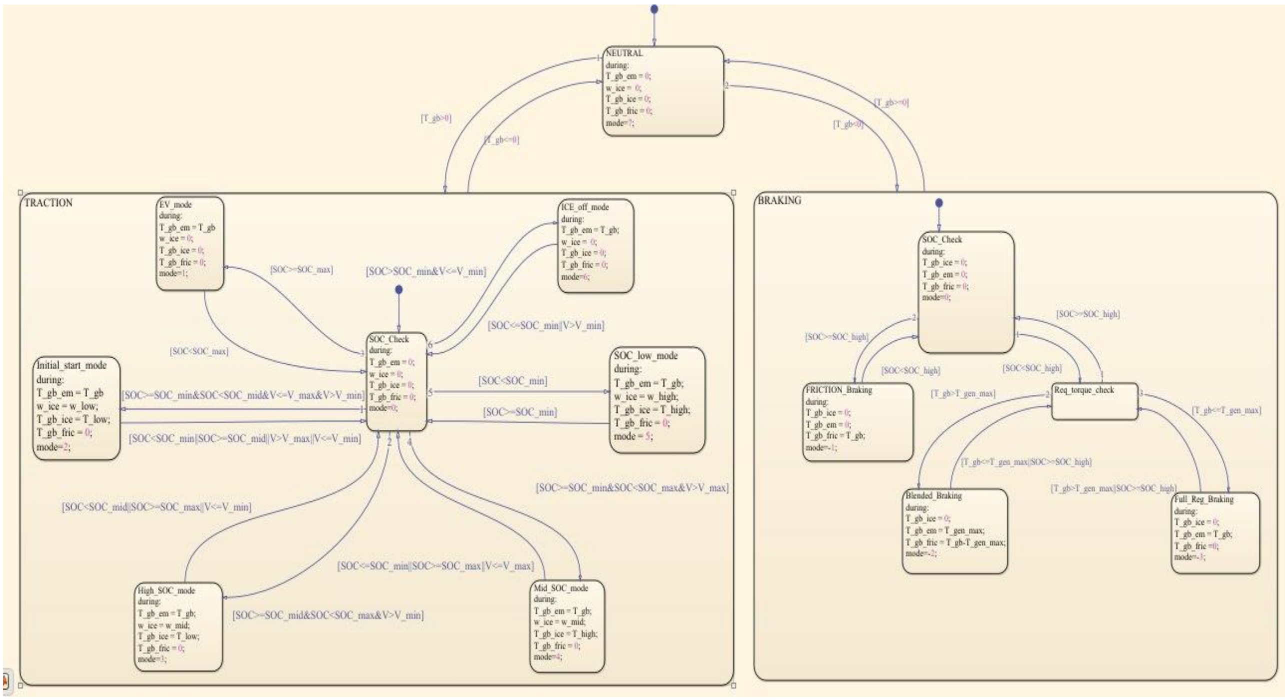

Figure 27. Design of the controller

Firstly, there is NEUTRAL state defines each parameter is zero. We know that, there is the requested torque is greater than zero, traction operation will be set whereas the torque is less and equal to zero vehicle operates at braking.

3.1.1 Control strategy for traction operation

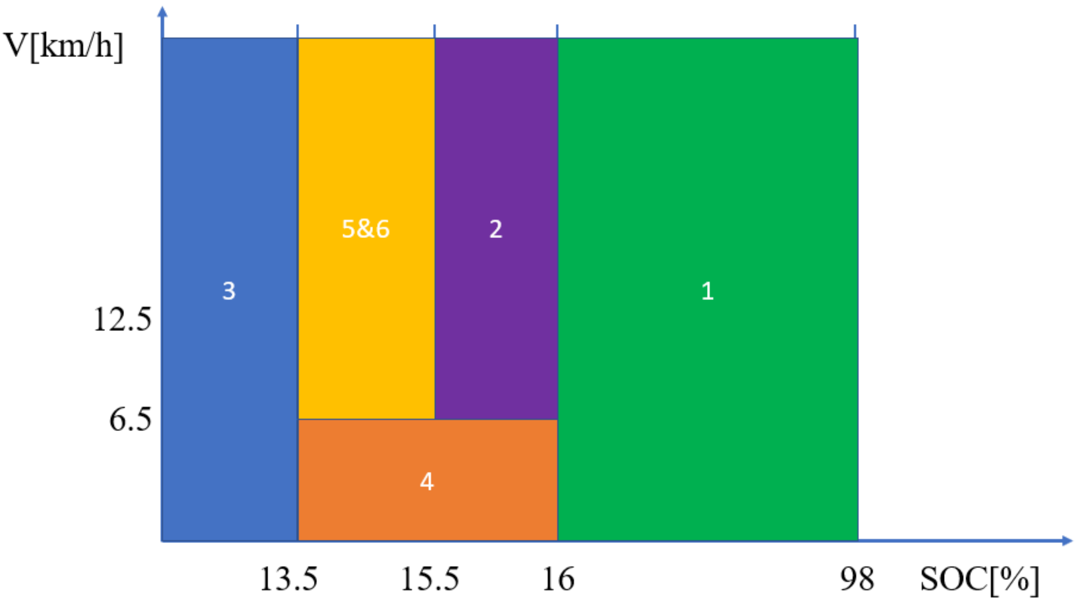

Figure 28. Traction operating modes

Traction operation of the vehicle is based on six type control modes and is determined by vehicle speed and battery SOC. From the real vehicle test results, it is defined the threshold value for changing CD and CS modes is equal to 16 % [30]. Below, we analyze each operating modes. SOC is divided to four ranges as SOC_{min}, SOC_{mid}, SOC_{max} and SOC_{high} as well as the vehicle velocity is determined V_{min} and V_{max}.

When the vehicle enters to the CS mode, the engine should deliver requested power to the propulsion. Of course, required power is defined by engine operating speed and torque. From the experimental data, we found that engine operating speed can be divided into low, medium and high values as well as engine operating torques can be split into low and high ranges. Each mode describes vehicle operating state respectively.

1- **EV mode.** When the vehicle drives in CD mode, ICE is turned off and an electric motor receives required power from the battery. SOC is decreased till threshold value. This mode defines the engine operating torque and speed are equal to zero.

   $SOC >= SOC_{max}$,

   $T_{em} = T_{gb}$;

   $w_{ice} = 0$;

   $T_{ice} = 0$;

   $T_{gb.fric} = 0$;

2- **Initial start mode.** When the engine initially starts to work, operating engine speed and torque can be reach low value.

   $SOC_{min} <= SOC < SOC_{mid}$, $V_{min} < V <= V_{max}$,

   $T_{em} = T_{gb}$;

   $w_{ice} = w_{low}$;

   $T_{ice} = T_{low}$;

   $T_{gb.fric} = 0$;

3- **High SOC mode.** When the SOC is over than medium set point but in CS mode, the battery tries to discharge in this mode. The engine and battery together supply power to the drivetrain. Operating engine speed reaches its medium and engine torque reaches its low value.

$\mathbf{SOC_{mid} <= SOC < SOC_{max}, V >= V_{min},}$

$T_{em} = T_{gb};$

$w_{ice} = w_{mid};$

$T_{ice} = T_{low};$

$T_{gb.fric} = 0;$

4- **Mid SOC mode.** The SOC decreases till the minimum set value and the battery does not supply power to the propulsion anymore. The battery keeps its proper state. All required power delivered by the engine at medium operating speed and high value of torque.

$\mathbf{SOC_{min} < SOC <= SOC_{mid}, V > V_{max},}$

$T_{em} = T_{gb};$

$w_{ice} = w_{mid};$

$T_{ice} = T_{high};$

$T_{gb.fric} = 0;$

5- **Low SOC mode.** When the SOC is lower than minimum set value, the vehicle needs more power not only for propulsion but also charging the battery. The engine operating at high speed and high torque.

$\mathbf{SOC <= SOC_{min},}$

$T_{em} = T_{gb};$

$w_{ice} = w_{high};$

$T_{ice} = T_{high};$

$T_{gb.fric} = 0;$

6- **ICE off mode.** This mode is described by vehicle speed and battery SOC. When the vehicle speed is lower than its low value, engine will turn off.

$\mathbf{SOC > SOC_{min} , V <= V_{min},}$

$T_{em} = T_{gb}$;

$w_{ice} = 0$;

$T_{ice} = 0$;

$T_{gb.fric} = 0$;

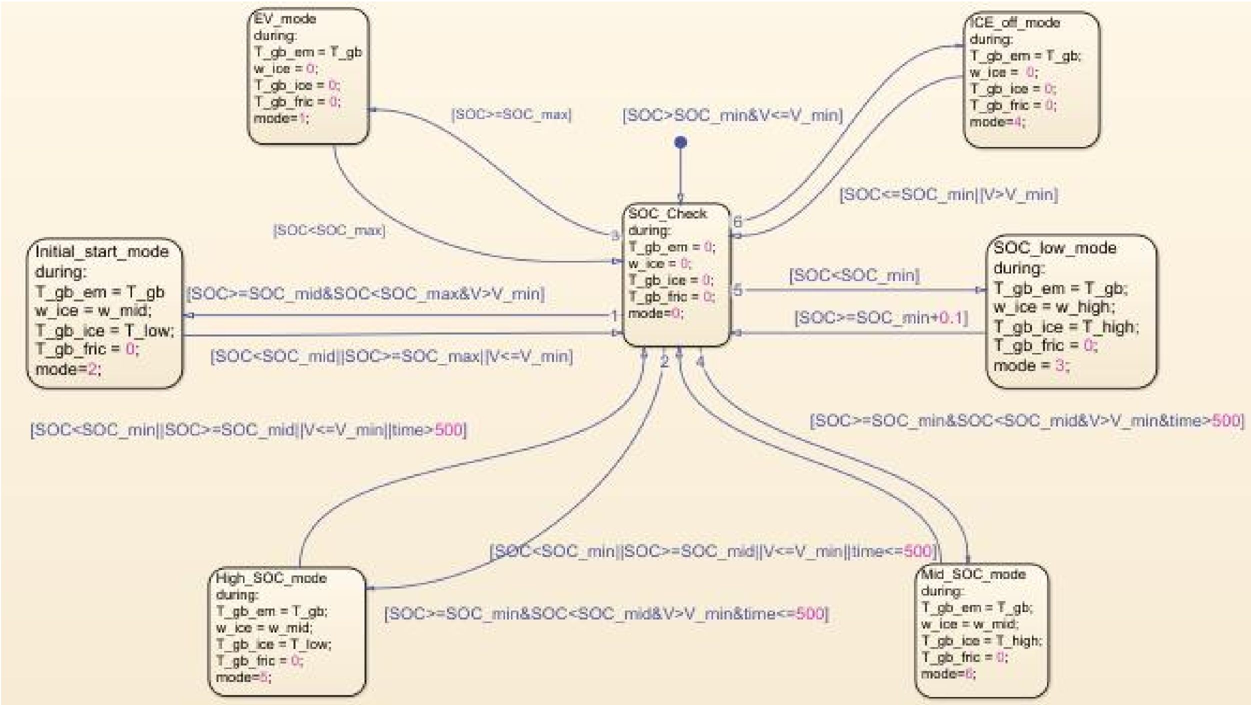

Figure 29. Traction operation control design

3.1.2 Control strategy for braking operation

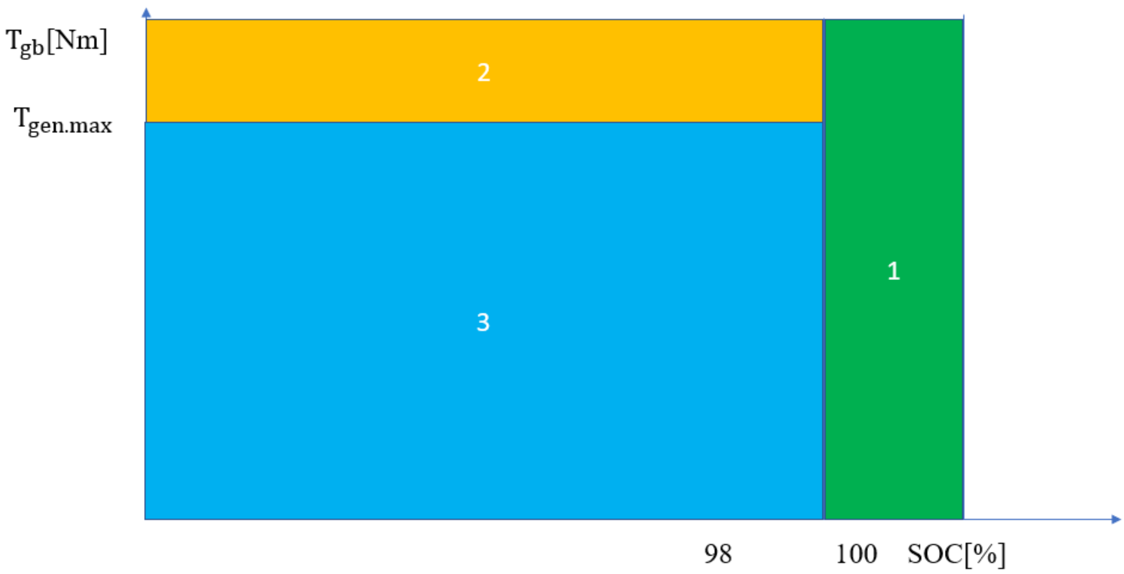

Figure 30. Braking operating modes

Operation of the vehicle is divided into three modes in the braking. Each mode is defined by battery SOC and torque of the generator.

Mode -1, Friction braking:

$SOC>=SOC_{high}$,

$T_{ice} = 0$;

$T_{em} = 0$;

$T_{gb.fric} = T_{fric}$;

Mode -2, Blended braking:

$SOC<SOC_{high}$ & $T_{gb} >T_{gen.max}$,

$T_{ice} = 0$;

$T_{em} = T_{gen.max}$;

$T_{gb.fric} = T_{gb} - T_{gen.max}$;

Mode -3, Full regenerative braking:

$SOC<SOC_{high}$ & $T_{gb} >T_{gen.max}$,

$T_{ice} = 0$;

$T_{em} = T_{gb}$;

$T_{gb.fric} = 0$;.

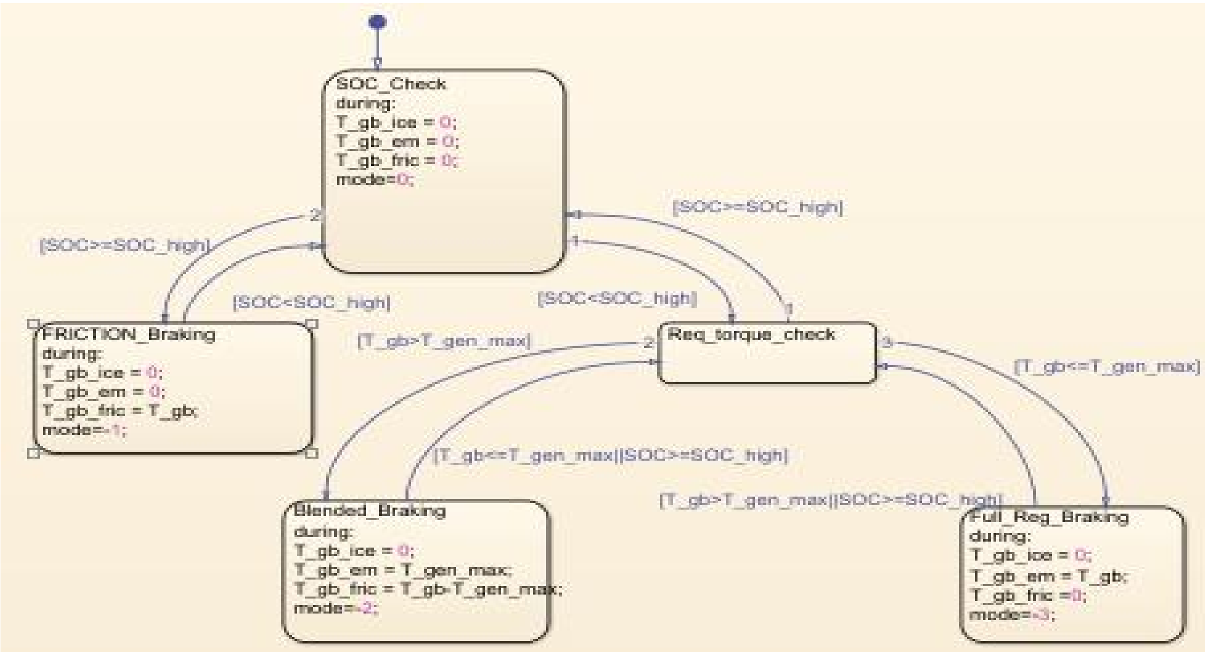

Figure 31. Braking operation control design

4 Experimental model validation and comparison of results

In order to validate our model, experimental test data is taken from Downloadable Dynamometer Database (D3) testing results which experimented at Argonne National Laboratory [31]. Argonne National Laboratory is a U.S Department of Energy multidisciplinary science and engineering research center, where talented researchers work together to answer the biggest questions facing humanity.

a) b)

Figure 32. Front and rear view of BMW i3 REX during Chassis Dynamometer Testing at Argonne National Lab’s Advanced Powertrain Research Facility [32].

Downloadable dynamometer testing was conducted on the BMW i3 REX 2014 vehicle model over several standard drive cycles (UDDS, US06, HWFET and others) at three different temperatures of 35 °C, 22 °C and -7 °C. Instrumentation was installed on the vehicle until dynamometer evaluation in order to catch power consumption by the vehicle.

The test vehicle was instrumented with current and voltage sensors as well as controller area network message monitoring (CAN) equipment. On-board data acquisition systems (DAS) from Isaac Instruments where installed in the vehicle to record the current, voltage and CAN messages. This information was used to determine the vehicle operating conditions, utilization patterns and the auxiliary loads during given conditions.

During the test, vehicle speed, the force acting on the wheel of the vehicle, test cell temperature, battery voltage, battery current, fuel consumption, battery SOC, range extender current and other parameters are measured and reported as a test data.

A backward model of the vehicle including drive cycle, vehicle dynamics, gearbox, electric motor, generator, engine and controller has been simulated on MATLAB/Simulink. As well as the results were compared and contrasted with experimental test data during the simulation.

Table 5.1 shows the vehicle setup information during the test.

Table 5.1

Vehicle dynamometer input	
Test weight [kg]	1567.6
Target A [N]	106
Target B [N/(m/s)]	6.42
Target C [N/(m/s)^2]	0.265
Test fuel information	
Fuel type	EPATier II EEE HF0437
Fuel density [kg/m^3]	740
Fuel net HV [MJ/kg]	42.691

4.1 Range Extender charge depleting results

The operation of BMW i3 REX is divided into two driving modes which are charge depleting and charge sustaining according to the battery SOC. As mentioned above, there is a threshold value of the SOC (16%) exists between CD and CS modes. In a range extended electric vehicle at standard temperature, a vehicle is driven as a pure electric vehicle in charge depleting mode firstly. In order to validate the vehicle simulation model, simulations are conducted in various conditions including 35° C, 22 ° C and -7 ° C ambient temperature with different auxiliary loads.

A specific auxiliary load tests was conducted on vehicle model at different ambient temperature to measure the load of individual components and accessories. Table 5.1.1 shows the value of auxiliary loads at three different ambient temperature during charge depleting mode.

Table 5.1.1

Vehicle model	Mode	Ambient temperature [° C]	Effected auxiliary load [W]
2014 BMW i3 Rex	CD (SOC>=16%)	35	800
2014 BMW i3 Rex	CD	22	0
2014 BMW i3 Rex	CD	-7	4500

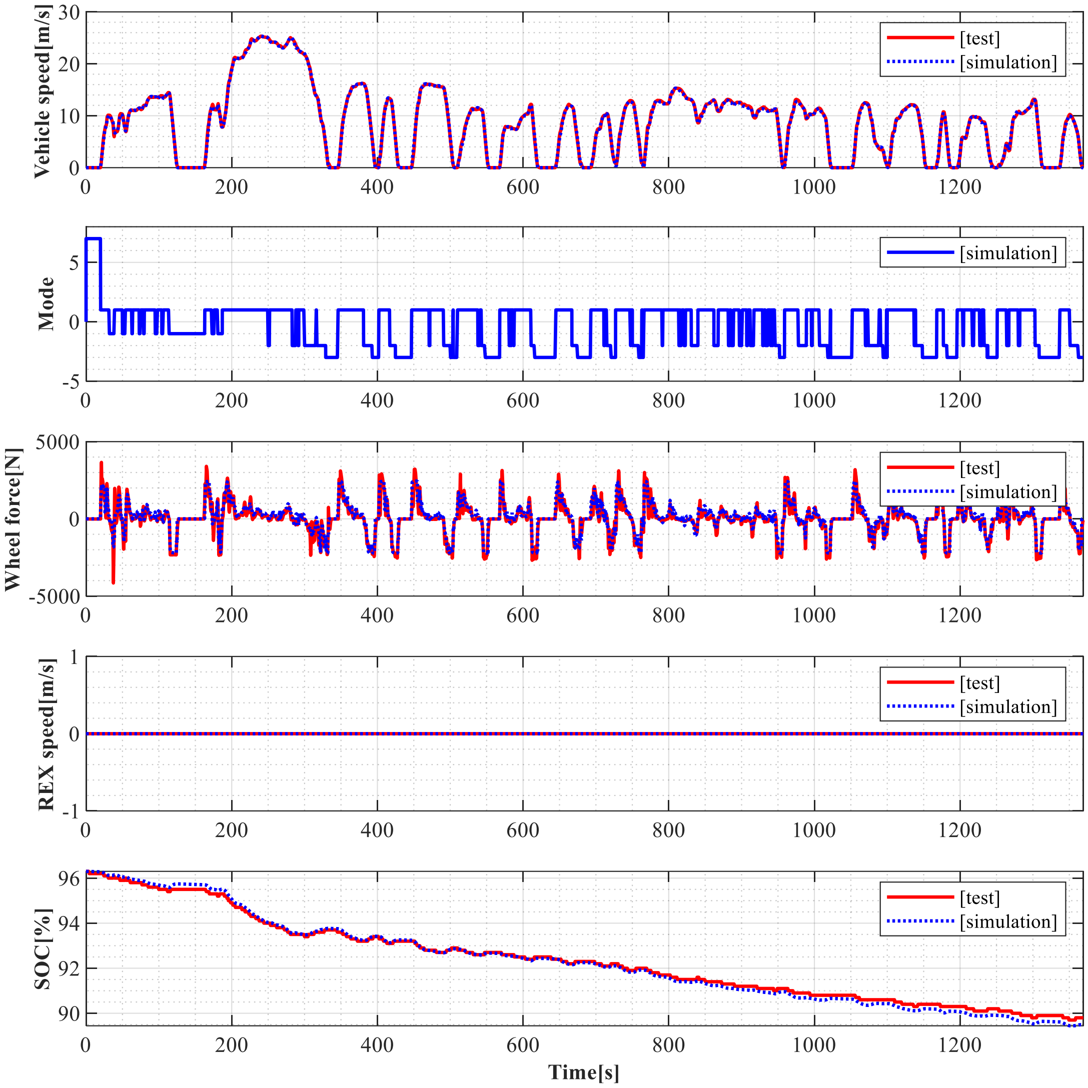

Figure 33. Comparative results of vehicle speed, operating mode, wheel force, engine speed and battery SOC on UDDS cycle at 35° C in CD mode with 800 W auxiliary load.

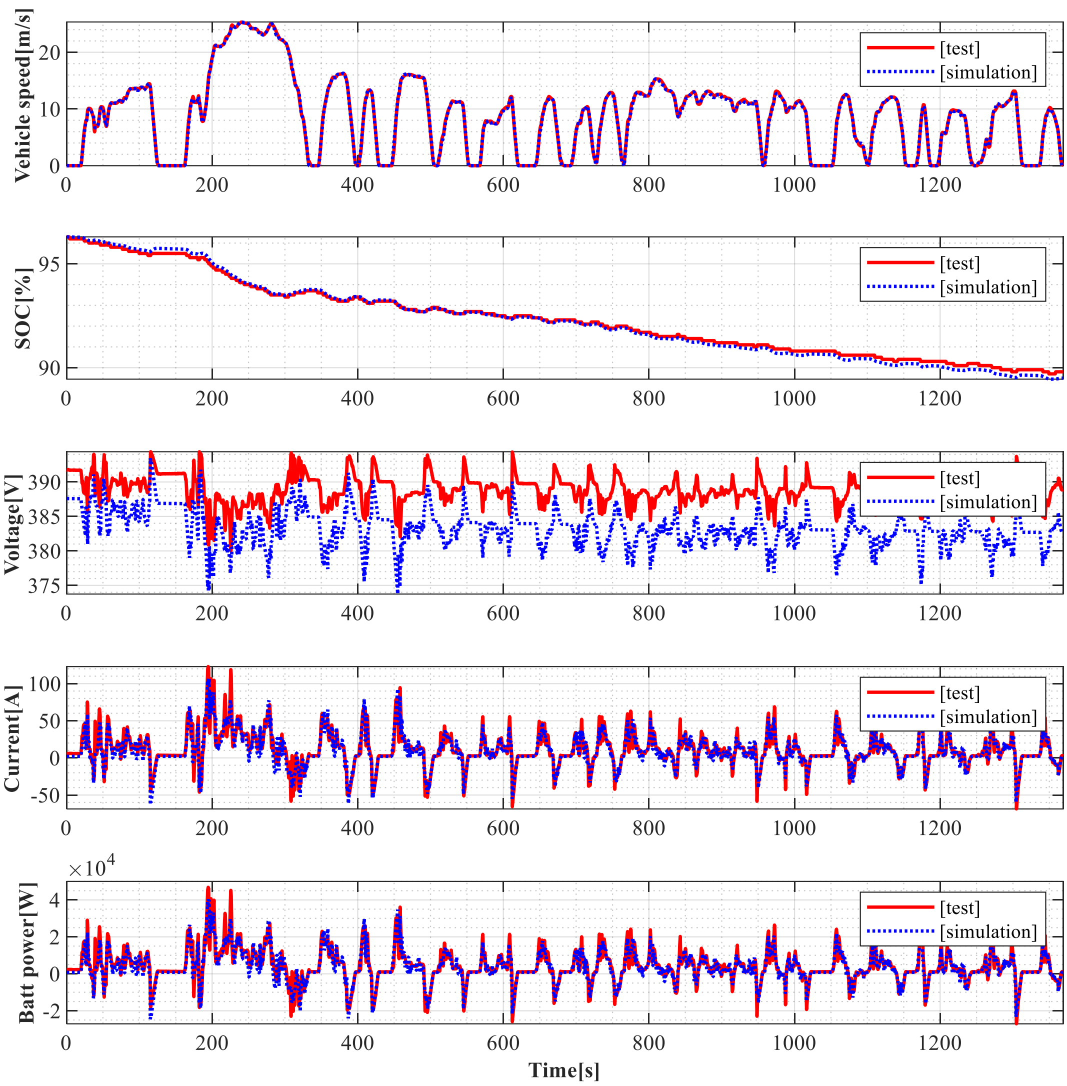

Figure 34. Comparative results of vehicle speed, battery SOC, battery voltage, battery current and battery power on UDDS cycle at 35° C in CD mode with 800 W auxiliary load.

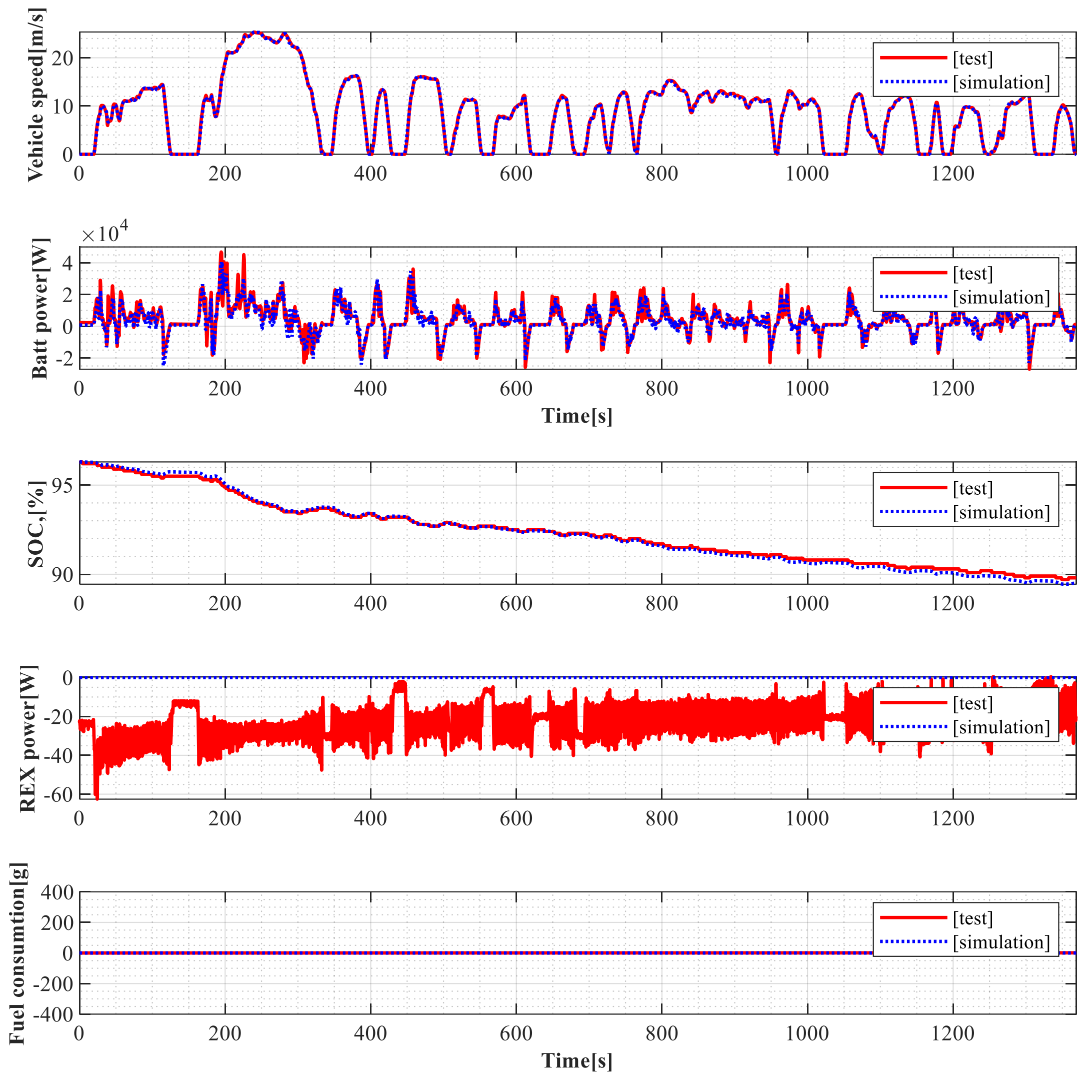

Figure 35. Comparative results of vehicle speed, battery power, battery SOC, REX power and fuel consumption on UDDS cycle at 35° C in CD mode with 800 W auxiliary load.

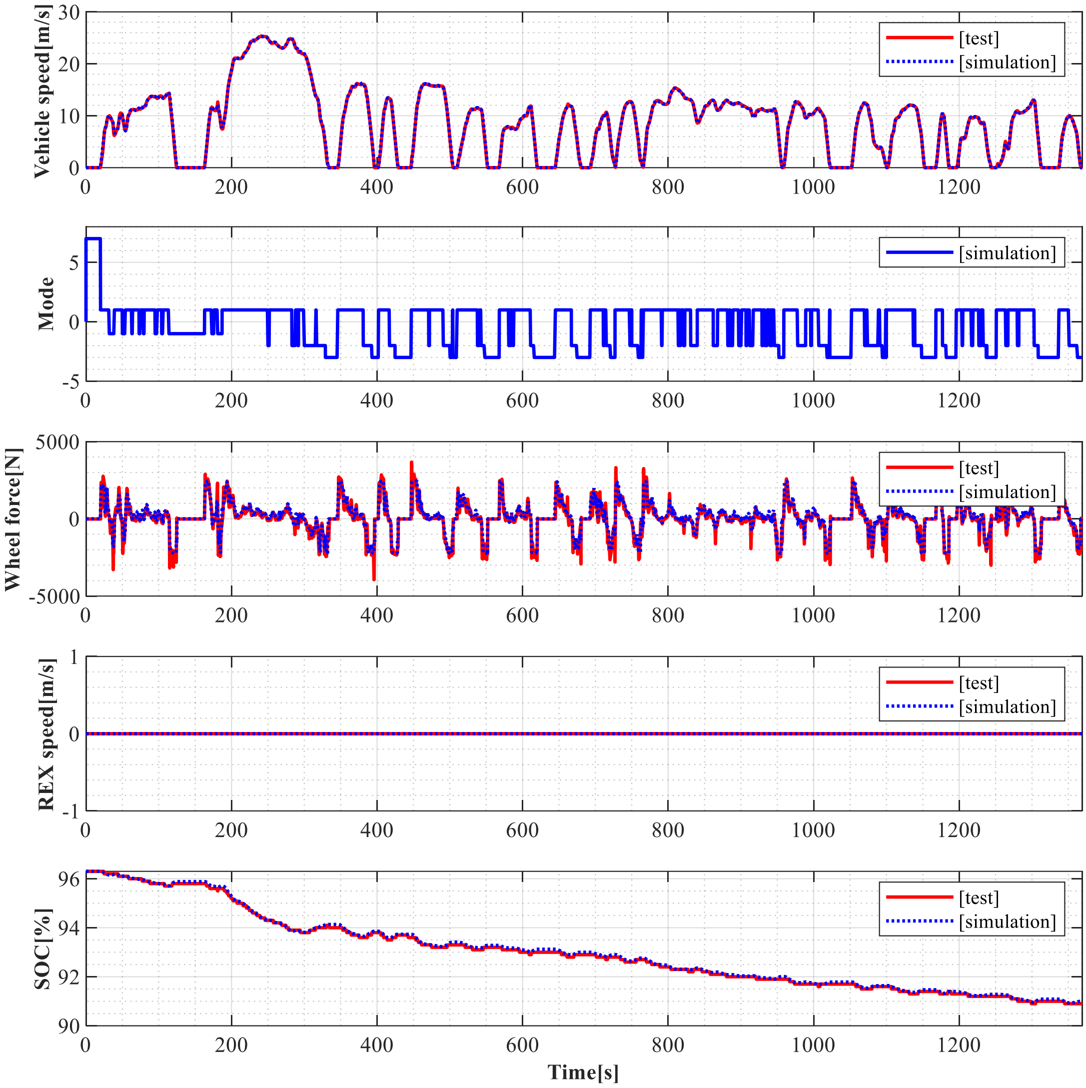

Figure 36. Comparative results of vehicle speed, operating mode, wheel force, engine speed and battery SOC on UDDS cycle at 22° C in CD mode with 0 W auxiliary load

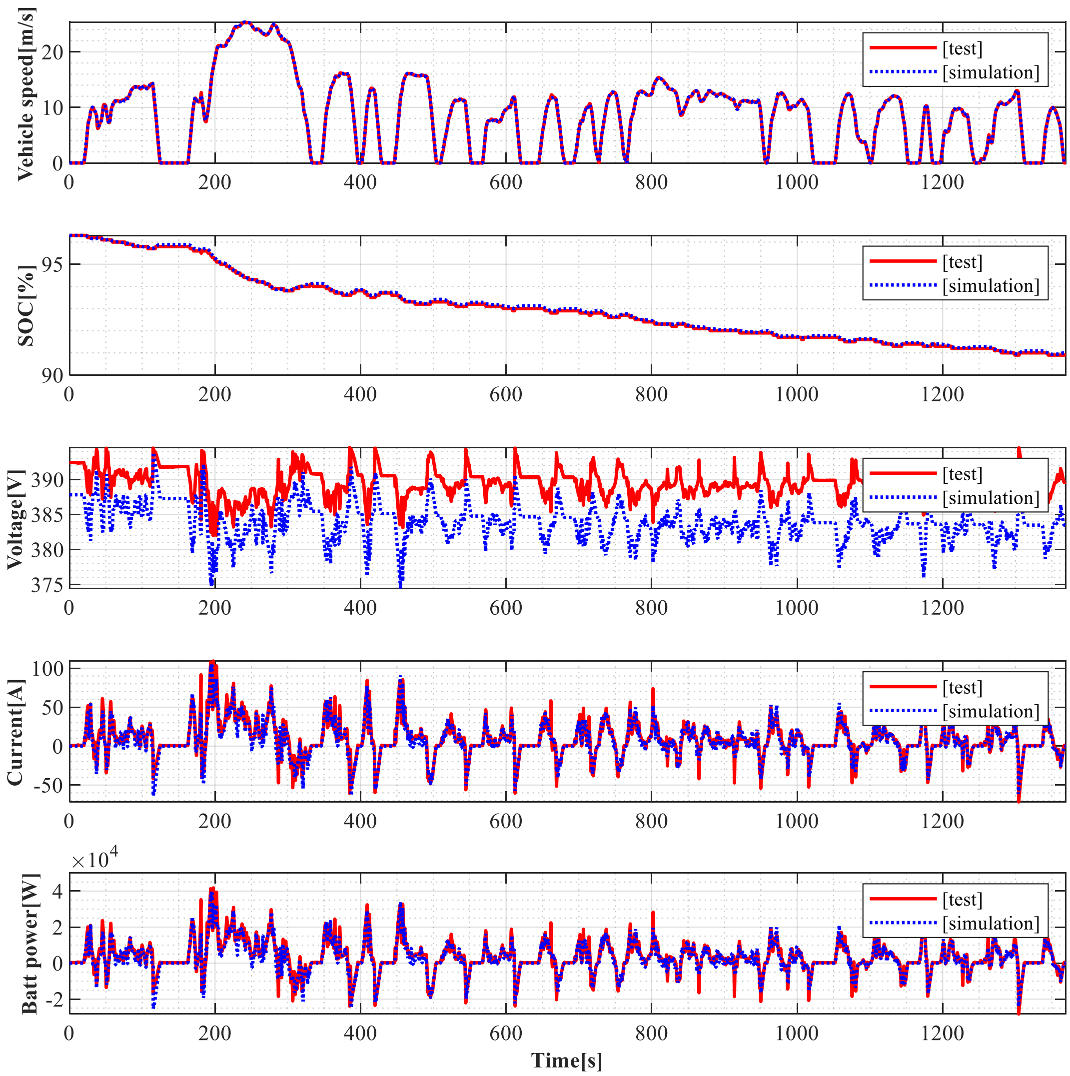

Figure 37. Comparative results of vehicle speed, battery SOC, battery voltage, battery current and battery power on UDDS cycle at 22° C in CD mode with 0 W auxiliary load

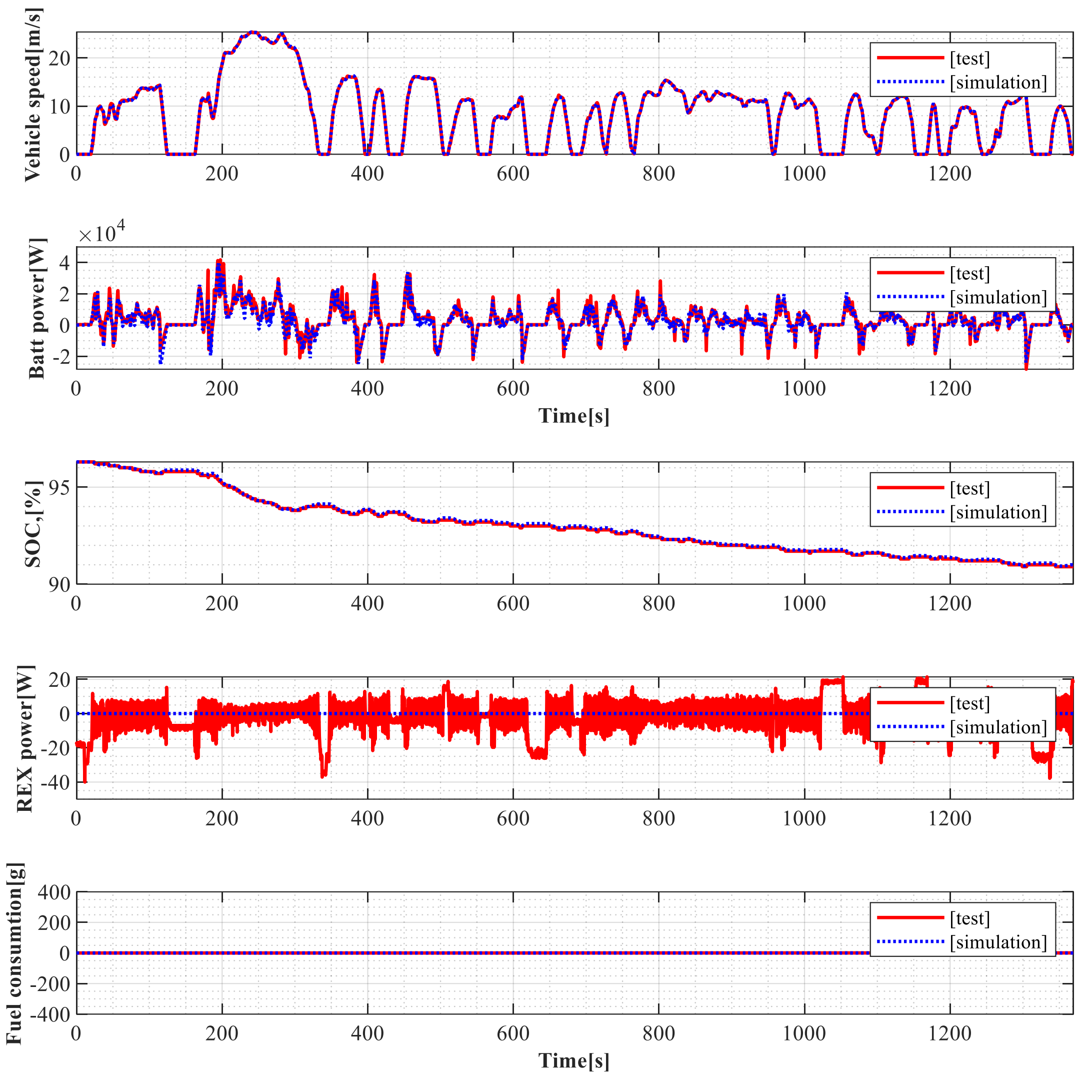

Figure 38. Comparative results of vehicle speed, battery power, battery SOC, REX power and fuel consumption on UDDS cycle at 22° C in CD mode with 0 W auxiliary load

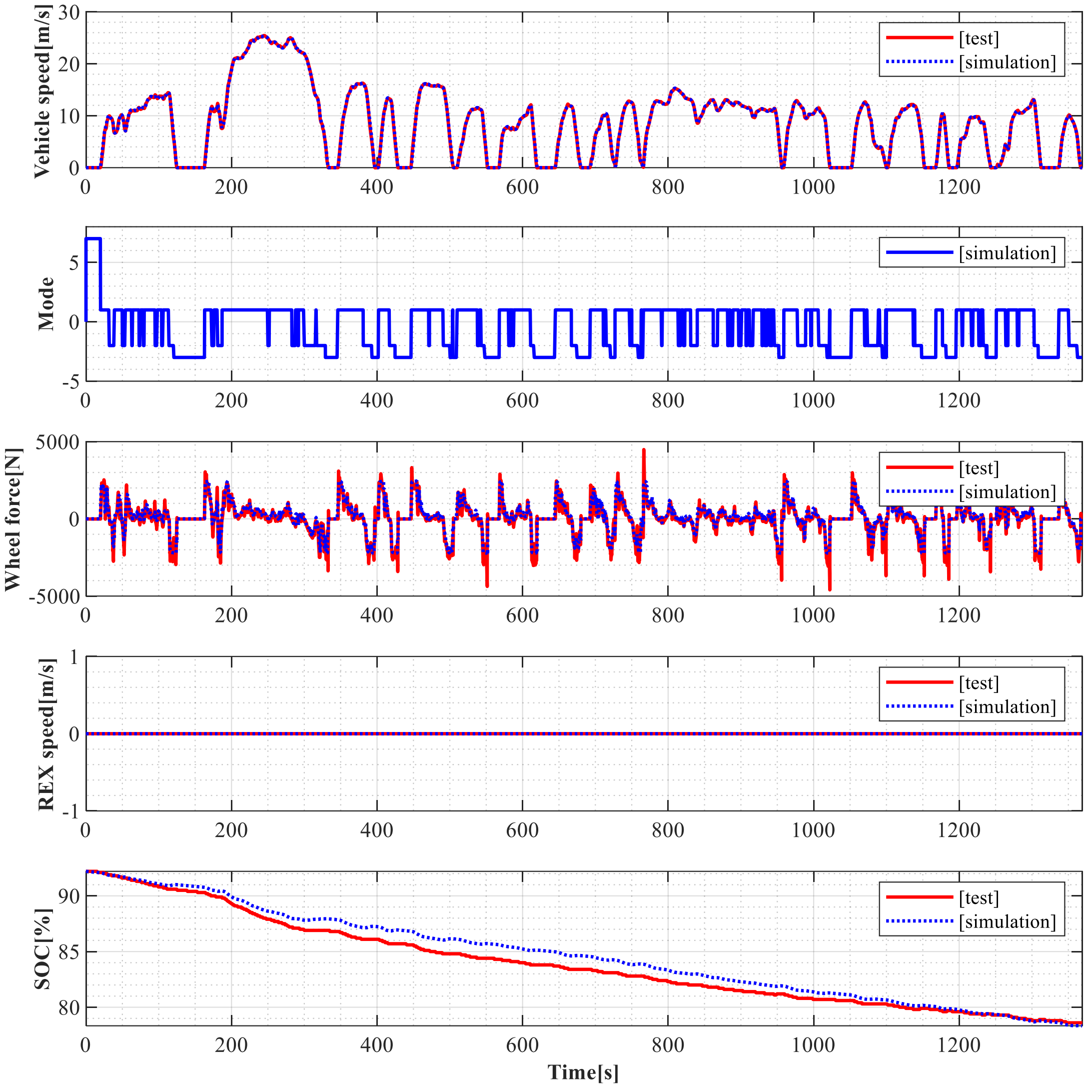

Figure 39. Comparative results of vehicle speed, operating mode, wheel force, engine speed and battery SOC on UDDS cycle at -7° C in CD mode with 4500 W auxiliary load.

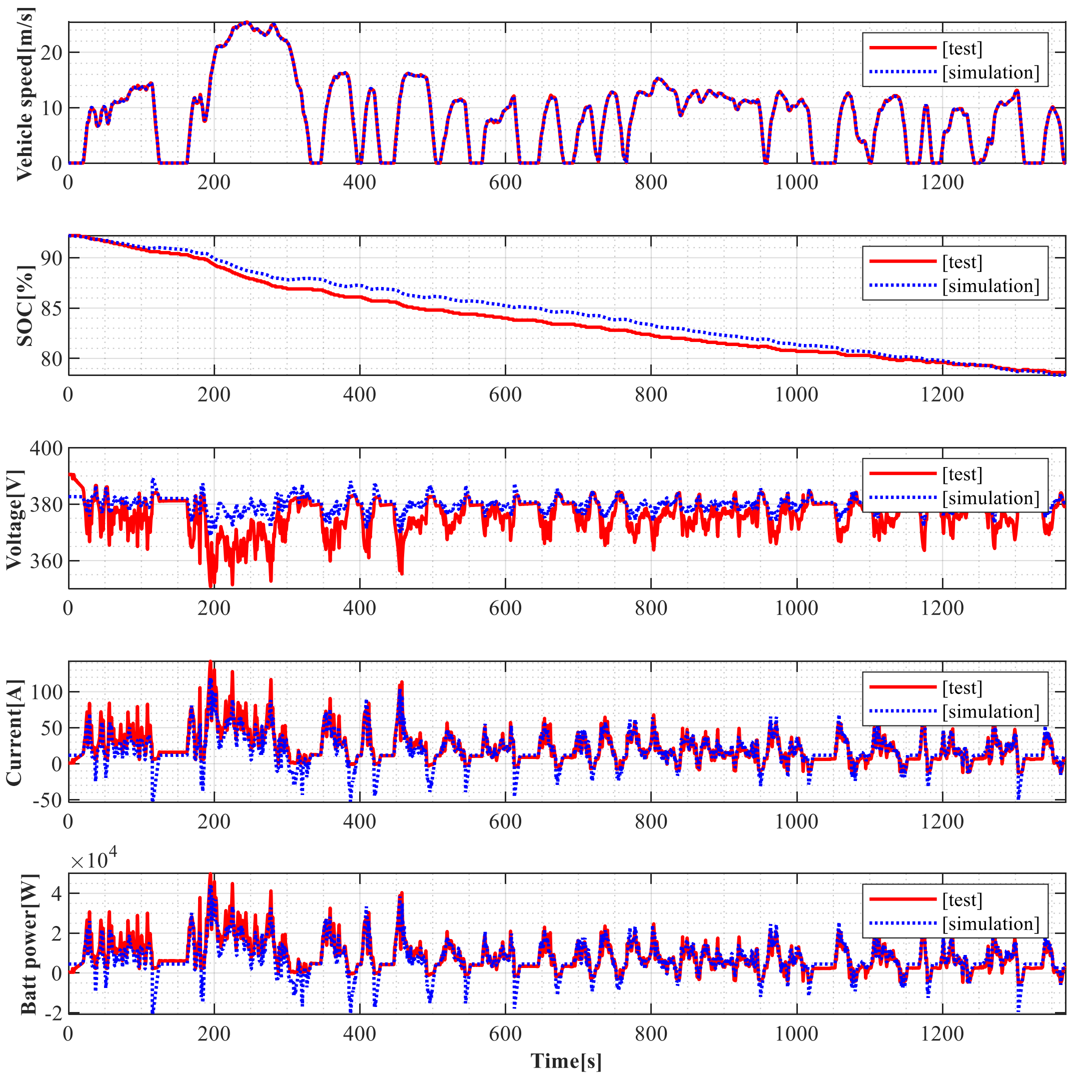

Figure 40. Comparative results of vehicle speed, battery SOC, battery voltage, battery current and battery power on UDDS cycle at -7° C in CD mode with 4500 W auxiliary load.

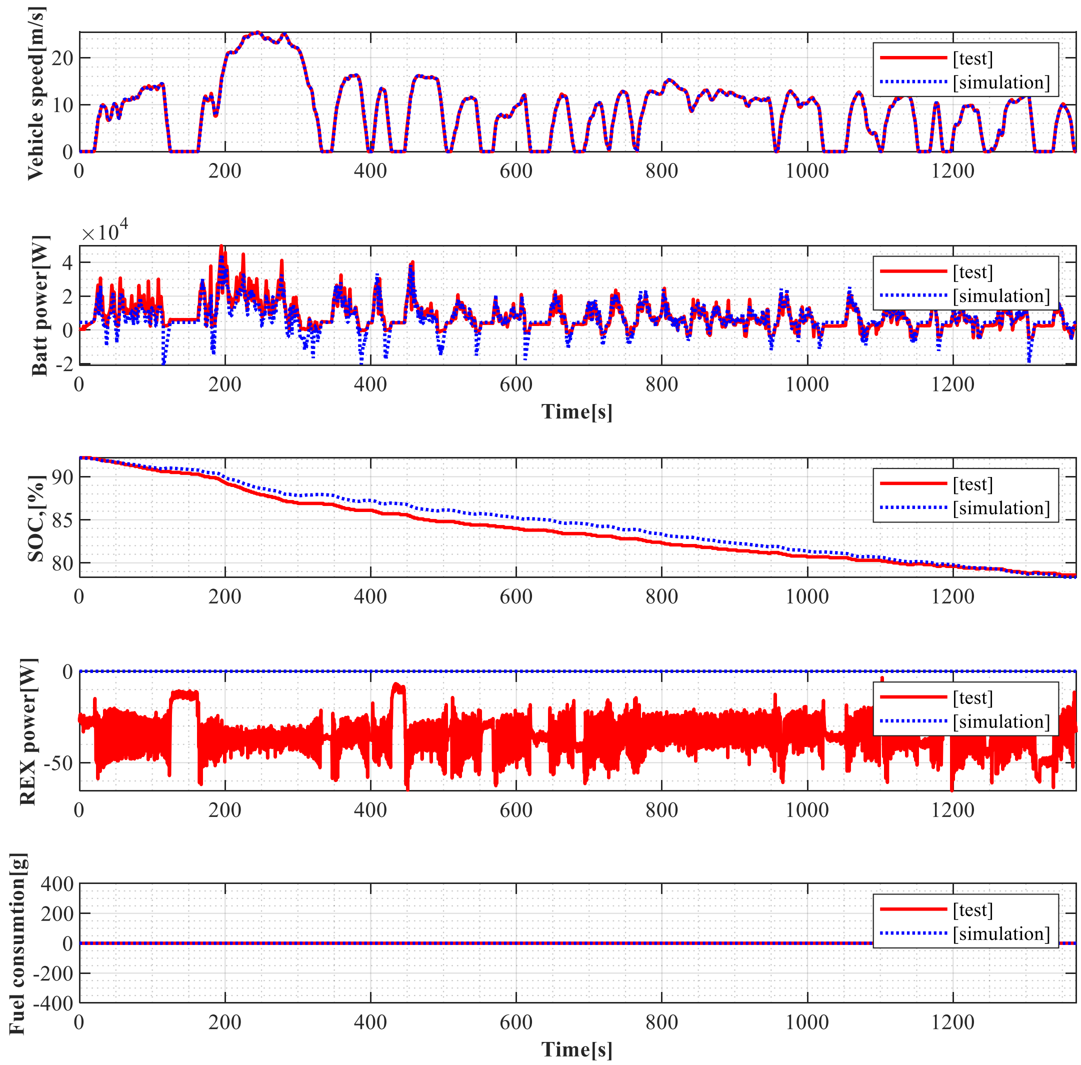

Figure 41. Comparative results of vehicle speed, battery power, battery SOC, REX power and fuel consumption on UDDS cycle at -7° C in CD mode with 4500 W auxiliary load.

4.2 Range Extender charge sustaining results

Vehicle model	Mode	Ambient temperature [° C]	Effected auxiliary load [W]
2014 BMW i3 Rex	CS(SOC<16%)	35	850
2014 BMW i3 Rex	CS	22	0
2014 BMW i3 Rex	CS	-7	1700

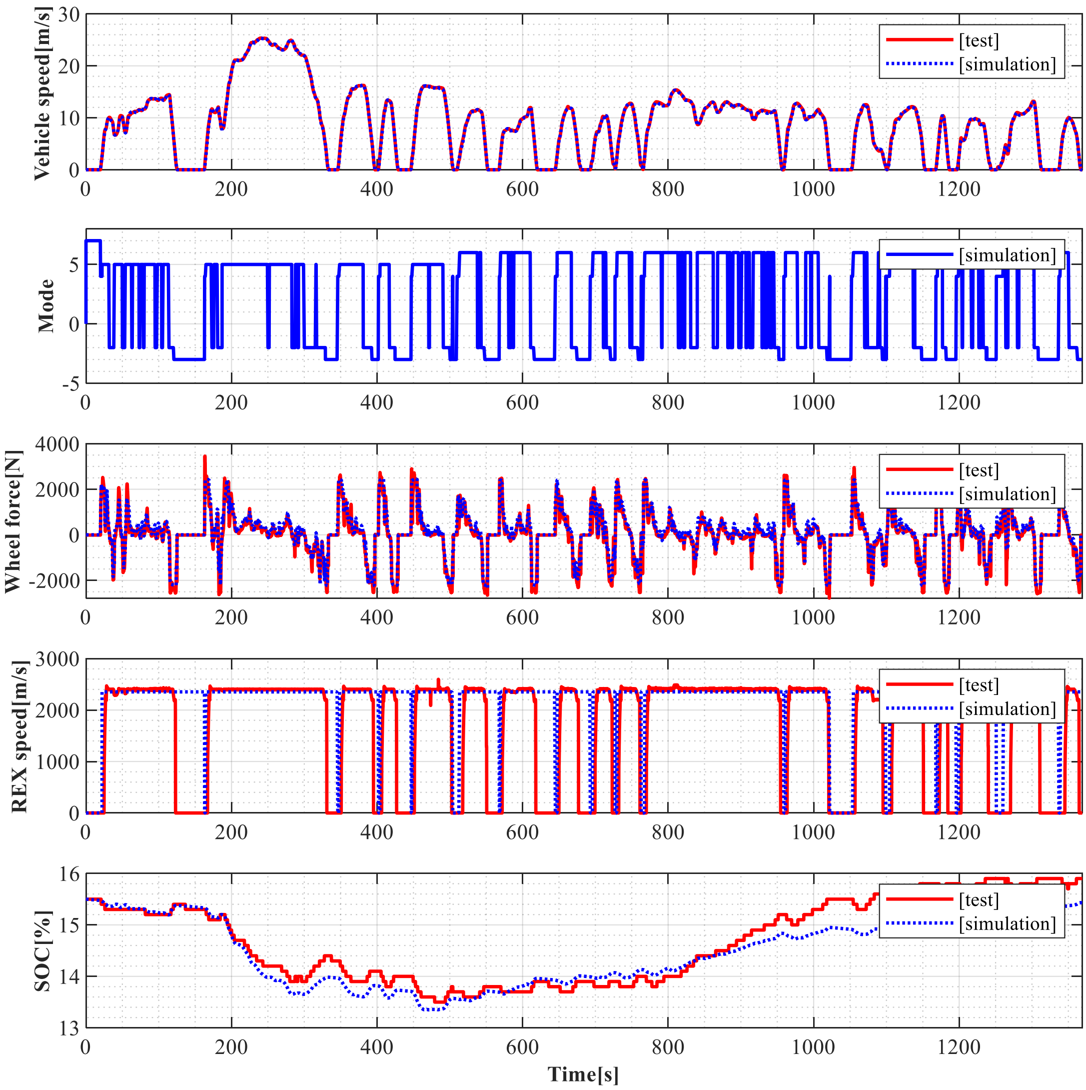

Figure 42. Comparative results of vehicle speed, operating mode, wheel force, REX speed and battery SOC on UDDS cycle at 35° C in CS mode with 850 W auxiliary load.

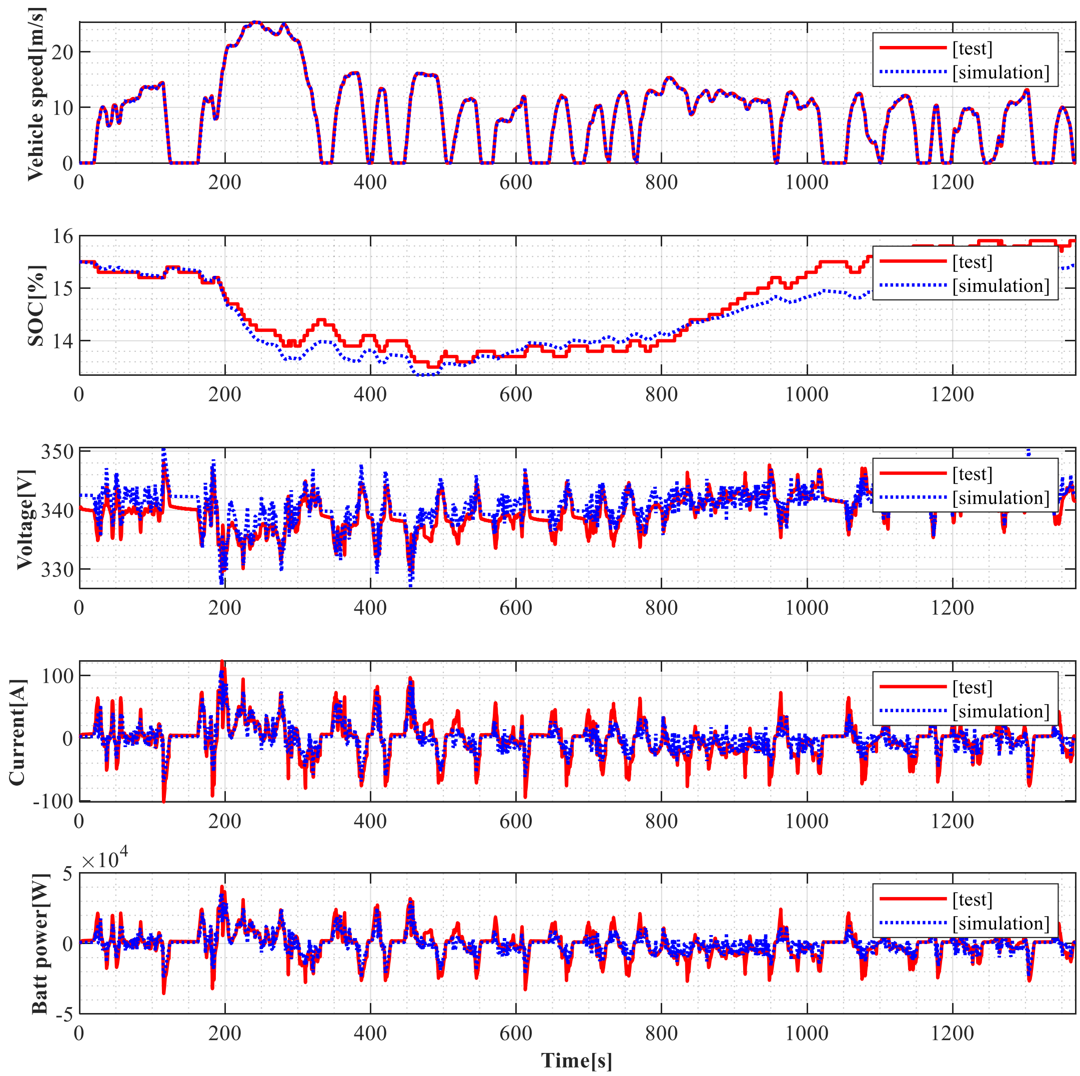

Figure 43. Comparative results of vehicle speed, battery SOC, battery voltage, battery current and battery power on UDDS cycle at 35° C in CS mode with 850 W auxiliary load.

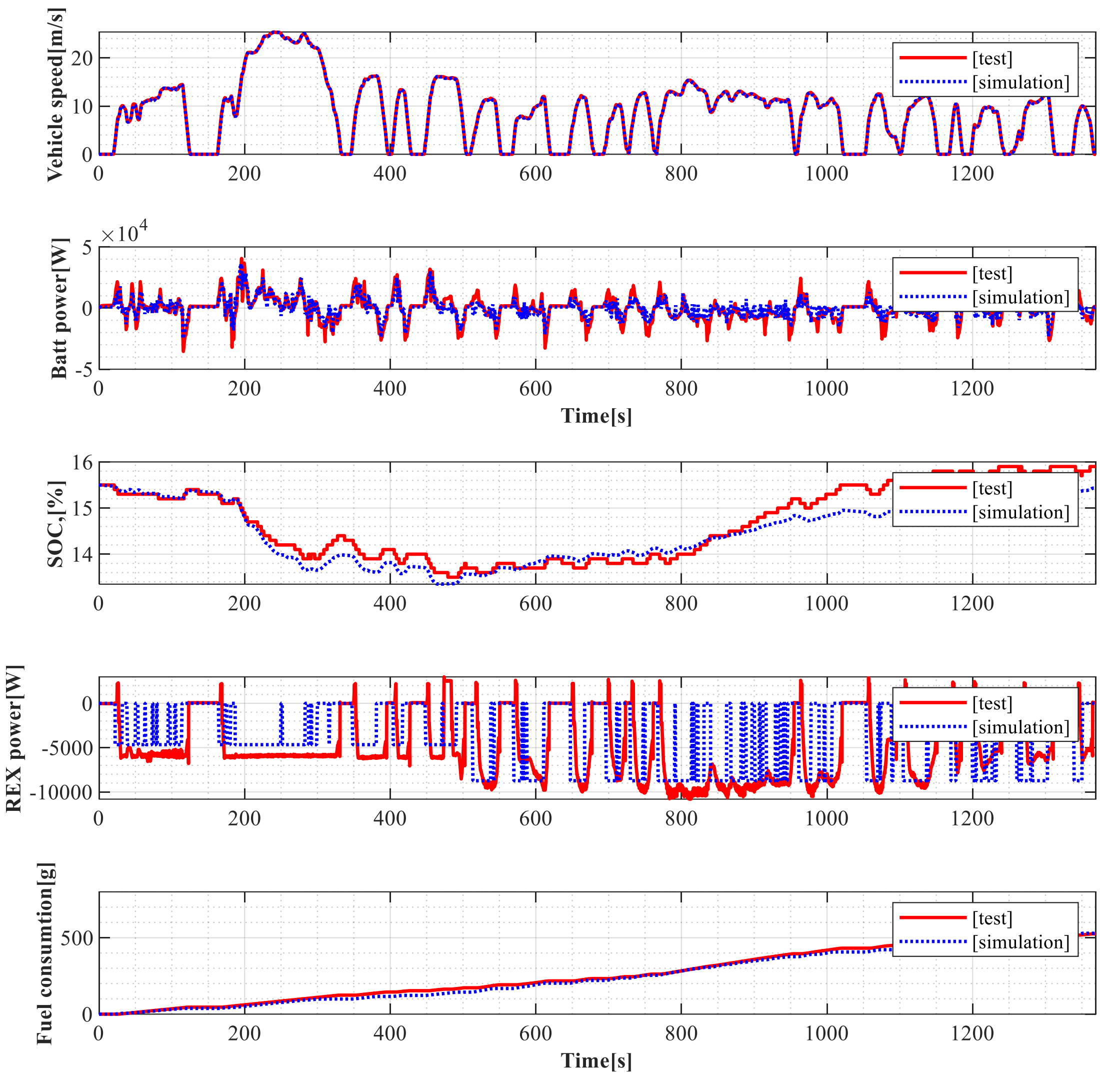

Figure 44. Comparative results of vehicle speed, battery power, battery SOC, REX power and fuel consumption on UDDS cycle at 35° C in CS mode with 850 W auxiliary load.

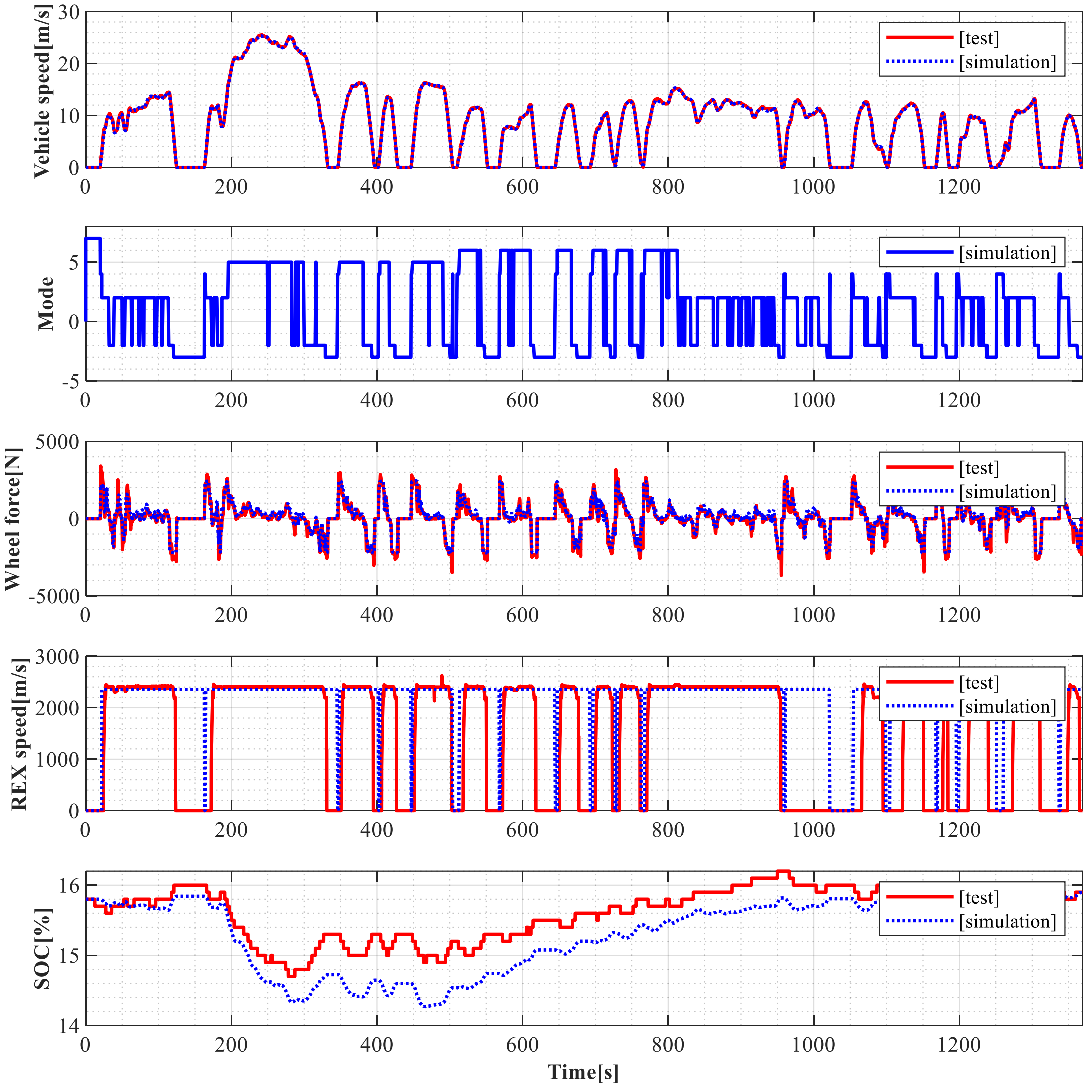

Figure 45. Comparative results of vehicle speed, operating mode, wheel force, REX speed and battery SOC on UDDS cycle at 22° C in CS mode with 0 W auxiliary load.

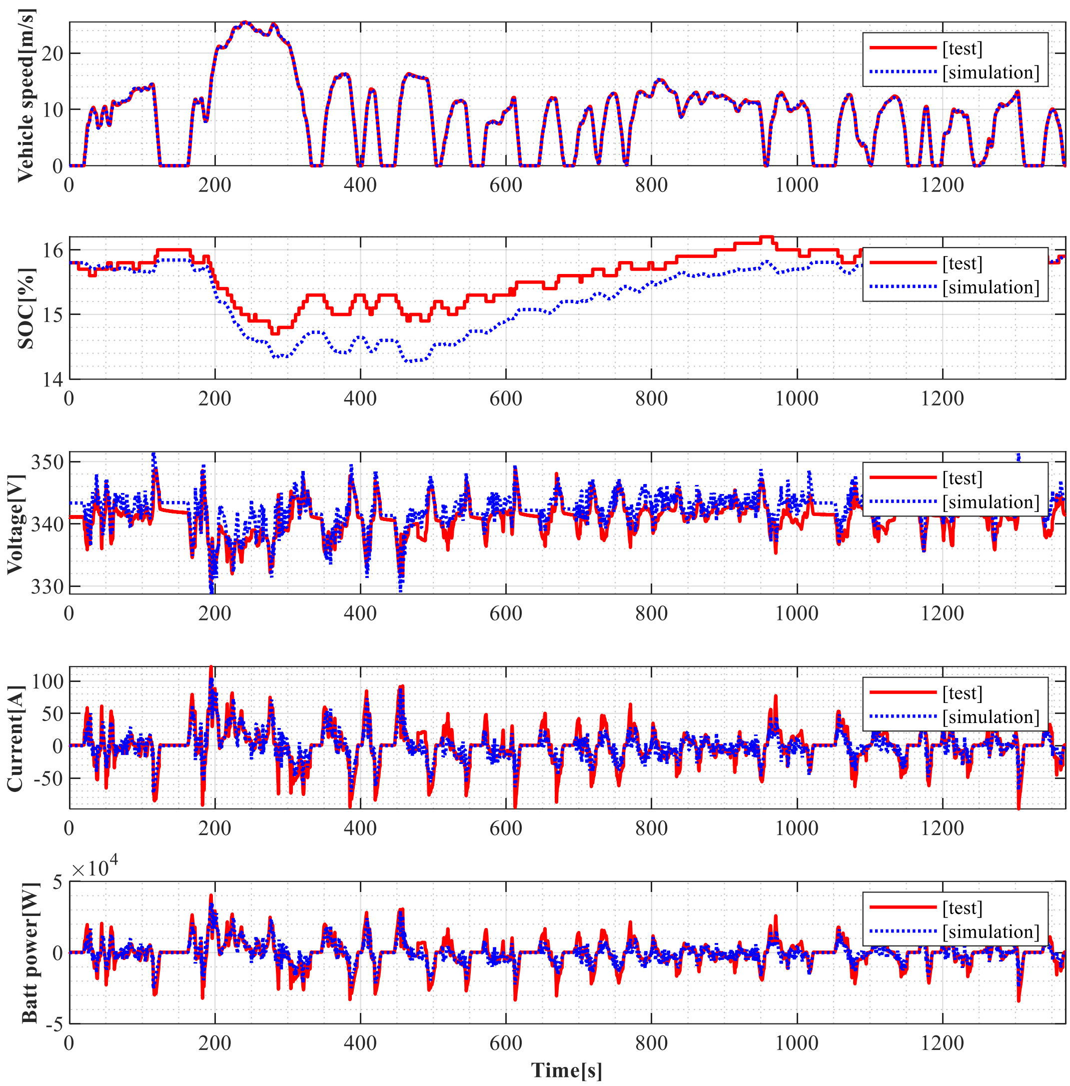

Figure 46. Comparative results of vehicle speed, battery SOC, battery voltage, battery current and battery power on UDDS cycle at 22° C in CS mode with 0 W auxiliary load.

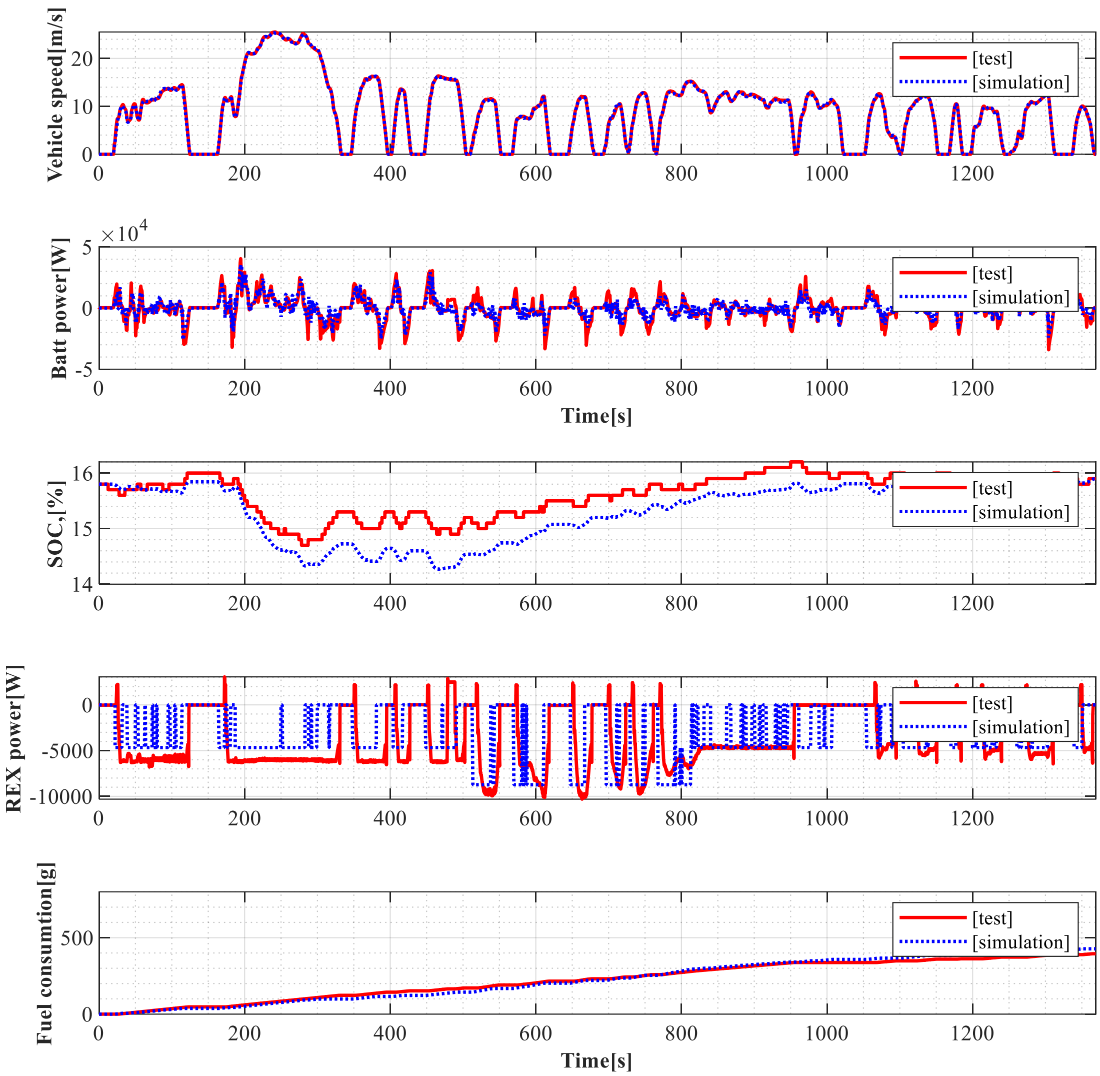

Figure 47. Comparative results of vehicle speed, battery power, battery SOC, REX power and fuel consumption on UDDS cycle at 22° C in CS mode with 0 W auxiliary load.

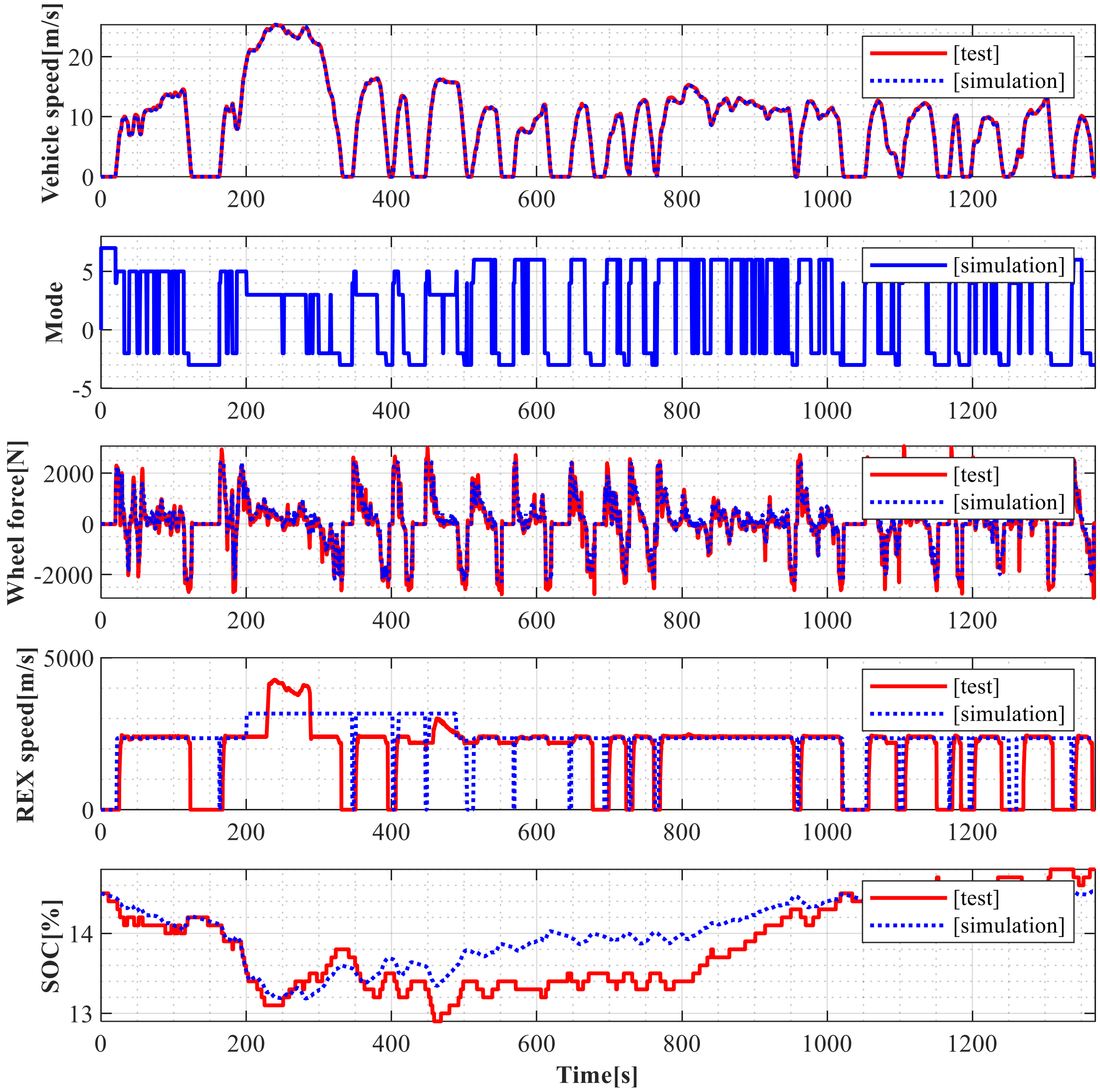

Figure 48. Comparative results of vehicle speed, operating mode, wheel force, REX speed and battery SOC on UDDS cycle at -7° C in CS mode with 1700 W auxiliary load.

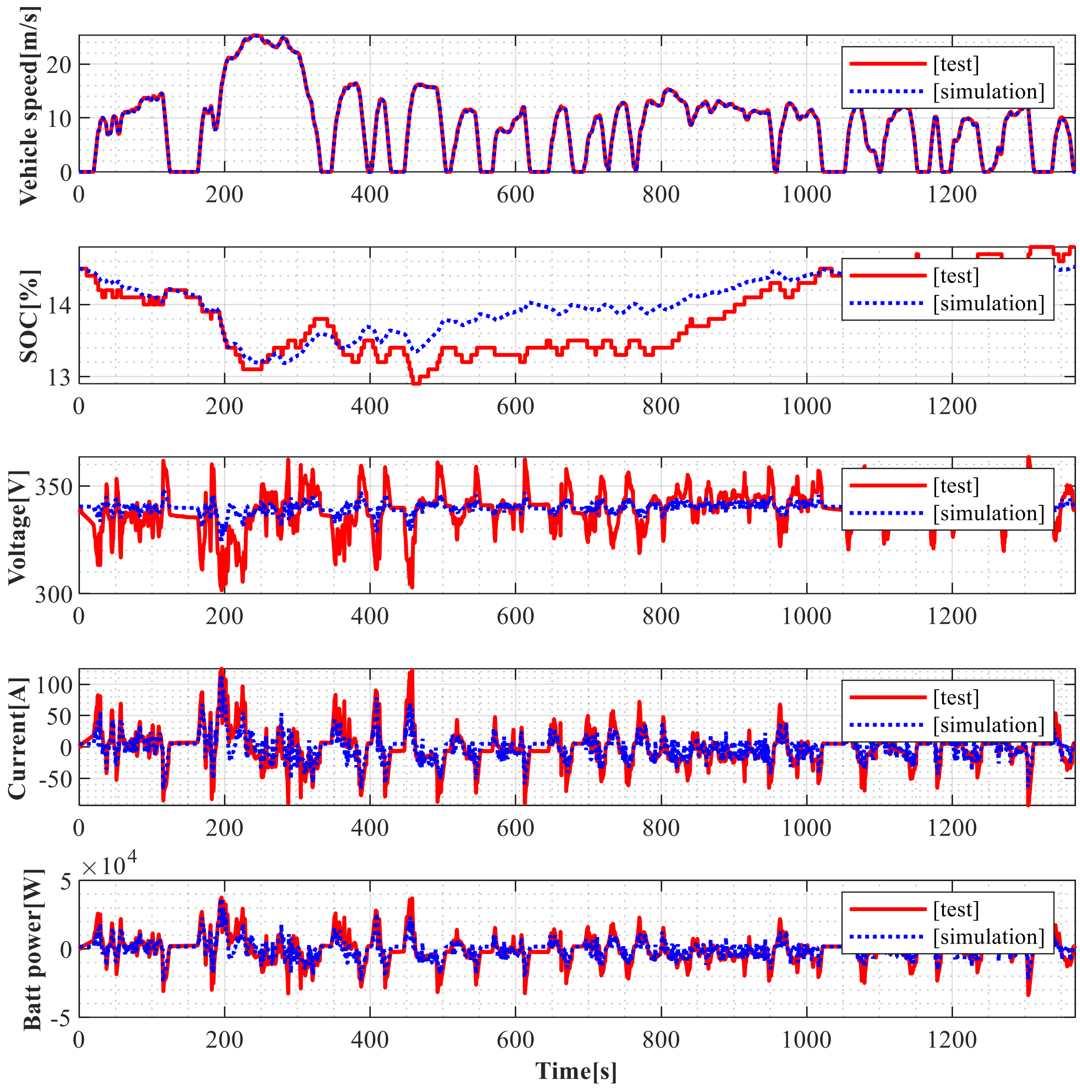

Figure 49. Comparative results of vehicle speed, battery SOC, battery voltage, battery current and battery power on UDDS cycle at -7° C in CS mode with 1700 W auxiliary load.

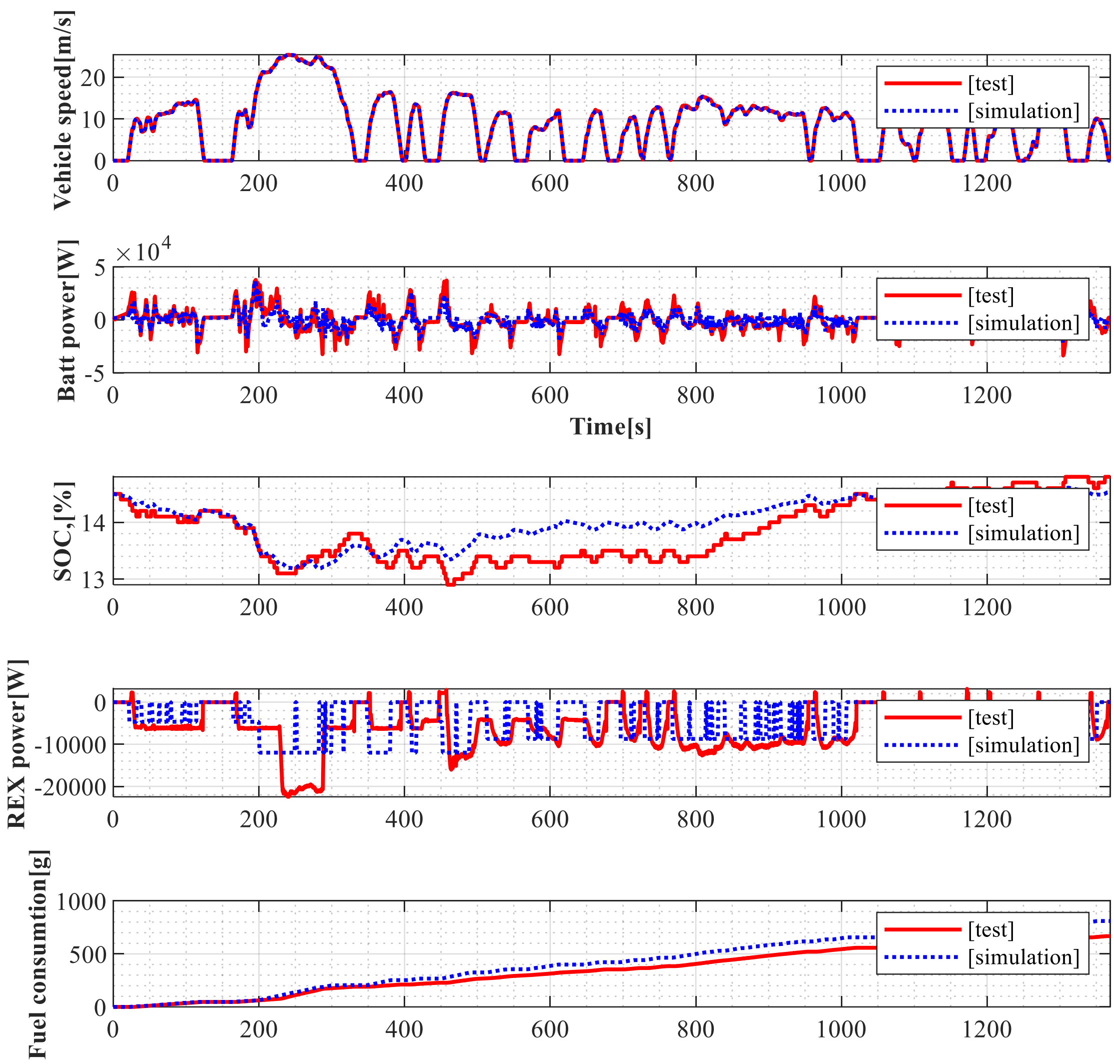

Figure 50. Comparative results of vehicle speed, battery power, battery SOC, REX power and fuel consumption on UDDS cycle at -7° C in CS mode with 1700 W auxiliary load.

5 Summary

5.1 Results and discussion

The backward simulation model for 2014 BMW i3 Range Extender was implemented in MATLAB/Simulink with all components. To validate the vehicle simulation model, simulations are conducted at three ambient conditions as detailed shown in Table 5.1.1. During the validation vehicle speed, operation mode, wheel force, REX speed, battery SOC, battery voltage, battery current, battery power, REX power and fuel consumption have been compared with the experimental test data in both CD and CS modes with different auxiliary power. The difference of battery SOC and fuel consumption is given in percentage.

Table 5.1.1

Ambient temperature (°C)	**Driving mode**	**Auxiliary power [W]**	**Fuel consumption [g]**		**Final SOC [%]**	
			Test	Simulation	Test	Simulation
35	CD	800	0	0	89.8	89.5(0.35%)
	CS	850	525	529(0.76%)	15.9	15.4(1.89%)
22	CD	0	0	0	90.9	91(-0.11%)
	CS	0	395	427(8%)	15.9	15.9 (0%)
-7	CD	4500	0	0	78.3	78.3(0.38%)
	CS	1700	668	607(10%)	14.8	14.5(2.02%)

As we can see from the table, fuel consumption is different from the experimental value during the test at 22 °C and -7 °C in simulation. However, it is still in acceptable range. In my side, the reason of the discrepancies may be that, the controllers of the model and the real vehicle were not the same or the auxiliary power may not be constant during the experiment.

5.2 Conclusions

This thesis includes a vehicle simulation model of 2014 BMW i3 REX which was modelled in MATLAB/Simulink based on the test data from Argonne National Laboratory. Initially, UDDC data was loaded in MATLAB/Simulink as a drive cycle. Secondly, in order to compare with simulation results an experimental test data was imported and each component was analyzed at three different temperatures. Additionally, a supervisory controller by Stateflow chart was designed based on the developed control strategies during the study. According to the control strategy, engine speed and engine torque are divided into three and two different values respectively. In a charge sustaining zone of the battery SOC, five different modes are developed by variance of SOC and vehicle speed. Taking into account the full model validation, fuel consumption of the model and battery SOC were compared and discussed. The maximum discrepancies between test and simulation values of battery SOC and fuel consumption are not excess 2.5% and 10% respectively and the values are in acceptable range.

In the future, some researches are pointed out below,

- Regarding the vehicle model, many improvements can be done in order to make it more real. For example, ICE fuel consumption map, EM and generator efficiency maps as well as auxiliary loads in real life should be included.

- With respect to the controller, optimal operating point and equivalent consumption strategies in order to reach minimum fuel consumption can be done.

- One of the most interesting points that solving of component sizing issues.

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