

POLYTECHNIC UNIVERSITY OF BUCHAREST

DOCTORAL SCHOOL OF TRANSPORT

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RESEARCH ON THE ENERGY CONSUMPTION OF ELECTRIC VEHICLES IN DIFFERENT STANDARDIZED CYCLES

DOCTORAL THESIS

EXTENDED SUMMARY

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BUCHAREST
2025

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"Progress is impossible without change, and those who cannot change their minds cannot change anything."

(George Bernard Shaw)

Preface

Given the topicality and complexity of the subject addressed in this doctoral thesis, its development required the use of all available resources for conducting experimental research and, respectively, through modeling and simulation, between October 2020 and June 2025 by the National University of Science and Technology POLITEHNICA Bucharest.

First of all, I would like to express my deep gratitude and sincere thanks to Professor Emeritus Gheorghe FRĂȚILĂ, PhD, the scientific coordinator of this work, who guided me throughout my doctoral studies with great competence and academic rigor.

Secondly, I would like to express my gratitude to the TRANSPORT doctoral school and the teaching staff of the Road Vehicles Department for their scientific support and suggestions provided during this period.

I would also like to express my gratitude to the professors at the Faculty of Transportation Engineering at the Polytechnic University of Bucharest, who trained me as an engineer in the fascinating field of road vehicles.

Finally, I would like to express my gratitude to my family members for their understanding during my doctoral studies and for their moral support during difficult times.

PhD student in engineering Constantin-Corneliu MÎNZATU
Bucharest, September 2025

0. INTRODUCTION

An electric car is a vehicle that uses one or more electric motors for propulsion. Unlike vehicles with internal combustion engines that run on fossil fuels, electric cars are powered by electricity stored in batteries or received while driving through a charging system.

There are two main types of electric vehicles:

- Battery electric vehicles (BEVs).
- Range-extended electric vehicles (REEVs) or vehicles with a range extender.

0.1 The purpose of the doctoral thesis

One of the main objectives of the doctoral thesis that the author aims to achieve is the development of a mathematical model using the modeling and simulation platform (AMESIM), with which aspects related to current testing methods applicable to electric vehicles can be simulated in order to establish electricity consumption and determine autonomy, namely the World -wide harmonized Light duty Test Cycle, characterized by the four driving ranges at low, medium, high, and very high speeds that the electric vehicle must satisfy.

The second objective consists of measurements of the range of electric vehicles, simulated and measured under the same conditions, on different circuits, only in the case of the RDE cycle, as this is currently the most representative. The measurement and simulation are performed individually, with the results obtained through simulation being compared with those obtained under similar conditions on the roller bench.

0.2 Chapters covered in order to complete the doctoral thesis

In order to achieve the proposed objectives, several stages of documentation and analysis were necessary during the course of the work, as presented in the following chapters:

Chapter 1 A brief history of the electric car, provides a retrospective overview of the evolution of electric vehicles over time.

Chapter 2 Current state of electric vehicle development , In the first presentation, an analysis of the different types of electric vehicles will be carried out, and in the second phase, an analysis of the specific components related to these electric vehicles will be carried out.

Chapter 3 Equipment specific to electric vehicles, highlights in detail the main components of an electric vehicle used by vehicle manufacturers, in order to operate with low energy consumption and, implicitly, with a high degree of traction battery autonomy, as well as the operating strategies applied by electric vehicle computers according to system requirements, one of the goals being to ensure high traction performance.

Chapter 4 Modeling and simulation of energy performance when driving an electric vehicle in various standardized cycles. This chapter describes in detail the model created using the AMESIM platform to simulate the operation of the electric vehicle studied, according to the WLTC and RDE cycles. The calculation formulas used by the model are detailed, and at the end of the simulation, the values relating to the simulated and measured range of electric vehicles are highlighted, as well as

the depletion of the charge status of the traction batteries that equip electric vehicles when running at different speed intervals.

Chapter 5 Experimental research on electric vehicles. This chapter highlights the results of the research conducted after testing, using a roller bench, where the main energy performance indicators corresponding to the vehicle under investigation in the case of electric vehicles are also highlighted. A comparative analysis was also carried out with the results obtained through simulation, with the aim of validating the model in relation to the measurement.

Chapter 6 Final conclusions. Personal contribution. Dissemination of results. which presents the main conclusions drawn from research activities, new developments, and future objectives oriented toward research in this direction.

A BRIEF HISTORY OF THE ELECTRIC VEHICLE

1.1. The beginnings of electric vehicles

The beginnings of electric vehicles can be traced back to the 19th century, when the first experiments with electric motors were carried out in an attempt to develop efficient and non-polluting means of transport.

During this period, numerous notable figures emerged who contributed to the development of electric vehicles. Among them were:

- **Thomas Davenport (1802-1851)**: An American inventor who created one of the first electric vehicle designs in the mid-19th century.
- **Robert Anderson (1805-1871)**: A Scottish inventor who developed an electric vehicle with a non-acid electric battery. It is often recognized as one of the first electric vehicles.



Figure 3. Robert Anderson and his electric vehicle [3]

1.2. The pioneering period

This section will provide a detailed overview of the early stages of electric vehicle development, highlighting the key contributions of pioneers and significant events during the pioneering period.

1.2.1. The first experiments with electric vehicles

Pioneers such as Thomas Davenport and Robert Anderson, as described in the previous subchapter, made a significant contribution to the further development of electric vehicle technologies.

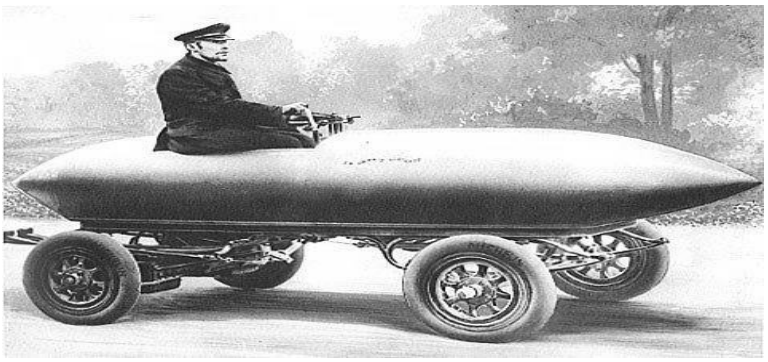


Figure 4. "La Jamais Contente," torpedo-shaped [4]

"La Jamais Contente" is the name of the electric car designed and driven by Belgian Camille Jénatzy, which was the first automobile to exceed 100 km/h in 1899, in Archères, in Yvelines. It reached a speed of exactly 105.882 km/h. The record was made possible by two Postel-Vinay electric motors with a total maximum power of 50 kW (approximately 68 horsepower), located at the rear between the wheels.

1.2.2. Thomas Edison's significant contribution

Thomas Edison was a prolific inventor and contributed significantly to the development of battery technology during his career. He is best known for inventions such as the electric light bulb, but he also had an interest in batteries.

1.2.3. The first generation of electric vehicles in the 1800s and early 1900s

The first electric vehicles appeared in the 19th century, long before the proliferation of internal combustion engine cars.

1. CURRENT STATE OF ELECTRIC VEHICLE DEVELOPMENT

To today, electric vehicles (EVs) have continued to have a significant impact on the automotive industry.

2.1. Configurations for the electric vehicle

A mid-range electric car would require a specific energy source of 220 Wh/kg and a specific power of 150-170 W/kg for a range of 300 km [6].

Classifying electric vehicles according to the number and position of their motors can provide greater detail about their configuration. Here is a classification based on these aspects:

1. Electric vehicles with a single motor on the front axle (FWD - Front-Wheel Drive):

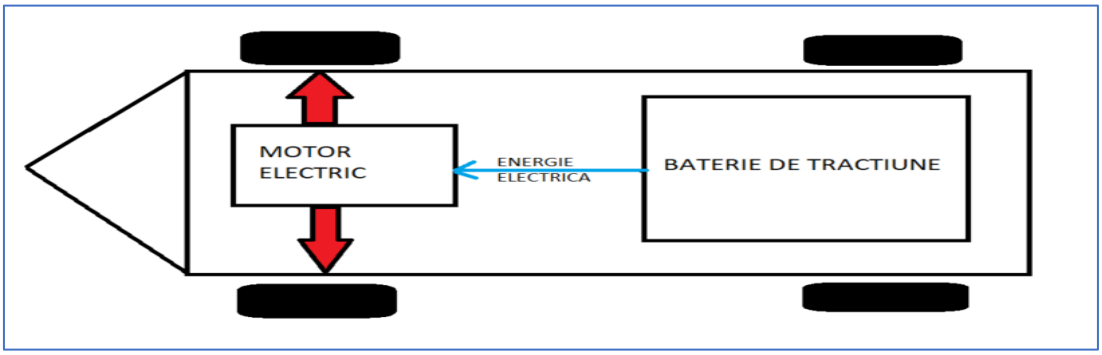


Figure 6. Schema cinematica vehicul electric cu un singur motor pe puntea fata

Features:

- Economical and compact.
- Good maneuverability under normal conditions.
- Simple to manufacture.

Examples of vehicles:

- Nissan Leaf.
- Renault Zoe.
- Chevrolet Bolt EV.
- Hyundai Kona Electric.

2. Electric vehicles with a single motor on the rear axle (RWD - Rear-Wheel Drive):

Features:

- Superior performance and traction.
- Improved handling on dry roads.

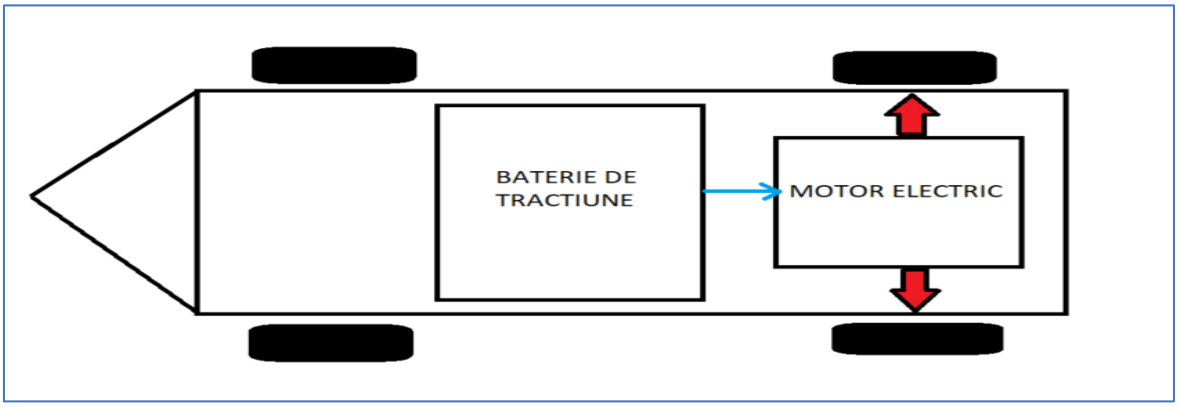


Figure 8. Kinematic diagram of an electric vehicle with a single motor on the rear axle

- - Dynamic driving experience.

Examples of vehicles:

- - Tesla Model 3.
- - Porsche Taycan.
- - BMW i3.
- - Rivian R1T.

3. Electric vehicles with two motors (AWD - All-Wheel Drive):

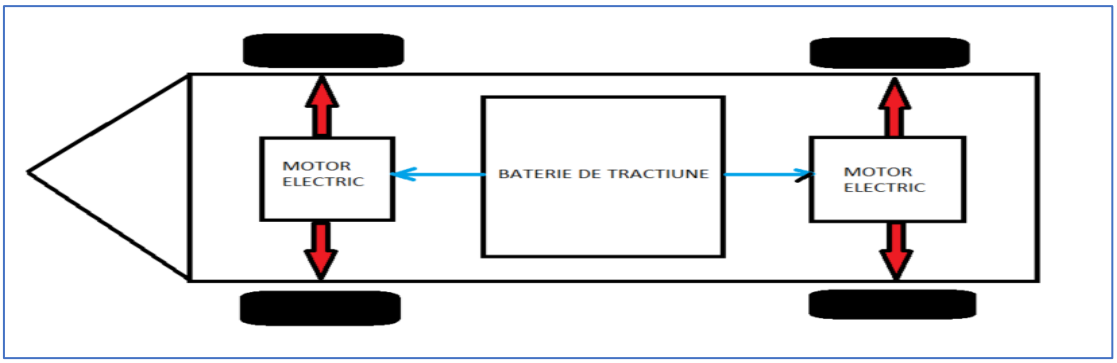


Figure 10. Kinematic diagram of an electric vehicle with two motors (AWD - All-Wheel Drive)

Features:

- All-wheel drive.
- Improved performance.
- Increased safety.

Examples of vehicles:

- Tesla Model S Dual Motor / Model X Dual Motor.
- Audi e-tron.
- Polestar 2.
- Ford Mustang Mach-E.

4. Electric vehicles with independent motors on each wheel:

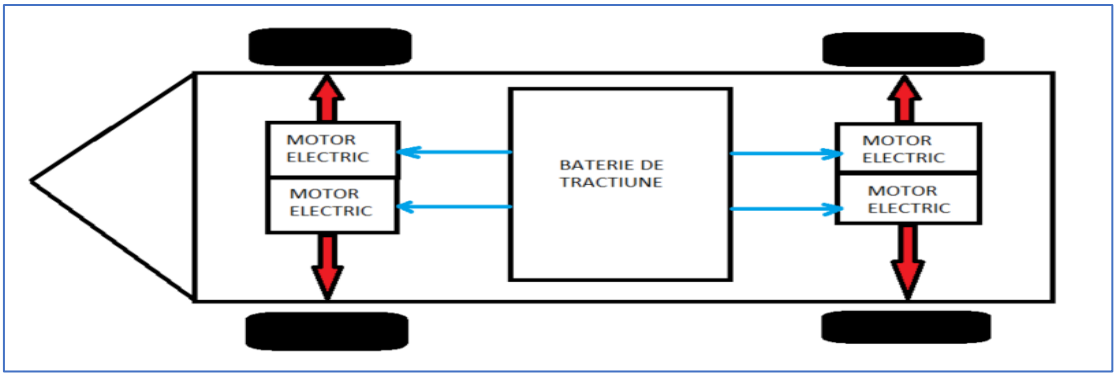


Figure 12. Kinematic diagram of an electric vehicle with independent motors on each wheel

Features:

- Precise traction control.
- Quick response.
- Improved performance.

Examples of vehicles:

- Rimac C_Two si Rimac Concept_.
- Lucid Air.
- Tesla Roadster.

5. Electric vehicles with motors integrated into the wheels (In-Wheel Motors):
   Features:

- Redundancy and reliability.
- Precise traction control.
- Simplification of vehicle architecture.

   Examples of vehicles:

- Hiriko Fold.
- Quadro Qooder.
- Lingyun Intelligent Vehicle (LY).

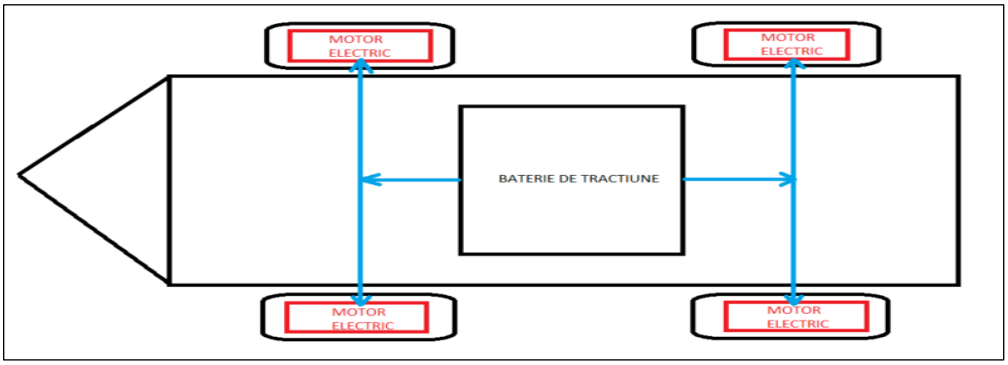


Figure 12. Kinematic diagram of an electric vehicle with in-wheel motors

2.2. Sources of electrical energy.

Electric batteries and storage batteries used in electric vehicles can be divided into several types, depending on the electrochemical processes that occur during charging and discharging and their chemical composition. Here are some types of electric batteries and storage batteries used in electric vehicles.

2.3. Characteristics of storage batteries.

Storage batteries play a crucial role in the operation of electric vehicles (EVs). These batteries are designed to store and supply electrical energy to power the electric motors of motor vehicles.

2.4. Fuel cells.

Fuel cells are electrochemical devices that convert chemical energy directly into electrical energy without producing polluting emissions during operation. They consist of a series of electrochemical cells that function similarly to batteries, but differ in that they require a continuous supply of fuel and oxidant to produce electricity and water as by-products.

2.5. Components specific to electric vehicles.

Electric vehicles (EVs) are built with a number of specific components that enable them to run on electricity stored in batteries.

2.6. Electric motors for electric vehicles. Types of construction.

Electric motors are key components of electric vehicles and are responsible for converting the electrical energy stored in batteries into mechanical motion to propel the vehicle. There are several types of electric motors used in electric vehicles, and the most common are:

1. Direct current (DC) electric motors:

- Brushed motor.
- Brushless motor.

2. Alternating current (AC) electric motors:

- Synchronous motor.
- Three-phase asynchronous motor (induction).

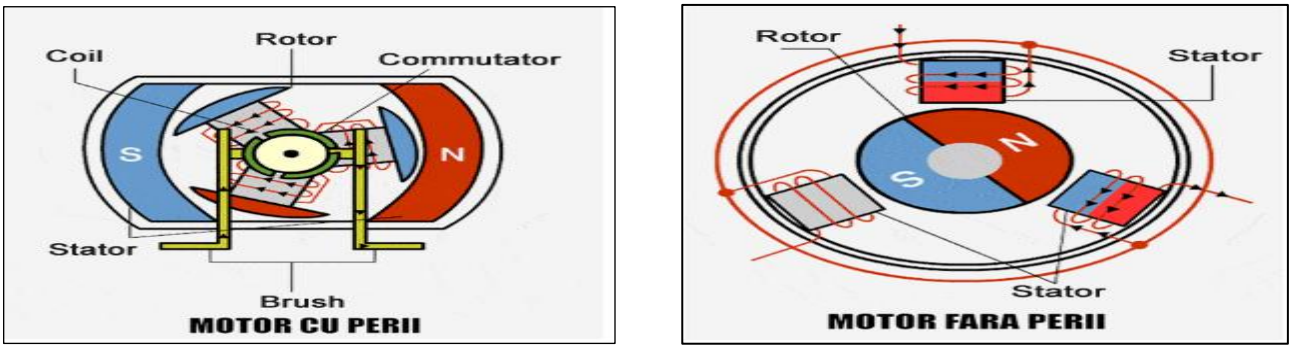


Figure 14. Schematic representation of brushed and brushless electric motors [12]

3. Axial flux electric motors.
4. Variable reluctance electric motors.

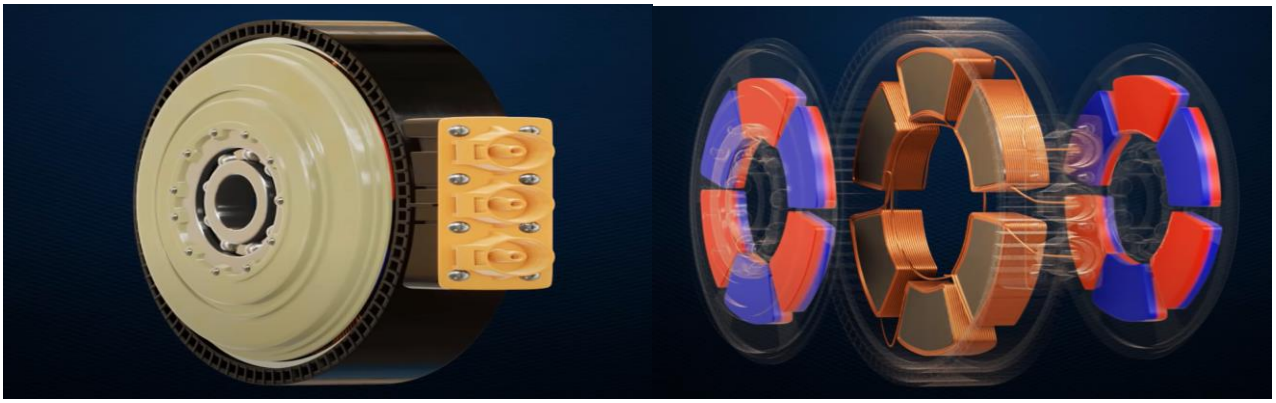


Figure 17. Overview and schematic diagram for the axial flow motor [15]

2.7. Advantages and disadvantages of electric motors compared to internal combustion engines.

The comparison between electric motors and internal combustion engines (internal combustion engines) includes a number of mechanical aspects, performance, and operating characteristics.

2.10. Types of transducers used in electric vehicles.

In the context of motor vehicles, the transducers through which the driver's commands are transmitted to the speed variator via the accelerator pedal or brake pedal are called position sensors or control sensors. These sensors detect the position or action of the accelerator and brake pedals and transmit this information to the speed variator or engine controller.

2.11. Charging traction batteries suitable for electric vehicles.

Electric vehicle charging can be classified in several ways, depending on various factors such as charging speed, type of connector used, power supply method, and charging system capacity.

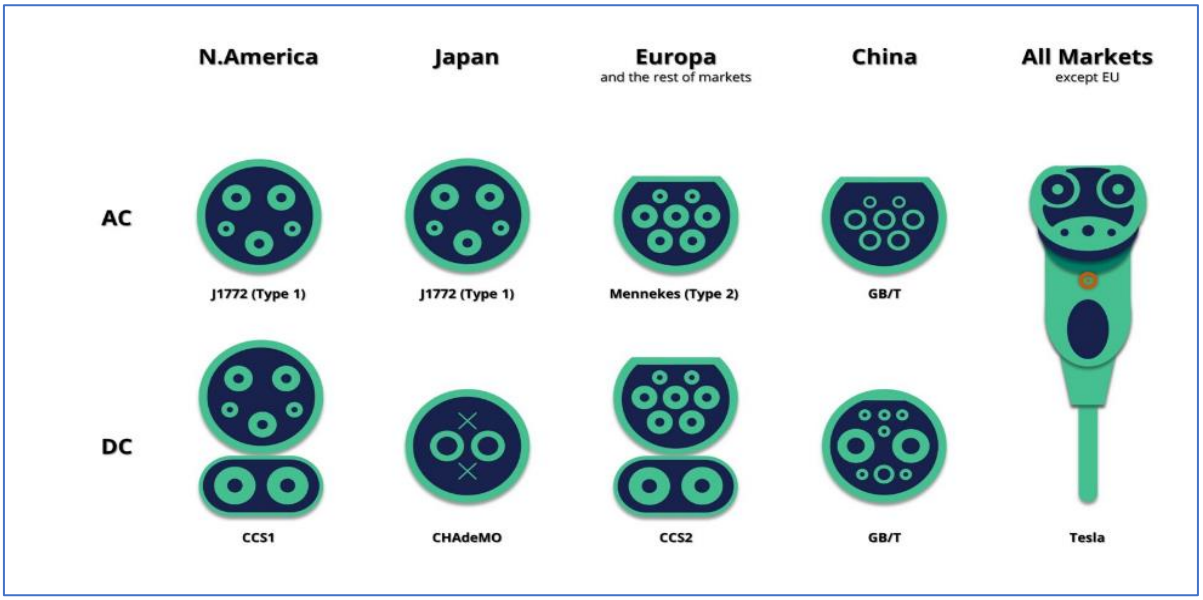


Figure 20. Types of cables and connectors for electric vehicles [18]

3. SPECIFIC EQUIPMENT FOR ELECTRIC VEHICLES

The specific equipment of electric vehicles includes essential components that differentiate them from vehicles with internal combustion engines. Here is the main equipment:

1. **Traction battery** – Stores the electrical energy needed to power the electric motor. The most common types are lithium-ion batteries due to their high energy density and longer life span.
2. **Electric motor** – Converts electrical energy into mechanical energy to propel the vehicle. It can be synchronous or asynchronous.
3. **Inverter** – Converts direct current (DC) from the battery into alternating current (AC) required by the electric motor.
4. **Rectifier/DC-DC Converter** – Reduces voltage from the traction battery to power the vehicle's auxiliary equipment, such as lights, electronic systems, and air conditioning.
5. **Electronic Control Unit (ECU) –** Coordinates the operation of electrical components and optimizes vehicle efficiency.
6. **On-Board Charger (OBC) –** Allows the battery to be charged from an external source, controlling voltage and current for safe and efficient charging.
7. **Brake energy recovery system –** Recovers kinetic energy during braking and converts it into electrical energy to recharge the battery.

8. **Charging port –** The connector through which the vehicle is charged from public or private charging stations.
9. **Digital control panel and infotainment system** – Displays information about range, energy consumption, driving modes, and offers connectivity features.

3.1. Traction battery

Traction batteries for electric vehicles can be classified according to their chemistry, which determines their performance and lifespan. Lead-acid batteries - these are the oldest and cheapest traction batteries, but they have very low energy density and a short lifespan.

3.1.1. Lithium-ion (Li-ion) batteries

These are the most common types of batteries used in electric vehicles.

3.1.2. Solid-state batteries

Solid-state batteries are a new emerging technology in the field of electric vehicle batteries.



Figure 23. Detail of Solid-State Battery from manufacturer NIO[19]

3.1.3. Liquid Electrolyte Batteries

Liquid electrolyte batteries are a type of rechargeable battery that uses a liquid electrolyte to facilitate the transfer of ions between electrodes.

3.1.4. Sodium-ion (Na-ion) batteries

Na-ion batteries are an emerging technology that offers a promising alternative to lithium-ion (Li-ion) batteries.

3.1.5. Lead-acid batteries (Pb-acid)

Lead-acid batteries are one of the oldest and most widely used energy storage technologies.

3.2. Electric motor

The electric motor is the main component that converts electrical energy from the battery into mechanical energy for vehicle propulsion. Unlike internal combustion engines, electric motors are more efficient, more reliable, and provide instant torque.

Types of electric motors used in electric vehicles:

1. Permanent magnet synchronous motor (PMSM)
2. Induction motor (IM)
3. Electrically excited synchronous motor (EESM)
4. Switched reluctance motor (SRM)

3.3. The inverter

The inverter is an essential component of an electric vehicle (EV) propulsion system. It converts direct current (DC) from the traction battery into alternating current (AC) required to drive the electric motor.

3.4. Rectifier/DC-DC Converter

The DC-DC converter is an essential electronic device in electric vehicles (EVs), serving to convert the direct current (DC) voltage from the traction battery to a level suitable for powering other vehicle systems.

4. MODELING AND SIMULATION OF ENERGY PERFORMANCE WHEN DRIVING AN ELECTRIC VEHICLE IN DIFFERENT STANDARDIZED CYCLES

4.1 Theoretical considerations on modeling and simulation

When modeling, certain objectives are taken into account, namely the creation of the physical model and the creation of the mathematical model. The physical model is used to identify and model the characteristics or phenomena that define the system or process under study. The mathematical model is a phase based on a series of calculation formulas and mathematical relationships representative of the system or process under study, with the aim of obtaining useful research results that introduce as few errors as possible.

4.2 Development of the model used for simulation

In this subchapter, we will present the sequence of steps followed in developing the simulation model, as well as the general conditions established and the main characteristics of the reference vehicle used to validate the model.

4.2.1 Characteristics of the dynamic model of the electric vehicle

The dynamic model of an electric vehicle involves the implementation of all forces acting on the vehicle while driving in different conditions. To develop this model, it is necessary to have the general mathematical relationships that define the resistance to forward motion and traction balance, based on which the general equation of the rectilinear motion of a vehicle can be determined.

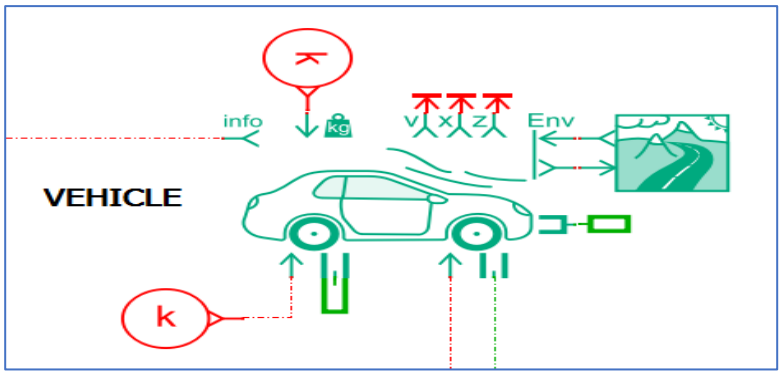


Figura 32. Reprezentare grafica in Amesim pentru un vehicul electric

4.2.2 Implementation of electric propulsion system components

The main objective of this article is to identify suitable simulation models for electric vehicle components to ensure good correlation with experimental results.

The Renault ZOE, Figure 33, is a publicly available electric car offering a range of 300 km.



Figure 33. Renault Zoe electric vehicle

4.2.2.1. Electro-thermal modeling of traction batteries.

I . Battery models

Electricity storage is a functional requirement for many multiphysics systems. The Simcenter Amesim platform contains three types of battery models in the electrical storage library:

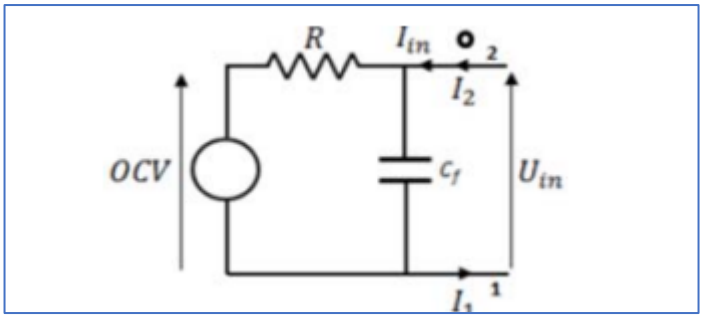


Figure 34. Equivalent circuit model of the traction battery for quasi-static simulation

The advanced (dynamic) equivalent circuit model, Figure 35, includes the addition of RC circuits to accurately characterize the dynamic performance of the battery related to diffusion (C_{diff}, R_{diff}) and charge transfer (C_{ct},\ R_{ct}).\ This model can be used to simulate the dynamic behavior and thermal transition of the battery.

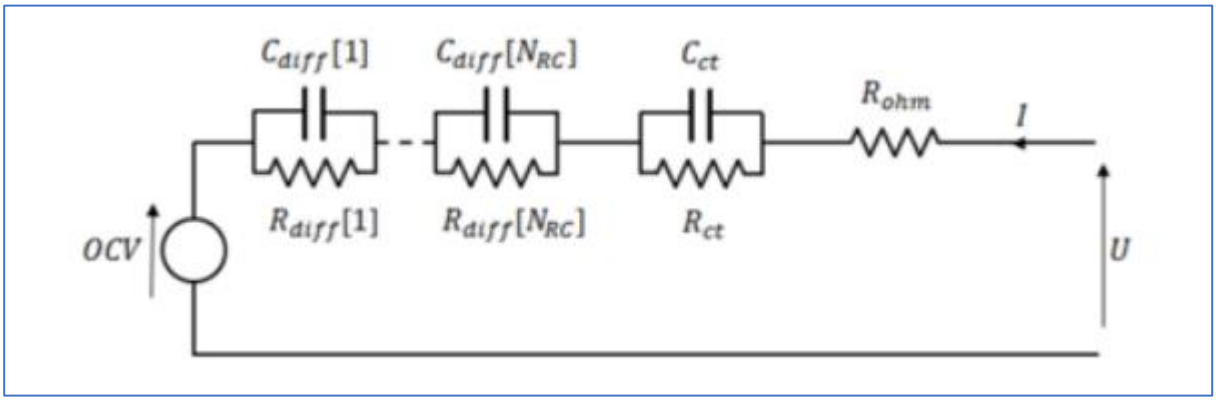


Figure 35. Equivalent circuit model of the traction battery for dynamic simulation

II. Li-ion battery – comparison between model and experiment

Li-ion batteries are one of the most promising energy storage systems (ESS) for electric, hybrid, and plug-in hybrid vehicles. A simulation model of a virtual test bench was developed using the Simcenter Amesim platform. This model includes two battery options: the quasi-static model and the dynamic model.

The batteries are powered by an adjustable current source, with the control signal being the battery current profile measured during the test. Figure 37 shows the virtual test bench used for the comparative analysis of the two types of batteries analyzed.

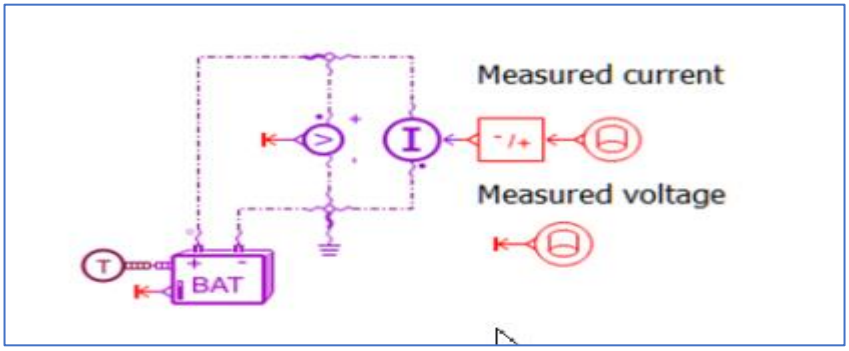


Figure 37. Virtual test bench model in Amesim

The battery installed in the Renault ZOE has 96 cells connected in series, as well as two branches connected in parallel. Each cell has a capacity of 36 Ah.

Figure 38 shows the measured current profile and a comparative analysis of the experimentally measured voltage with the simulation results in the first 2000 seconds.

1.2.2.1 Modeling and simulation of an electric vehicle.

Figure 40 shows a model of a Renault ZOE electric car using the IFP drive library available in Amesim.

The most important parts of the model are: the vehicle, the driver, the vehicle control unit (VCU), the electric motor, and the battery. In the simulation process, the vehicle must follow a specific speed profile. The driver model calculates the signals for the brake pedal and accelerator pedal to comply with the speed profile. The control unit translates the acceleration command into a motor torque ratio command.

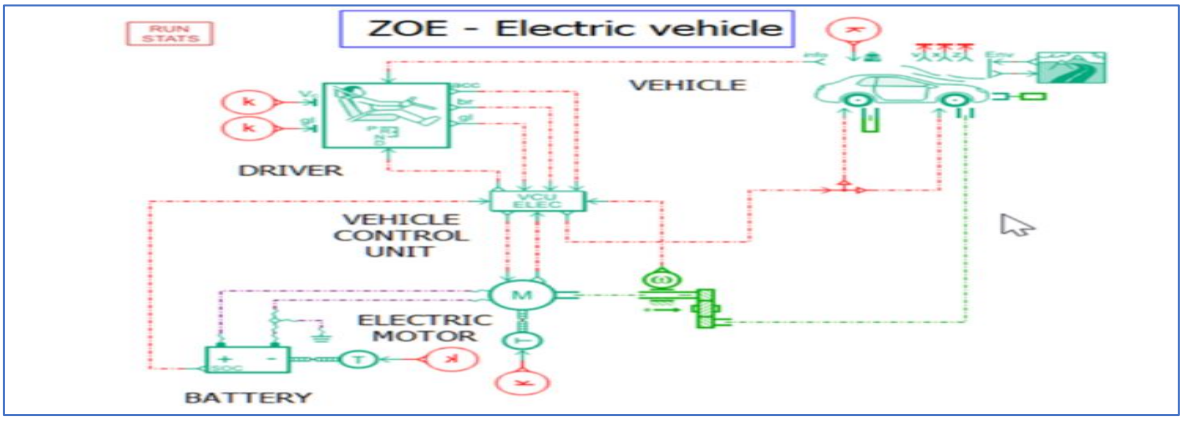


Figure 40. Representation of the Renault Zoe vehicle model using the Amesim platform

I. The driver model

This model calculates several commands: acceleration command "acc", braking command "br" and gear shift command "gl".

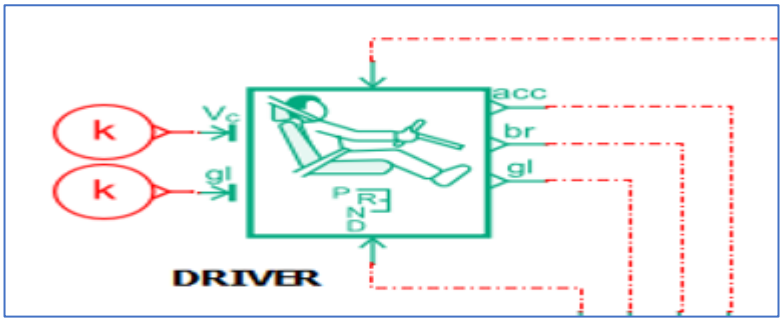


Figure 41. Representation of the driver model using the Amesim platform

II. Vehicle Control Unit Model – VCU EV

This VCU EV (Vehicle Control Unit for Electric Vehicle) receives information from the driver, the traction battery, and the electric motor.

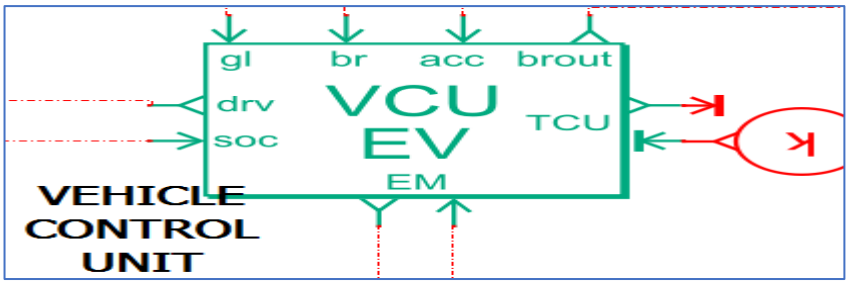


Figure 42. Representation of the VCU EV model using the Amesim platform

III. Electric Motor

The electric motor in the electric vehicle model simulation is a model of an electric motor/generator together with its converter. The output torque and power losses can be determined either using data files or characteristic parameters. The model is bidirectional (motor/generator) and independent of the motor and converter technology.

IV. Vehicle model

The vehicle model represents the structure of the electric vehicle (EV). Both the front and rear axles are modeled. The braking torque for each axle is determined from the input signal, the maximum overall braking torque, and the distribution of braking between the front and rear axles. The rotary mechanical ports receive the drive torque and return the rotational speed for each axle.

V. Simulation results.

This subchapter presents the Model-In-the-Loop (MiL) simulation for an electric vehicle powered by a synchronous motor. MiL simulation is a tool for validating a closed-loop control algorithm.

In order to achieve the speed required by the speed profile, the driver must control the acceleration and braking of the vehicle. During the braking process, regenerative braking occurs when the battery charge level falls below a specified level. Figure 48 shows the moment when regenerative braking is authorized by the electronic control unit.

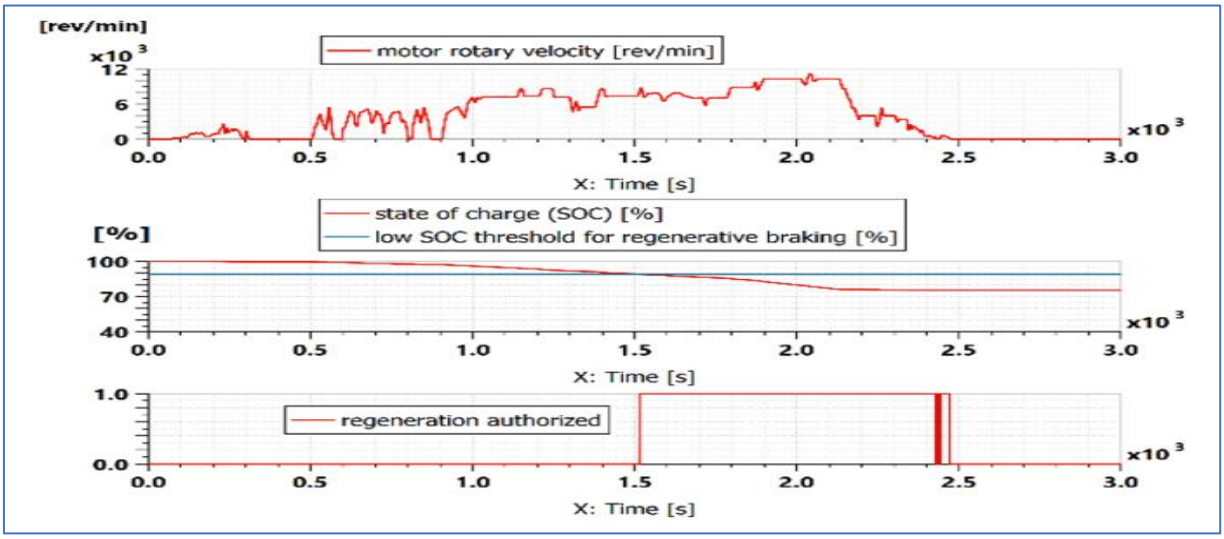


Figure 48. Motor speed, SOC, and authorized regenerative braking

To better visualize the evolution of the analyzed curves, the time interval of the x-axis was reduced to 3000 seconds for Figure 48.

VI. Conclusions

The models presented in this demonstration provide an efficient MiL simulation. The physical models and environment are easy to model thanks to Simcenter Amesim libraries. In addition, the simulation is performed using the Simcenter Amesim variable-step solver with discontinuity handling. This guarantees good accuracy and reliability.

4.3 Numerical simulation of the energy consumption of electric vehicles in different standardized cycles

This subchapter aims to verify the model developed with the introduction of the technical data of the reference vehicle by analyzing the energy consumption of the electric vehicle subjected to simulation in different standardized cycles, in different driving modes: when driving at low and medium speeds and when driving at high and very high speeds.

4.3.1. WLTC driving cycle

This cycle has four parts, namely low, medium, high, and very high speed.

WLTP uses the new Worldwide Harmonized Light Vehicle Test Cycle (WLTC) to measure fuel consumption, CO2 emissions, and pollutants emitted by passenger cars and light commercial vehicles. RDE driving cycle.

With RDE, a car is driven on public roads and is therefore exposed to a wide range of different conditions. Specific equipment installed on the vehicle collects data to verify that legal limits for pollutants such as NOx are not exceeded. Driving conditions include:

- Low and high altitudes
- Temperatures throughout the year
- Additional vehicle payload
- Driving uphill and downhill
- Urban roads (low speed)
- Rural roads (medium speed)
- Highways (high speed)

4.4. Research on energy consumption and range of electric cars in WLTC cycle tests.

Among the main objectives expected by both manufacturers and end users of electric vehicles are electricity consumption and range, which must clearly replace the results of vehicles with thermal energy sources.

In the second part of the paper, after testing the electric vehicle on the dynamic roller test bench, the specific areas of the test cycle in which the propulsion battery range shows a significant decrease are highlighted. The analysis of the range evolution is supported by data collection from the main electronic control units of the electric propulsion system.

4.4.1. Insight into energy consumption and range simulation for electric cars in WLTC cycle testing.

The WLTC test cycle also introduced three different test classes specific to the power-to-weight ratio: the first class up to 22 kW/t, characterized by a maximum test speed of 70 km/h, the second class up to 34 kW/t, characterized by a maximum test speed of 90 km/h, and the third class at 35 kW/t, in this case with a maximum test speed of approximately 131 km/h.

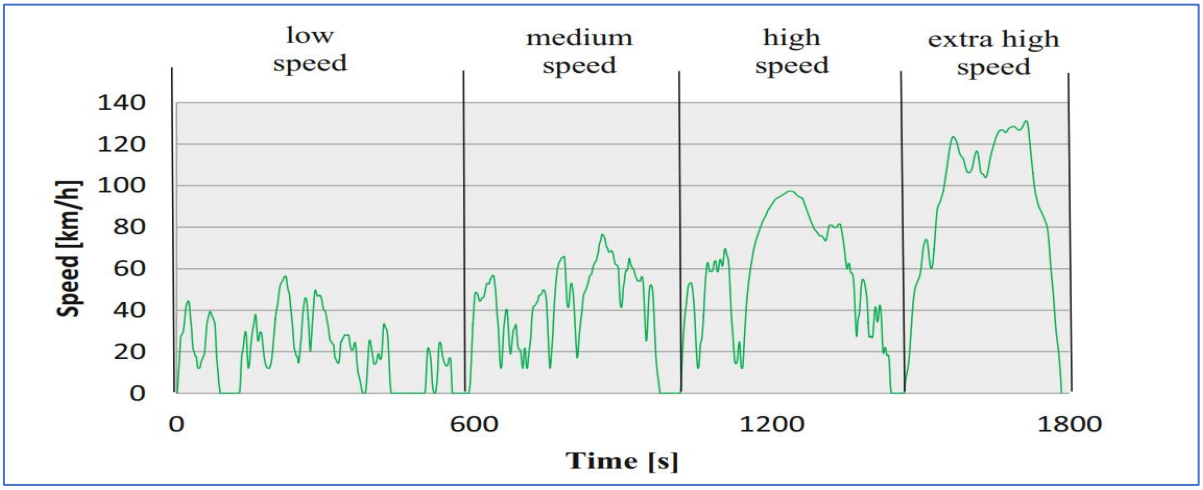


Figure 52. Worldwide harmonized light vehicle test cycle (WLTC)

4.4.2. Simulation of energy consumption and range of electric cars in WLTC cycle tests.

The experimental study was conducted after driving the vehicle on a dynamometer, following the speed and load profile described by WLTC. Before the test, the traction battery was charged to 100%. After charging, the vehicle was preconditioned, i.e., it was kept at a controlled temperature for approximately 12 hours.

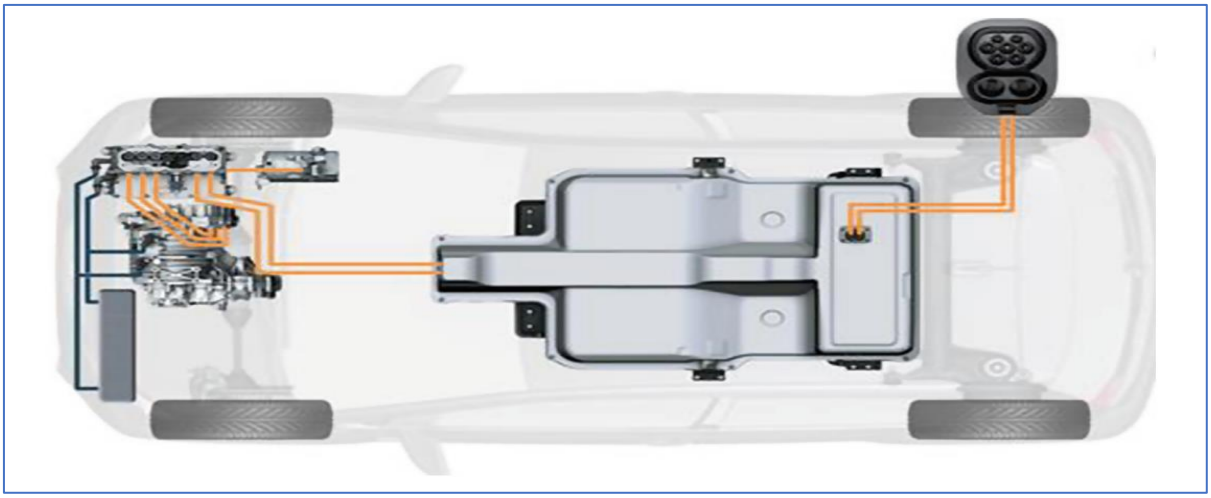


Figure 53. General architecture of an electric vehicle undergoing testing

The vehicle presented for testing is mid-sized, with a general architecture similar to that shown in the diagram above, and has the following technical characteristics:

- Weight: 1135 kg;
- Inertia: 1250 kg;
- Front-wheel drive;
- Electric motor type: synchronous with spiral rotor;
- Maximum power: 65 kW;
- Maximum torque: 200 Nm;
- Traction battery power: 22 kWh;
- Traction battery technology: Li-Ion, 400 V

To simulate the inertia and load requirements of the dynamometer, the following data were used:

- Power and load supported by the roller bench at 85 km/h: 6.8 kW;
- Rolling resistance coefficients: a (N) 6.9; b [N/(km/h)2] 0.0455;

Figure 54 shows that the speed profile was maintained throughout the test period, indicating that the vehicle was able to respond dynamically to the demands placed on it. In order to accurately analyze the cause of the decrease in traction battery charge, which leads to a reduction in range, several cycles were performed, establishing average values for each of the four specific areas of the WLTC cycle.

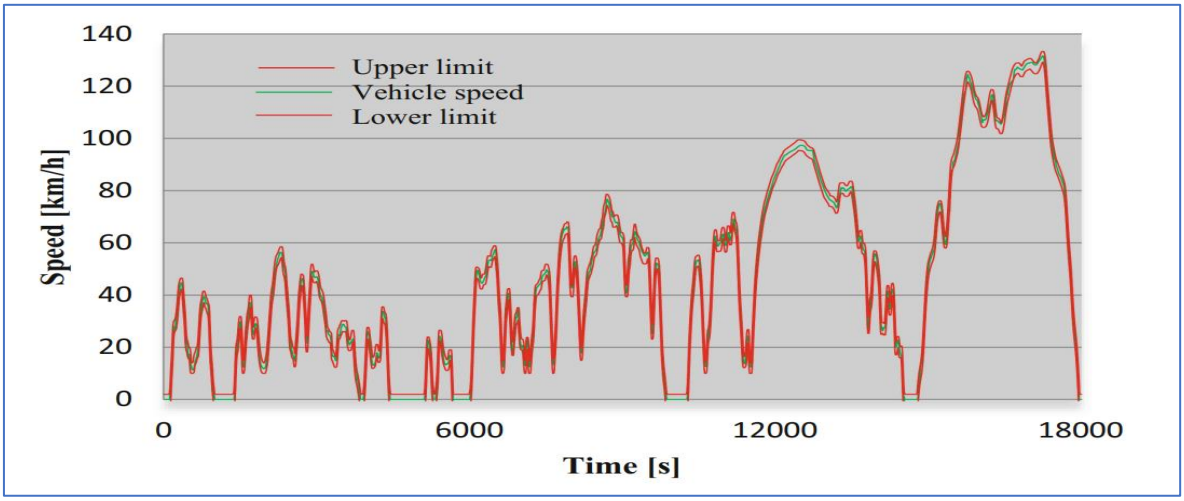


Figure 54. WLTC speed profile followed by the tested vehicle

From the information provided by the electronic control units that manage the traction battery, it was possible to analyze the energy balance, as well as the ratio between the energy transferred to the traction system by the battery and the energy recovered by the battery through regenerative braking.

4.4.3. Simulation results regarding energy consumption and range of electric cars, in the case of WLTC cycle tests.

Simulations and experimental research have also highlighted graphs of the specific load level of the traction battery, specific to each speed range included in the WLTC component.

4.4.4. Conclusions of the simulation regarding energy consumption and range of electric cars in WLTC cycle tests.

Experimental research indicates that the state of charge, i.e., the range of traction batteries, performs very well in low- and medium-speed driving conditions typical of urban areas characterized by heavy traffic.

4.5. Research on the range and energy consumption of electric vehicles, simulated and measured, when driving at low and medium speeds, as specified in the WLTC test.

The most important features expected from current electric vehicles include energy consumption and range, which must be able to unequivocally replace the performance of vehicles equipped with internal combustion engines. These expectations come from both manufacturers and end users.

4.5.1. Calculation of the range and energy consumption of electric vehicles, simulated and measured, when driving at low and medium speeds, as specified in the WLTC test, using the AMESIM modeling and simulation platform.

Electric vehicles (EVs) have become increasingly popular in recent years, with many governments around the world committing to reducing carbon emissions by moving away from fossil fuels. One of the most important aspects of electric vehicle performance is their range, which is influenced by several factors. In recent years, simulations have become a popular tool for predicting the range of electric vehicles, but their accuracy has often been questioned.

4.5.2. The results of the simulation regarding energy consumption and the range of electric cars, in the case of WLTC cycle tests, when driving at low and medium speeds, specific to the WLTC test, using the AMESIM modeling and simulation platform.

As a result of experimental research, graphs were produced showing the traction battery charge level specific to each speed range included in the WLTC test. Furthermore, based on data acquired using specific equipment, conclusions could be drawn regarding how traction battery energy is consumed and recovered.

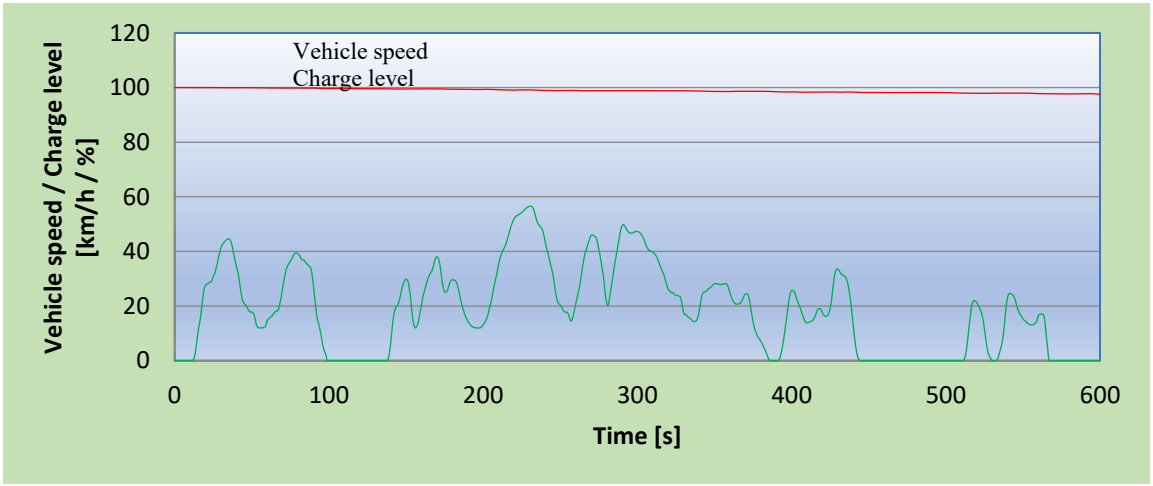


Figure 63. Traction battery charge level, low speed range

The car's low-speed driving range is shown in Figure 63, which is characterized by a very low load level. As you can see, this type of driving simulates the specifics of areas with heavy traffic, with an

average speed of about 18.9 km/h and a maximum speed of about 56.5 km/h. In such situations, the traction battery performs very well, characterised by low energy consumption and multiple regenerative braking, where obviously the impact on the charge level and implicitly on the range is not significant.

Experimental research indicates that the best performance in terms of traction battery range is achieved in these types of driving at low speed and load, which is why certain types of electric vehicles are intended for use in urban areas with heavy traffic. Driving in the medium speed range described in Figure 64 is also not problematic in terms of range, as in this situation we are also talking about low loads and moderate speeds, with an average speed of 39.5 km/h and a maximum speed of approximately 76.6 km/h.

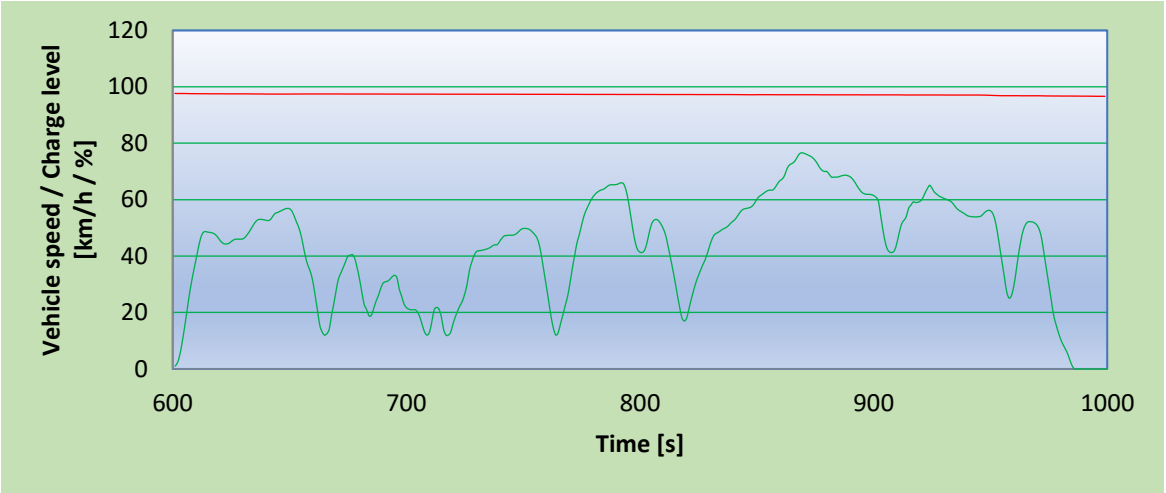


Figure 64. Traction battery charge level, medium speed range

4.5.3. The conclusions of the simulation regarding energy consumption and the range of electric cars, in the case of WLTC cycle tests, when driving at low and medium speeds, specific to the WLTC test, using the AMESIM modeling and simulation platform.

Experimental research indicates that the state of charge, respectively the autonomy of traction batteries, exhibits very good behavior in low and medium speed driving conditions, specific to urban agglomerations characterized by heavy road traffic.

Also, a very high influence in establishing very good performance of traction battery range in low and medium speed driving conditions is the driving mode chosen recently by all electric vehicle manufacturers, with the ECO driving mode also available, which provides slow, progressive acceleration.

4.6. Research on the range and energy consumption of electric vehicles, simulated and measured, when driving at high and very high speeds, as specified in the WLTC test.

The first part details theoretical aspects regarding the electric vehicle tested and the applicable test procedure, specific to the WLTC cycle, corresponding to the test area for high speed and very high speed.

4.6.1. Calculation of the range and energy consumption of electric vehicles, simulated and measured, when driving at speeds specified by the WLTC test, using the Simcenter AMESIM simulation and modeling platform.

Two performance criteria are perhaps among the most important expectations that users have of electric vehicles: range and electricity consumption.

The Simcenter AMESIM platform offers a wide range of simulation functions used by automotive manufacturers and other industrial sectors such as machinery, shipbuilding, aviation, etc.

4.6.2. The results of the simulation regarding energy consumption and the range of electric cars, in the case of WLTC cycle tests, when driving at high and very high speeds, specific to the WLTC test, using the AMESIM modeling and simulation platform.

The Simcenter AMESIM platform was used for modeling and simulation. The program was run by simulating a mid-range vehicle equipped with an electric motor and gearbox. The data relating to the car subjected to modeling and simulation are similar to those of a real car that is to be tested on the roller test bench to validate the results obtained through simulation.

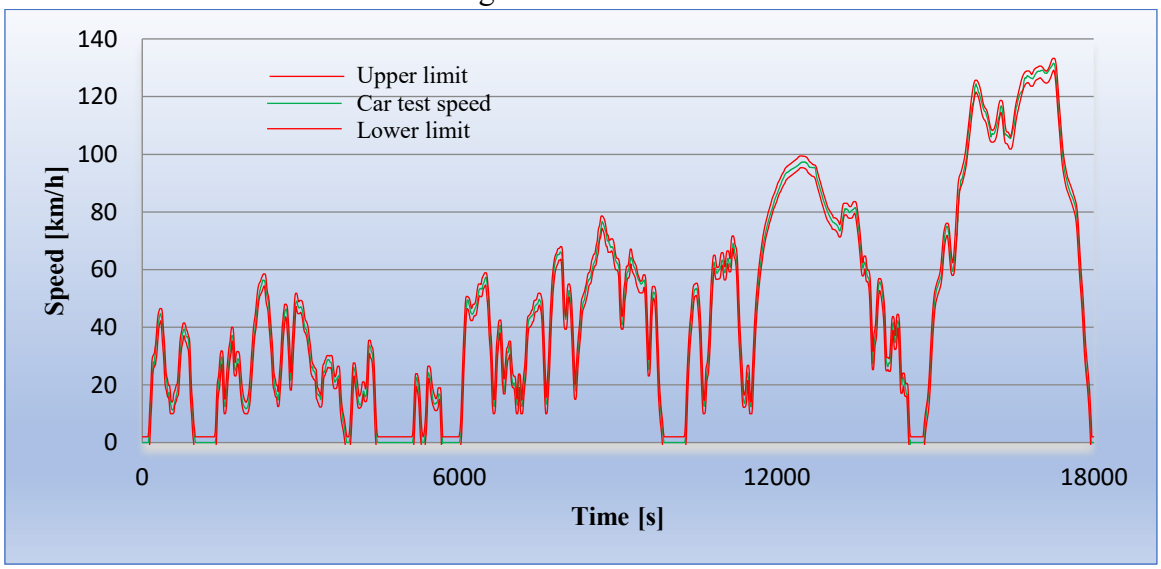


Figure 65. WLTC speed profile followed by the tested vehicle

Figure 65 shows that the speed profile was maintained throughout the test, indicating that the car was able to meet the dynamic requirements to which it was subjected.

4.6.3. The conclusions of the simulation regarding energy consumption and the range of electric cars, in the case of WLTC cycle tests, when driving at high and very high speeds, specific to the WLTC test, using the AMESIM modeling and simulation platform.

Thus, the simulated behavior of the traction battery charge status was analyzed in relation to the load and speed of the electric motor, obviously generated by the speed of travel and the dynamics of the cycle. The simulation was run until the traction battery charge status was completely depleted. Last but not least, based on this information, the speed ranges in which the electric vehicle performs best in terms of economy, characterized by low electricity consumption, were also identified.

Figure 66 shows the variation in regenerative charging over time for the vehicle tested at high and very high speeds specific to simulated driving on the WLTC cycle, for one test cycle. It can be seen how the SOC charging state decreases significantly over time, despite regenerative braking with very high inertia at high and very high speeds. Studies show that temperature also plays a very important role in the evolution of the regenerative charging state in electric vehicles [49].

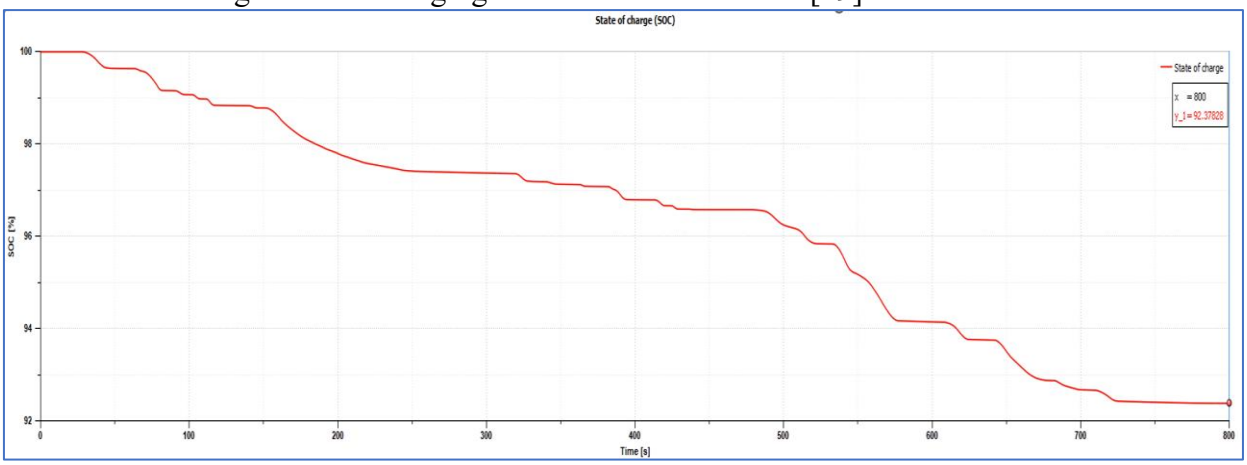


Figure 66. Variation in regenerative charging status for the car tested at high and very high speeds for a WLTC test cycle

In fact, studies have shown that, in addition to temperature, the number of complete charge and discharge cycles of the traction battery plays a very important role in how quickly the traction batteries that power electric vehicles are depleted when driving at high and very high speeds.

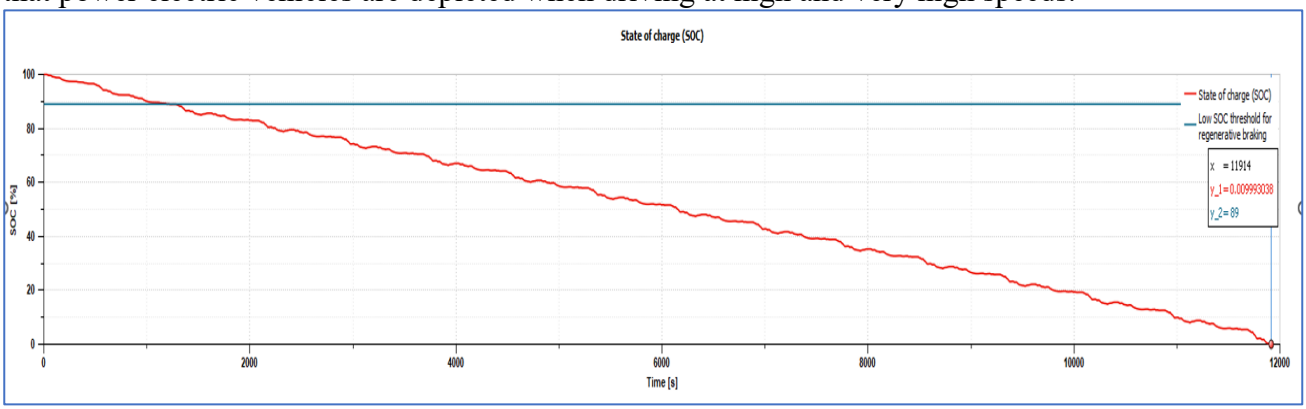


Figure 67. Variation in regenerative charging status for the car tested at high and very high speeds for 15 test cycles in WLTC

Figure 67 shows the variation in regenerative charging over time for the vehicle tested at high and very high speeds specific to simulated driving on the WLTC cycle, for 15 test cycles. It can be seen how the SOC charging state decreases significantly over time, despite regenerative braking with very high inertia at high and very high speeds. Studies show that temperature also plays a very important role in the evolution of the regenerative charging state in electric vehicles.

Several test cycles were also chosen, given that these tests were carried out under different temperature and climatic conditions, and at certain speed ranges, at high and very high speeds of the vehicle under test.

Thus, the accuracy of the results of these tests is much closer to reality, given the multitude of factors that influence these measurements.

In Figure 68, in such situations where we are talking about an average speed of 56.6 km/h and a maximum speed of approximately 97.4 km/h, the contribution of recovered energy is usually practically insignificant, with the reduction in the charge level and, implicitly, in the range being smooth and gradual.

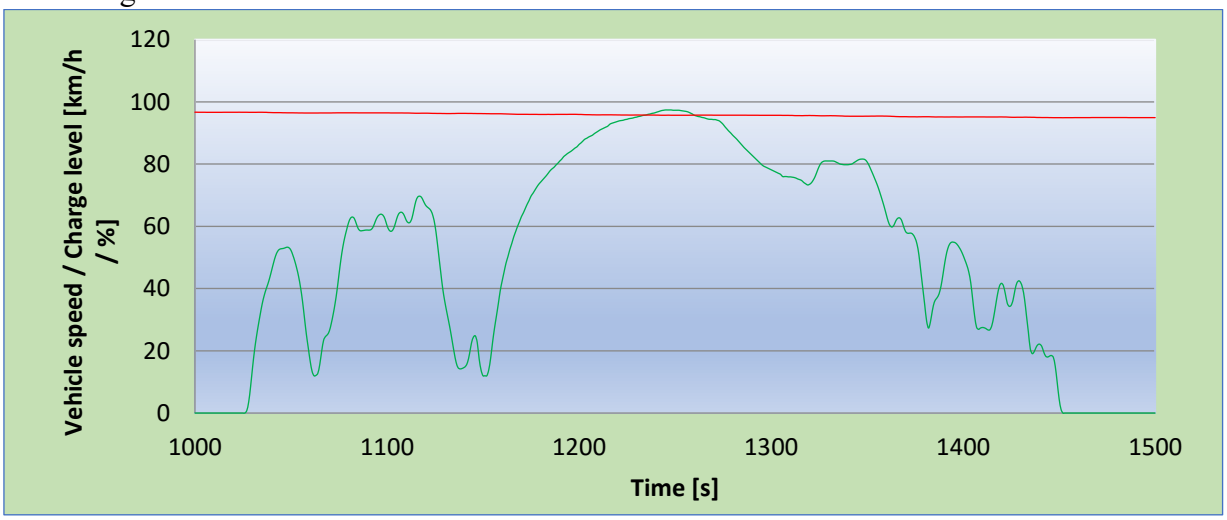


Figure 68. Traction battery charge level, high speed range

The high-speed running range, shown graphically in Figure 69, has a special character in terms of maintaining the charge level in the traction battery. In such driving conditions, the average speed reaches 92 km/h and the maximum speed reaches 131.3 km/h. As a rule, in this range, the vast majority of series-production electric vehicles reach their maximum design speed, characterised by full load where energy recovery is non-existent.

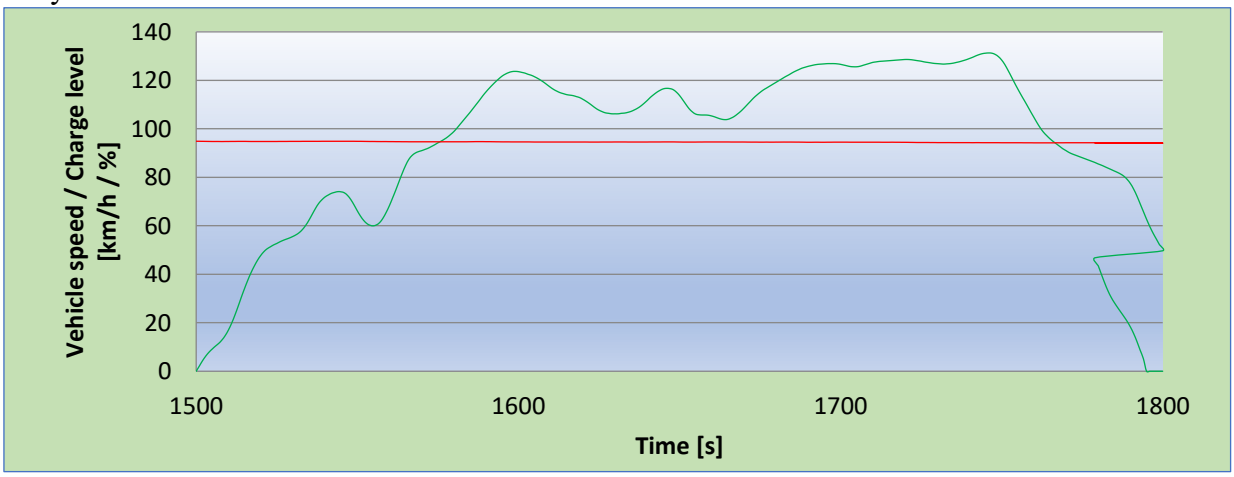


Figure 69. Traction battery charge level, very high speed range

At this speed, the traction battery charge level drops rapidly, immediately affecting the range. This is the most unfavorable situation for the energy stored in the traction battery due to the very high consumption generated by the electric traction motor.

The tests applied to the electric vehicle under investigation were repeated until the traction battery's range was completely exhausted, i.e., until the vehicle could no longer maintain the specified speed.

As a result of the simulated driving, it was found that when cars are driven at high and very high speeds, characterized by high and very high dynamic demands, maintaining the state of charge is difficult to achieve, with a very high effect on electric range. With direct reference to the high and very high speeds of the simulated WLTC cycle, this can be likened to the use of cars in extra-urban and motorway conditions. In such conditions, with virtually no regenerative braking, the energy recovered by the traction battery is non-existent, so the impact on electric range is very high.

The simulated evolution of the traction battery's state of charge with an effect on electric range when running on the WLTC cycle indicates that electric cars are very useful in urban driving and satisfactory for extra-urban or highway driving. The evolution of traction battery manufacturing technologies and their increased power can compensate for the range of vehicles used in extra-urban or highway driving.

Studies have also shown that temperature, climatic conditions, and the number of complete charge and discharge cycles of the traction battery play a very important role in the depletion of the charge state of traction batteries in electric vehicles when driving at high and very high speeds.

4.7. Research on energy consumption and range of electric cars in RDE cycle tests using the Simcenter Amesim platform.

The entry into force of the Euro6 standard invites us to determine actual gas emissions on a specific route: one third in the city, one third on secondary roads, and one third on highways.

The EU6d emissions regulation requires, between 2017 and 2020, that emissions under real driving conditions be taken into account as an additional requirement for type approval, in order to take into account the influence of road profile, environmental conditions, traffic conditions, and driver behavior. The new test uses a portable emissions monitoring system (PEMS) to measure emissions on board. But also to assess the energy consumption of an electric vehicle. Electric vehicles do not produce polluting emissions, so measurement in a real cycle is reduced to determining electricity consumption, range, and other relevant factors that demonstrate the dynamic and energy performance of these vehicles.

The route must include an urban section, a rural section, and a highway section, with specific requirements regarding distance and average speed for each section. For example, the total duration of the route must be between 90 and 120 minutes. Due to these strict requirements, RDE measurements must be preceded by precise route planning in order to reduce the risk of test failure and, consequently, experimental costs. The objective of this study is to present a procedure that allows the establishment of a cycle for emissions under real driving conditions that minimises distance, is robust in the face of uncertainties related to traffic conditions and meets regulatory requirements. The procedure was applied on routes with the starting point and destination in the innovation engineering department. In addition, a preliminary analysis of the effect of instantaneous speed and acceleration on energy consumption under real conditions was performed.

4.7.1. Insight into energy consumption and range simulation for electric cars in RDE (Real Driving Emission) testing.

As already specified, electric vehicles do not produce polluting emissions, so measurement in a real cycle boils down to determining electricity consumption, range, and other relevant factors that demonstrate the dynamic and energy performance of these vehicles.

RDE cycles are defined to represent real-life scenarios. They must take into account a variable environment, road gradients, wind, traffic, and different driving behaviors. A list of criteria is defined to verify whether a cycle is compatible with "RDE." A simplified list is presented below:

Cycle Distribution Table

Parameter	Low	Medium	High
Cycle Distribution (+/- 10%)	29% < ratio ≤ 34%	33%	33%
Speed	V < 60 km/h	60 km/h ≤ V < 90 km/h	V > 90 km/h
Maximum Speed (±15 km/h for less than 3% of driving time)	-	-	145 km/h
Average Speed (including stops)	15 km/h ≤ Vavg ≤ 30 km/h	-	-
Minimum Distance Travelled	16 km	16 km	16 km
Altitude Difference (start/end)	100 m	100 m	100 m
Maximum Slope	1200 m/100 km	1200 m/100 km	1200 m/100 km

Figure 71. List of criteria for verifying whether a cycle is compatible with "RDE."

To complete the model configuration, the cycle files generated in the previous section must be configured in the driver submodel.

Fuel or energy consumption estimates can also be made for electric vehicles. Now that the model is fully defined and the RDE cycle imported into Simcenter Amesim, the simulation can be launched. Continuous improvement of existing solutions.

4.7.2. Calculation of energy consumption and range of electric cars in RDE cycle tests using the Simcenter Amesim platform.

4.7.2.1. Introduction

This study describes the methodology, modeling, simulations, and analysis of results for evaluating the energy consumption and range of an electric vehicle (EV) on Real Driving Emissions (RDE) cycles using the Simcenter Amesim platform. The goal is to provide a reproducible, robust, and validated framework for estimating consumption (Wh/km, kWh/100 km), regenerated energy, and estimated range based on the SOC window and environmental scenarios (temperature, wind, altitude).

Simcenter Amesim's role in this evaluation:

- Detailed physical modeling.
- RDE cycle integration.
- Parametric analysis.
- Optimization.

Benefits for design and validation:

- Reduced development costs and time.
- Predictability.

Purpose of the study

The purpose of the study is to use the Simcenter Amesim platform to simulate the energy behavior of an electric vehicle on the RDE cycle, in order to evaluate energy consumption and range under real traffic conditions.

4.8.2.2. Methodology

Description of the Simcenter Amesim platform

Below is a schematic representation of the vehicle undergoing simulation, Renault ZOE, 5AM engine, corresponding to an RDE cycle, using the Simcenter Amesim platform.

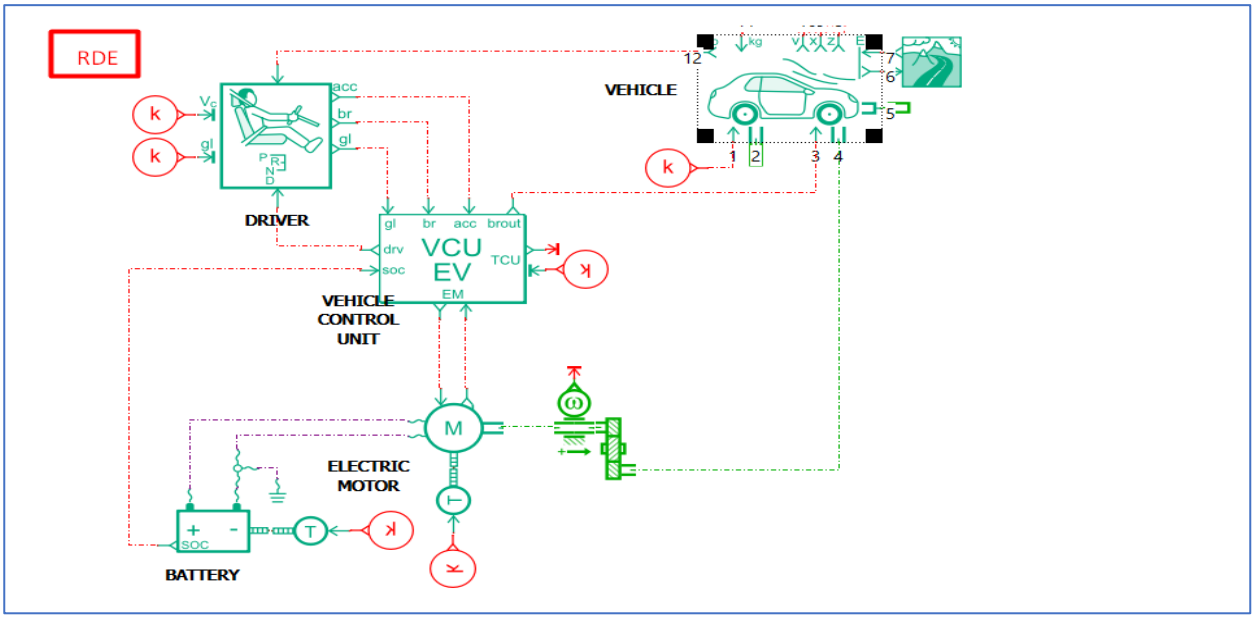


Figure 75. Schematic representation of the vehicle subjected to simulation, Renault ZOE, 5AM engine

4.8.2.3. Electric vehicle model configuration

The vehicle presented for testing is a mid-range Renault ZOE with a 5AM engine, with the technical characteristics mentioned in the previous chapter.

4.8.2.3. Implementation of the RDE cycle for testing the simulated model.

For the simulation, a basic "RDE Graz" cycle was used, remodeled by extending it to almost 3 continuous cycles, the purpose of the simulation being to run the electric vehicle according to the "RDE

Graz" cycle until the vehicle came to a complete stop due to the complete depletion of the traction battery.

A mid-range electric vehicle, Renault ZOE, 5AM engine, from the "SKETCH" section, "IFP Drive" file, from the "Library tree" corresponding to the Simcenter Amesim 2504 version, was used to select the simulation model.

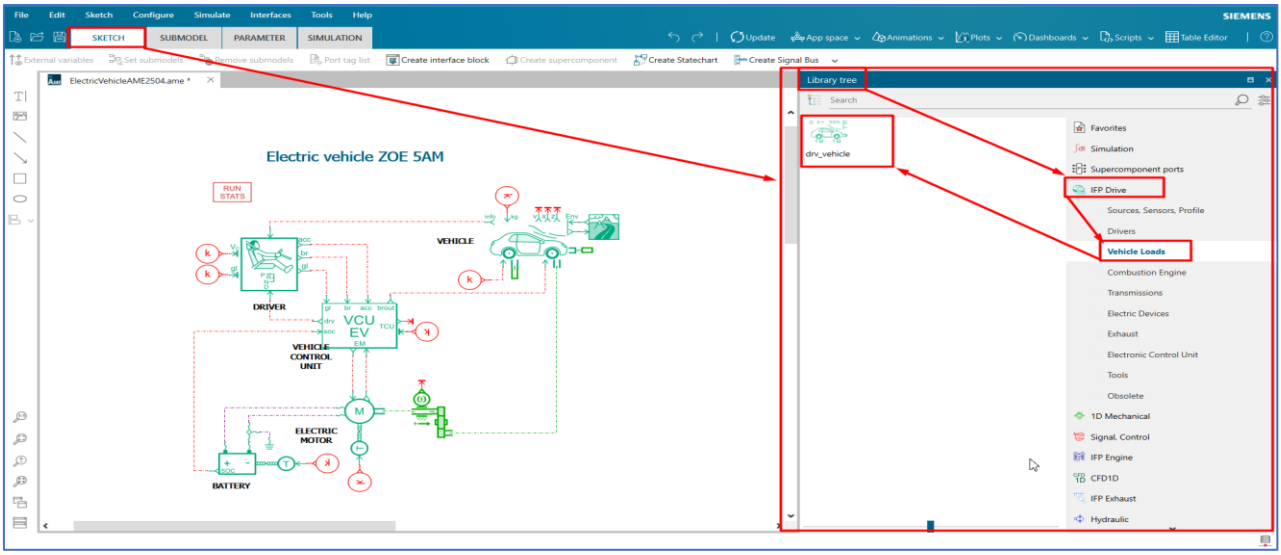


Figure 77. Graphical representation of the "IFP Drive" file in the "Library tree" library corresponding to version

"SKETCH" is basically the graphic space where the user builds the physical model of the system by placing and connecting components from the Amesim libraries.

Next, in Figure 78, you can see how, in the "SUBMODEL" section of the "Model explorer" file, we were able to define the components, input and output signals, parameters, and drivers under the models used to create the simulation model.

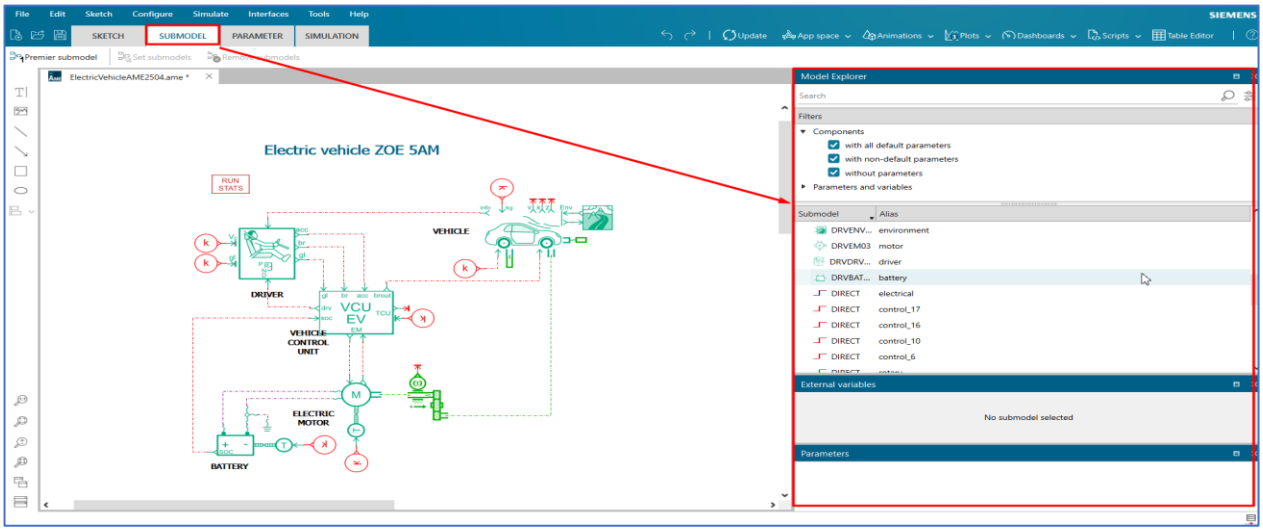


Figure 78. Graphical representation of the "Model Explorer" file in the "SUBMODEL" section corresponding to Simcenter Amesim version 2504.

In Simcenter Amesim, the "SUBMODEL" section plays a key role in defining the behavior of components in the model built in the "SKETCH" area.

In Simcenter Amesim, the "PARAMETER" section is essential for defining the actual behavior of the components in the model built in the "SKETCH" area.

The "PARAMETER" section is basically where the user enters the physical, technical, and operating values of each component in the model. These define how the components behave during the simulation.

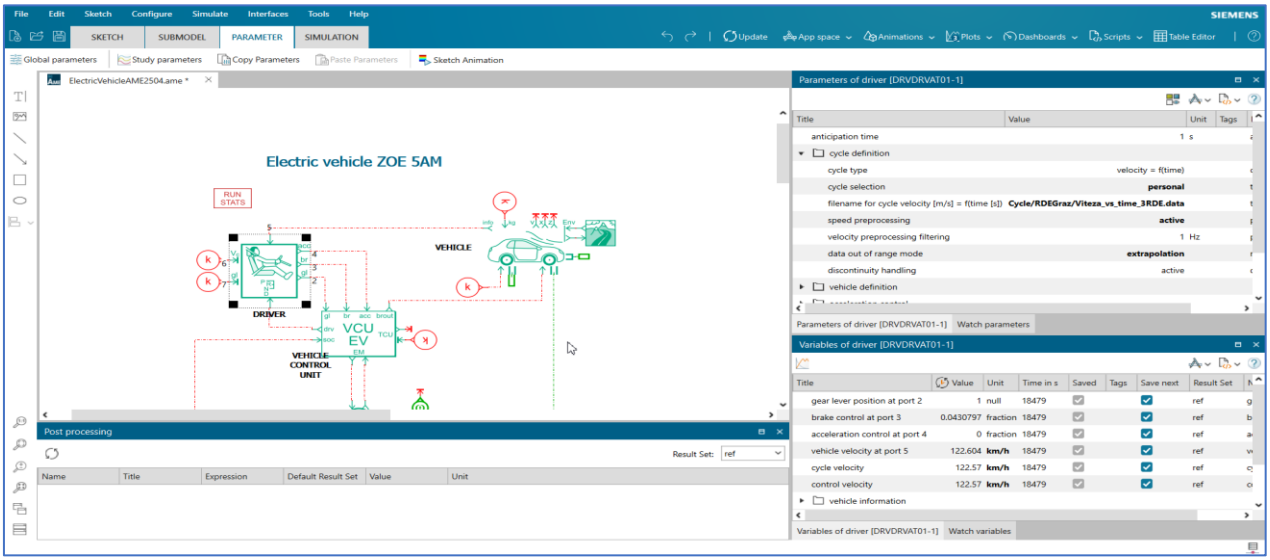


Figure 78. Graphical representation of the "PARAMETER" section corresponding to Simcenter Amesim version 2504.

In Figure 79, in the "SIMULATION" section, we first access the "Run Parameters" file, where we enter the data necessary to run the simulation (Simulation Settings, Simulation type, Integrator type, Miscellaneous, Result file(s), Information), then we run the "Run simulation" scenario, after which we will obtain the results we are interested in, following the execution of this scenario.

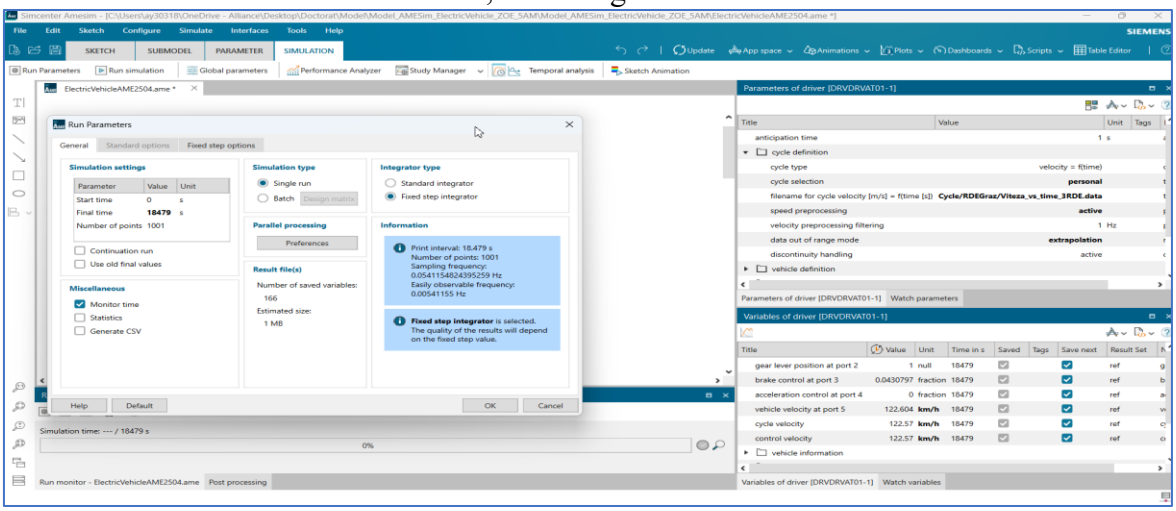


Figure 79. Graphical representation of the "SIMULATION" section corresponding to Simcenter Amesim 2504 version.

I would like to reiterate that I ran the scenario in such a way that the simulation ended exactly when the traction battery was completely discharged, i.e. after exactly 18479 seconds.

4.8.2.4. Results and analysis.

Purpose of the analysis: to evaluate the energy consumption and efficiency of the electric vehicle in an RDE cycle.

1. Diagram of the operating points of the electric motor.

Figure 80 shows the diagram of the operating points of the motor for the Renault Zoe 5AM.

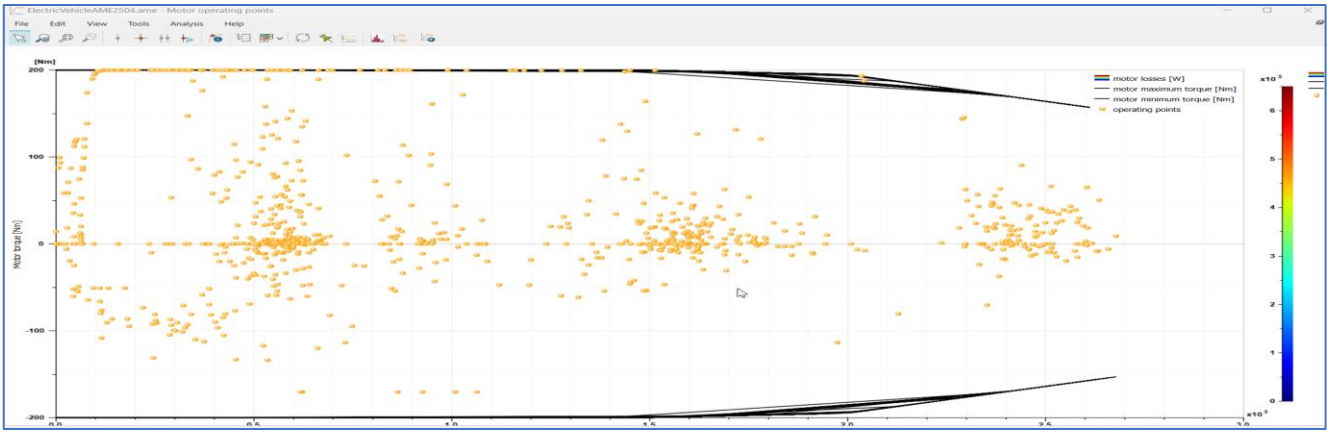


Figure 80. Diagram of the operating points of the electric motor.

2. RDE cycle speed profile

Figure 81 shows the speed profile of the RDE cycle.

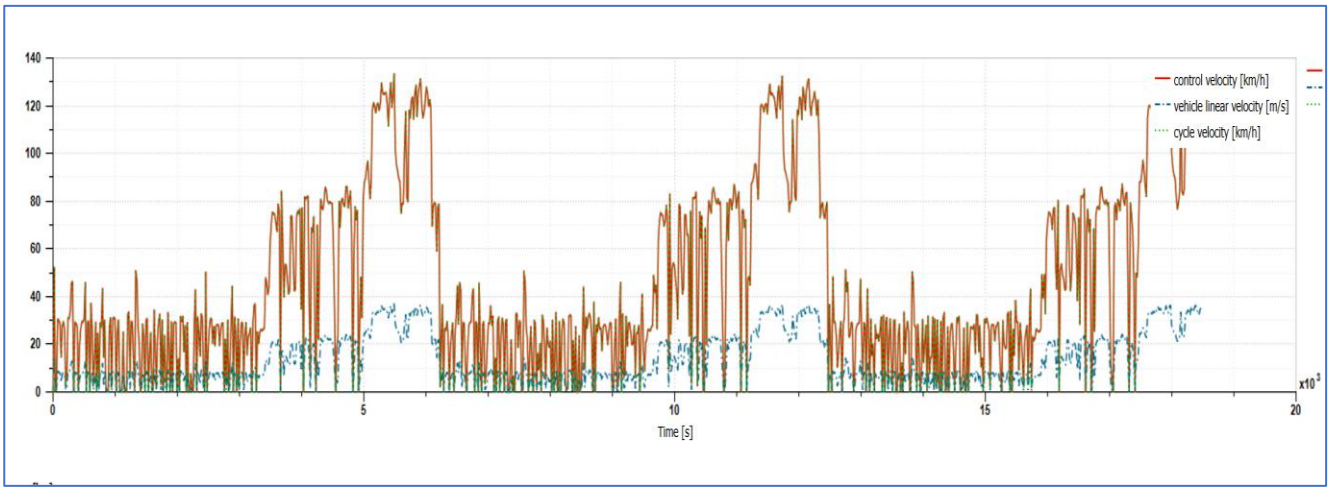


Figure 81. Speed profile diagram in the RDE cycle for the simulated vehicle

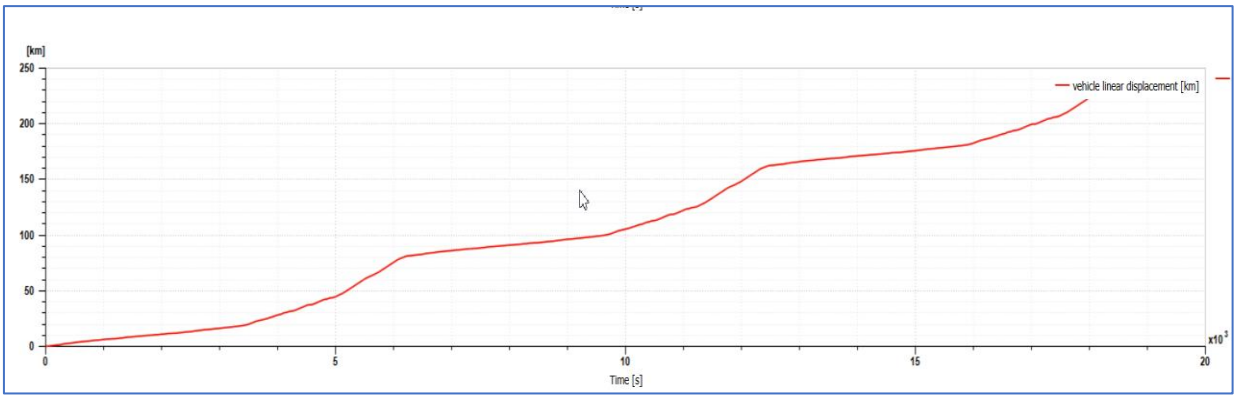


Figure 82. Graphical representation of the linear displacement of the vehicle as a function of time

In Figure 82, we can study the graphical representation of the linear displacement of the vehicle as a function of time.

3. The state of charge of the traction battery.

In Figure 83, we can see a graphical representation of the evolution of the battery charge level (State of Charge - SOC) over time.

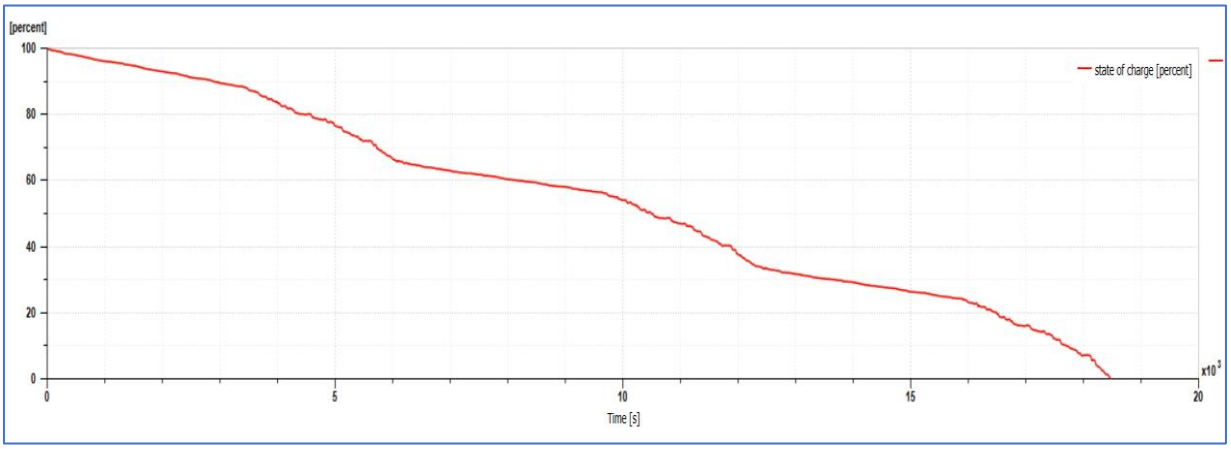


Figure 83. Graphical representation of the evolution of the battery charge level (State of Charge - SOC)

4. Regeneration of the traction battery.

The graph in Figure 84 shows the rotary velocity as a function of time.

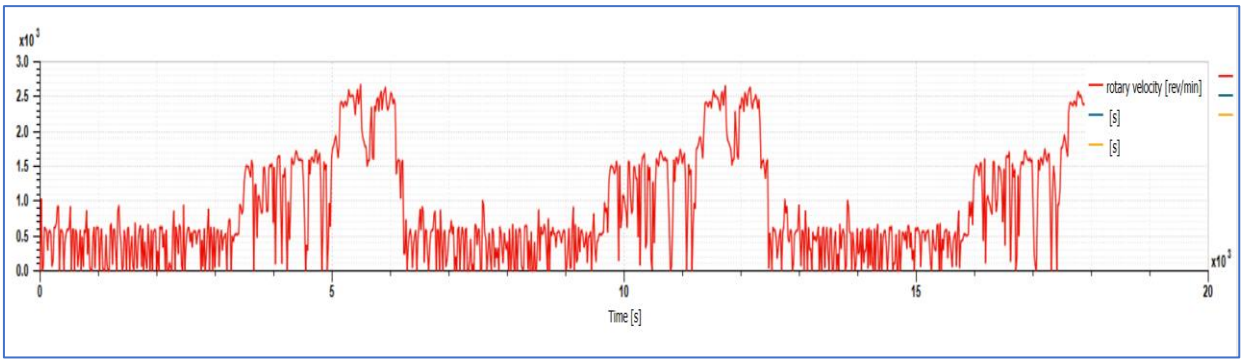


Figure 84. Graphical representation of rotational speed.

In Figure 85, we can again observe the evolution of the battery charge level (State of Charge - SOC) over time.

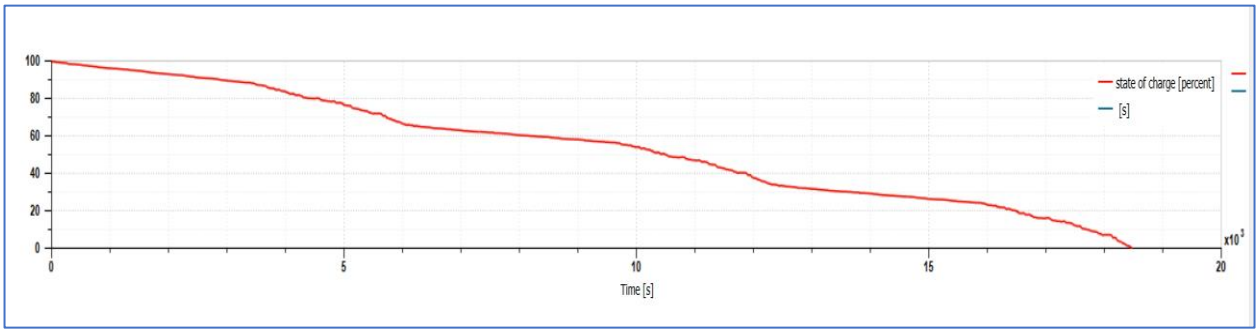


Figure 85. Graphical representation of the evolution of the battery charge level (State of Charge - SOC)

In conclusion, the graph confirms controlled and efficient battery discharge, which is ideal for evaluating energy performance under test conditions. It is a valuable indicator for validating simulation models in Amesim.

4. Brake system performance.

The graph in Figure 86 analyzes the behavior of the vehicle's braking system and shows frequent fluctuations, with peaks and troughs.

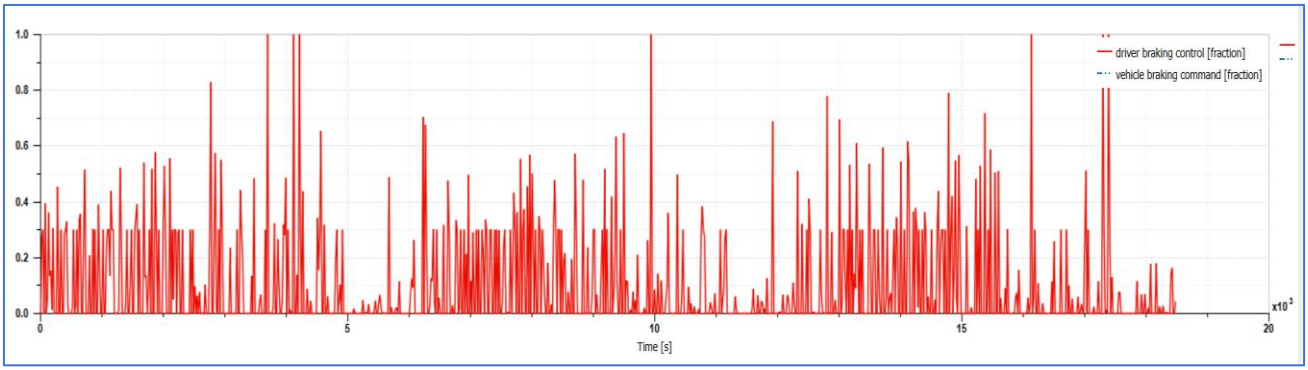


Figure 86. Graphical representation of the braking system behavior.

5. **Analysis of the electric motor torque.**The graph in Figure 87 shows the evolution of motor torque and motor torque command over time during a 20.000-second test.

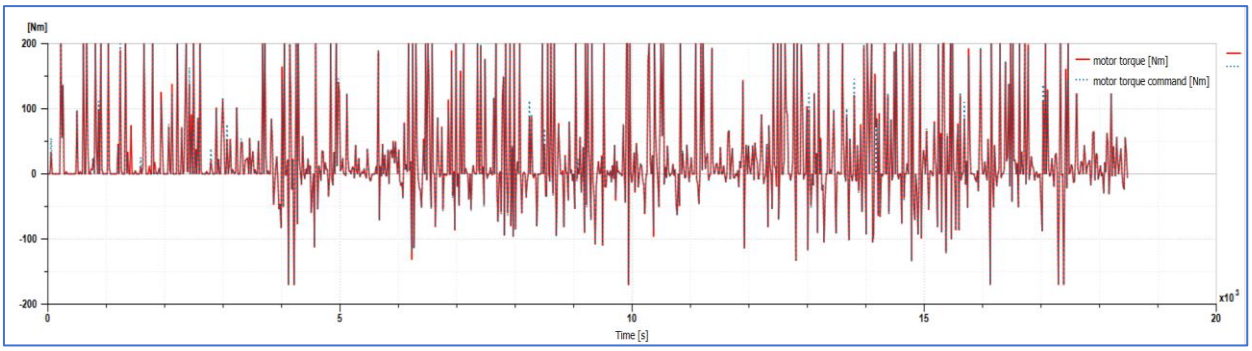


Figure 87. The graph shows the evolution of motor torque and motor torque command.

6. General conclusions.

Based on all the graphs analysed above, including the one in Figure 88 and the comparison between the RDE and WLTP cycles, we can draw the following general conclusions regarding the energy and dynamic behaviour of an electric vehicle under real-world conditions.

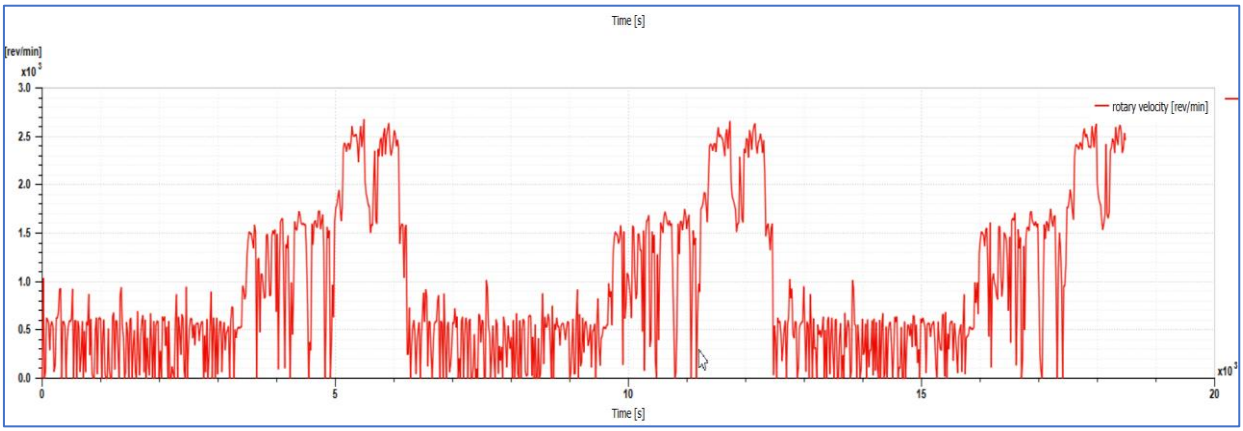


Figure 88. General diagram of the speed profile in the RDE cycle for the simulated vehicle

6.1. General conclusions on RDE cycle simulation

1. Energy consumption and autonomy:

• The SOC decreases almost linearly from 100% to 20% in 20,000 seconds, indicating constant consumption.

• Based on the distance traveled (approximately 250 km), the estimated total range is approximately 312 km, with an average consumption of approximately 192 Wh/km.

• These values are realistic and reflect variable traffic conditions specific to the RDE cycle.

2. Engine dynamics and torque control:

• Engine torque and torque control show rapid and wide variations between -200 and +200 Nm, indicating:

• Prompt response to acceleration/deceleration requirements

• Efficient operation of regenerative braking

• Engine speed varies frequently, with peaks of up to 3000 rpm, reflecting dynamic driving.

3. Braking behavior:

- Braking activity is intermittent, with multiple peaks in intensity.
- The correlation between driver input and vehicle response is good, suggesting a well-calibrated braking system.

4. Travel and driving profile:

- The vehicle travels approximately 250 km in 20.000 seconds, with an average speed of approximately 45 km/h.
- The travel graph is almost linear, indicating a stable but realistic simulation.

6.2. Compared to the WLTP cycle

Comparison of RDE (Simulated) and WLTP (Standardized)

Aspect	RDE (Simulated)	WLTP (Standardized)
Testing conditions	Real, variable	Controlled, ideal
Estimated range	~312 km	Usually higher (~350–400 km)
Specific consumption	~192 Wh/km	140–180 Wh/km
Torque/speed variations	Large, frequent	Moderate, predictable
User relevance	High	Medium

Figure 88. Comparative aspects between the RDE and WLTP test cycles

Final conclusions

- The RDE cycle provides a more realistic assessment of the energy performance of electric vehicles.
- Simcenter Amesim is an effective tool for validating control strategies and optimizing consumption under real-world conditions.
- Integrating real onboard data (e.g., CAN logs) could further improve simulation accuracy.

5. EXPERIMENTAL RESEARCH ON ELECTRIC VEHICLES.

5.1. General Considerations.

5.1.1. General context of research in the field of electric vehicles

Over the past two decades, the automotive industry has undergone a major transformation, driven by the need to reduce dependence on fossil fuels and increasingly stringent environmental protection requirements. Electric vehicles (EVs) have emerged as a viable alternative to internal combustion engine (ICE) vehicles due to their advantages in terms of zero local emissions and energy efficiency.

5.1.2. The need for experimental research

Although numerical models and computer simulations provide a solid basis for designing electric vehicles, they cannot fully capture the complexity of real-world phenomena, which are influenced by multiple factors: climatic conditions, topography, driving style, and component degradation over time.

5.1.6.Final considerations

Experimental research on electric vehicles is an interdisciplinary field at the intersection of electrical engineering, mechanical engineering, and environmental science. In the current context of energy

transition, it not only ensures the validation of technical performance but also provides the basis for strategic decisions regarding the widespread adoption of electromobility.

5.2.Structure of the propulsion system with which the electric vehicle used for testing is equipped.

5.2.1. General considerations

The Renault Zoe is one of the most widespread series-produced electric vehicles in Europe, frequently used in experimental research due to its market availability and representative technological configuration.

5.2.2. Main components of the propulsion system

The propulsion system consists of the following major subsystems:

5.2.2.1. Traction battery

- Technology: lithium-ion (Li-ion).
- Useful capacity (depending on generation):
  - ~22 kWh (first generation, 2012–2016),
  - ~41 kWh (Z.E.40, 2017–2019),
  - ~52 kWh (Z.E.50, after 2019).
- Nominal voltage: 350–400 V.
- Cooling: passive/active forced air system.
- Function: storage of electrical energy required for propulsion and auxiliary consumers.

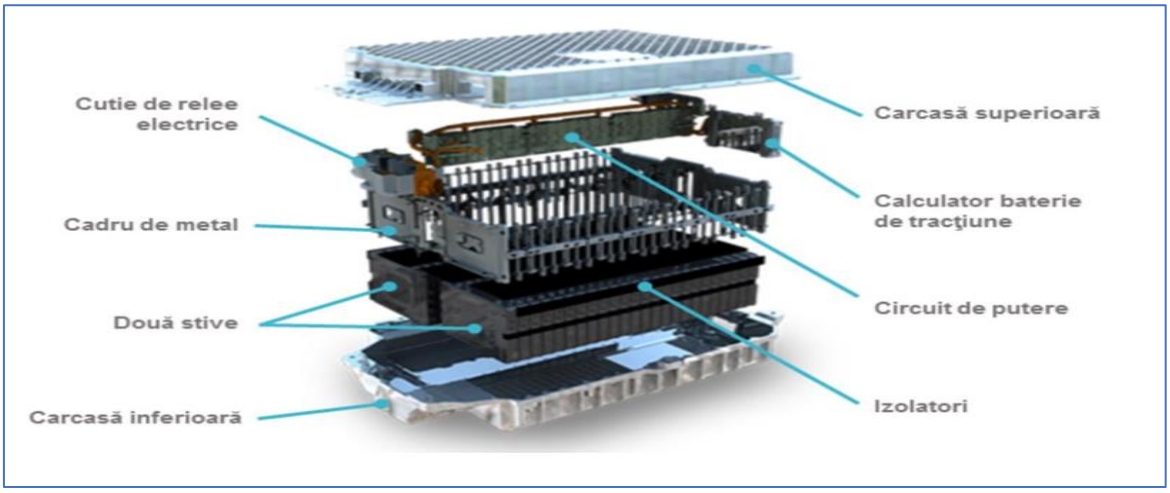


Figure 89. Traction battery component of a Renault ZOE electric vehicle, 5AM

The modules slide onto the metal frame. Metal rods are used to secure the stack elements. The modules are separated from each other by spacers and inserts. A battery consists of several stacks.

5.2.2.2. Electric motor

- Type: synchronous motor with wound rotor (no permanent magnets).
- Power:

- o 65 kW (R90 – older generation),
- o 80 kW (R110, 5AM – frequently used test variant).
- Maximum torque: ~225 Nm.
- Advantages: high efficiency, advanced flux control, elimination of dependence on permanent magnets (reducing costs and dependence on rare earths).
- The rotor is based on the principle of an electromagnet. It must be supplied with energy to create a magnetic field.
- On a synchronous motor, the rotor rotates at the same speed as the magnetic field of the stator.

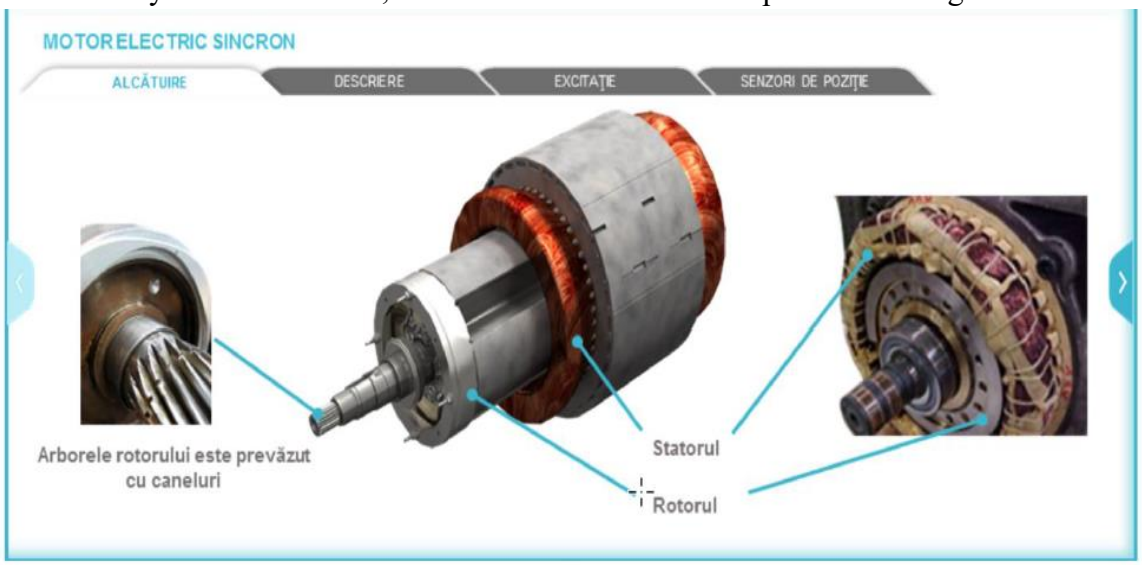


Figure 92. Electric motor of the Renault Zoe electric vehicle, 5AM

5.2.2.3. Inverter / Electronic power converter

- Converts DC (direct current) electrical energy from the battery into three-phase AC (alternating current) for the motor.

5.2.2.4. Transmission

- Type: single-speed transmission (1 gear), with mechanical reducer.

5.2.2.5. Traction battery charger

- Charging power: up to 22 kW AC (depending on the grid).

5.2.2.6. Auxiliary systems

- Battery Management System (BMS) – monitors cell voltage, current, and temperature, balances the load between cells, and protects against overcharging/deep discharge.
- Cooling and Air Conditioning System – includes pumps, heat exchangers, and air conditioning to maintain optimal battery and motor temperatures.
- Vehicle control unit (EVC) – coordinates the operation of all components and interfaces with the driver.

The EVC (electric vehicle control) computer in an electric vehicle performs the same role as the injection computer (engine control) in a combustion engine vehicle.

The EVC computer manages the display of various messages on the dashboard.

The EVC computer monitors the insulation level between the vehicle and the high-voltage network.

5.2.3.Functional diagram of the propulsion system

Main energy flow:

Traction battery → Inverter → Electric motor → Fixed ratio transmission → Wheels.

Auxiliary flows:

- Braking energy recovery: Wheels → Motor (generator) → Inverter → Battery.
- Power supply to auxiliary equipment (air conditioning, lighting, multimedia) via a DC/DC converter → 12 V battery.
- Pre-conditioning is a function provided by the electric vehicle.
- When the electric vehicle is charging and charging is complete, the EVC computer can request thermal conditioning of the vehicle.
- The EVC computer also manages the "Auxiliary Heater" function.

The EVC computer has a LIN connection that allows it to manage and communicate with:

- the vacuum pump (braking),
- the additional resistance unit (PTC)
- the air conditioning compressor

The EVC computer has standard wiring connections that allow it to control the engine coolant pumps, the thermal comfort pump, or the optional auxiliary heater.

5.2.4. Features of the Renault Zoe 5AM (R110) variant

- Integration of the motor and power electronics into a compact assembly to reduce weight and losses.
- Use of a separately excited motor, which allows for more flexible current control and optimization of efficiency in variable modes.
- Possibility of fast three-phase charging (22 kW), advantageous for experimental tests with multiple discharge/charge cycles.
- Real range: 250–350 km (depending on battery and driving conditions).

5.2.5. Conclusions

The propulsion system of the Renault Zoe electric vehicle, in its 5AM configuration, is an ideal platform for experimental research due to:

- The simplicity of the transmission design,
- The efficient integration of electrical components,
- Its balanced dynamic and energy performance,
- Its relevance as a mass-produced vehicle widely used in Europe.

5.3. Legal requirements for experimental research on electric vehicles.

Regulation (EU) 2018/1832, Annex III A, sets out several types of requirements and conditions that must be taken into account when performing RDE type-approval tests.

Limit conditions, [56],[57]:

1. Load and test mass of the vehicle.
2. Ambient conditions.

3. Dynamic conditions.

4. Vehicle condition and operation.

Trip requirements:

- The test always starts with urban driving, followed by rural and highway driving, in the proportions indicated.
- The proportions of urban, rural, and highway driving, classified according to instantaneous speed, are expressed as a percentage of the total distance traveled, as follows (R. (EU) 2017/1151):
  - Urban driving is characterized by speeds of up to 60 km/h.
  - Rural driving is characterized by speeds greater than 60 km/h and maximum speeds of 90 km/h.
  - Highway driving is defined as driving at speeds greater than 90 km/h.
  - The route must include approximately 34% urban driving, 33% rural driving, and 33% highway driving, based on the speeds described above. "Approximately" means a deviation of ± 10 percentage points from the specified percentages. However, the proportion of urban driving must not be less than 29% of the total mileage.
- In general, the speed of the vehicle must not exceed 145 km/h. This maximum speed may be exceeded by 15 km/h for a maximum of 3% of the time spent on the motorway. Local speed limits remain in force during the test, without prejudice to other legal consequences. Violation of local speed limits does not in itself invalidate the test results.
- The average speed (including stops) on an urban road section must be between 15 and 40 km/h. Stopping periods, defined as periods when the vehicle speed is less than 1 km/h, must represent between 6 and 30 % of the total driving time in urban areas. Driving in urban areas must include several stopping periods lasting 10 seconds or more.
- The speed range for motorway driving must adequately cover speeds between 90 and at least 110 km/h. The vehicle speed must be above 100 km/h for at least 5 minutes.
- The duration of the journey must be between 90 and 120 minutes.
- The starting and ending points of the journey must not have a difference in elevation of more than 100 m. In addition, the cumulative positive elevation difference must be less than 1200 meters / 100 km.
- The minimum distance for each type of driving (in urban areas, rural areas, and on highways) must be 16 km.

Operational requirements:

- The route shall be planned so that the test is conducted without interruption and the data is recorded continuously in order to achieve the minimum test duration defined in the previous point.
- Tests under real driving conditions shall be carried out on working days as defined for the Union in Regulation (EEC, Euratom) No 1182/71 (*** Regulation (EEC, Euratom) No 1182/71.
- Real-world driving tests shall be conducted on paved roads and streets (e.g., off-road driving is not permitted).

5.4. Equipment used to perform experimental tests

Renault Group, in partnership with Bosch Automotive Service Solutions (part of Bosch Automotive Aftermarket), has launched a new generation of diagnostic tools for vehicle repair [58]. Renault Group is thus introducing a new connected and continuous diagnostic solution that uses artificial intelligence and data processing to continuously analyze and detect vehicle maintenance needs while performing diagnostics.

The Bosch VCI ADT RNM MTS 6534 device is dedicated to both diagnostics for Dacia and Renault Group repair units and research and development within the Group. It is generally used for diagnostics, using the CLIP and Alliance Diagnosis Tool (ADT) diagnostic programs.

The Bosch MTS 6531 device is dedicated exclusively to the research and development process within the Renault and Dacia Group, being used with various specific data acquisition and processing programs.



Figure 100. The MTS 6531 device and the VCI ADT RNM MTS 6534 device from Bosch

The programs used to diagnose Dacia and Renault vehicles are the CLIP diagnostic program (Figure 106), dedicated to models with a simpler basic electrical architecture, as well as the new Alliance Diagnosis Tool (ADT) diagnostic program, dedicated to new vehicle models within the Renault and Dacia Group, which have a more complex electrical architecture and incorporate a larger number of computers and systems. Due to this electrical architecture complexity, the new Alliance Diagnosis Tool (ADT) diagnostic program operates exclusively online, while the less complex CLIP diagnostic program, up to a certain version, operates both offline and online.



Figure 106. CLIP diagnostic program

With the Alliance Diagnosis Tool (ADT) (Figure 107) and its connected environment, where all data is shared, before the vehicle enters the workshop, technicians will know everything about the operation to be performed on vehicles increasingly equipped with electronic control units. This should reduce downtime in the garage, increasing customer satisfaction and optimizing workflow, thereby reducing waiting times for appointments.

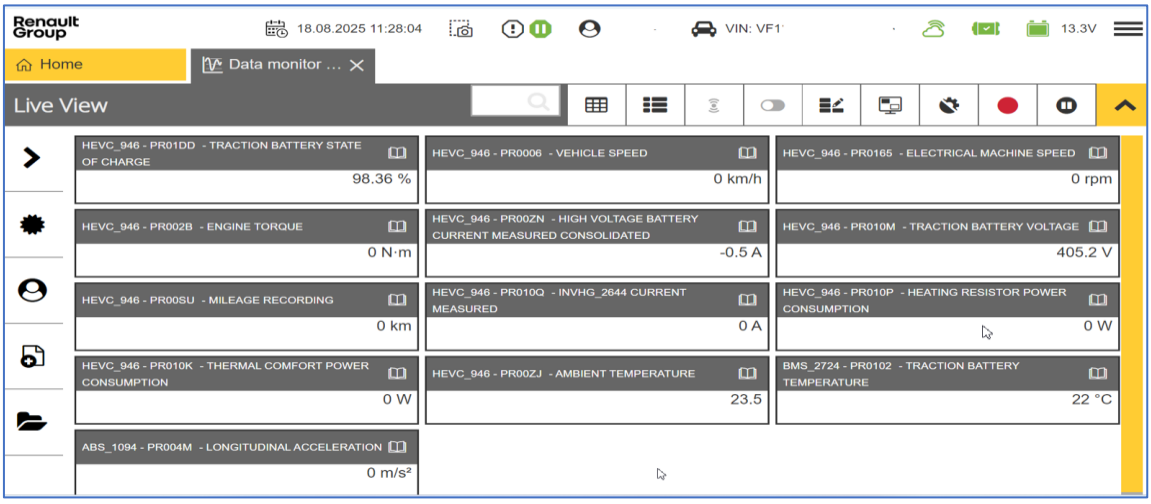


Figure 107. Alliance Diagnosis Tool (ADT) diagnostic program

Using the connection to the car's computers via the OBD connector and exchanging data with the VCI ADT RNM (Alliance Diagnosis Tool) and MTS 6531 modules allows the measurement of several characteristic values in real time, over a set movement cycle, and, in addition, allows the graphs obtained to be saved as a function of time and the subsequent conversion of the files that are automatically saved in the memory of the corresponding working programs into ".csv" or ".txt" files, which allow rapid processing of the measured data and assist in the detailed analysis of the experimental results obtained.

5.5. Performing the tests

5.5.1. Preparing the test vehicle and selecting the test route.

Once the vehicle used for testing had been determined, in accordance with the conditions set out in Regulation (EU) 1832/2018 regarding real-world testing, it was necessary to select and define a route that best combined and met the conditions specified in subsection 5.3. The tests were carried out at the Titu Technical Center. Here, it provides testing for vehicles developed by design offices.

The technology used in the test center allows the same standards and validation criteria to be used as for all Renault Group vehicles; all this to manufacture vehicles with the best level of performance, quality, comfort, safety, and endurance.

Here is a brief overview of the Titu Technical Center[59]:

- 350 hectares;
- 66.682 m² of buildings;
- 32 km of tracks, 10 in number, which allow the behavior of vehicles to be analyzed in the smallest detail under various conditions of use, on different types of tracks such as the fast track, city track, slope tracks, stone projection areas under the bodywork, and water crossing areas;
- Dozens of test benches and workshops: virtual testing laboratory (CAVE), semi-anechoic chamber, solar simulator, infrared cabin, materials resistance study laboratory, vehicle prototype workshop.

Figure 108 shows an overview of the track complex where the tests were carried out [60]:



Figure 108. Overview of the test track complex at the Titu Technical Center

The sections used for testing were as follows:

- City track for tests performed in the 0-60 km/h range

- High-speed track, in highway mode, for tests performed in the 60-90 km/h speed range and for tests performed at speeds above 90 km/h.

The vehicle was charged at the Titu Technical Center, at a 22 kW charging station.

The tests were carried out on weekdays, at different times of the day, at outside temperatures between 30° and 35° Celsius.

In accordance with the conditions set out in subsection 5.3, a series of basic assumptions were established to serve as predefined benchmarks for route modeling and the creation of a cycle that was as reliable as possible for the analysis and study of the characteristics of the electric vehicle used for testing.

The instrumentation of the electric vehicle consisted of connecting the two Bosch modules, one by one, to the vehicle's OBD connector, located on the left side, in the "A" pillar area, inside the vehicle, and establishing the connection between the module and the laptop with the specific Engineering interface and the ADT (Alliance Diagnosis Tool) diagnostic interface, where the parameters monitored during the tests were monitored and stored. To ensure the best possible contact during the tests and to avoid disconnecting the diagnostic module in the event of vibrations or accidental contact by the driver, the cable was secured at certain points in the dashboard area, and the OBD connector was secured with adhesive tape and plastic ties. Figure 110 shows the vehicle's equipment and instrumentation prior to the start of the tests:



Figure 110. Diagnostic/data acquisition module and its connection to the test vehicle

Figure 111 shows an overview of the positioning of the station (laptop) and the diagnostic/data acquisition module in the test vehicle.

Communication via the ADT (Alliance Diagnosis Tool) program and a specific development and testing program for vehicles allowed real-time monitoring of several parameters, as follows:

- Battery voltage (12V)
- Vehicle speed (km/h)
- SOC – State of Charge (%)
- Calculated traction battery current (A)
- Total distance traveled (km)
- Traction battery temperature (°C)

- Ambient temperature (°C)
- Current produced by the traction battery (A)

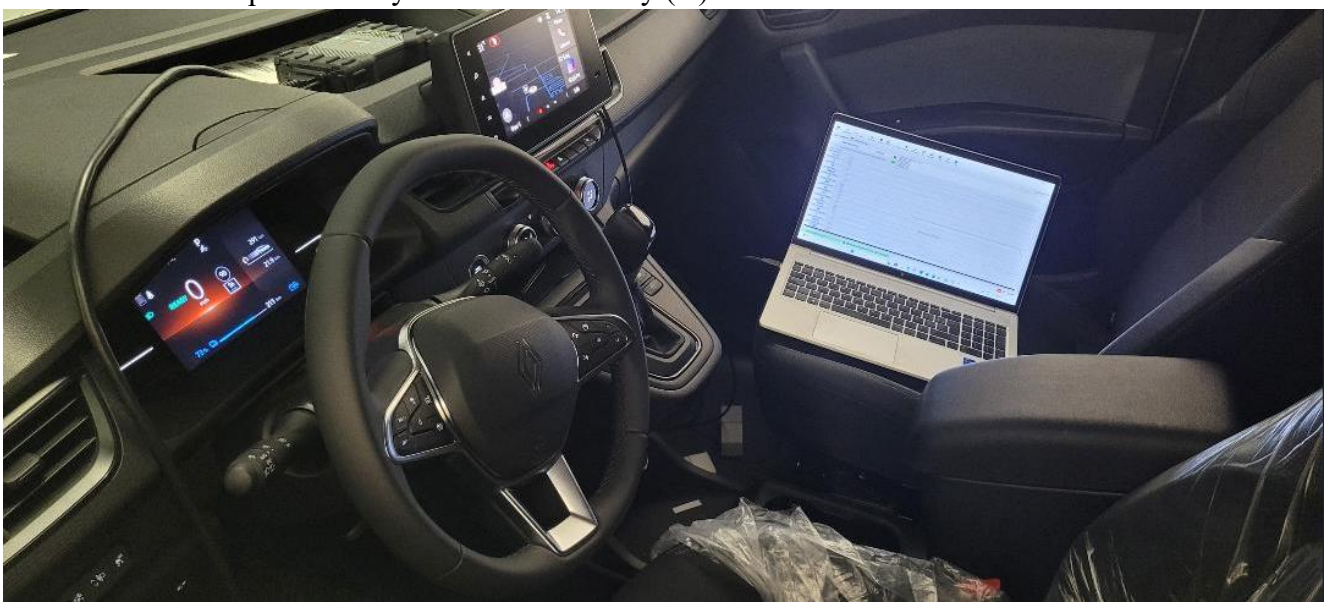


Figure 111. Overview of the positioning of the station (laptop) and the diagnostic/data acquisition module in the test vehicle

5.5.2. Results obtained from experiments conducted to determine energy consumption.

The results obtained from experiments conducted using the MTS 6531 modules and the VCI ADT RNM MTS 6534 device from Bosch were stored in the workstation memory (laptop) in specific folders, using alternatively the specific data acquisition and processing engineering program, in ".txt" format, as well as the ADT (Alliance Diagnosis Tool) diagnostic program, where the data is first saved on a dedicated server and can then be downloaded to any workstation in ".csv" format.
The reason for taking separate measurements at these speed intervals in the RDE context for an electric vehicle is related to how energy consumption and vehicle behavior vary with speed:
1. Differences in consumption between speed intervals:
At $V < 60$ km/h (urban traffic, stop & go):

- Frequent acceleration and braking affect energy consumption.
- Energy recovery during braking (regeneration) can reduce losses, but efficiency varies depending on driving style and road topology.

At $60 \leq V < 90$ km/h (moderate suburban/extra-urban traffic):

- Consumption stabilizes more, as acceleration and braking are less frequent.
- Aerodynamics begin to play a role, but are not yet dominant.

At $V > 90$ km/h (highway):

- Aerodynamic drag increases proportionally to the square of the speed, so energy consumption increases significantly.
- Braking recovery is less relevant because acceleration and deceleration are less frequent.

2.The reason we make separate determinations is as follows:

- More accurate analysis.

- Validation for battery management strategies.
- Compatibility with RDE requirements.
- We clearly understand how actual range varies with speed.
- We can optimize recommendations for drivers (e.g., "at over 90 km/h, range decreases by X% compared to urban driving").
- We can also assess the impact of auxiliary systems (air conditioning, battery heating) differently for each interval.

5.5.2.1. 0-60 km/h test cycle

Following experimental measurements carried out on city roads at speeds ranging from 0 to 60 km/h over a distance of 16 km, we simulated exact traffic conditions, staying within the limits specific to this speed range.

This range generally corresponds to urban traffic and includes many stops, starts, and constant low speeds.

A. General characteristics of the 0–60 km/h range:

• Speed profile:

o Frequently varies between 0 and 60 km/h.

o Includes many accelerations and decelerations (stop & go).

• Road type:

o Urban: streets with traffic lights, pedestrian crossings, traffic jams.

- Relative duration in RDE:

o In a complete RDE cycle, urban driving can account for ~30–40% of the total distance.

B. Electric vehicle behavior:

1. Acceleration:

o EVs have instant torque, so acceleration is energy efficient.

o However, frequent acceleration increases energy consumption.

2. Braking and energy recovery:

o Regenerative braking converts kinetic energy into electrical energy and recharges the battery.

o The efficiency of recovery depends on the type of system and driving style.

3. Energy consumption:

o At low speeds, aerodynamic drag is negligible.

o The main losses come from acceleration, auxiliary systems (air conditioning, heating), and mechanical friction.

o Average kWh/100 km consumption may be lower than at high speeds, but it is more variable due to stop-and-go driving.

C. Measurement objectives at 0–60 km/h

- Determining average energy consumption in urban traffic.
- Evaluating the efficiency of energy regeneration during braking.
- Monitoring the operation of auxiliary systems in heavy traffic conditions.
- Identifying the impact of frequent acceleration on range.

Following the experimental measurements, the actual cycle lasted 1804 seconds, or approximately 30 minutes, and the total distance traveled on the established route, the city route, was 16 km.

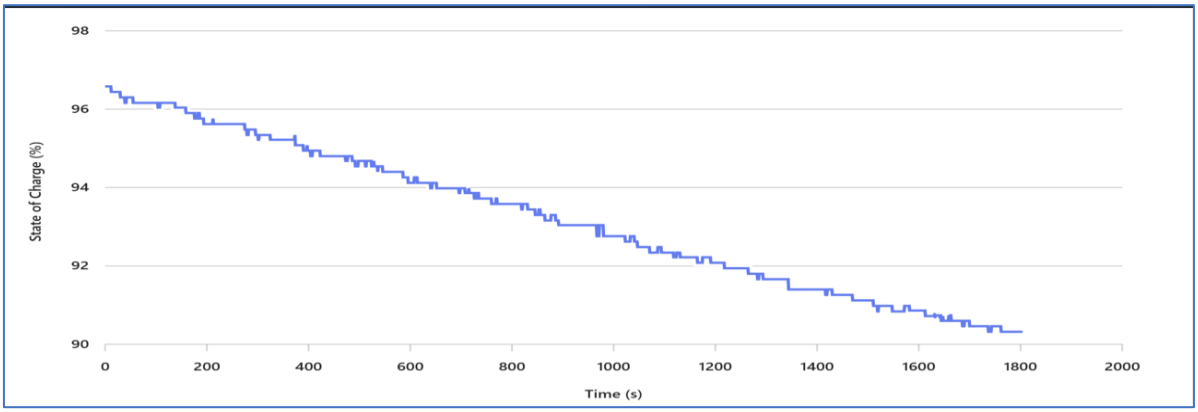


Figure 112. State of Charge (SOC) over time for the speed range 0-60 km/h

We can see the graph for State of Charge (SOC) over time, generated from the Excel file, in Figure 112, for the speed range 0-60 km/h.

The graph shows a slight decrease in SOC during the test, which is normal under discharge conditions.

We can also see the comparative graph between State of Charge (SOC) and traction battery voltage over time:

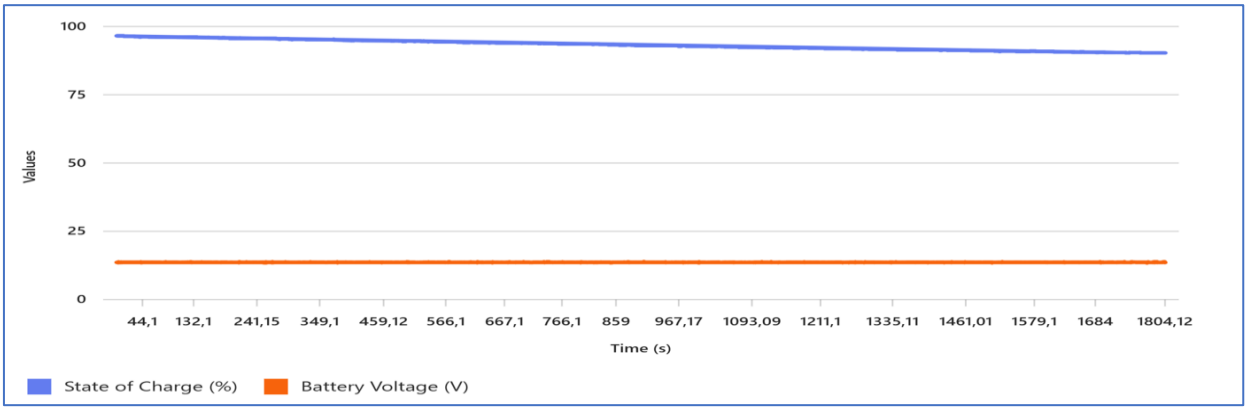


Figure 113. Comparative graph between State of Charge (SOC) and Traction Battery Voltage as a function of time

This graph highlights the relationship between battery charge level and voltage variations during the test. Observations may include:

- SOC remains relatively constant, with minor variations.
- Battery voltage shows more noticeable fluctuations, possibly correlated with power requirements or speed variations.

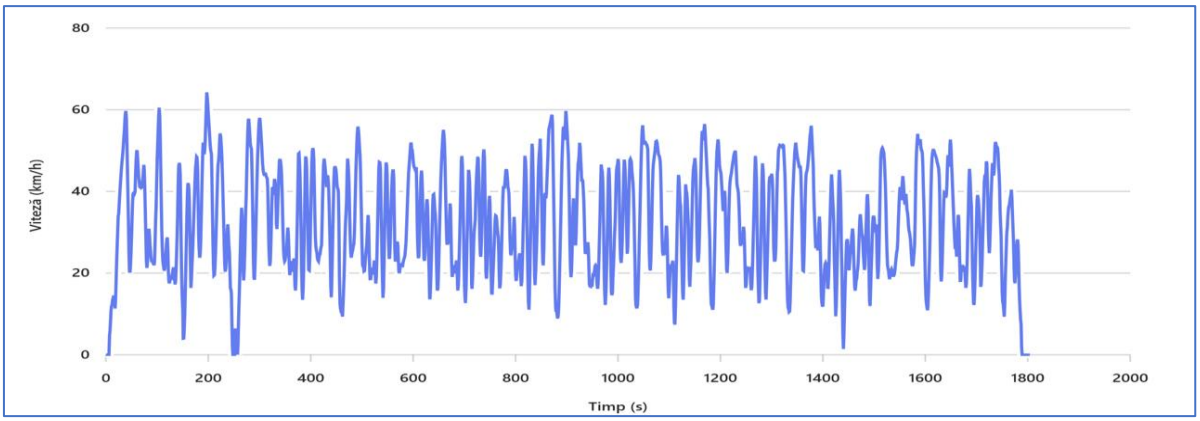


Figure 114. Speed evolution over time during the speed cycle, 0-60 km/h.

In Figure 114, we can see the evolution of speed over time during the speed cycle, 0-60 km/h.
The average speed calculated during the test is approximately 32.28 km/h.
This is a simple arithmetic mean, calculated based on all valid values in the speed column.

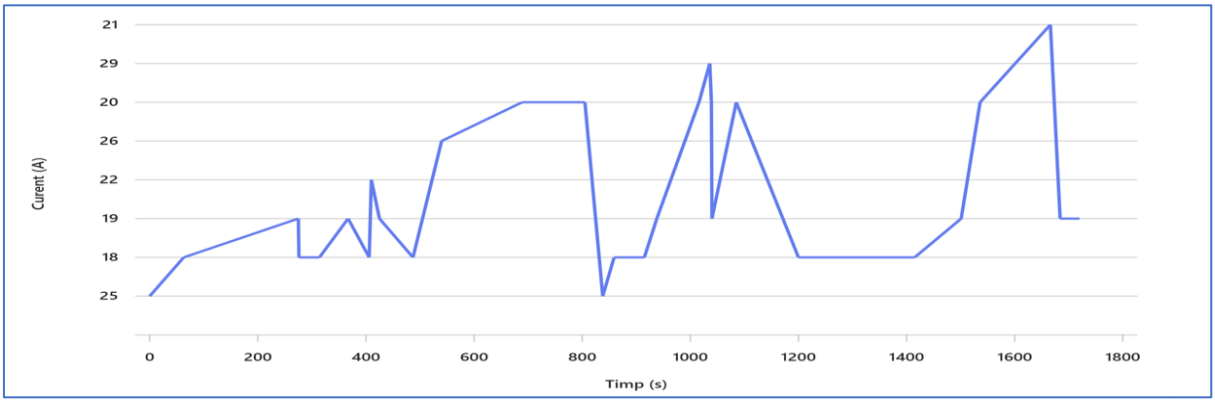


Figure 115. Battery current evolution over time

We can see in Figure 115 the evolution of the battery current over time, highlighting the current variations in the high-voltage network of the electric vehicle's traction battery.

Here we can observe the following aspects:

- Maximum current: ~15883 A – indicates a significant peak, possibly a measurement error or an intense regeneration event.
- Minimum current: -500 A – signals a strong discharge, probably during acceleration.
- Average current: ~-348.4 A – suggests that, on average, the battery was in discharge mode.
- Standard deviation: ~108.3 A – indicates moderate current variability.
- Number of sudden variations (>100 A): 49 – shows instability or rapid transitions between operating modes (e.g., regenerative braking ↔ acceleration).

We can draw the following conclusions:

• Dynamic modes: the vehicle frequently switched between regenerative braking and acceleration.

• Suspicious peaks: extreme values (e.g., 15883 A) may require further investigation – they may be artifacts or actual overload signals.

• Typical behavior: constant negative discharges indicate a performance test or sustained acceleration.

We can also visualize the graphical variation of the vehicle's acceleration during the proposed cycle, calculated based on the difference in speed over time, in Figure 116, where we can observe the following aspects:

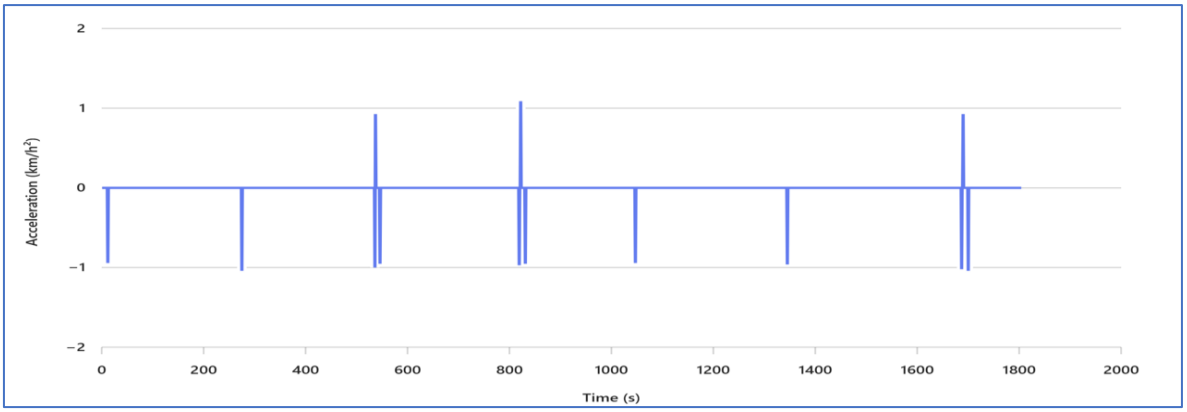


Figure 116. Graphical variation of vehicle acceleration over the speed range 0-60 km/h

1. Acceleration is not constant:

• The graph shows significant fluctuations in acceleration, indicating that the vehicle is not accelerating smoothly.

• These variations may be caused by:

• traction control system interventions,

• limitations in available power,

• road or test conditions.

2. Areas of negative acceleration:

• There are times when acceleration becomes negative, meaning that the vehicle temporarily slows down.

• These decelerations may be voluntary (braking) or involuntary (loss of traction, system limitations).

3. Acceleration peaks:

• Acceleration peaks are observed at certain intervals, which may indicate moments when the motor or propulsion system delivers a power surge.

• These peaks may be correlated with variations in battery current or torque requirements.

Figure 117 shows the variation in estimated electric motor torque and vehicle speed.

From the comparative graph of estimated electric motor torque and vehicle speed during the test cycle, we can draw the following conclusions:

1. Direct relationship between torque and speed:

• During acceleration phases, the estimated torque increases, indicating a higher traction requirement.
• As the speed stabilizes, the torque decreases or becomes negative, signaling a reduction in engine effort or regenerative braking.

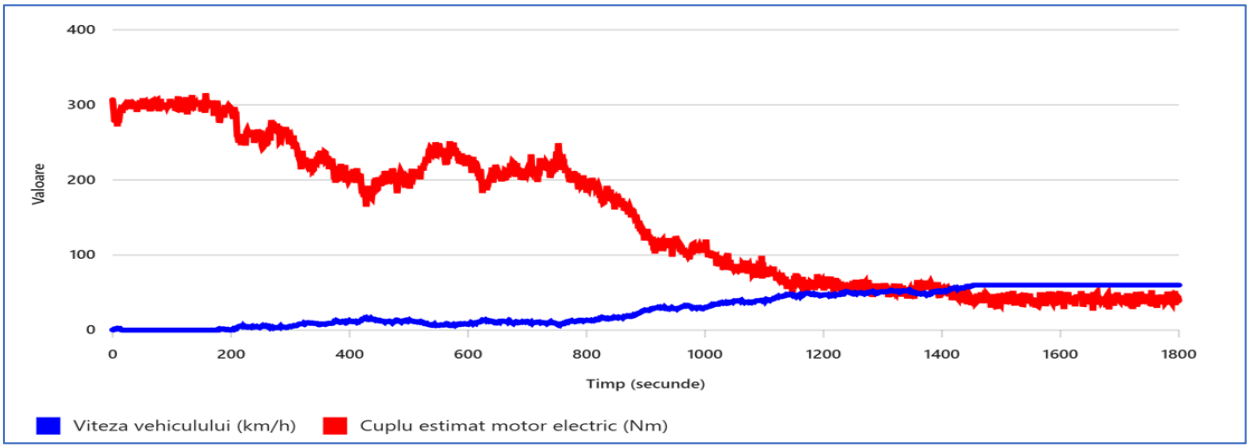


Figure 117. Variation of estimated electric motor torque and vehicle speed in the range 0-60 km/h

2. Frequent negative torque:
- Negative torque occurs in many sequences, suggesting:
- regenerative braking (energy recovery),
- or a control strategy that keeps the vehicle in an energy-efficient mode.

3. Long acceleration time:
- Speed increases slowly and torque does not peak, indicating:
- a conservative acceleration strategy,
- or limitations imposed by the propulsion system (e.g., thermal protection, current limitations).

4. Lack of perfect synchronization:
- There are times when torque varies without a significant change in speed, which may indicate:
- system reactions to external conditions (temperature, demands from auxiliary systems),
- or fine adjustments to engine control.

5. Optimization possibilities:
- Comparative analysis can be used to:
- optimize the torque curve according to speed requirements,
- improve energy efficiency,
- or adjust the control strategy for a faster response.

From the analysis of the graph in Figure 118, showing the evolution of the high-voltage battery (HVB) temperature during the 0–60 km/h acceleration test, we can draw the following conclusions:

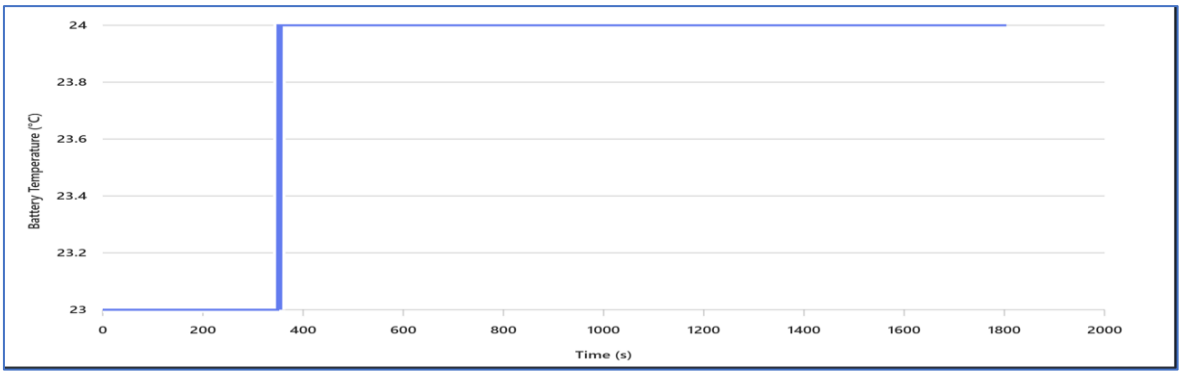


Figure 118. Evolution of traction battery temperature over time

1. Constant initial temperature:

• At the start of the test, the HVB battery temperature is stable at around 23°C, indicating a balanced thermal state before the vehicle is started.

2. Gradual increase during acceleration:

• As the vehicle accelerates, the battery temperature rises slightly but not sharply, suggesting that the cooling system is working efficiently and that the battery is not overloaded.

3. Stabilization at constant speed:

• After reaching a speed of 60 km/h, the temperature stabilizes, indicating good thermal management during continuous operation.

4. Minor fluctuations:

• Small temperature variations are observed, probably caused by changes in discharge current or environmental variations, but these remain within safe limits.

Technical conclusions:

• Good thermal performance: The traction battery performs well thermally during the test, with no signs of overheating.

• The cooling system is effective: There are no sudden temperature increases, indicating effective heat dissipation.

• The test does not induce major thermal stress: The temperature remains within a safe range, suggesting that the 0–60 km/h test is not thermally critical for the HVB – traction battery.

Figure 119 shows a comparative graph of the evolution of the traction battery temperature and the ambient temperature during the test:

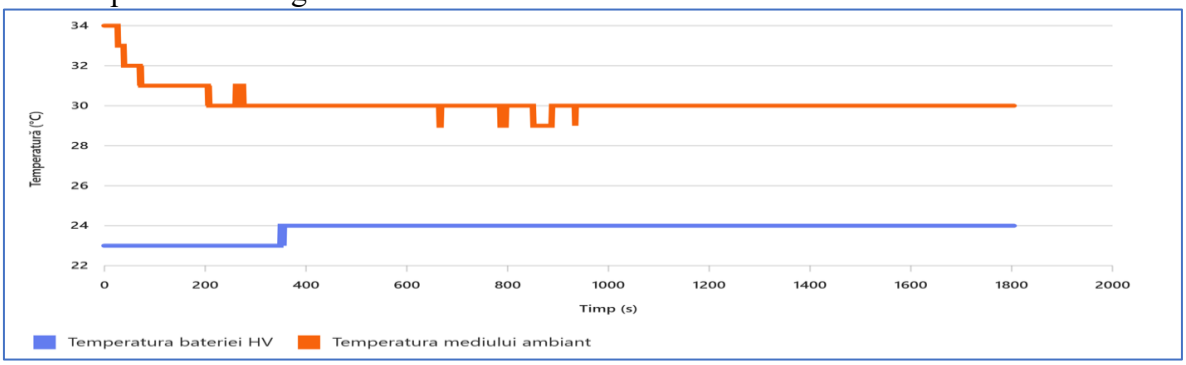


Figure 119. Comparative graph showing the evolution of the traction battery temperature and the ambient temperature during the test

Conclusions from the comparison:

1. Ambient temperature:

• Remains relatively constant throughout the test, around 34°C, with minor variations. This indicates a stable test environment.

2. HVB battery temperature:

• Starts at a value similar to the ambient temperature (~23°C), but gradually increases as the vehicle accelerates and then stabilizes.

• This increase is modest, suggesting efficient heat dissipation and good thermal performance of the system.

3. Difference between the two temperatures:

• Throughout the test, the battery temperature remains below the ambient temperature, indicating that the battery cooling system is working efficiently and no excessive heat is building up.

From the analysis of the graph and the data in the Excel file, we can draw the following conclusions regarding the variation in available power at discharge (kW) (Figure 120):

Main conclusions:

- Maximum available power: 20.00 kW at 0.00 seconds
- Minimum available power: 20.00 kW at 0.00 seconds
- Average available power during the test: 20.00 kW

It appears that the values recorded for the power available at discharge are throughout the test, which may indicate:

- a limitation imposed by the battery management system (BMS),
- a test stage in which the load did not vary,
- or an error in data recording (all values being identical).

After rigorously testing the battery management system, we concluded that the traction battery's BMS worked flawlessly, maintaining a constant power of 20.00 kW throughout the vehicle's operation.

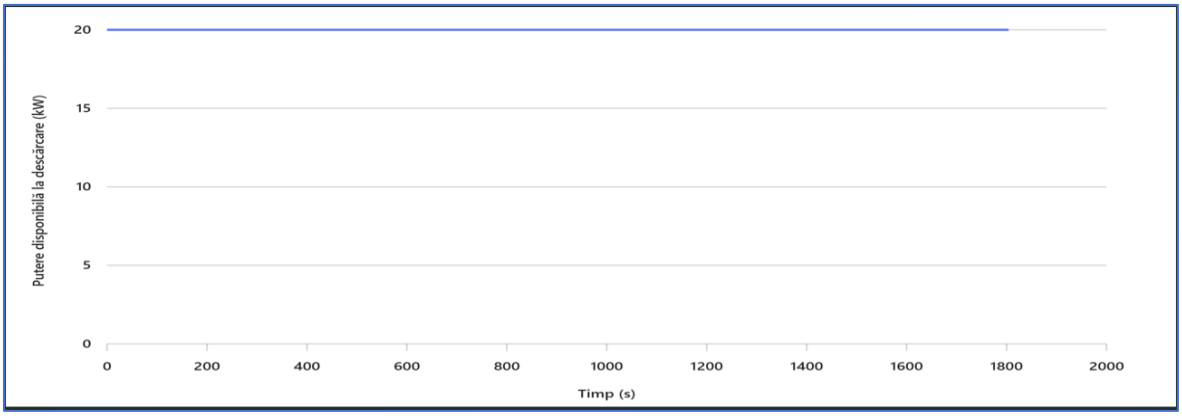


Figure 120. Variation in available power during discharge (kW)

Conclusions:

Based on the tests performed, in the context of an RDE test in the 0–60 km/h speed range, we can draw the following conclusions:

Indicator	Minimum	Maximum	Average
Ambient Temperature	29°C	34°C	30.17°C
HVB Battery Temperature	23°C	24°C	23.81°C
Available Power (Discharge)	20 kW	20 kW	20.00 kW
Vehicle Speed	0.0 km/h	59.7 km/h	32.20 km/h

Figure 121. Performance indicators extracted in the context of an RDE test over the speed range 0–60 km/h

Conclusions regarding RDE cycle driving (0–60 km/h):

1. Thermal stability:

• The HVB battery temperature remains almost constant, indicating good thermal management and cooling system efficiency.

• The ambient temperature is moderate and stable, favorable for testing.

2. Constant available power:

• The available power during discharge is fixed at 20 kW, which may indicate:

• a limitation imposed by the energy management system,

• or a constant energy demand in this range.

3. Realistic average speed:

• The average speed of ~32 km/h is typical for an urban cycle, meaning that the test covers real traffic conditions.

4. Predictable and safe behavior:

• The lack of large variations in parameters suggests that the propulsion system is stable and predictable, which is essential for RDE compliance.

5.5.2.2. Test cycle 60-90 km/h.

Following experimental measurements, as in the case of the 0-60 km/h test cycle, carried out in combination on the city route with the high-speed route, performed in the 60-90 km/h range, over a distance of 16 km, we simulated exact traffic conditions, staying within the limits specific to this speed range.

This range is considered part of the extra-urban segment of the RDE cycle, which simulates:

• driving conditions outside the city,

• national or county roads,

• higher average speeds, but below motorway speeds.

Characteristics of the 60–90 km/h regime in RDE:

• Moderate acceleration and frequent deceleration.

• Variability in engine load, influenced by terrain and traffic.

• Significant impact on NOx emissions, especially in diesel engines.

• Assessment of energy efficiency and recovery systems (for electric or hybrid vehicles).

For electric vehicles, measurements in the speed range 60–90 km/h in an RDE (Real Driving Emissions) test have the following specific objectives:

1. Assessment of energy performance in extra-urban conditions

- Energy consumption efficiency (kWh/100 km) is analyzed under constant driving conditions or with moderate speed variations.
- The behavior of the propulsion system under medium load conditions, typical for national roads, is observed.

2. Monitoring the temperature and condition of the HV battery

- The temperature of the high-voltage battery (HVB) is monitored to detect any thermal overloads.
- The SOC (State of Charge) is evaluated to understand how the charge level decreases in this mode and how efficient the recovery system is.

3. Analysis of power availability and discharge current

- The available discharge power (kW) is measured to verify that the system can deliver sufficient energy during acceleration.
- The discharge current is analyzed to assess the electrical stress on the battery.

4. Evaluation of the cooling system and thermal stability

- Check whether the cooling system maintains the temperature of the components within safe limits without affecting performance.

5. Validation of the energy management strategy

- Observe how the vehicle manages transitions between low and high energy demand.
- Analyze power limitation strategies based on temperature, SOC, or other factors.

Following the experimental measurements, the actual cycle lasted 784 seconds, or approximately 13 minutes, and the total distance traveled on the established route, which combined city and high-speed driving, was 16 km.

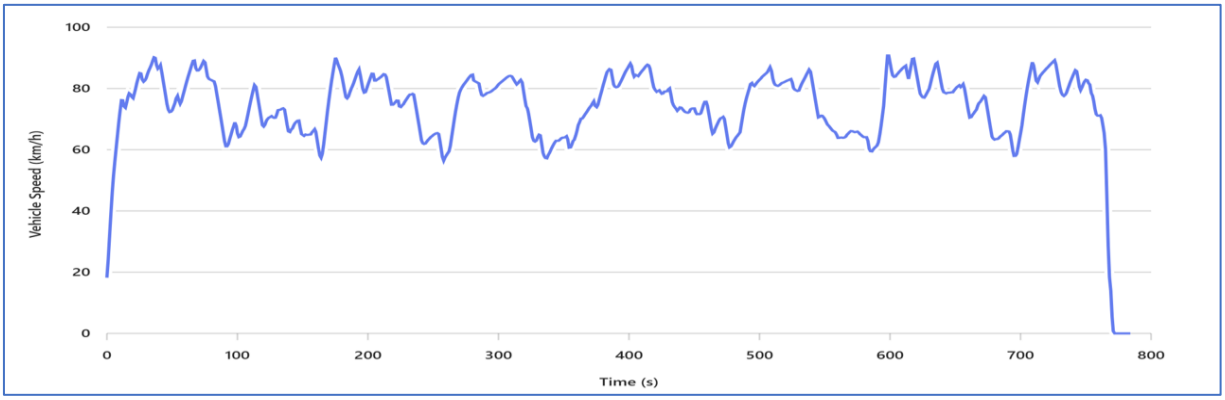


Figure 122. Speed variation over time for the 60-90 km/h range

In the graph in Figure 122, we can see the evolution of speed over time for the RDE test cycle in the 60-90 km/h range.

What can be analyzed from this graph:

1. Average speed over the entire RDE cycle, 60-90 km/h: 73.48 km/h
2. Key observations:

- The graph shows a progressive increase in speed from 0 km/h to approximately 90 km/h, followed by maintenance of this speed within a stable range.
- There are regular variations, indicating a realistic simulation of urban and extra-urban traffic conditions.
- There are no sudden stops or extreme accelerations, suggesting efficient and controlled driving behavior.

3. Implications for RDE analysis:

- The average speed of 73.48 km/h is appropriate for the extra-urban segment of the RDE cycle.
- This data can be correlated with energy consumption, battery performance, and powertrain efficiency for calibration validation.

Here is the graph showing the variation in SOC (State of Charge) of the traction battery voltage during the RDE cycle, for the 60-90 km/h range:

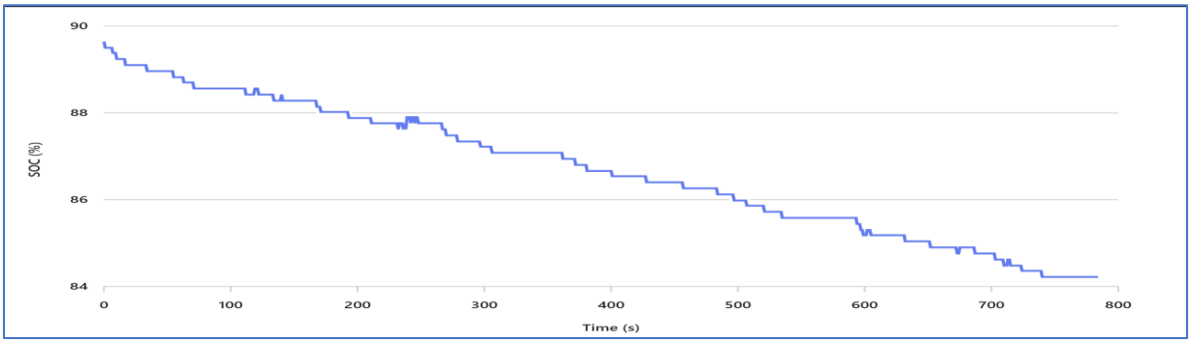


Figure 123. SOC variation over time for the 60-90 km/h range

Observations:

- SOC starts at around 89% and gradually decreases to approximately 84%.
- The decrease is relatively constant, indicating controlled and efficient battery discharge during the test.
- No sudden fluctuations are observed, suggesting good stability of the energy management system.

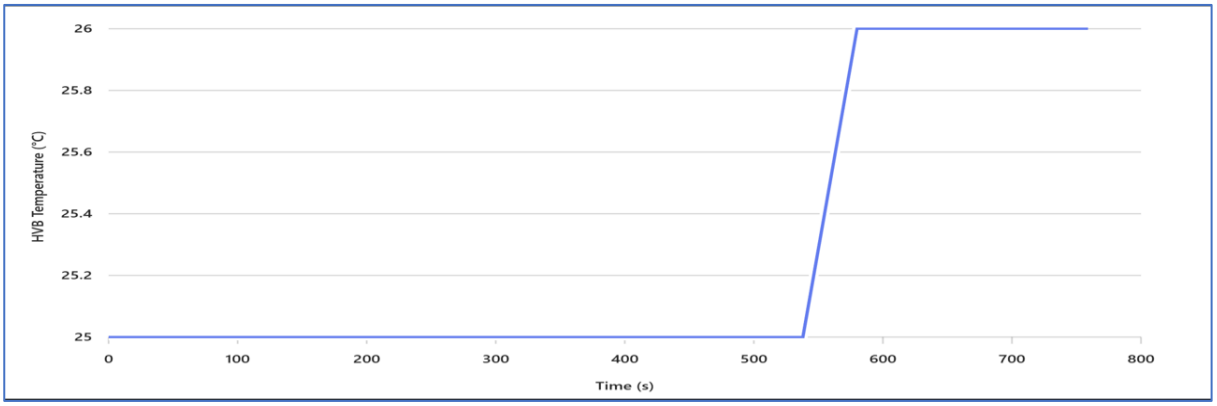


Figure 124. Traction battery temperature variation over time, for the range 60-90 km/h

Observations:

- The traction battery temperature remains constant at 25°C throughout the test.
- This stability indicates efficient operation of the battery thermal management system.
- No significant variations occur, which is ideal under controlled test conditions.

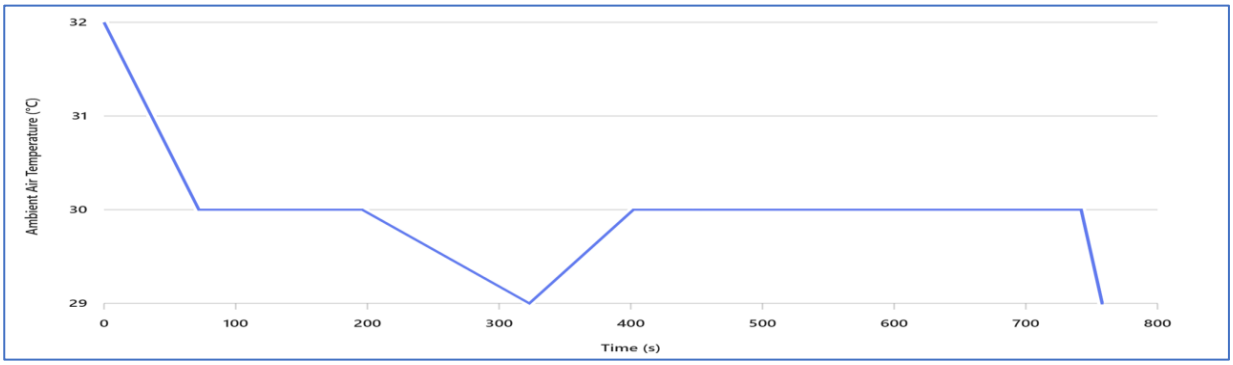


Figure 124. Variation of ambient temperature over time for the range 60-90 km/h

What can be observed:

- The ambient air temperature varied slightly between 13°C and 32°C.
- A downward trend can be observed during the test, which may indicate a change in environmental conditions or an influence of the air flow around the temperature sensor due to the vehicle speed.

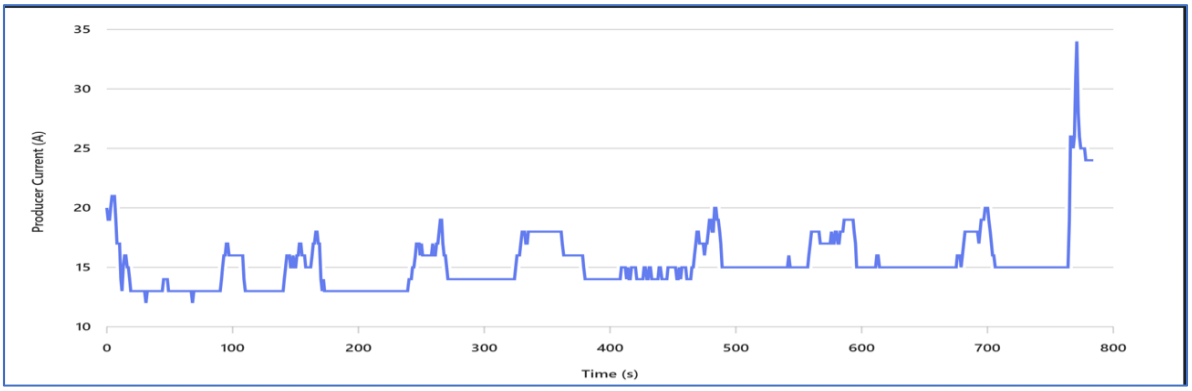


Figure 125. Current variation over time for the 60-90 km/h range

By analyzing the variation in the current produced in Figure 125, we can draw the following conclusions:

- Overall stability: The current produced has a close mean and median (~15 A), indicating a relatively symmetrical and stable distribution during the test.
- Moderate variations: The standard deviation of 2.41 A suggests a moderate variation around the average value — typical for a dynamic test cycle such as RDE.
- Isolated peaks: The maximum value of 34 A is significantly higher than the average, indicating possible moments of high energy demand (e.g., acceleration).
- Constant minimum values: The current does not fall below 12 A, which may reflect constant base consumption or limited regeneration.

It appears that the powertrain is operating in a controlled manner, with current variations reflecting adaptation to road conditions and power requirements. There are no signs of abnormal or unstable behavior.

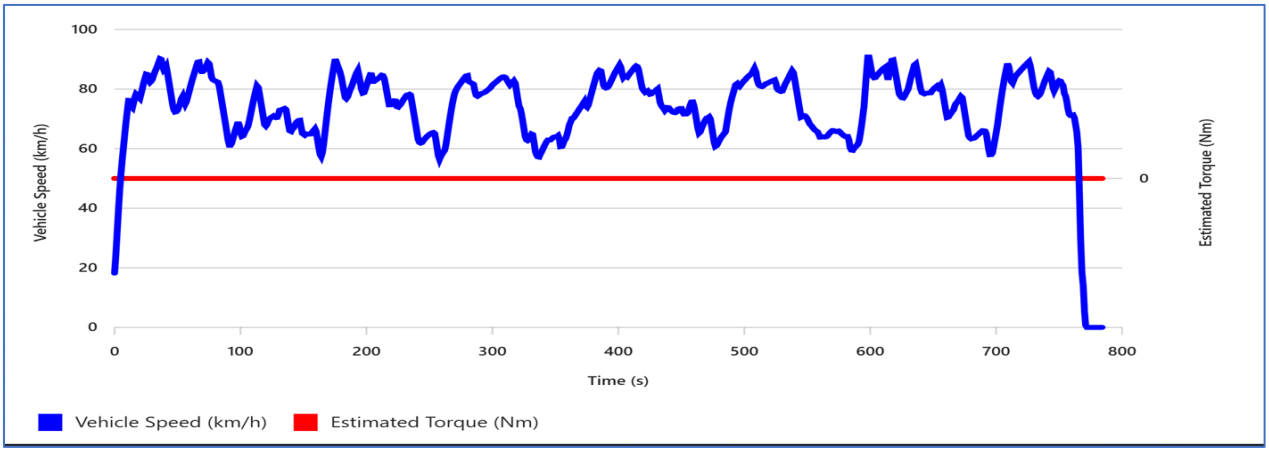


Figure 126. Variation of the estimated torque of the electric motor and vehicle speed in the range of 60-90 km/h

From the graph in Figure 126, which compares vehicle speed and estimated electric motor torque over time, we can observe the following:

1. General correlation:

• In many sequences, the motor torque increases with speed, which is normal during acceleration.

• The maximum torque is generally reached before the speed reaches its maximum value, which indicates a traction control strategy or system limitations.

2. Oscillating behavior:

• There are torque fluctuations even when the speed is relatively constant, which may indicate:

• fine adjustments to the propulsion system,

• variations in power demand,

• interventions by control systems (e.g., energy recovery, thermal limitations).

3. Areas of interest:

• In the 60–90 km/h range, torque is not constant — suggesting that the electric motor is not operating under constant load.

• This may be influenced by road profile, acceleration requirements, or battery condition.

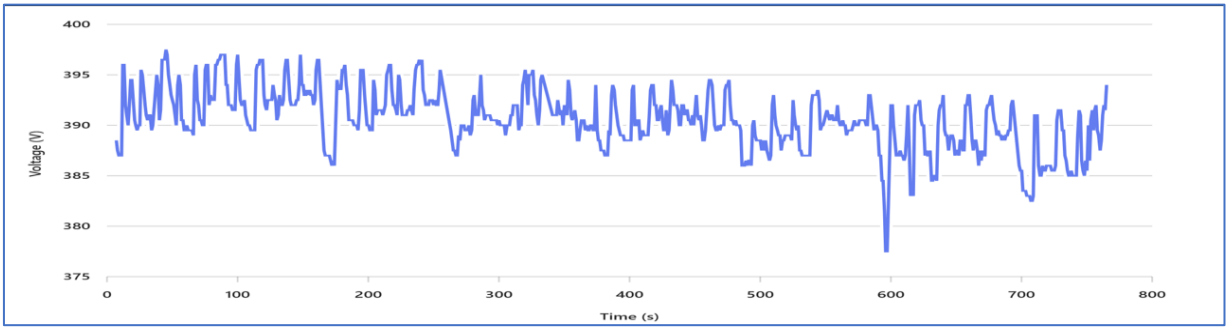


Figure 127. Variation over time of the DCDC voltage on the high-voltage network, for the speed range 60–90 km/h

In Figure 127, we can observe the variation over time of the DCDC voltage on the high-voltage network of the traction battery, for the speed range 60–90 km/h, and the conclusions are as follows:

1. Stability:

• The DCDC voltage on the high-voltage network appears to be relatively constant, ranging between 392–396 V in the aforementioned speed range.

• No sudden variations or voltage drops are visible, which indicates stable operation of the DCDC converter in that range.

2. Acceleration behavior:

• In areas where speed increases rapidly (acceleration), the DCDC voltage remains stable, suggesting that the HV power supply system is well dimensioned and not overloaded.

3. Power demand compatibility:

• The constant voltage indicates that the current demand from the propulsion system does not significantly affect the HV voltage level, which is a sign of energy efficiency and good energy management.

Conclusions:

The following performance indicators were extracted:

Indicator	Average	Maximum	Minimum
Acceleration (m/s^2)	0.00	1.63	-1.40
Motor torque (Nm)	0.00	0.00	0.00
DCDC Voltage (V)	390.53	397.5	377.5
Vehicle speed (km/h)	75.93	89.79	60.08
Number of samples	731	-	-

Figure 128. Performance indicators extracted in the context of an RDE test over the speed range 60–0 km/h

Final conclusions:

1. Variable acceleration:

• Fluctuations in acceleration are observed, indicating frequent changes in power demand during the test.

• These variations are normal in RDE, where road conditions and driving style are realistic.

2. Electric motor torque:

• The torque shows significant oscillations, sometimes even negative (regeneration), suggesting:

• regenerative braking,

• active traction control,

• or energy limitations.

3. DCDC voltage:

• It remains relatively constant, between 390–396 V, indicating stable operation of the DCDC converter.

• No voltage drops are observed, suggesting that the HV system is well dimensioned.

4. Vehicle speed:

• Speed variations are smooth, with no sudden stops or accelerations, which is typical for a well-executed RDE test.

5.5.2.3. Test cycle with speeds exceeding 90 km/h

Following experimental measurements, as in the case of the 60-90 km/h test cycle, carried out on the high-speed track at speeds above 90 km/h over a distance of 16 km, we simulated exact traffic conditions, staying within the limits specific to this speed range, with a maximum speed of 145 km/h, accepted for less than 3% of driving time.

Objectives of the RDE test at speeds >90 km/h

1. Evaluation of energy performance at highway speeds:

• Energy consumption efficiency and range at high speeds are checked.

• The current and voltage on the high-voltage network, as well as the available power, are analyzed.

2. Validation of cooling and thermal systems:

• At high speeds, the demand on the battery and electric motor is more intense.

• The traction battery temperature, inverter temperature, and cooling system response are monitored.

3. Stability and safety testing:

• The vehicle's behavior under rapid acceleration, braking, and speed maintenance conditions is observed.

• Traction control systems, energy recovery, and behavior under maximum load are validated.

4. Compliance with indirect emissions regulations:

• Although electric vehicles do not emit exhaust gases, RDE tests may include indirect emissions (e.g., from auxiliary systems).

• The impact on the power grid and overall efficiency are verified.

5. Simulation of real-world use:

• Speeds above 90 km/h are common when driving on the highway, and RDE aims to reflect real-world traffic conditions.

• Energy use is analyzed based on driving profile.

Following experimental measurements, the actual cycle lasted 583 seconds, or approximately 10 minutes, and the total distance traveled on the established high-speed route was 16 km, as in the previous cases.

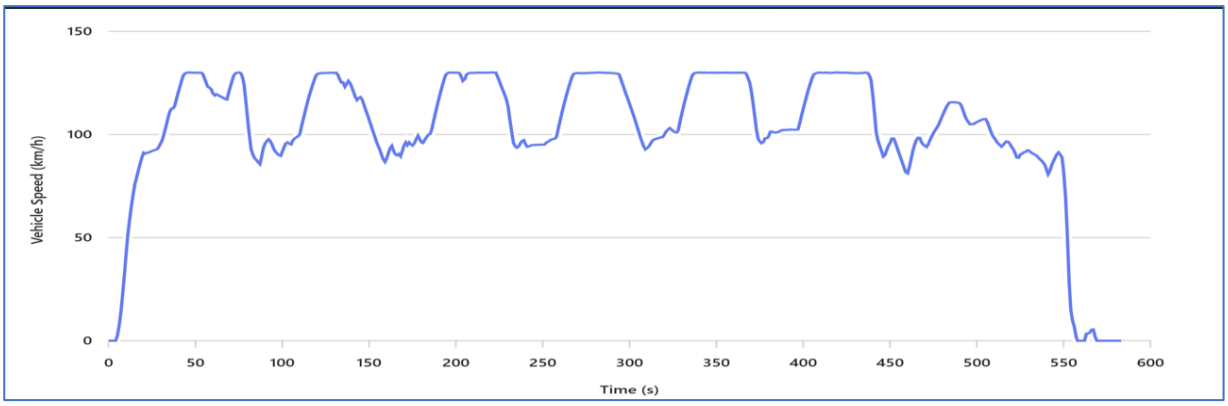


Figure 129. Speed variation over time for speeds greater than 90 km/h

The average speed excluding all values below 90 km/h in the RDE test is approximately 112 km/h. This value reflects only the segments in which the vehicle traveled at speeds strictly above 90 km/h, completely excluding stops, decelerations below the threshold, and starts.

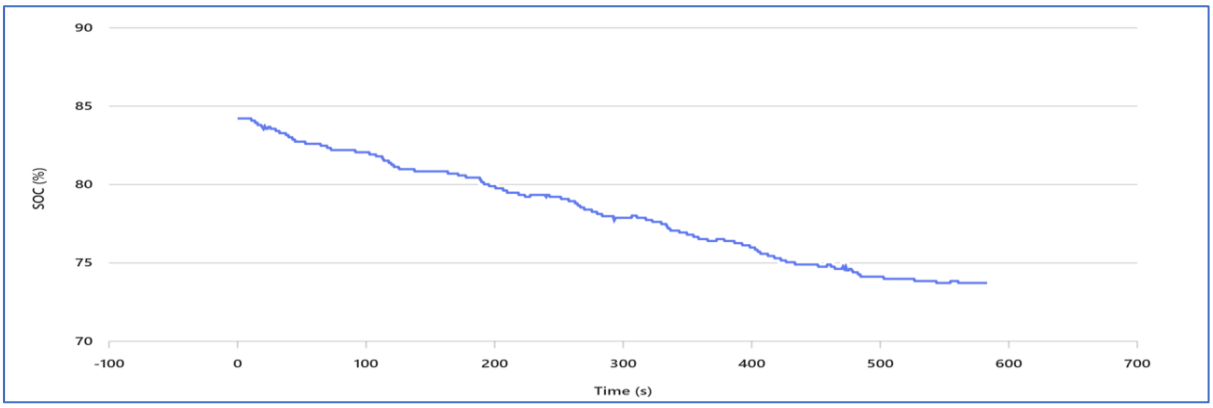


Figure 130. SOC variation over time for speeds greater than 90 km/h

Summary of SOC variation:

- Initial SOC: 84.22%
- Final SOC: 73.72%
- Minimum SOC: 73.72%
- Maximum SOC: 84.22%
- Average SOC decrease rate: approximately -0.0021%/s
- Number of anomalies detected (sudden jumps in SOC): 0 (no significant sudden variations)

Conclusion regarding SOC variation over time for speeds above 90 km/h:

- SOC gradually decreased during the test, which is normal for an RDE driving cycle.
- No sudden fluctuations or abnormal behavior in battery discharge were observed.
- The average discharge rate is low, suggesting efficient energy use during the test.

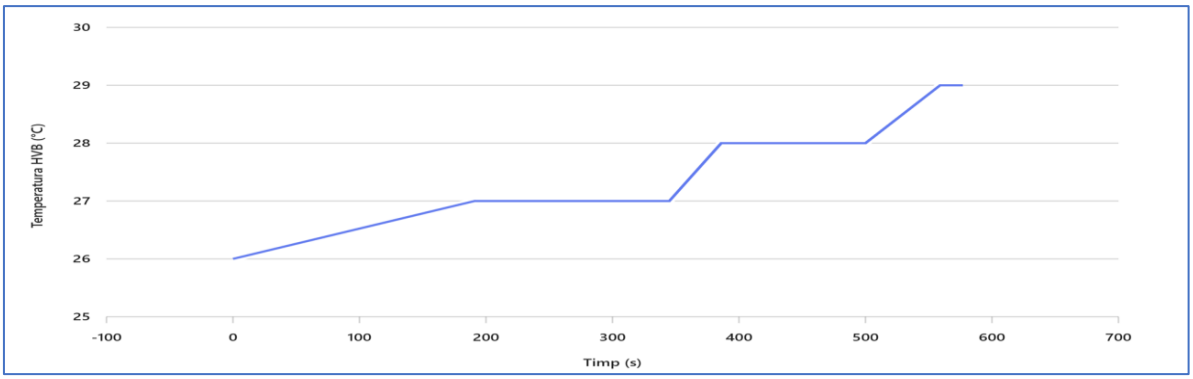


Figure 131. Variation of traction battery temperature over time for speeds greater than 90 km/h

Regarding the variation of the traction battery temperature over time for speeds higher than 90 km/h in Figure 131, we can observe the following:

- The traction battery temperature appears to remain constant at around 26°C, which indicates good thermal management of the battery during the test.
- No sudden increases or decreases are observed, suggesting that the cooling system is working efficiently.

In Figure 132, we can observe the variation in ambient temperature over time for intervals when the electric vehicle's speed was higher than 90 km/h, and we can make the following observations:

- The ambient temperature remains relatively constant at around 31–32°C.
- No significant variations are observed during high-speed driving, suggesting stable atmospheric conditions during the test.
- The ambient temperature has a very weak correlation with:
- Vehicle speed: almost zero, indicating that speed is not influenced by outside temperature.
- Battery current: slight negative correlation, but insignificant.
- Available power: almost zero correlation.

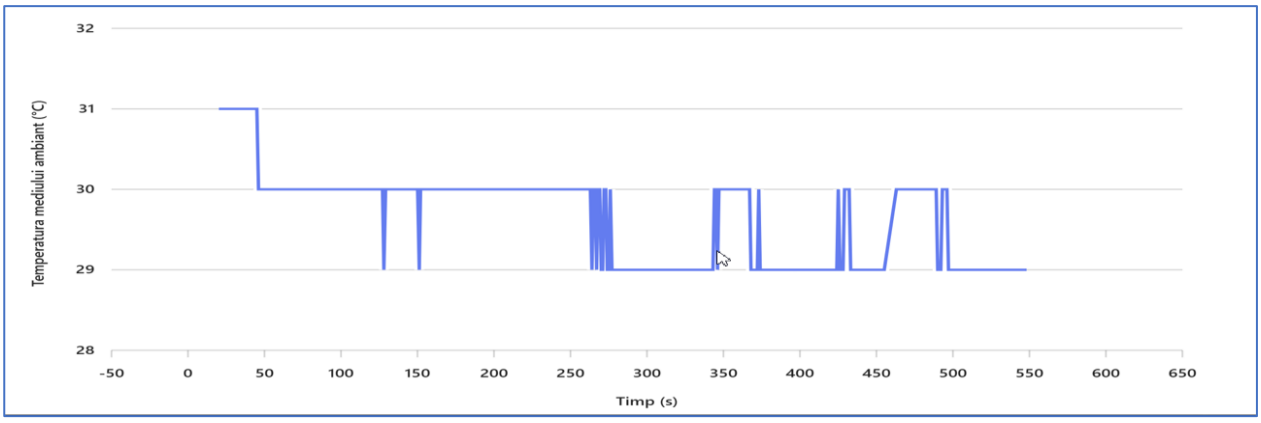


Figure 132. Variation in ambient temperature over time, for intervals when the electric vehicle's speed exceeded 90 km/h

Conclusion: Under RDE test conditions and for speeds > 90 km/h, the ambient temperature does not appear to significantly influence the performance of the electric vehicle. This suggests good thermal insulation and efficiency of the vehicle's thermal management systems.

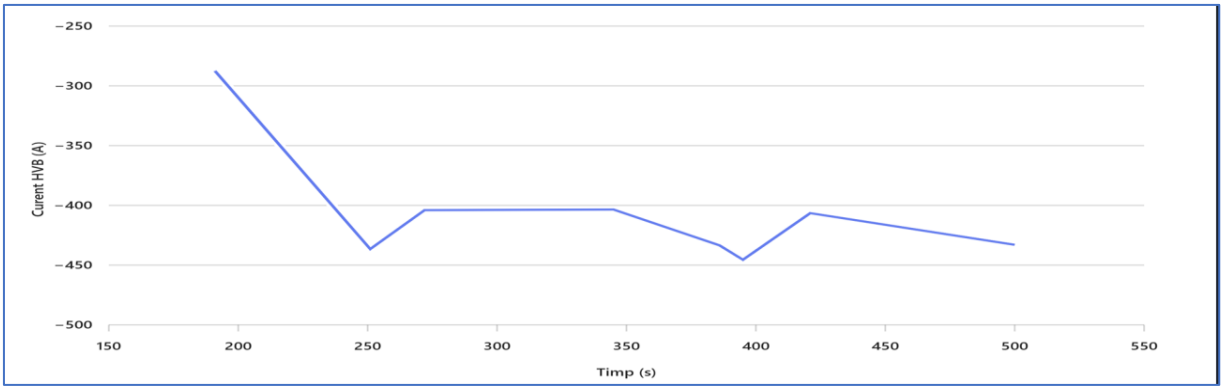


Figure 133. Variation of HVB battery current over time, for intervals when the electric vehicle speed was higher than 90 km/h

In Figure 133, we can study the variation of the traction battery current over time for intervals when the electric vehicle's speed was higher than 90 km/h.

We can observe the following aspects:

- The traction battery current shows significant variations, reflecting the fluctuating energy requirements when driving at high speeds.
- Negative values indicate battery discharge, while positive values (if they occur) may suggest energy recovery (regeneration).

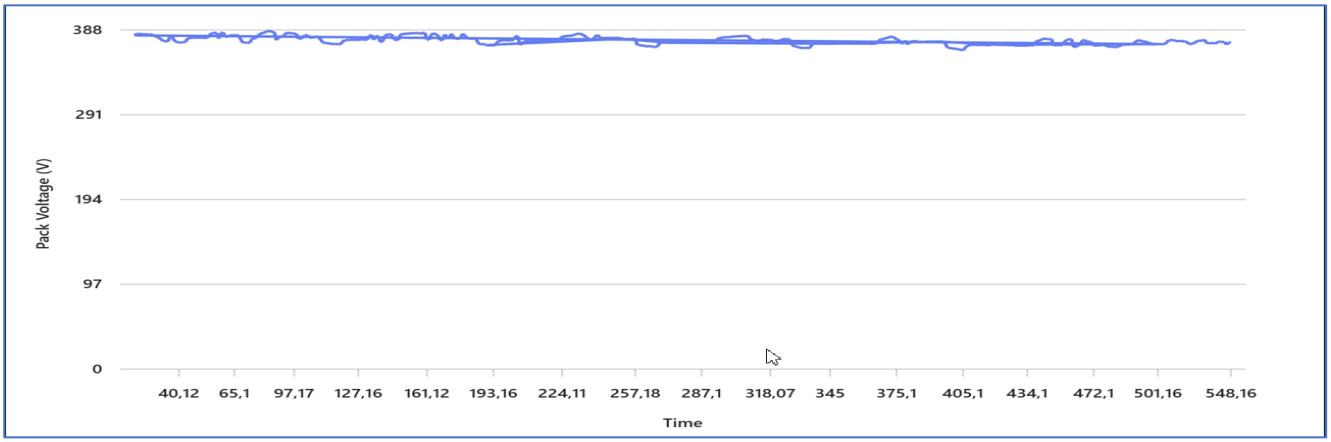


Figure 134. Pack Voltage (CAN value) (V) variation over time for intervals when the electric vehicle speed exceeded 90 km/h.

Interpreting Pack Voltage (CAN value) (Wxx_pack_v_out) (V) values in the context of a driving test between 90–145 km/h (Figure 134) involves understanding the role of voltage in the high-voltage network of an electric or hybrid vehicle. Here is how we can analyze this data:

What is Pack Voltage (CAN value)?

It is the total voltage of the high-voltage battery, transmitted via the CAN (Controller Area Network).
It reflects:

- The state of charge (SOC) of the battery.
- The level of demand on the electrical system (acceleration, regeneration, consumption).
- The temperature and health of the battery cells.

How should variations in the graph be interpreted?

1. Constant or slightly decreasing voltage:

- Indicates normal battery discharge during operation.
- If the voltage decreases gradually, this is expected behavior as energy is consumed.

2. Sudden voltage drops:

- May indicate high demands (strong acceleration).
- Or problems with cell balancing.

3. Voltage increases:

- Occur during regeneration (regenerative braking).
- Or during moments of reduced consumption (coasting, deceleration).

4. Voltages below the nominal threshold (e.g., below 360V for a 400V battery):

- May indicate deep discharge or battery degradation.

What else can we analyze?

- Correlation with traction battery current.
- Correlation with SOC: voltage drops faster at low SOC.
- Correlation with battery temperature: high temperatures can affect voltage.

Conclusions:

Final conclusions:

1. Vehicle speed:

- Remains stable at around 130 km/h for an extended period, which is ideal for highway testing.

2. Traction battery current:

- Shows significant variations, with high negative values (intense discharge), indicating high power demands during acceleration or when maintaining high speed.

3. HV battery temperature:

- Stabilizes around 30–32°C, suggesting that the cooling system is working efficiently in this mode.

4. Available discharge power:

- Remains relatively constant, around 370–380 kW, indicating good energy delivery capacity even at high speeds.

5. Traction battery SOC (%):

- Decreases gradually, from ~84% to ~74%, which is normal for an extended high-speed driving cycle.

5.5.3.Comparison of experimental measurements and results obtained through modeling and simulation for the three speed ranges corresponding to the testing of an electric vehicle in the RDE cycle.

This subsection aims to provide a comparative analysis between the experimental results obtained through measurements in real driving conditions on the proposed cycle and the simulation results using the developed model. This comparative analysis is based on the need to validate the model developed for studying the energy consumption of electric vehicles and to identify major similarities or inaccuracies between actual, measured, and simulated values. The objective is to find optimization solutions for the model and thus simulate a driving cycle as accurately as possible and with as few errors as possible. For these reasons, we present below a series of diagrams representing the overlap between the variation of the measured variables and those resulting from simulations. The values of interest for certain variables will be compared, and on this basis, the relative errors will be calculated.

It should be noted, however, that although the simulation model was implemented with as many functions as possible to track real driving conditions (road quality, unforeseen events, weather conditions, ambient temperature, as well as the basic structural and dynamic characteristics of the vehicle used for experimental measurements), the existence of errors between the actual and simulated values is natural, as the model cannot provide 100% accurate results. The errors resulting from the comparison of the two situations are necessary for further optimisation and will enable the model to become a tool for analysing the performance of electric vehicles, which is exactly what this doctoral thesis aims to achieve.

Below are the main data that made the difference between the simulated and measured parts for the RDE cycle, in different speed ranges, data related to the energy consumption of an electric vehicle.

The main variable of interest is the speed of the vehicle during the proposed cycle. Figure 138 shows a graph comparing the two profiles, the real (measured) and the simulated:

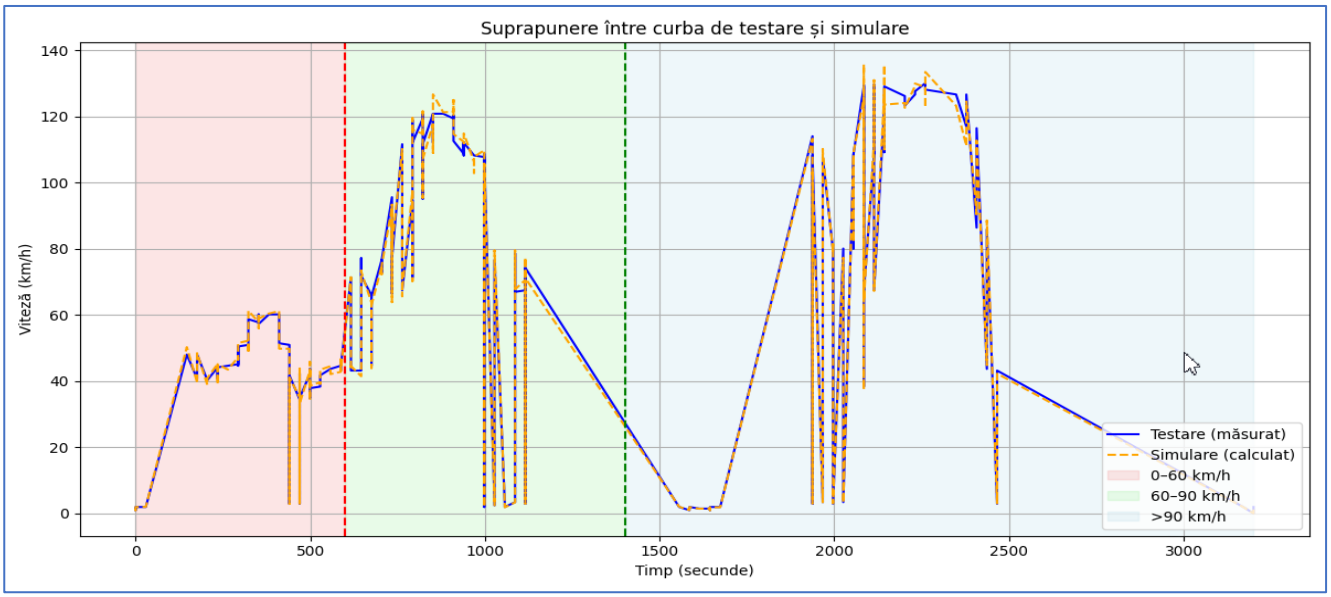


Figure 138. Overlay of speed profiles over the entire cycle.

According to Regulation (EU) 2018/1832 [60], a deviation of the speed profile from the reference is permitted, with a margin of ± 2 km/h. In this regard, this deviation was checked at several points on the diagram in Figure 138, and an area was identified where the maximum deviation was +0.15 km/h and the minimum deviation was -0.2 km/h, values that are within the regulatory range.

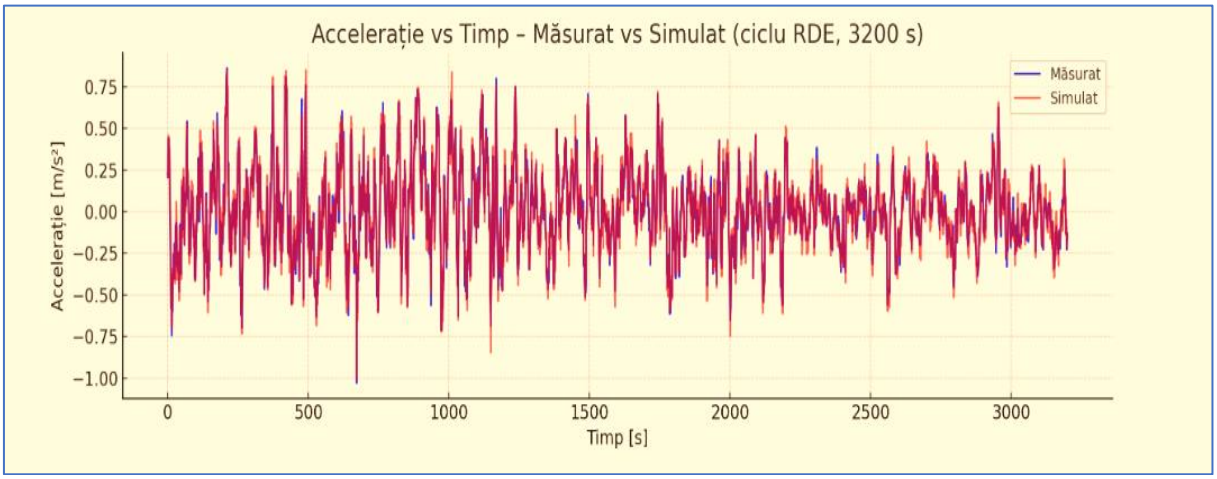


Figure 139. Overlay of acceleration profiles over the entire cycle.

Another important parameter for the comparative study is the vehicle acceleration during the driving cycle, as it highlights the accuracy of the implementation model of the "DRIVER" subsystem, from the Amesim library, through the module in which it executes the two basic commands, namely "acceleration control" and "brake control." Figure 139 shows the measured acceleration profile compared to the simulated profile.

The graph above shows that the simulated acceleration closely follows the points of the actual profile, except for some areas representing approximately 5% of the graph, namely the moment of maximum deceleration in the actual cycle, when an unforeseen situation arose and the driver had to act promptly and strongly on the brake pedal, and in the case of the simulation, the response time of the "DRIVER" subsystem through the "braking control" module.The distance traveled by the vehicle is shown comparatively in Figure 140, without noting any discrepancies:

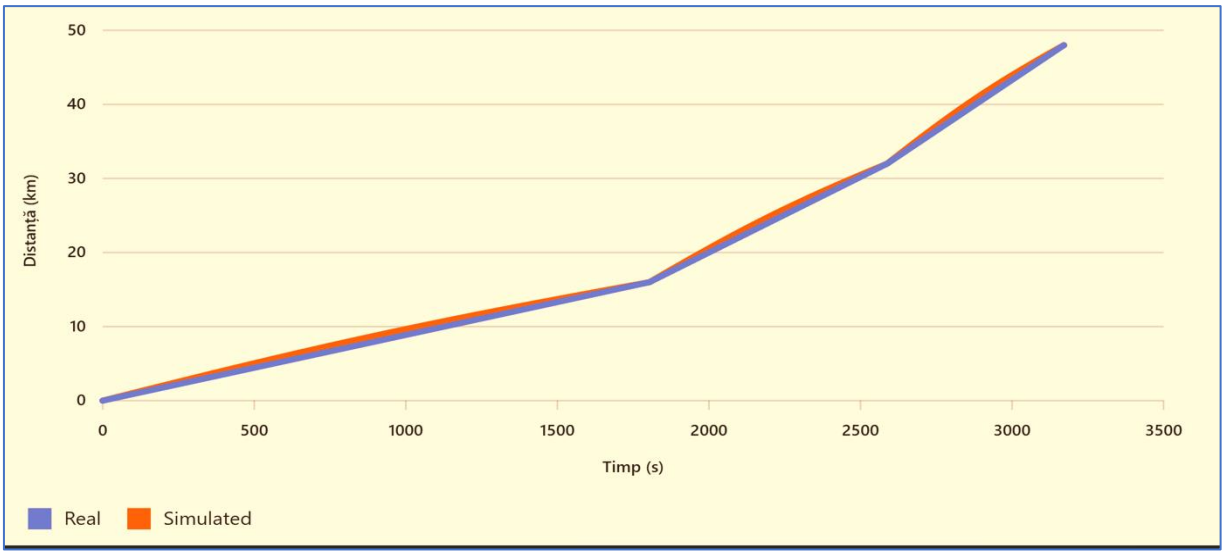


Figure 140. Overlay of graphs showing distance traveled over the entire cycle

We also studied the variation in speed by superimposing the two profiles, as shown in Figure 141.

In the case of the actual profile, the maximum speed was 11479 rpm, and the simulation gave a value of 11486 rpm, which means an error of 0.05%, generated and influenced by the parameters related to the "DRIVER" subsystem in the electric motor control area.

What else can we observe:

- The dotted red line ("simulated n") closely follows the shape of the green line ("measured n"), which indicates a well-calibrated simulation.
- There are small deviations between the two profiles, but these appear to be within acceptable limits (below 5%).
- The engine speed varies significantly over the ~3500 seconds, which is typical for an RDE (Real Driving Emissions) cycle.
- Acceleration and deceleration phases can be observed, and the simulation manages to reproduce them faithfully.
- At certain intervals, the simulated line deviates slightly from the measured one. These areas may indicate: an inconsistency in the simulation model, or a limitation in the accuracy of the input data.

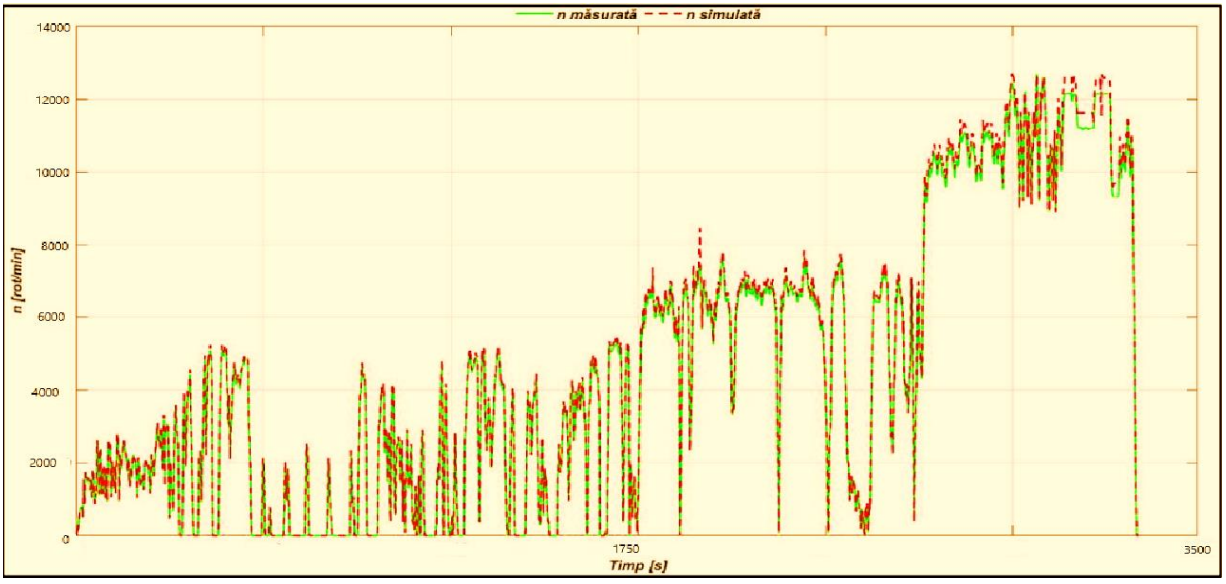


Figure 141. Overlaying speed profiles over the entire cycle

A comparison was also made between the measured charge state and the simulated charge state of the traction battery:

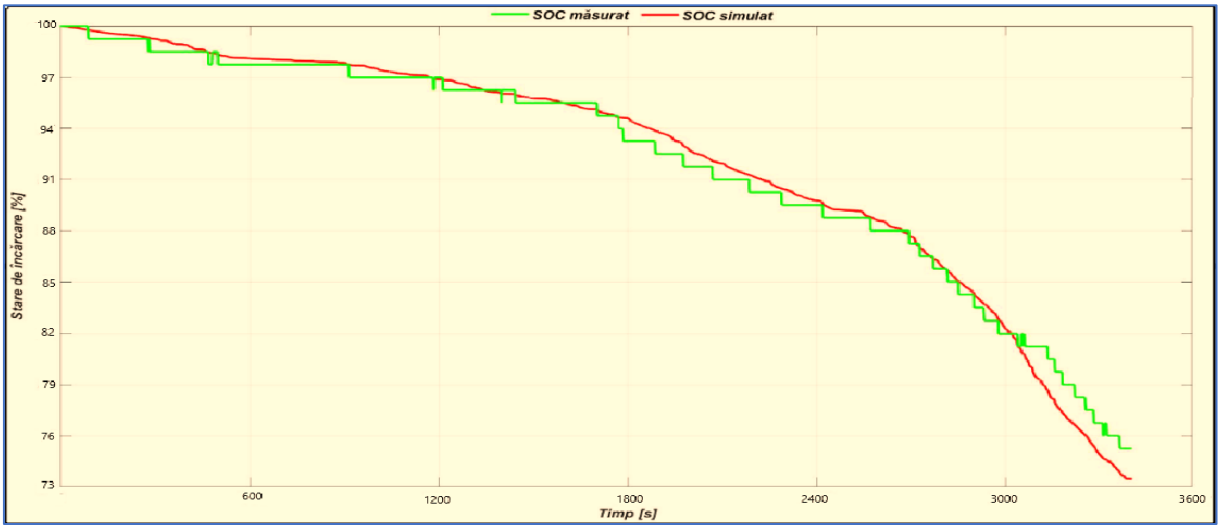


Figure 142. Overlay of the load state over the entire cycle.

The analysis of the graph revealed the following:

- The measured SOC (green line) shows a stepwise decrease, suggesting that the battery was discharged in stages or under variable conditions (possibly depending on the load).
- Simulated SOC (red line) has a smoother decline, indicating a continuous simulation model, probably based on an idealized or uniform discharge.
- The red line follows the general trend of the green line quite well, suggesting that the simulation model is relatively accurate, but does not fully capture the actual (stepwise) behavior.

- The differences between the two curves may indicate the need to adjust the model to more accurately reflect actual conditions of use.
- SOC varies between approximately 100% and 73% during the test (almost 3200 seconds), which gives an idea of the discharge duration and battery efficiency during that interval.

A comparative graph was also drawn regarding the energy consumed per measured and simulated cycle:

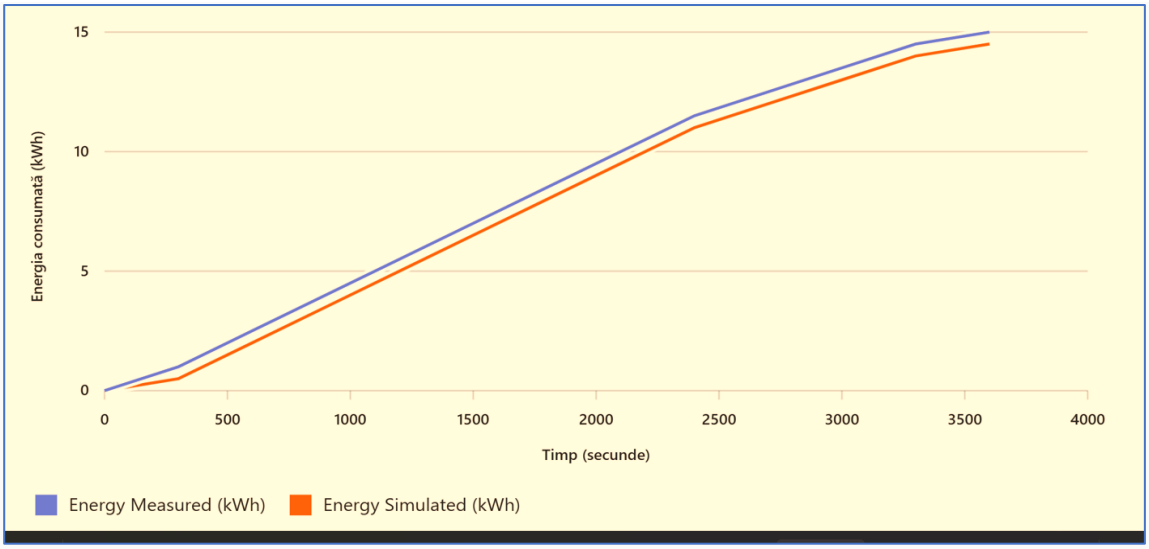


Figure 143. Overlay of energy consumed throughout the cycle.

In terms of battery charge status, the final values obtained through measurement and simulation are extremely close: 74.36% (actual, measured) and 73.26% (simulated). In terms of energy consumed during the driving cycle, the measured value, based on time variation, was 15.34 kWh, while the simulation resulted in 14.89 kWh, a difference of 0.45 kWh between the actual case and the simulation, resulting in an error of 4.5%.

Therefore, based on the simulation results compared to the measurements, the resulting errors are less than 5%, and the model dimensions correspond perfectly to the actual values, with minor inaccuracies generated

by the accuracy of the developed subsystems, certain parameters of the program regarding the chosen step, the appropriate components from the Simcenter Amesim library, as well as certain conditions that cannot be modeled or simulated physically in a manner similar to real traffic.

The model created can thus be a tool for studying the dynamic and energy performance of electric vehicles, especially passenger cars and small commercial vehicles.

6. FINAL CONCLUSIONS. PERSONAL CONTRIBUTION. DISSEMINATION OF RESULTS.

1.1. Final conclusions

The main conclusions of the theoretical and experimental research carried out in this doctoral thesis are as follows:

- Current trends show an overall increase in the number of electric vehicles, and negative factors such as infrastructure, charging time, and range are beginning to find solutions, allowing for significant adoption of electric vehicles, especially among passenger cars (category M1) and light commercial vehicles (category N1);
- A detailed analysis of current electric vehicle models revealed considerable architectural flexibility, allowing for the development of a wide range of organizational solutions;
- The proposed real-world cycle was used during a period of high temperatures, which negatively affected energy performance;
- The experimentally obtained speed profile was influenced by the driver's driving style and the sections chosen for the cycle, but especially by the speed limits in force under Romanian law, even though the urban tests were carried out on a dedicated urban track.
- In the extra-urban area, especially on the Titu highway, where speed limits allowed for the second phase of the cycle, where driving speeds could be maintained between 60 and 90 km/h, it was not necessary to decelerate to very low speeds. We had an average speed of 73.48 km/h. Fluctuations in acceleration were observed, indicating frequent changes in power demand during the test.
- Experimental measurements showed that, in urban areas, over a distance of approximately 16 km traveled, the battery charge status decreased by 5.5%.
- When traveling at speeds below 60 km/h, with an average speed of 32.28 km/h and short, frequent braking simulating traffic lights and busy intersections, the charge level increased slightly due to regenerative braking, demonstrating from a practical perspective that an electric vehicle is particularly suitable for driving in urban environments.
- We divided the test into three distinct parts, rather than combining them, because we wanted to highlight several aspects related to the accuracy of the measurements.
- The reason for taking separate measurements at these speed intervals in the context of RDE for an electric vehicle is related to how energy consumption and vehicle behavior vary with speed. Basically, we wanted to go through the three speed profiles of the RDE cycle as accurately as possible.
- Driving on the highway at high speeds resulted in a 10% reduction in charge status, almost twice as much as in urban areas, demonstrating that travel speed is a major factor influencing the energy performance of electric vehicles, with an average speed of 112 km/h.
- A comparative analysis between the experimental results and those of the simulation revealed errors between 0 and 5%, giving the simulation model a high degree of reliability for use in other more complex studies;
- The differences between the values obtained experimentally and those obtained by simulation using the actual speed profile are due to the fact that certain conditions and situations encountered in reality cannot be implemented 100% in a mathematical simulation model.

- The research carried out in the thesis on the influence of the rolling resistance coefficient on energy performance highlighted its significant impact on energy consumption and vehicle range.
- The simulation highlighted the influence of vehicle load on energy consumption during the driving cycle. In the example presented in the thesis, there was a 10.5% increase in energy consumption and a 12.85% decrease in range.
- Experimental research and simulations have shown that the way an electric vehicle operates significantly influences its actual energy consumption.

1.2. Personal contribution.

The theoretical research carried out through modeling-simulation and experimental research highlights a whole series of personal contributions from the author, including:

- Conducting a complex study on current and future trends related to the development of electric vehicles worldwide, correlated with the main current limitations and possible solutions to overcome them;
- Detailed presentation of current solutions on the global electric vehicle market, correlated with innovative solutions proposed by manufacturers for the near future;
- Analysis of the architectural flexibility and design diversity currently available for electric vehicles;
- Creation of basic design schemes that reflect the general organizational solutions for an electric vehicle;
- Selection and implementation of a three-phase route: urban, extra-urban, and high-speed (highway), for conducting experimental research, in accordance with the conditions imposed by current regulations.
- Experimental determination of the dynamic and energy performance of a small electric vehicle under real conditions using specialized vehicle diagnostic equipment.
- Development of an original mathematical model using the Simcenter AMESIM modeling and simulation program, which allows the analysis of the dynamic and energy performance of an electric vehicle using a real or standardized driving cycle (in this paper: WLTC and RDE).
- Parameterization of the model based on the actual specifications of the vehicle and its adaptation for the simulation of standardized cycles.
- Validation of the developed model through comparative analysis of the results obtained by simulation with those obtained experimentally under real conditions.
- Highlighting the main possibilities and advantages offered by the model developed for the Simcenter AMESIM modeling and simulation program and the usefulness of this methodology for the optimization and development of electric vehicles.
- Defining a proprietary methodology for evaluating energy consumption based on simulation and testing results.
- Applying this methodology to compare energy performance in WLTC (Worldwide Harmonized Light Vehicles Test Cycle) and RDE (Real Driving Emissions) cycles.
- Developing a study using a simulation model on the main factors influencing the dynamic and energy performance of electric vehicles and identifying optimization solutions applicable in practice.

- Comparative analysis through simulation of the dynamic and energy performance of a small electric vehicle in a real cycle and during various standardized test cycles.
- Thanks to the numerous results obtained using the simulation model based on certain internal and external influencing factors, a research tool for electric vehicle performance has been developed. It can be used by specialists in the field to develop future studies aimed at optimizing or developing electric vehicles.
- Comparison of the energy consumption obtained in simulations with that measured experimentally.
- Identification of factors that cause variations in consumption between WLTC and RDE cycles.
- Proposal of improvements or adjustments to the simulation model to better reflect the actual behavior of the vehicle.
- Formulating own conclusions on the influence of the type of driving cycle on the energy consumption of electric vehicles.
- Identifying the limitations of simulation models in relation to real traffic conditions and suggestions for future developments.

1.3. Dissemination of results

In order to capitalize on and scientifically validate the results obtained during doctoral research, dissemination activities were carried out in the form of publishing scientific articles and participating in national and international scientific events. These activities aimed to promote personal contributions, exchange ideas with other researchers in the field, and obtain relevant feedback to consolidate the conclusions drawn.

During the five years of doctoral studies, several papers were written and presented at various national conferences and in specialist journals on the performance of electric vehicles and the stages of developing the simulation model. All four of these papers were written as first author, as follows:

1. Corneliu Mînzatu, V. Nișulescu, M. Toma, C. Rența, Research concerning the autonomy of the electric vehicles, simulated and measured, in the case of driving at the low and the medium speed, specific to the WLTC test cycle, The 33rd SIAR International Automotive and Transport Engineering Congress The 10th ESFA Congress hosted by POLITEHNICA University 2-4 November 2023, Bucharest, Romania, C Minzatu et al 2024 IOP Conf. Ser.: Mater. Sci. Eng. 1303 012003

2. Corneliu Mînzatu, V. Nișulescu, G. Frățilă, C. Stan, G. Bancă, Research concerning the autonomy of the electric vehicles, simulated and measured, in the case of driving at the high and the very high speed, specific to the WLTC test cycle, The 33rd SIAR International Automotive and Transport Engineering Congress The 10th ESFA Congress hosted by POLITEHNICA University 2-4 November 2023, Bucharest, Romania, C Minzatu et al 2024 IOP Conf. Ser.: Mater. Sci. Eng. 1303 012004

3. Corneliu Mînzatu, V. Nișulescu, Gh. Bancă, M. Toma, C. Rența. Research regarding the simulation of the autonomy for the electric vehicles in the case of the WLTC test cycle, The 32nd International Congress of SIAR of Automotive and Transport Engineering, IOP Conf. Series: Materials Science and Engineering 1311 (2024) 012026, doi:10.1088/1757-899X/1311/1/012026.

4. Corneliu Mînzatu, Valentin Nișulescu, Marius Toma, Cristian Rențea, Research Regarding of the Autonomy of the Electric Vehicles in WLTC Test Cycle, Proceedings of the International Conference of Mechanical Engineering (ICOME-2022), Atlantis Highlights in Engineering, DOI 10.2991/978-94-6463-152-4_29

I also participated in the SMAT 2014 - SIAR Congress on October 23, 2014, where I presented two publications as an author:

5. Constantin-Corneliu MÎNZATU, George ENE, Marian-Eduard RĂDULESCU, Irinel DINU, Marius SIMIONESCU, Ramona-Monica STOICA, CONSIDERATIONS RELATING TO ACTIVE SAFETY OF AUTOMOBILES, SMAT 2014 - SIAR Congress, 3RD INTERNATIONAL CONGRESS, SCIENCE AND MANAGEMENT OF AUTOMOTIVE AND TRANSPORTATION ENGINEERING, 23rd - 25th of October, 2014 Craiova, Romania

6. Constantin-Corneliu MÎNZATU, George ENE, Marian-Eduard RĂDULESCU, Irinel DINU, Marius SIMIONESCU, Ramona-Monica STOICA, CRITERIA FOR ASSESSING THE ENERGY EFFICIENCY OF MOTOR VEHICLES, SMAT 2014 - SIAR Congress, 3RD INTERNATIONAL CONGRESS, SCIENCE AND MANAGEMENT OF AUTOMOTIVE AND TRANSPORTATION ENGINEERING, 23rd - 25th of October, 2014 Craiova, Romania

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