National University of Science and Technology POLITEHNICA Bucharest

Faculty of Transport

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RESEARCH ON DETERMINING THE DYANMIC AND ENERGETIC PERFORMANCES OF ELECTRIC VEHICLES

DOCTORAL THESIS

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BUCHAREST 2024

CONTENT

„Don’t go where the road takes tou go where there is no road and leave a trail”.

(Ralph Waldo Emerson)

Preface

Taking into account the topicality and complexity of the subject addressed in this doctoral thesis, its development required the use of all the available resources in carrying out experimental research and respectively, through modeling and simulation, resources made available in the period October 2021 - June 2024 by the National University of Science and Technology POLITEHNICA Bucharest.

First of all, I start by expressing my gratitude and thanks for Prof. em. Dr. Eng. Gheorghe FRĂTILĂ, the scientific supervisor, who guided my steps with high competence and exactingness during the doctoral years, as well as for the elaboration of this thesis.

Secondly, I would like to convey my appreciation to Prof. Dr. Eng. Grigore DANCIU, the one who paved the way for me in my teaching career, advised me and motivated me with the same parental love at every stage of my professional development.

I would also like to convey my gratitude to Mr. Vice-Dean Associate Dr. Eng. Marius-Florin TOMA, for the help and trust he gave me and for all the efforts undertaken in carrying out the experimental tests; Mr. Prof. Dr. Eng. Marius-Valentin BĂȚUȘ for the special suggestions offered every time and, of course, to my colleague and good friend, Mr. ș.l. Dr. Eng. Cristian-Alexandru RENțEA, without whom things would not have been oriented on this trajectory.

I would also like to express my gratitude to Mr. Eng. Marius SĂVESCU and the PORSCHE București Nord Group for the collaboration, openness and support offered in carrying out experimental research by making the electric car available.

At the same time, I would like to express my gratitude to the teaching staff of the Department of Road Vehicles, and especially to Mr. Associate Director Dr. Eng. Daniel-Mihail IOZSA, for the high level of training they offered me and for the warmth with which they integrated me in the collective of this Department.

Finally, I want to thank my fiancee, Alice for every moment she has been there for me unconditionally and my parents for everything I am today and what I will become tomorrow.

Finally, I thank God for giving me the strength, confidence and health to complete this work.

Ph.D.eng. Alexandru-Adrian ANCUȚA
Bucharest, June 2024

INTRODUCTION

In the global automotive industry, according to the strong trend to reduce pollutant emissions resulting from the combustion of petroleum fuels, the electric propulsion system has become an option to support this trend and as a result of this the optimization of dynamic and energetic performances is a short medium and long term objective for producers anchored in this process.

Now the problem is posed on the one hand through the prism of infrastructure limitations and on the other hand through the prism of energy performance, especially the autonomy of electric vehicles in relation to conventional ones. However, most of the world's established car manufacturers have adopted different solutions and put on the market a multitude of variants that start easily, easily meet the expectations of users.

Through modeling and simulation in different environments, the dynamic and energetic performances of electric vehicles can be determined without the need for a real vehicle and a specialized stand to carry out a test cycle.

So, taking into account the complexity of the problems that characterize such a study, a well-structured simulation model that takes into account all the internal and external conditions that can influence the performance of an electric vehicle is imperative.

OBIECTIVELE PROPUSE

The first objective of the thesis is to develop and optimize a mathematical simulation model using the MatLAB-Simulink program, capable of determining the dynamic and energetic performances of an electric vehicle, initially from the M1 and N1 categories. Based on this model, the goal is to create a scientific tool that will later allow the creation of other more complex models.

Another objective is the process of validating the model by using experimental tests under real driving conditions, using a reference electric vehicle, measuring equipment and implementing a route based on which to obtain a real cycle with which the model used at simulation to be verified by comparing the results obtained in the two situations. This objective is based on the determination of dynamic and energetic performances by modeling and pulling and experimentally.

In conclusion, the main objective of the thesis is to develop a simulation model to determine the dynamic and energetic performances, which can be validated by experimental results and which can become a useful research tool for other specialists in the field.

The doctoral thesis is divided into five chapters:

Chapter I. EVOLUTION OF ELECTRIC VEHICLES, carries out an analysis of the events that shape the history of electric vehicles from the first moments of its appearance until now, pointing out certain notable moments. Also, this chapter presents the trends regarding the spread of electric vehicles alongside the general causes underlying this phenomenon and obviously correlated with the existing limitations at the moment. The chapter ends with a comparative analysis between an electric vehicle and a conventional one, equipped with a thermal engine, from the point of view of construction, operation, performance, aspects related to maintenance and reliability, and last but not least in relation to the costs related to each system of propulsion in part.

Chapter II. CURRENT STAGE OF ELECTRIC VEHICLE CONSTRUCTION, extensively develops the current state of the constructive solutions made by manufacturers worldwide to increase and optimize the performance of electric vehicles. Also, each component of the electric propulsion system (engine, speed variator, battery, transmission) is analyzed in particular from a functional point of view and the new solutions to be implemented in the near future are also presented.

Chapter III. NUMERICAL MODELING AND SIMULATION OF AN ELECTRIC VEHICLE is the basis of the doctoral thesis detailing the development steps of the simulation model starting from the general equation of the movement of the motor vehicles, after which the components of the electric propulsion system will be implemented one by one. At the same time, this chapter presents the results obtained from simulations when running on a real cycle developed by the author and when running on the standardized WLTC and NEDC cycles, regarding the autonomy, the state of charge of the battery, the total energy consumed, as well as the specific consumption . At the end of the chapter, various current solutions are presented that can be benchmarks for performance optimization, such as the 2-speed transmission, the reduction of the rolling resistance coefficient or the temperature of the ambient environment.

Chapter IV. EXPERIMENTAL RESEARCH OF AN ELECTRIC VEHICLE has as its main purpose the validation of the model developed for simulation. This chapter presents the way of choosing the route in accordance with the regulations in force for the tests in real conditions and also presents the equipment used for the measurements and the results obtained, and finally a comparison of the results obtained experimentally with those obtained from the simulation is made.

Chapter V. FINAL CONCLUSIONS. PERSONAL CONTRIBUTIONS. DISSEMINATION OF RESULTS, is the chapter that concludes the doctoral thesis and points out the final conclusions identified following the research carried out both through experimental measurements and through modeling and simulation. Through this chapter, the main theoretical and experimental personal contributions are highlighted along with future research perspectives for the purpose of developing more studies on electric vehicles.

CHAPTER I. EVOLUTION OF ELECTRIC VEHICLES

In the following, a chronological analysis will be developed related to the origins of the electric vehicle and its evolution until now, also the causes underlying the development will be highlighted and of course some accurate data about the impact of the electric vehicle on both producers and consumers, of motor vehicle users and their adaptability to this type of propulsion system. Finally, this first chapter will end with a detailed comparison between the conventional vehicle equipped with MAI and one equipped with an electric propulsion system.

The emergence and spread of electric vehicles

For many, the electric vehicle and the modernity around it seems to be a current topic and contemporary with the evolution of technology and systems in the road vehicle industry, but the truth is that the idea of an electric vehicle and the first trends in the appearance of such a vehicle they originated about 200 years ago. At that time, certain researchers were proposing different constructive solutions of electric propulsion vehicles, which were obviously characterized by extremely low performance and the irreversibility of the energy storage source, which had to be changed after discharging, and this aspect posed various problems.

The evolution of the electric vehicle can be seen in the following image, which practically shows the stages starting from the classic vehicle equipped with a thermal engine:

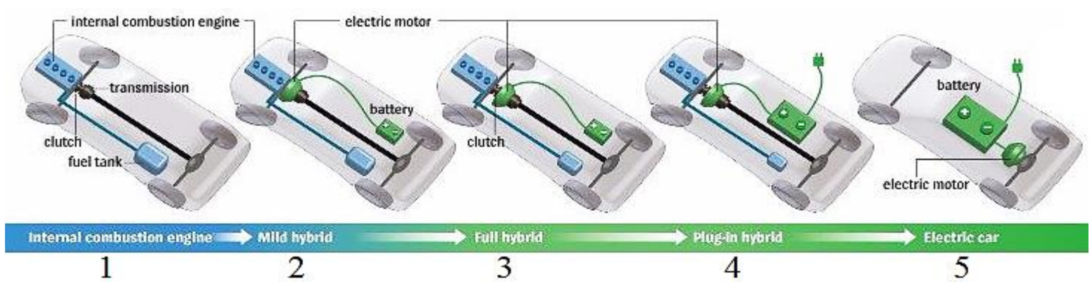


Figura 1.1. Stages of the development of an electric vehicle starting from the conventional one, [2].

Legend:

1 – Conventional motor vehicle equipped with internal combustion engine, clutch and gear shift

2 – Electric-hybrid propulsion system in which the electric motor is used for the recovery braking regime, to supplement the power of the thermal engine, without being able to achieve the traction on its own

3 – Electric-hybrid propulsion system in which the thermal engine is not directly connected to the vehicle's running system, and the electric engine can achieve the traction on its own depending on the state of charge of the battery

4 – Electric-hybrid propulsion system that can operate in "all electric" mode as long as the battery is sufficiently charged, including a charging plug from an external energy source

5 – The electric vehicle

The causes underlying the development in electric vehicles

The fundamentals related to the evolution of the electric vehicle are based on the emergence of more and more hypotheses related to urban pollution and drastic changes in the global climate. Thus, with the scandal of 2015, the special commissions determined to deal with the effects of pollution and obviously to find feasible solutions to reduce these effects drastically changed the maximum admissible limits for all categories of road vehicles and also imposed a series of important sanctions for producers who do not comply with the new regulations.

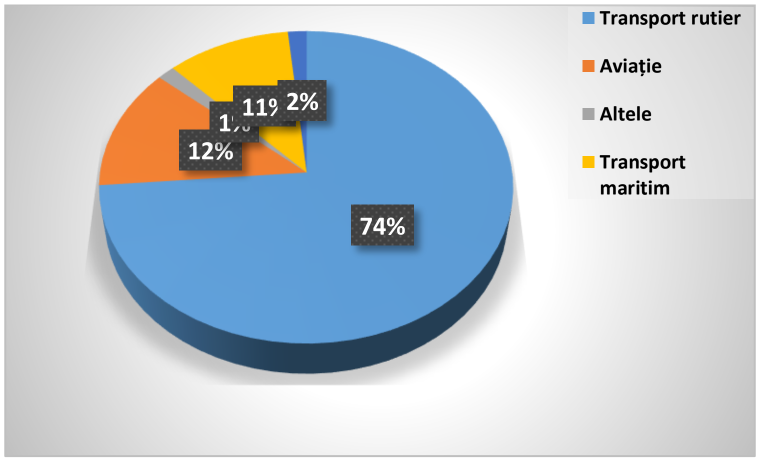


Figura 1.2. Fuel demand in relation to the transport branch, [3].

On the same note as the previous diagram, an analogy is made related to the percentage of use of each individual fuel, of course, taking into account the entire category of road transport, and it is noted that diesel and immediately after gasoline represent an overwhelming percentage in terms of use. Another aspect that determines the need to develop propulsion systems that can operate with a lower amount of fuel or with another type of energy that is not harmful to the environment.

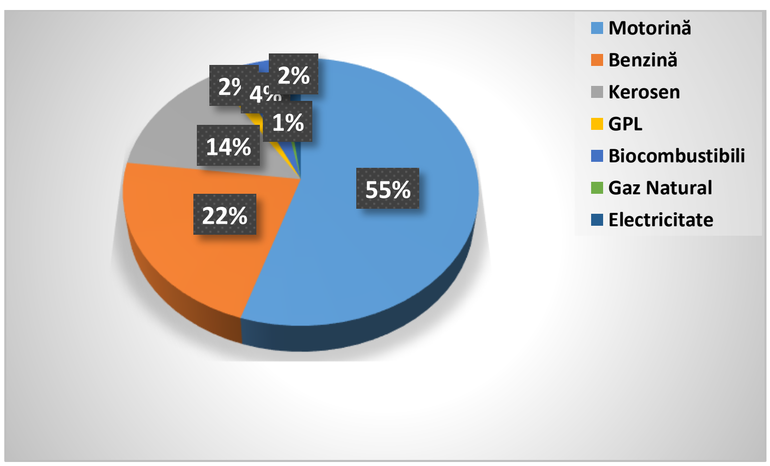


Figura 1.3. Share of use of different types of fuels, [3].

So a main cause underlying the development of the electric vehicle industry is the reduction of polluting emissions produced as a result of the combustion of petroleum fuels in the chemical process that takes place in the thermal engine, and in particular we refer again to CO2, correlating this emission reduction with a maintaining or even increasing the traction performance of a vehicle, which for the internal combustion engine becomes a problem considering that it, in order to produce mechanical work, must consume, and here the electric motor makes its presence felt, which in addition to the operation "clean", without harmful factors, also comes with better traction performance than the thermal engine, especially at low and medium speeds where the thermal engine is much more unstable and disadvantageous. A more thorough comparison between these two will be covered in a future sub-chapter.

Impact and spread of electric vehicles worldwide

Fig. 1.4 suggests the effect of the pandemic on the number of electric vehicles and shows the trends until 2030, which after the effects of the pandemic appear to be more promising than before COVID 19, namely an increase of 7 million vehicles on the road is predicted, i.e. 40 million, compared to the initial figure of 33 million, which denotes that in the automotive industry, the pandemic has had a beneficial effect.

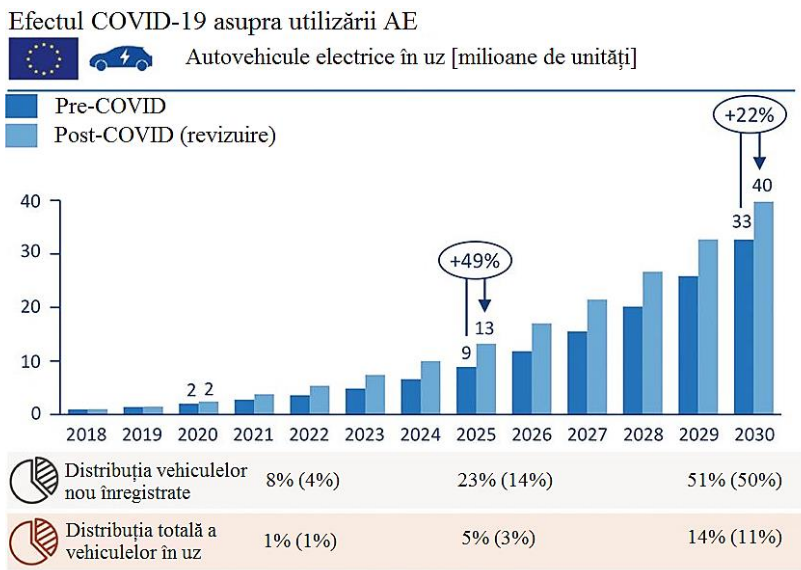


Figura 1.4. Analysis of sales and the impact of the pandemic on the electric vehicle industry, [4].

Infrastructure necessary for the supply of electricity

In order to observe more concretely the current state of the battery charging infrastructure, some statistical diagrams will be presented and analyzed that highlight the evolution of recent years and the trends until the year 2035. For Europe, a map with the number of charging stations according to the number of electric vehicles to see if at this time the increased sales of electric vehicles are offset by charging stations or if there is a shortfall in the middle.

To begin with fig. 1.5 proposes the map of Europe in 2020 showing the number of charging stations for 10,000 vehicles in relation to all areas on the continent.

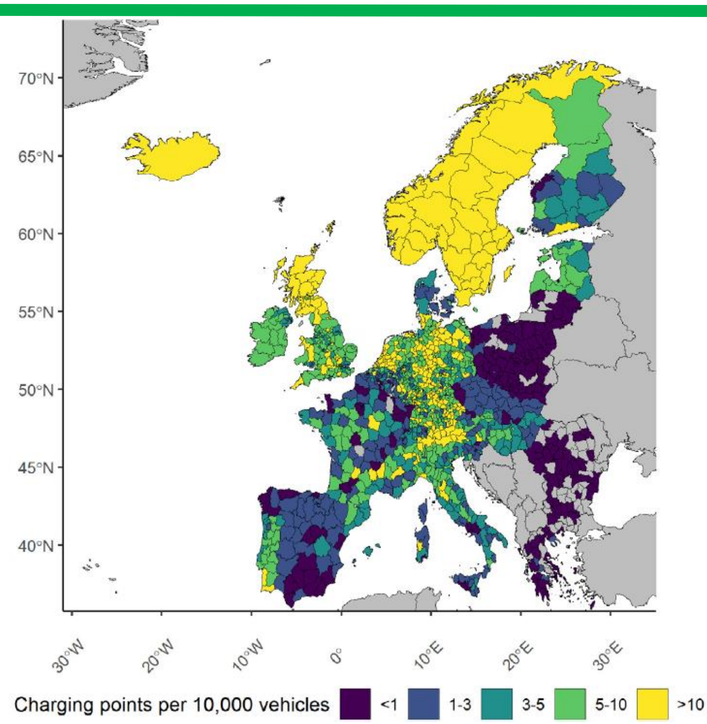


Figura 1.5. Map of Europe showing the number of charging stations in relation to a number of 10,000 vehicles, [5].

The American manufacturer TESLA is already investing heavily in a new type of extremely fast charging stations also called "Ultrafast Charging" or "Supercharger", which it has also brought to the European continent considering the high sales market of the models of electric vehicles produced by them. In figure 1.6 you can see the map of Europe regarding the "Supercharger" stations produced by TESLA.

Figura 1.6. Station map of Europe „Supercharger”, [6].

The comparative study between an electric vehicle and a conventional one, equipped with an internal combustion engine

Constructive-functional analysis:

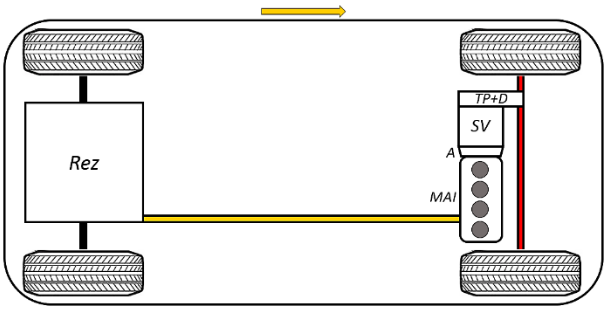


Figura 1.7. Schematic diagram of a conventional vehicle equipped with MAI:
Rez – Fuel tank; MAI – Internal combustion engine; A – clutch; SV – Gear shifter; TP+D – Main Drive + Differential.

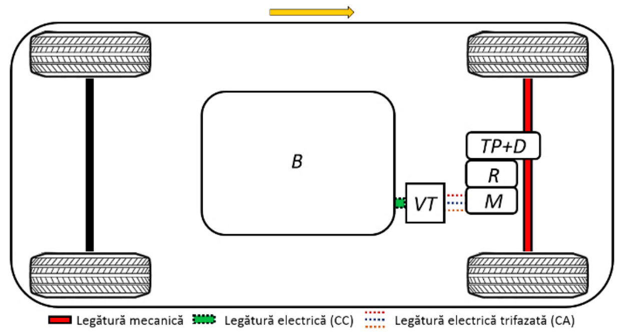
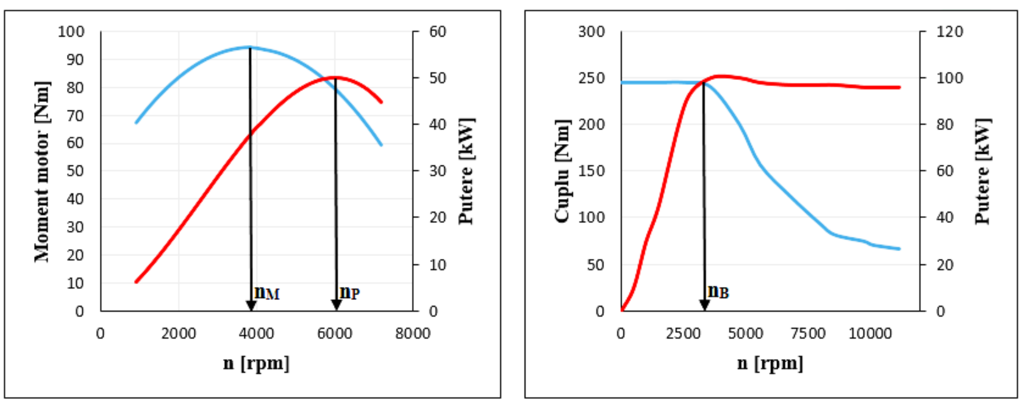


Figura 1.8. Schematic diagram of an electric vehicle:
B – Battery; VT – Speed variator; M – Electric motor; R – Reducer; TP+D – Main Drive + Differential.

Mechanical characteristics: Another extremely important comparison criterion is the mechanical characteristics of the two engines, which actually signify the traction performance of each and suggest which of the two has a positive impact on the dynamics of the vehicle.

Figure 1.9 shows two mechanical characteristics for a conventional vehicle equipped with MAS and an electric one. The charts use real data of the two vehicles in question and are modeled based on the values of interest; these have been used in various works, and are now extremely useful to flesh out the similarities and/or differences between MAI and ME:



a) b)

Figura 1.9. Mechanical characteristic of a ice (a) and an EM (b).

Maintenance and reliability: Two extremely important aspects regarding a motor vehicle are the maintenance and reliability of the entire assembly, but also of each individual subassembly. From here also arise the financial problems for a car user for his own use, because, if we are talking about a conventional one, the reliability is not exactly long, and the maintenance operations, either preventive or corrective, are also not among the simplest and cheapest and even with a new model under warranty, some of the costs must be covered by the owner.

Thus, from these points of view the electric vehicle is more advantageous, but there is a trade-off related to the purchase cost and the possible cost of the battery in the event of a failure, but overall, at the moment it is more reliable than a conventional vehicle.

Pollutant emissions and noise: It is obvious that at the level of an electric vehicle there is no longer any system that produces pollutant emissions while running like an internal combustion engine. The electric motor is a "clean" subassembly, producing mechanical energy without any residual element. As for batteries, a whole rather contentious and divided discussion can develop here, as there are specialists who affirm the character of an electric vehicle as a Zero Emissions Vehicle (ZEV) from the moment it hits the road, but with an extremely high compromise regarding the pollution generated by the manufacturing process of the batteries and their possible recycling respectively. Another aspect related to the pollution of the two types of vehicles is noise pollution, the noise produced while driving the vehicle on the road. From this point of view, the electric vehicle is again a winner because there is no longer any noise similar to that produced by the exhaust system or the combustion engine in various operating regimes at high revs.

Energy/fuel consumption and related costs: It is another comparison criterion that directly involves the point of view of the user, who most often considers consumption to be a fundamental factor in choosing a vehicle.

Regenerative braking: This process is exclusively specific to an electric vehicle and is made possible by the characteristics of the variable speed drive, the electric motor, which is a reversible three-phase alternating current electric machine, so it can change its direction of rotation and work as a generator of electricity and of course the battery, which is a reversible storage source and allows the energy obtained from the regenerative braking process to be stored.

Production and purchase cost: To make this aspect more concrete, a comparative diagram is presentedin figure 1.10:

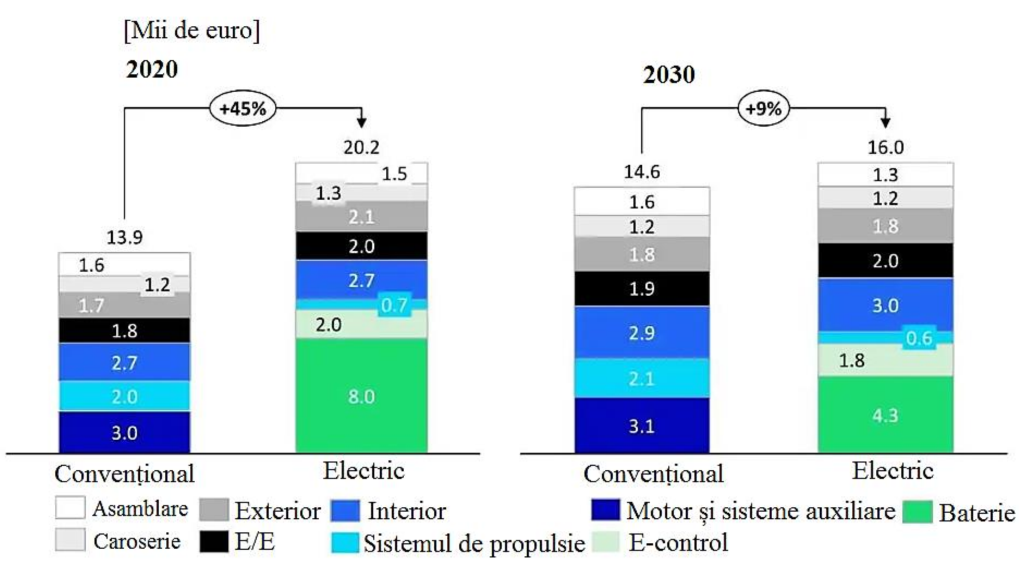


Figura 1.10. Comparison of the production cost of the two types of vehicles, [7].

Tabel 1.1. Avantajele și dezavantjele unui autovehicul electric, [1].

Advantages	***Dizadvantages***
✓ *High constructive simplicity* ✓ *High architectural flexibility* ✓ *The advantageous mechanical characteristic of EM compared to that of an ICE* ✓ *Pollutant emissions eliminated* ✓ *Low noise in operation* ✓ *High reliability* ✓ *Reduced maintenance operations* ✓ *EM Speed control is smoother and more efficient* ✓ *High yield of EM (>90%)* ✓ *EM can operate at much higher speeds (>12000 rpm)* ✓ *Higher needle power* ✓ *Enable the regenerative braking process* ✓ *Favorable fuel price*	- *High production and purchase price* - *Low specific energy* - *Battery manufacturing and recycling process* - *Autonomy still reduced* - *High reload time* - *The danger generated by working with the high voltages in the system (300 ... 400 V)*

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CHAPTER II. CURRENT STAGE OF ELECTRIC VEHICLE CONSTRUCTION

Constructive solutions of electric vehicles

The architecture in figure 2.1 thus defines the connections that take place between the components of the electric propulsion system, the storage source and the auxiliary systems. Regarding the communication between the electric car, the storage source and the vehicle is achieved by introducing new electronic command and control components, namely the power electronics or the speed variator for the control of the electric car and the BMS (Battery Management System) regarding storage source. These elements constantly communicate with the vehicle's computer (ECU) to correlate all the information necessary for its optimal operation.

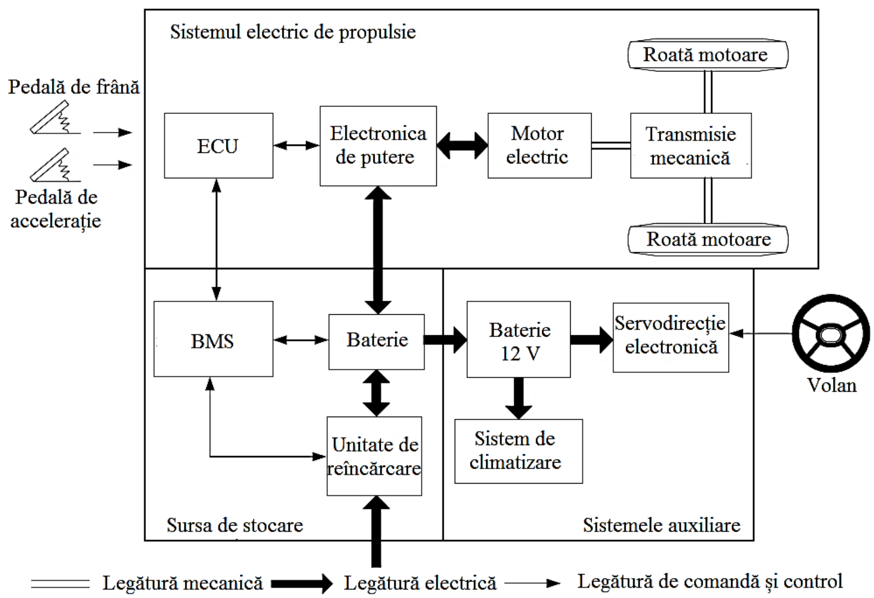


Figura 2.1. Configuration of an electric vehicle, [1].

Figure 2.2 shows a schematic diagram of an electric vehicle:

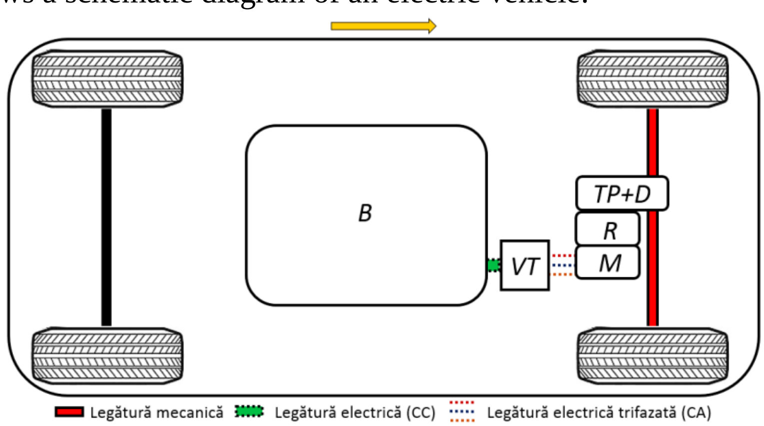


Figura 2.2. Schematic diagram of an electric vehicle organized according to the „In Front Wheel” solution: *B – Battery; VT – Speed variator; M – Electric motor; R – Reducer; TP+D – Main Drive + Differential.*

In this way, it can be seen that the electric propulsion system itself is formed by an electric traction machine (M - which can be alternating current or direct current) and the Speed Variator, which represents the control system and electric car control. The mechanical transmission consists of a simple Reducer with one or two reduction steps together with the Main Transmission and Differential assembly, and at the output 2 planetary shafts to drive the drive wheels. Battery – B is a reversible electrochemical source with high energy storage capacity, to which a hydrogen fuel cell or a supercapacitor battery can be added.

Architectural flexibility of electric vehicles – general organization solutions

The architectural flexibility of an electric vehicle can be defined as the multitude of solutions for organizing and placing the components of the electric propulsion system and optimizing the ergonomic conditions and the space in the passenger compartment. In order to highlight this important property, different constructive solutions already existing or at the prototype level will be analyzed, as well as the advantages or disadvantages of each individual solution. In order to better explain the construction of these constructive solutions, various constructive sketches similar to the one in figure 2.2 will be offered for analysis, together with at least one example of an electric vehicle that uses the respective solution.

❖ „Rear wheel drive” organization solution:

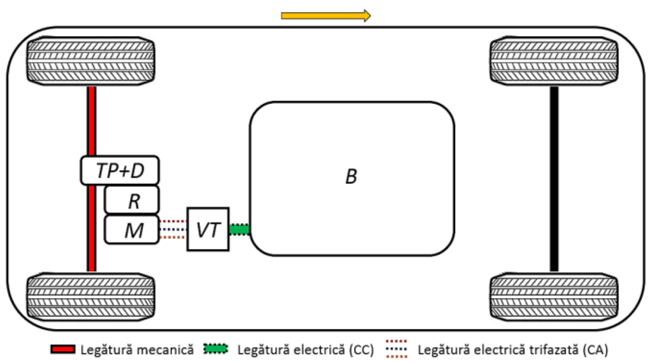


Figura 2.3. Electric vehicle with „Rear wheel drive” organization solution.

An electric vehicle model that uses the presented solution is the Tesla Model 3 produced in 2017:

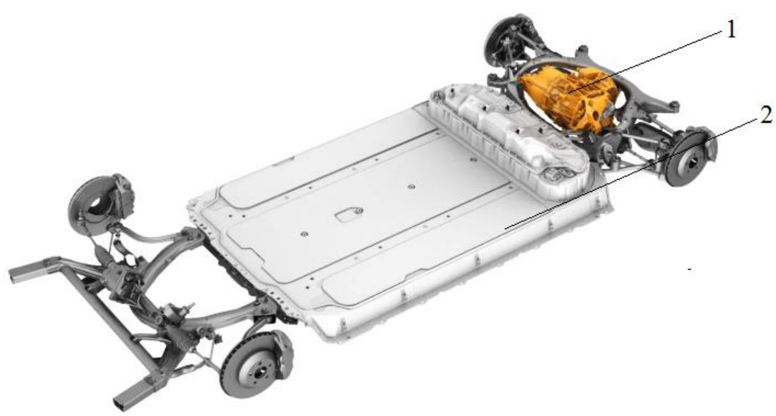


Figura 2.4. Architecture of the Tesla Model 3 vehicle, [11]:
1 – Electric motor+VT+R +TP+D; 2 – Lithium-ion battery.

As for Tesla's latest generation Model 3 - Performance, the traction is integral and likewise, each axle is driven by an electric motor along with its own speed variator and R+D+TP assembly.

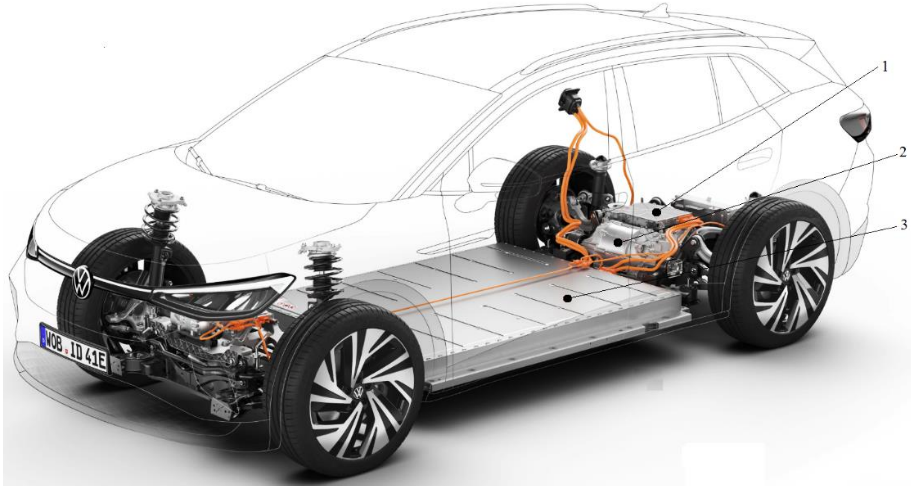


Figura 2.5. Architecture of the VW ID.4 vehicle, [13]:
1 – Speed variator; 2 – Electric motor; 3 – Lithium-ion battery.

Figure 2.6 shows a schematic diagram of a bridge with independent wheel drive:

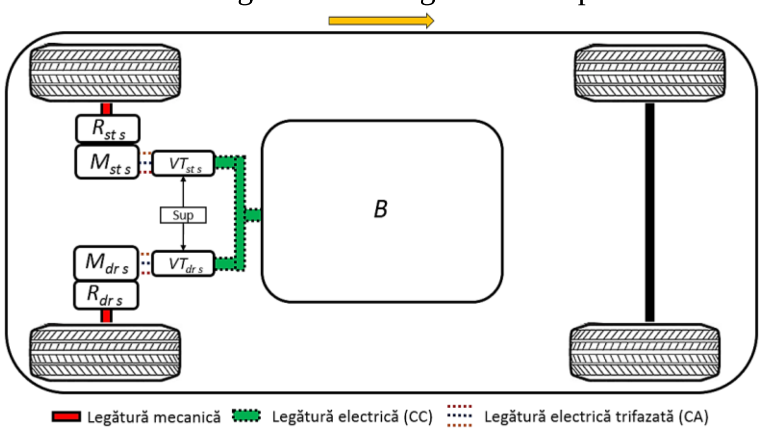


Figura 2.6. The electric vehicle organized according to the „Rear wheel drive” solution with independent drive of the drive axle wheels.

In fig. 2.9 each wheel is driven by an electric motor (Mst s and Mdr s – left/right rear) together with a reducer connected to a planetary shaft that drives each wheel (Rst s and Rdr s – left/ right rear) and of course, two speed variators (VTst s and VTdr s – rear left/right), one for each engine, powered separately from the same battery. In addition, the "Sup" component appears, which represents the supervisor, which is an electronic command and control device that allows communication between the two speed variators and to correlate their operation.

An example of such a bridge is the AVE 130 bridge manufactured by ZF that equips the Mercedes Citaro G BlueTec Hybrid bus, which can be found in figure 2.7:

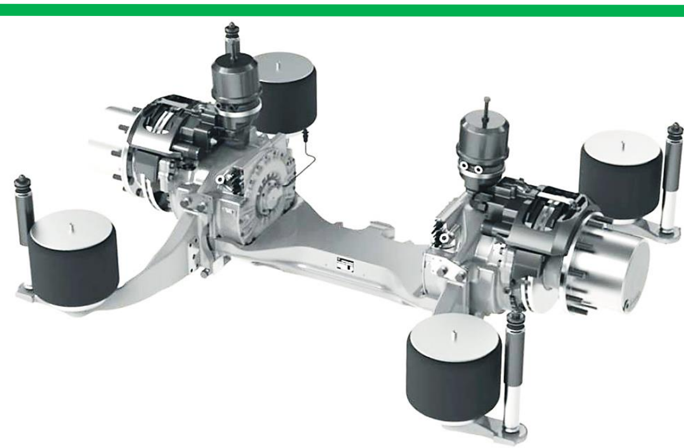


Figura 2.7. Construction of the AVE 130 bridge from ZF, [15].

It is obvious that this solution can be used to make heavy-duty multi-axle vehicles with electric and independent drive, but if we return to the area of passenger cars, such a 4x4 solution can provide extremely high traction performance and is obviously a solution used or which can be used on a certain type of luxury or "supercar" class vehicle. In figure 2.8, the principle diagram of the 4x4 organization solution with independent wheel drive is developed.

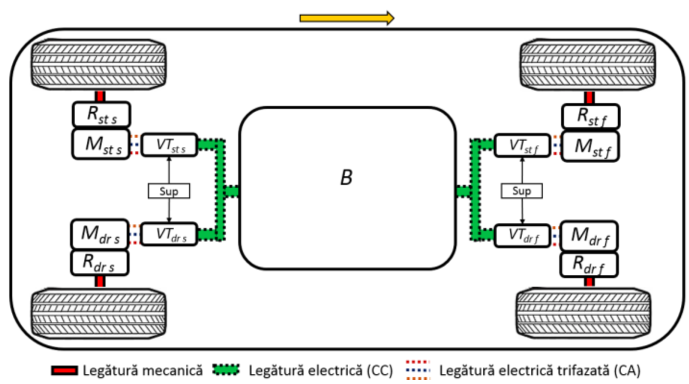


Figura 2.8. Electric vehicle organized according to the 4x4 solution with independent wheel drive.

- **„4x4” organization solution with independent rear axle wheel drive:**

This solution currently exists on the market and is actually an optimization of the electric propulsion system carried out by the major manufacturers with the aim of determining an increase in dynamic and traction performance. The principle diagram of this solution is presented in figure 2.9.

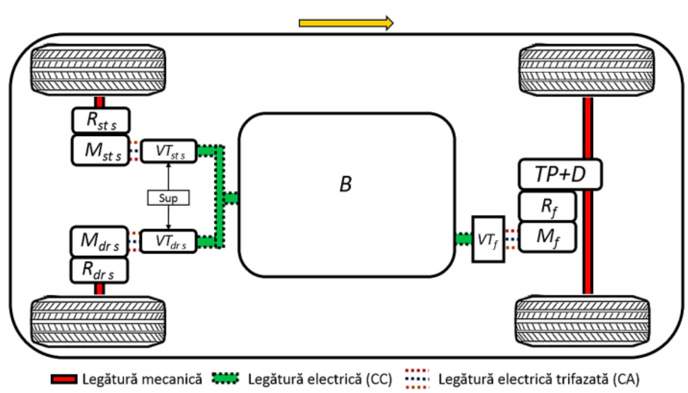


Figura 2.9. Electric vehicle with 4x4 solution with independent drive of rear axle wheels.

For this organizational solution, two vehicles existing on the market, with extremely high performance from a dynamic point of view, were analyzed, namely: the Tesla Roadster and the Audi e-Tron, with the observation that this constructive solution is also used by Tesla on the Model S with the same idea of performance optimization (see the S Plaid model with a total power of 760 kW – 1033 HP and the starting time from 0 to 100 km/h (t0-100) = 2.1 s). The Tesla Roadster model is presented in figure 2.10:

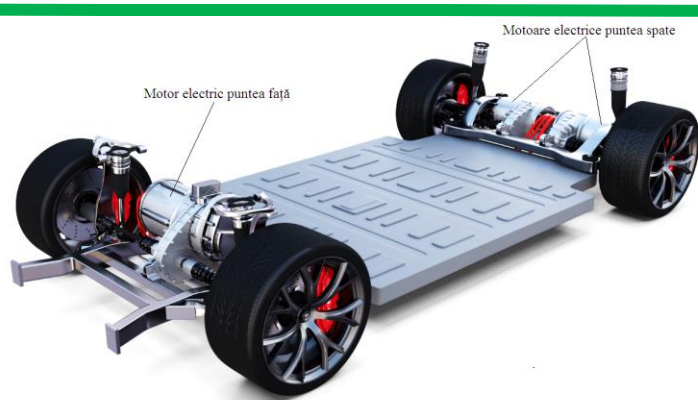


Figura 2.10. Architecture of the Tesla Roadster, [16].

❖ **<u>Solutions with independent wheel drive (with reducer in the wheel) or the "electric wheel":</u>**

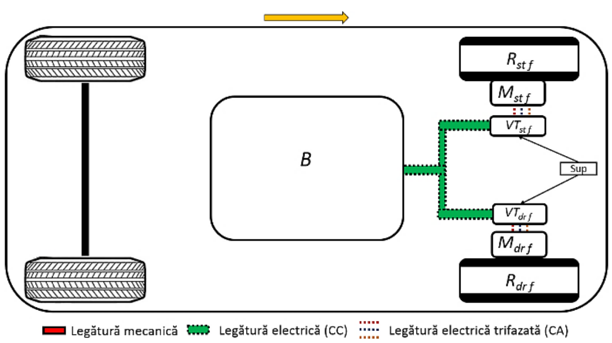


Figura 2.11. Electric vehicle with 4x2 solution with independent drive of the front axle wheels, with the reducer mounted in the wheel.

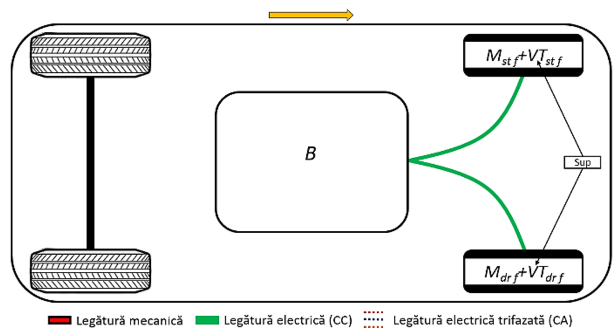


Figura 2.12. Electric vehicle with 4x2 solution with independent drive of the front axle wheels, without reducer with motor and variator mounted in the wheel – „Electric Wheel”.

The British manufacturer, which is now under Chinese patronage, Protean Electric has been intensively dealing with this constructive solution since 2013 when it announced at the SAE International Congress in Detroit the development of a special motor that can be mounted directly in the wheel that can develop in boost mode 77 kW (100 hp) and a torque of 1000 Nm, weighing about 31 kg; the constructive solution can be mounted on tires with a rim diameter between 18...24 inches, on several categories of vehicles, not only cars for personal use, but also buses, vans and trucks [20]. The constructive solution proposed by Protean Electric is presented in figure 2.13:

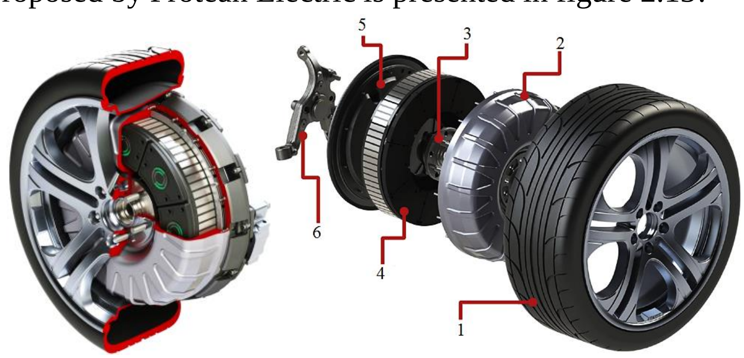


Figura 2.13. Construction of the „Electric Wheel”, [20]:
1 – Tire; 2 – Electric motor rotor; 3 – Wheel bearing; 4 – Power electronics/microinverters; 5 – Stator of the electric motor; 6 – The arm of the suspension system.

The structure of an electric truck with three axles, one of which drives:

At the end of this sub-chapter, a constructive solution of a truck is also presented, proposed and already used by VOLVO, which in 2022 announced that it will equip its entire fleet of heavy vehicles with an electric propulsion system by the end of 2024. For analysis the 26-ton VOLVO FE model was chosen, equipped with three axles, one of which is powered, the middle one. Figure 2.14 shows the basic diagram of a vehicle with the 6x2 organizational solution:

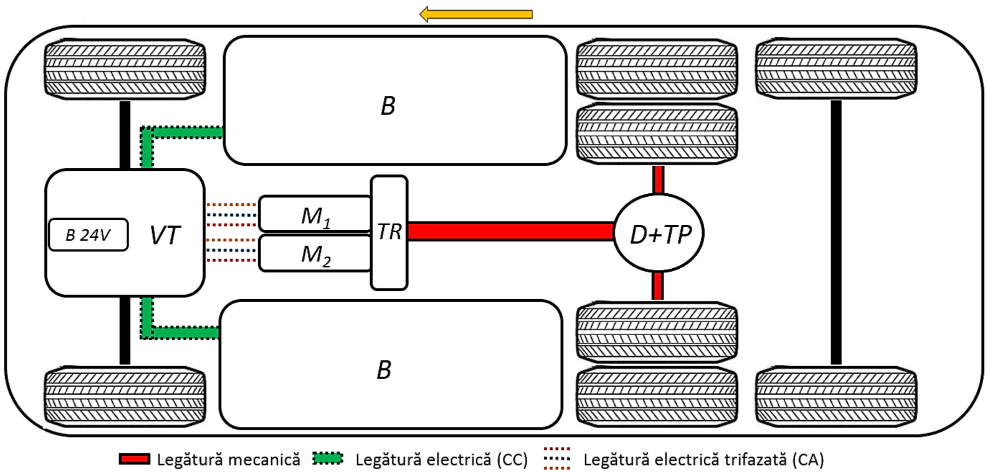


Figura 2.14. Electric vehicle with 6x2 solution.

Electric propulsion system

This subchapter follows the constructive and functional detailing of all the components that make up an electric propulsion system. Each component will be defined, classified and analyzed by presenting the principle of operation and the additional elements required for each. As established in the first chapter, in subchapter 1.5 where an electric propulsion system was compared with a conventional one equipped with a thermal engine, as well as in the first two subchapters preceding it, an electric propulsion system consists of the electric motor (one or more), the command and control unit or the speed variator, the transmission and the energy storage source together with the system that takes care of monitoring it, namely the BMS (Battery Management System).

Electric motor

Most of the time, in an electric propulsion system, the electric car works in motor mode, and for this a classification of electric motors used for traction will be presented, according to the type of working current and its construction:

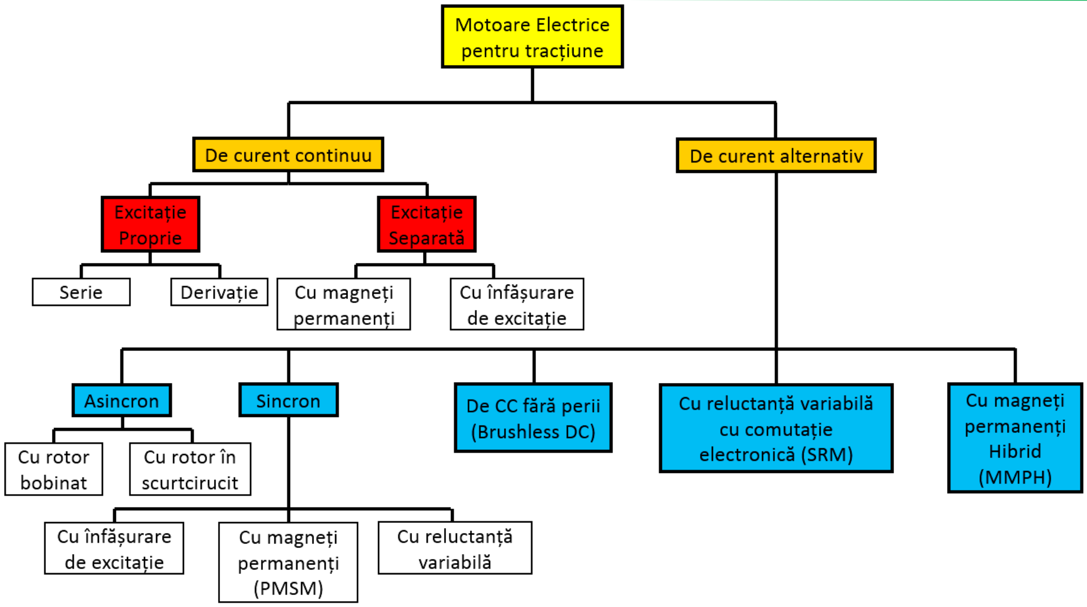


Figura 2.15. Classification of motors used in electric traction, [3].

Speed variator

The variable speed drive is an electronic command and control device that is responsible for continuously monitoring the operation of the electric motor and controlling and adjusting its speed according to the user's requirements. This device takes the direct voltage from the power source (battery) and transfers it in variable form to the power terminals of the electric motor; it also allows the engine to operate at overloads or in impulse mode for a few seconds (this mode involves increasing the performance offered by the engine by up to two times more than the nominal values - Pm and M). Figure 2.16 shows the basic structure of a speed variator:

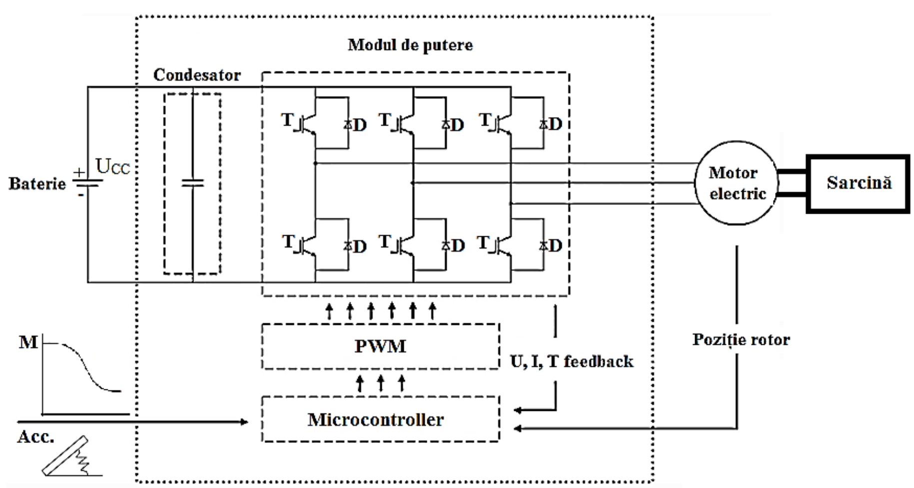


Figura 2.16. Functional diagram of a variable speed drive, [47].

Speed variator is an electronic unit consisting of the following elements:

- The engine-specific tuning system used, which uses the tuning algorithm analyzed in the previous pages – the PWM modulation technique;
- Transducers for measuring engine characteristic quantities;

- A microprocessor where all data is analyzed and processed, which communicates with the adjustment system;
- Switching device/Power electronics (inverter consisting of bipolar transistors and diodes for each winding of the electric motor);
- The high-voltage supply network from the traction battery (300...400 V d.c.) and the 12 V supply network;
- Communication with the vehicle's computer to retrieve and process the torque requirement using the CAN network;

Classification

The extremely large diversity of existing electric motors in traction, the type of supply voltage (d.c. or a.c.), as well as the field of use and application, speed variators can be classified into several categories, as follows:

Tabel 2.1. Classification of VT according to the input/output voltage and according to the field of application, [2].

$U_{intrare}$ [V]	$U_{ieșire}$ [V]	Denumire	Exemplu de aplicație
c.c.	c.c.	Chopper	• V.E.B. cu motor de c.c. • Tramvai cu motor dec.c. ($U_{intrare}$ = 750 V_{cc})
c.c	c.a.	Invertor	• V.E.B. cu m.c.a. • Tramvai cu motor de c.a. ($U_{intrare}$ = 750 V_{cc})
c.a.	c.c.	Redresor	• Locomotivă electrică cu motor de c.c. ($U_{intrare}$ = 27 kV_{cef})
c.a.	c.a.	Convertor (convertizor)	• Locomotivă electrică cu motor de c.a. ($U_{intrare}$ = 27 kV_{ef})

Transmission of an electric vehicle

According to the diagram in figure 2.17, the transmission of an electric vehicle, usually with a single reduction step, is characterized by two transmission ratios, namely iR – the transmission ratio of the reducer and i0 – the transmission ratio of the main transmission, which by multiplication gives us electric vehicle transmission ratio: iR·i0. The multiple constructive solutions of electric vehicles also generate diversity in the way the transmission is organized and positioned in relation to the electric motor and the running system, but in general, the two form a common body, and at the output, the reducer transfers the power flow through the shafts planetary gears on the wheels (cylindrical gearbox) or directly by means of a planetary gearbox mounted in the wheel.

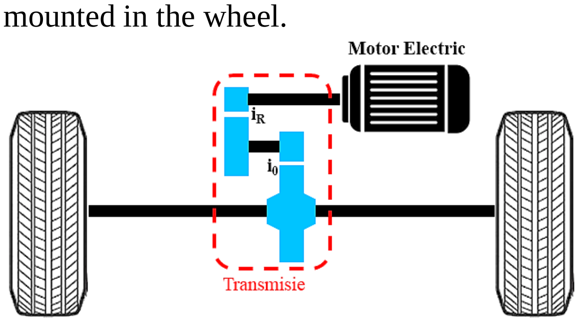


Figura 2.17. Construction of the electric vehicle transmission.

A possible constructive solution is the VW e-UP vehicle transmission detailed in figure 2.18:

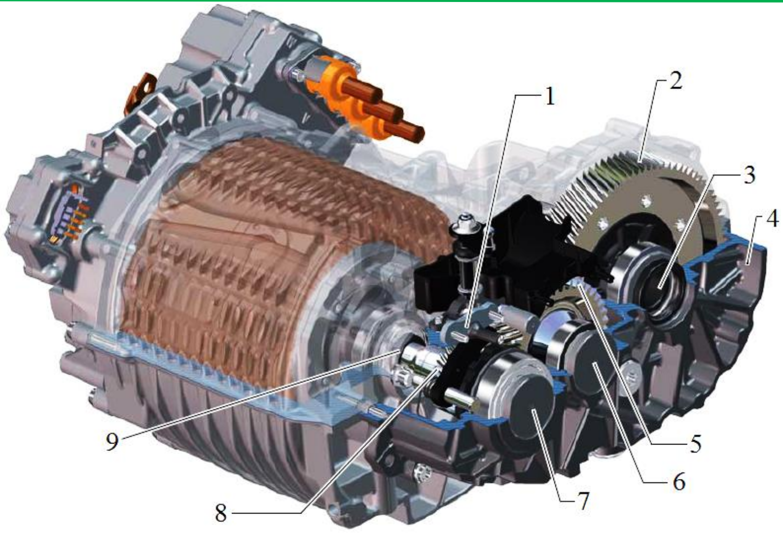


Figura 2.18. Electric motor-transmission assembly of the Volkswagen e-Up vehicle, [49]:
1 – Parking lock system (parking function); 2 – Crown of the main transmission; 3 – Differential; 4 – Transmission housing; 5 – Gear wheel; 6 – Transmission secondary shaft; 7 – Transmission primary shaft; 8 – Input pinion; 9 – Rotor shaft.

In this case, an electric vehicle that uses the planetary gear in its transmission, both for the reduction and for the differential, is the Audi e-Tron quattro. This vehicle has all-wheel drive, with a transverse motor at the front axle and a coaxial motor with the wheels at the rear axle. Each engine obviously has a single speed transmission using a planetary gear and additionally, the differential has a different construction using all the planetary gear. In the following, these constructive solutions are presented:

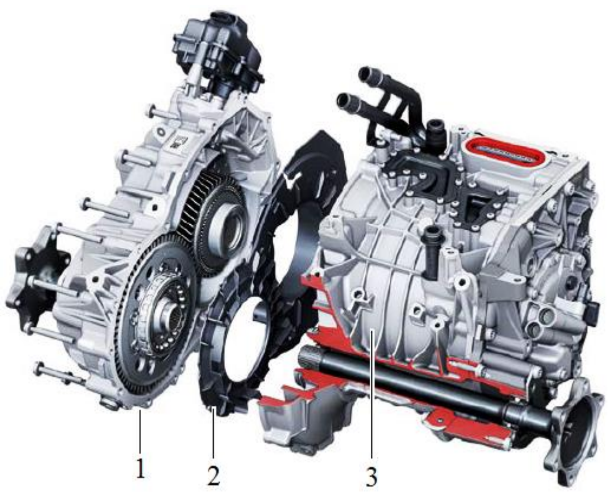


Figura 2.19.a. Electric motor transmission assembly for the front drive axle, [50]:
1 – Transmission for the front drive axle; 2 – Oil guide plate; 3 – The electric motor.

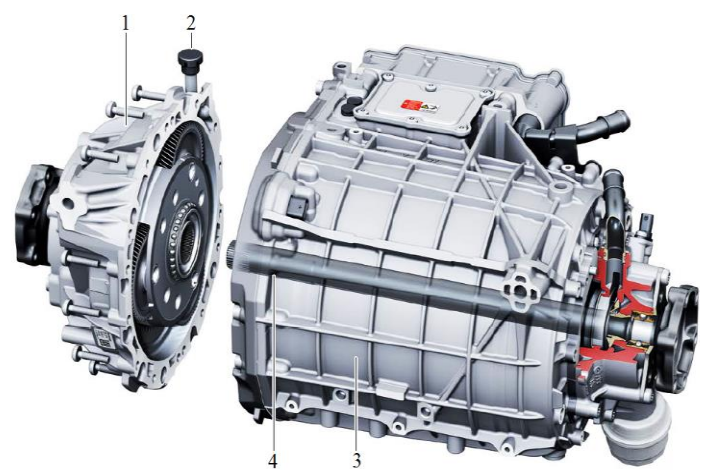


Figura 2.19.b. Electric motor transmission assembly for the rear drive axle, [50]:
1 – Transmission for the rear drive axle; 2 – Vent valve and transmission ventilation device; 3 – The electric motor; 4 – Planetary shaft with flange for driving the right wheel.

Porsche Taycan proposes a two-speed transmission solution, a solution innovated by the manufacturer and used for the rear drive axle, which generates an increase in performance. Depending on the version, this vehicle develops a total torque between 600...1000 Nm and a top speed of 260 km/h, with an acceleration time from 0 to 100 km of 2.6 s.

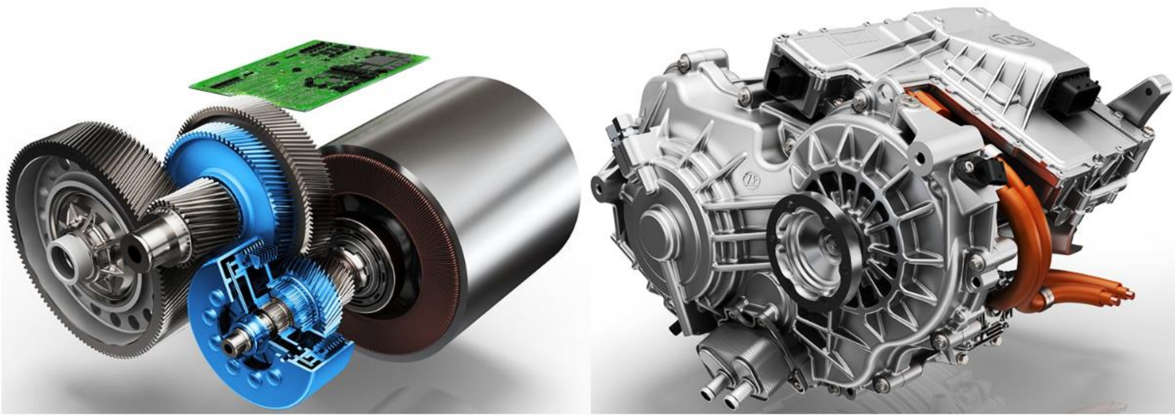


Figura 2.20. Two-speed transmission used by the Porsche Taycan, [51].

Thus, the transmission of a vehicle, although a much simplified system compared to the various types of gearboxes in conventional propulsion systems, is an extremely important sub-assembly in terms of the performance of an electric vehicle and can be a solution to improve performance of traction for certain classes of vehicles.

Sources of electrical energy storage on board the vehicle

Batteries

The main types of batteries that will be presented, depending on the storage capacity and the materials used, as well as the production cost, are: Pb batteries; Ni batteries; Na batteries and Li-ion batteries.

A. Pb battery

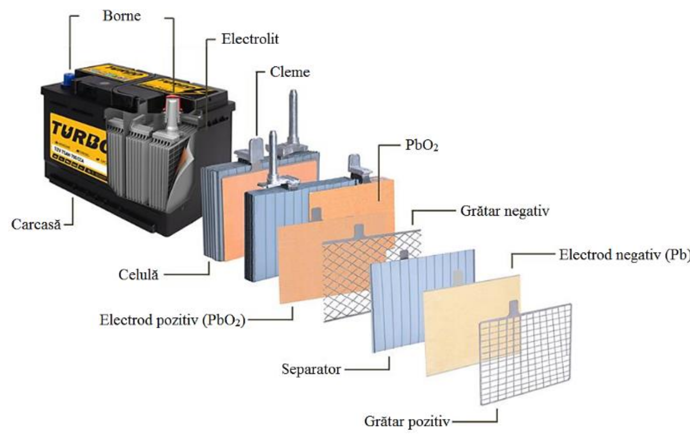


Figura 2.21. Pb battery construction, [52].

B. Ni battery

Ni batteries are another electrochemical source solution based on different chemical reactions depending on their type, with Edison's 19th century principles as the foundations of development. Compared to lead, nickel is a lighter metal and has very good electrochemical properties. Four constructive solutions of this battery are thus distinguished, namely: Ni-Fe, Ni-Zn, Ni-Cd and NiMH, the latter, nickel-metal hydride, being currently a solution used by certain manufacturers as an energy source for the system electric propulsion, the best example being Toyota, which until 2022, mainly used this type of storage source, until they later switched to the lithium-ion version.

Figures 2.22 a and b show a comparison of a Ni-Cd cell and a Ni-MH cell:

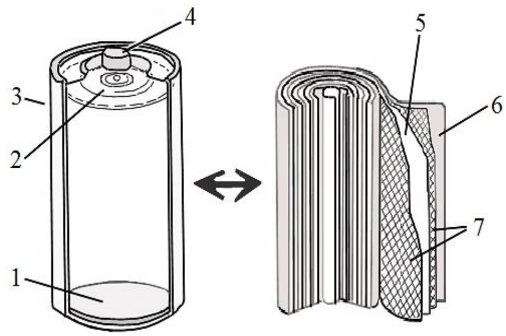


Figura 2.22.a. Ni-Cd cell, [54]:
1 – Insulating washer; 2 – Air vent; 3 – Metal casing; 4 – Cover; 5 – Anode (+) NiOOH; 6 – Cathode (-) Cd; 7 – Separator plate.

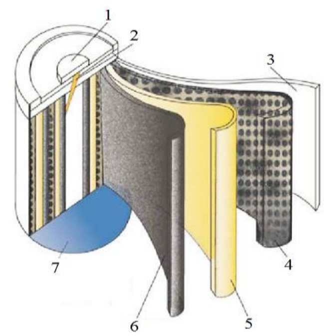


Figura 2.22.b. Ni-MH cell, [55]:
1 – Cover; 2 – Sealing gasket; 3 – Casing; 4 – Anode (+) NiOOH; 5 – Separator plate; 6 – Cathode (-) porous metal hydride; 7 – Isolation.

C. Na battery

This type of batteries is characterized by the operation at high temperatures, around 300°...350°C, which allows them to be used as storage sources for electric vehicles, but which causes a disadvantage regarding the control and monitoring of the operation at high temperatures. The main types of sodium-based batteries are: sodium-sulfur batteries and sodium-nickel chloride batteries called (Na2Sx) and ZEBRA (Zero Emissions Battery Research Association), [8].

D. Li battery

From a constructive point of view, a lithium cell can have several geometric shapes, namely: cylindrical, prismatic and envelope type. Figure 2.23 shows the construction of a cylindrical and a prismatic cell:

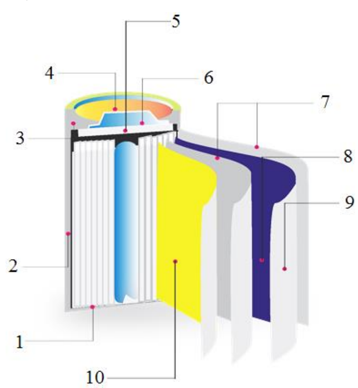


Figura 2.23.a. Cylindrical cell, [56]:
1 – Lower insulator; 2 – Casing; 3 – Sealing gasket; 4 – Upper cover; 5 – Positive terminal; 6 – Ventilation hole; 7

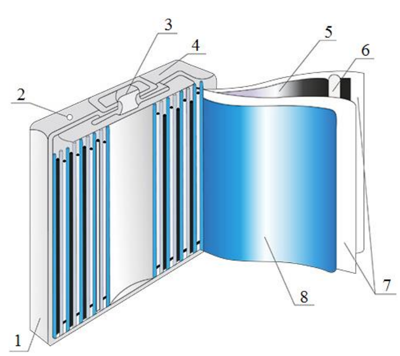


Figura 2.23.b. Prismatic cell, [57]:
1 – Housing; 2 – Ventilation hole; 3 – Positive terminal; 4 – Upper cover; 5 – Anode (+); 6 – Anode

– Separator plates; 8 – Cathode (-); 9 – Support grid; 10 – Anode (+).

support grid; 7 – Separating ceramic membrane; 8 – Cathode (-).

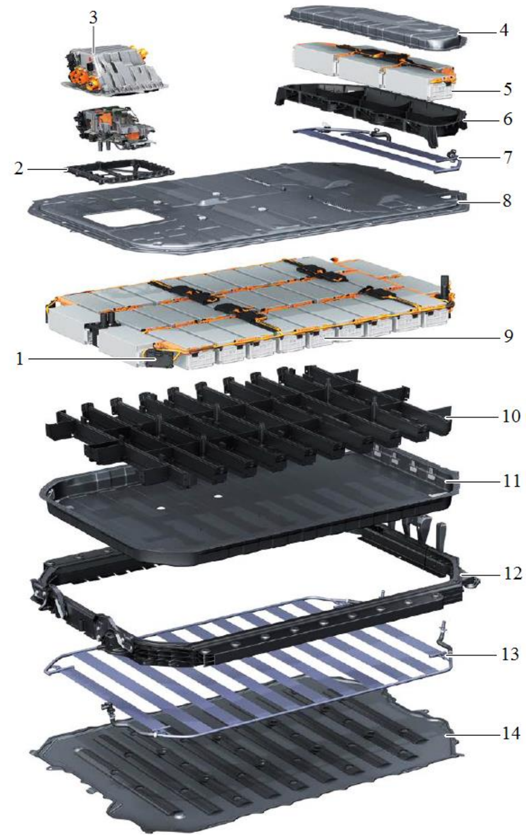


Figura 2.24. Construction of a lithium-ion battery, [50]:

1 – Battery Management System (BMS); 2 – Metal gasket; 3 – Module of terminals and high voltage contacts; 4 – Case cover; 5 – Cell module; 6 – Lower casing; 7 – Metal gasket; 8 – Cover; 9 – Cell module (12 cells/module); 10 – Support structure and compartmentalization of the modules; 11 – Support for 10; 12 – Support framework; 13 – Cooling system; 14 – Lower protection.

Lithium-ion battery control system

BMS (Battery Management System) is an electronic command and control device that constantly monitors the vehicle's high-voltage battery (lithium technologies), namely the following important parameters: state of charge and performance the reloading process; the level of gases emitted during operation; voltage value of a cell or the entire battery pack; the temperature of the battery and implicitly the way it is cooled. So the basic functions are: monitoring, determining cell/module/battery characteristic sizes, protection and optimization.

The functional diagram of a BMS in relation to all outputs and inputs and respectively monitored quantities is shown in figure 2.25:

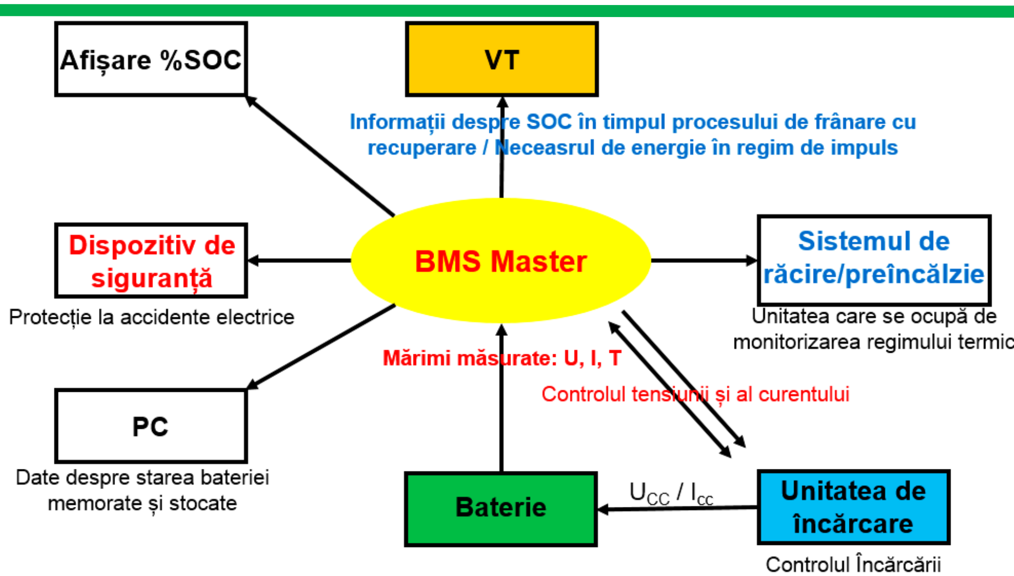
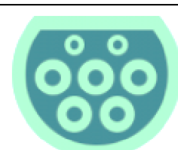
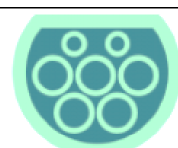
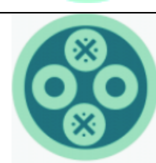


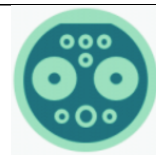
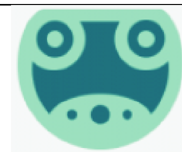
Figura 2.25. Functional diagram of a BMS.

Lithium-ion battery charging systems

Considering the classification of charging stations, there is obviously also a diversity at the level of connectors/plugs between the vehicle and the station. Table 2.2 shows the main types of connectors available on the world market for charging electric vehicles:

Tabelul 2.2. Types of connectors used for charging electric vehicles, [61].

Station type	Name and Use	Symbol	Description
AC	J1772 (type 1) - Japonia și America de Nord		It consists of 3 connectors for the three power phases and 2 connectors that ensure optimal connection and communication between the vehicle and the station. Parameters: U=240 V/Pmax=7.68 kW
	Mennekes (type 2) - Europa		It is the most common type of connector in Europe and has the largest use among electric vehicles. It can be used for single-phase and three-phase networks. Parameters: U=400 V/Pmax=12.8 kW
	GB/T - China		By the "Guobiao" standard, this station is actually the opposite of the Type2 variant in terms of construction. Parameters: U=380 V/Pmax=12.16 kW
DC	CHAdeMO - Japonia		Communication with the vehicle is done through the CAN network. Parameters: U=500V/Pmax=200 kW
	CCS1 – America de Nord		"Combined Charging System" - Type 1 model that also allows direct current charging. Parameters: U=600V/Pmax=75 kW

	CCS2 - Europa		"Combined Charging System" - Type 1 model that also allows direct current charging. Parameters: U=1000V/Pmax=200 kW
	GB/T - China		The Chinese solution to DC charging. Parameters: U=750V/Pmax=187.5 kW
Tesla	Tesla – în toată lumea		The Chinese solution to DC charging. Parameters: U=480V/Pmax=140 kW

Based on the types of charging stations and existing connectors, three charging levels of electric vehicles are defined:

1. Level 1 (Slow) – 1...1.8 kW
2. Level 2 (Fast) – 3...22 kW
3. Level 3 (Ultra-fast) – 15...350+ kW

Supercapacitors (SUPERCAP)

Another energy source that can be used as an alternative option by an electric propulsion system are supercapacitors/supercapacitors (SUPERCAP). The principle diagram of a hybrid-electric vehicle equipped with supercapacitors can be found in figure 2.26:

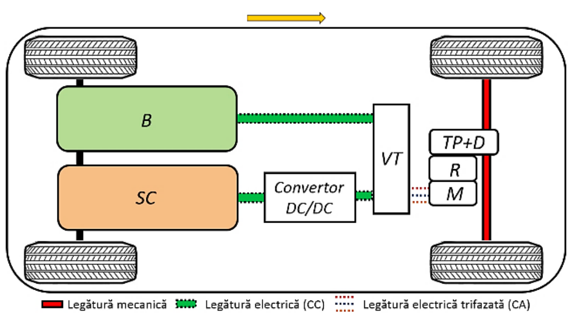


Figura 2.26. The architecture of a vehicle equipped with a supercapacitor battery.

Fuel cells

The trends of the last 20 years regarding the use of alternative fuel solutions to reduce global pollution have generated over time in the transport industry and automotive engineering an extensive process of research and development in several directions of interest; one of these directions consists in the development of fuel cells and their use as energy sources that can feed the propulsion system of a motor vehicle with a very high efficiency and also reducing pollution to zero.

Depending on the organizational solution of the Mirai model, a principle diagram was created that includes all the components of the electric propulsion system:

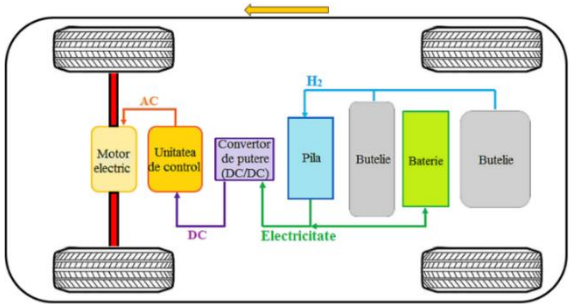


Figura 2.27. General architecture of an electric vehicle equipped with a fuel cell, [67].

Other modern energy sources for electric vehicles

Considering the accelerated development process and wider trends regarding the spread of electric vehicles, the industry is preparing new, innovative and highly efficient solutions regarding sources that can become alternatives to lithium batteries, which are characterized by performance high, but nevertheless also involve certain compromises when it comes to costs, manufacturing and recycling, sensitivity and the need for a complex monitoring and control system. Thus, in addition to the solutions presented: supercapacitors and fuel cells, there are more and more rumors and ideas related to certain energy sources that would increase the autonomy so that it no longer constitutes a disadvantage of electric vehicles. Some of these modern sources are mentioned below: photovoltaic cells, salt-water battery or the nuclear miroreactor.

Operating modes of an electric vehicle

After establishing the functional characteristics of each component that makes up an electric vehicle, its behavior during operation in the two fundamental regimes will be analyzed, namely:

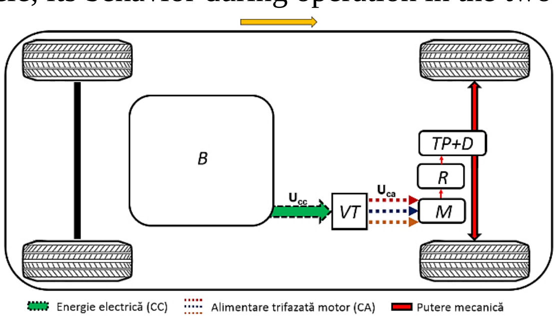


Figura 2.28. The path of the power flow in the traction regime of an electric vehicle.

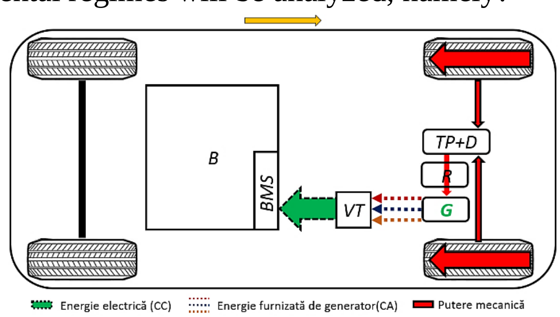


Figura 2.29. The path of the power flow in the braking regime of an electric vehicle.

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CHAPTER III. NUMERICAL MODELING AND SIMULATION OF AN ELECTRIC VEHICLE

Development of the model used for simulation

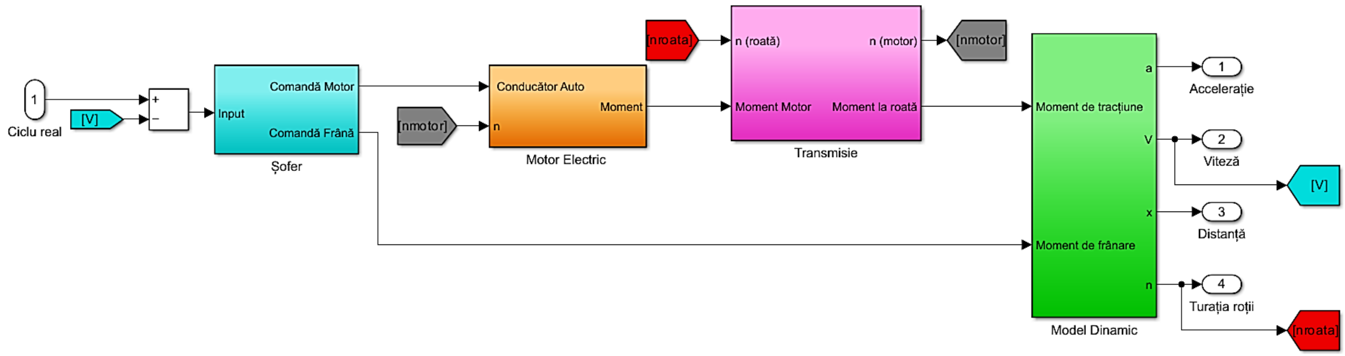

Figura 3.1. *„Electric vehicle” system.*

To simplify the final structure of the vehicle model, the assembly in figure 3.1 was reduced to a subsystem with one input and 4 outputs (figure 3.2). To this subsystem will be added other branches necessary to determine the performances of interest within the work, branches that will be built using mathematical operations implemented using already existing blocks that will help to fully model and simulate the electric vehicle used, taking into account all factors internal or external that can influence the results.

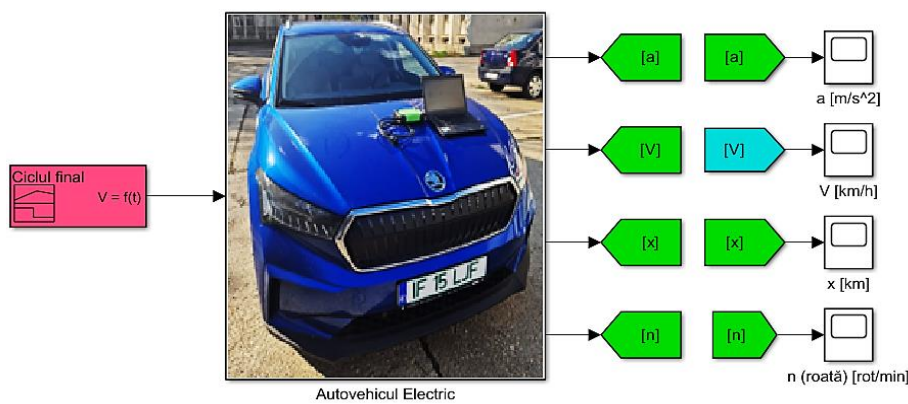

Figura 3.3. Final model of the electric vehicle.

Numerical simulation of an electric vehicle in real driving conditions

This subchapter aims to finalize the simulation model developed by analyzing the performance of an electric SUV type vehicle in real driving conditions. For this, the model required some modifications so that it could provide the necessary information related to the performance and behavior of the main components that make up the electric propulsion system.

The implementation of real cycle data was a limitation of using a „RepeatingSequence” block because the data package used consisted of a very large number of time and speed values, and this made it impossible to import data with the initial block chosen. Thus, for the actual run cycle, a „SignalBuilder” block was used, which has no limitations related to the number of entered values and allows the import of the signal as an .xlsx file where the data must be placed in consecutive columns, and each „sheet” must be private and contain only one quantity as a function of time.

Figure 3.4 shows the working interface of the „SignalBuilder” block and the cycle obtained by transferring the data package from Excel to Simulink:

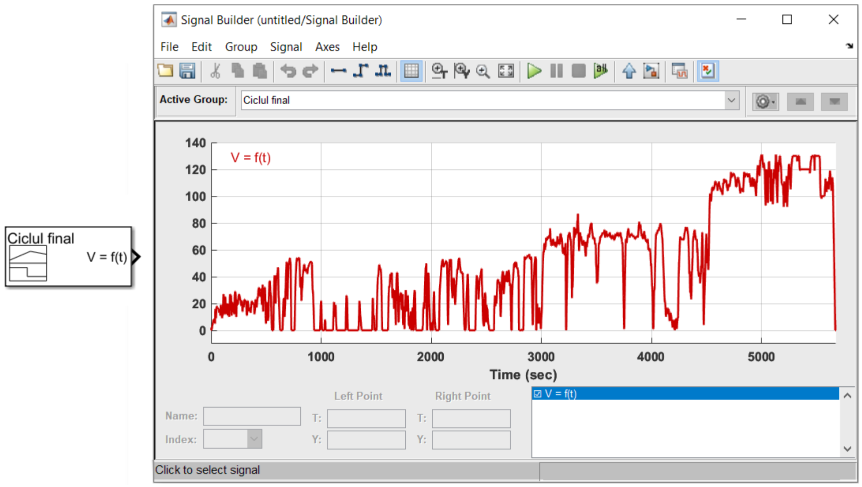

Figura 3.4. Implementation of the real cycle in the developed simulation model.

<u>Results obtained by simulation:</u>

By using the model developed for the simulation on the real cycle considered, the speed profile was extracted to check and identify the minimum and maximum deviation in relation to the reference profile - measured. Figure 3.5 shows the profile resulting from the simulation:

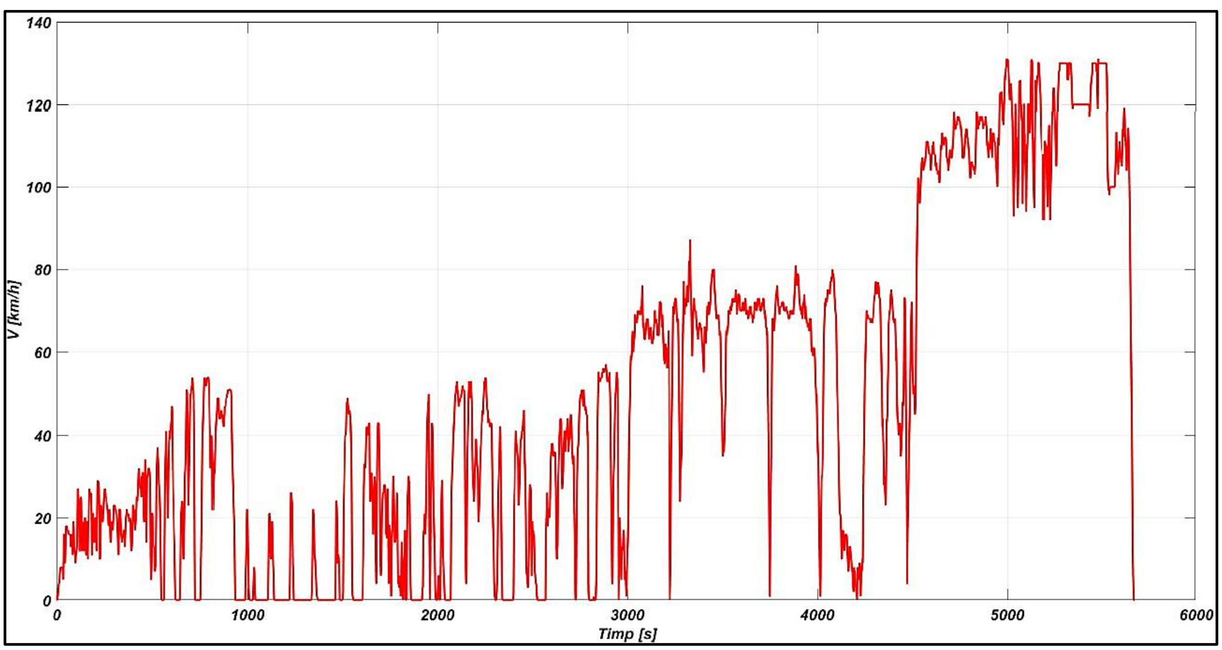

Figura 3.5. Vehicle speed resulting from the simulation.

Also, the state of charge of the battery was extracted from the simulation, which during the cycle decreased from 100% to 82.31%, which means a discharge of 17.69% for the 77 km traveled. The variation of the state of charge is shown in figure 3.6:

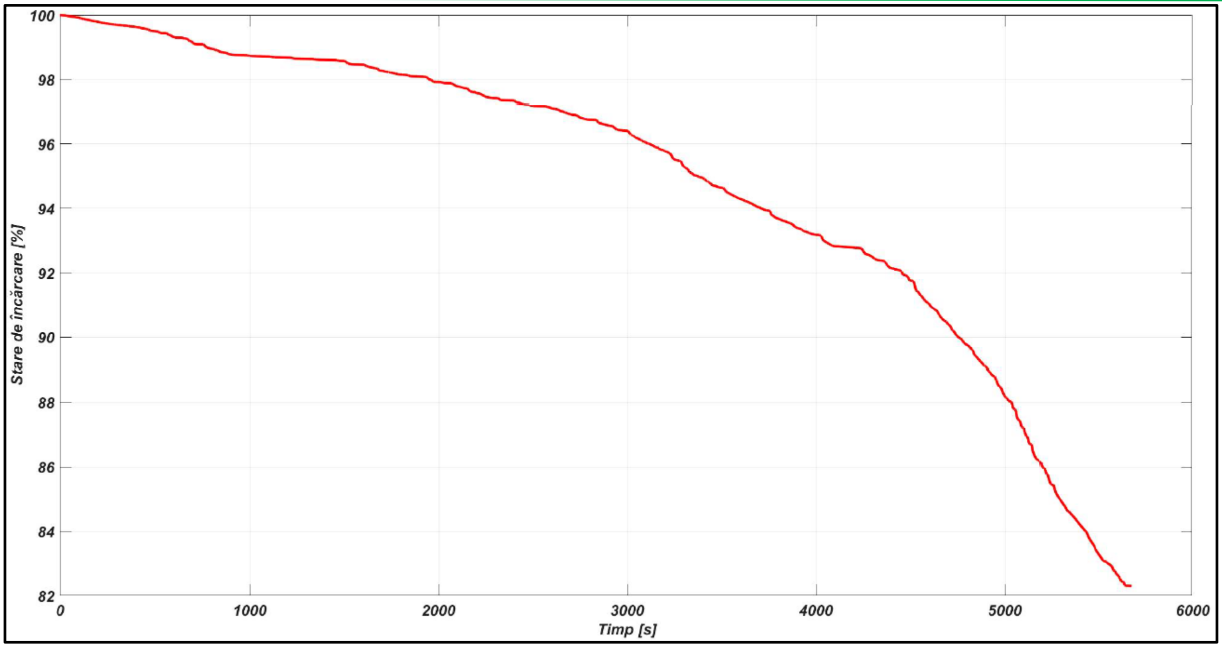

Figura 3.6. SOC of the battery resulting from the simulation.

As previously explained through figure 3.5, it was determined by simulation using the mathematical operation of integrating the power over time and the total energy consumed from the battery during the driving cycle, a variation that also takes into account the energy consumed by the active auxiliary systems during the cycle, present in figure 3.7 and the energy consumption shown in figure 3.8:

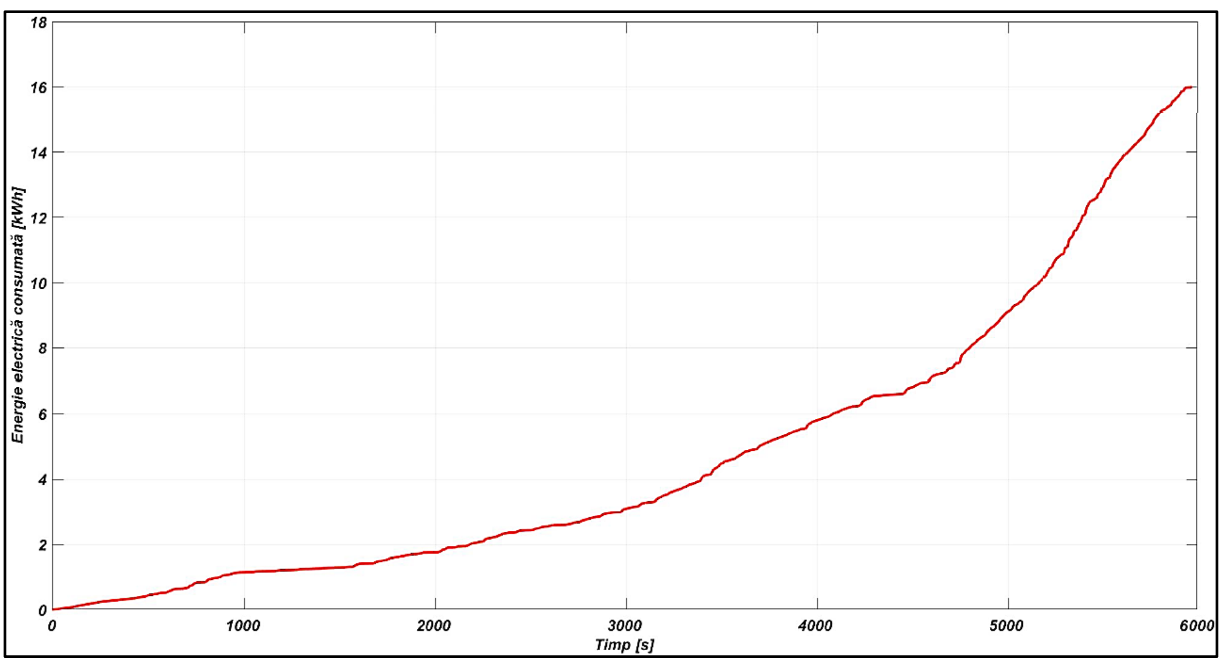

Figura 3.7. Total energy consumed resulting from the simulation.

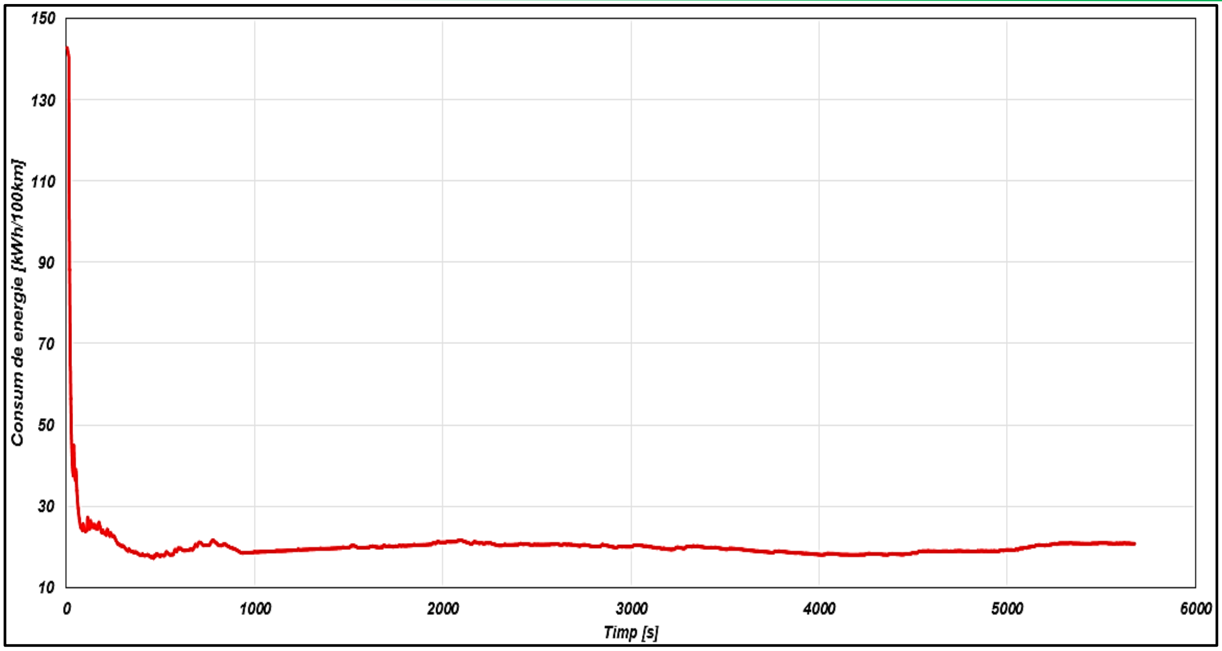

Figura 3.8. Energy consumption resulting from the simulation.

Determining the autonomy of the vehicle:

To determine the autonomy of the vehicle on the proposed real cycle, the simplest way is to implement a condition whereby the model operates until the battery discharges to the value at which recharging becomes necessary. As a rule, the BMS system allows the operation of the traction battery up to a state of charge of 20% and, in general, this value is specific to lithium batteries because if it is discharged below 20%, the charging process becomes complicated, there is a risk of cell imbalances which which can cause their irreparable damage, [3]. Thus, the imposed condition consisted of the „Load State” signal connected to a „Compare To Constant” operator and a „Stop Simulation” block. In this way, the comparison operator checks the state of charge values in real time during the simulation, and when it reaches the value of 20%, the „Stop Simulation” block comes into operation, which stops the simulation.

Obviously, the time set for such a simulation is very long, in the case of the simulation on the real cycle, a time of 40000 seconds was set. Once the value of 20% of the state of charge is reached and the simulation is stopped, the value of the distance traveled is obtained which actually represents the autonomy of the modeled and simulated vehicle in relation to the considered cycle. In the case of the simulation on the considered real cycle, the resulting autonomy was ~ 374 km.

Study of the dynamic and energetic performances of an electric SUV driving a standardized test cycle using the simulation model

For this sub-chapter, an analysis of the performance of the reference vehicle is proposed through which the experimental measurements were made and the actual driving cycle was developed using the two main standardized test cycles for the determination of fuel consumption and pollutant emissions, in the case of conventionally equipped vehicles with a thermal engine and with a hybrid-electric propulsion system, respectively for determining the energy consumption and autonomy of electric vehicles. The two cycles are:

- WLTC (Worldwide Harmonized Light Vehicles Test Cycle)
- NEDC (New European Driving Cycle)

Basically, NEDC is the predecessor of WLTC in terms of approval procedures for light vehicles. In 2017-2019, the transition was made from the European homologation cycle to WLTC, which can be and is used worldwide today. The new cycle is more advantageous from the point of view of driving style, being characterized by strong and frequent accelerations, followed by short braking, which causes the new procedure to be much closer to real driving conditions. Table 3.1 shows a comparison between the two cycles:

Tabel 3.1. Comparison between NEDC și WLTC, [7].

	NEDC	**WLTC**
Distanță [km]	~11	~23,3
Durată [s]	1180	1800
Faze	2	4
Viteza maximă [km/h]	120	131,1
Viteze medie [km/h]	33,6	46,5
Accelerație maximă [m/s^2]	~ 1	~ 1,7

The reference vehicle used in the simulation model developed in the first part of this chapter has a specific power of ~ 72.3 W/kg, so it falls into Class 3, and from the point of view of travel speed, in Class 3b having a maximum speed of 160 km/h. Figure 3.9 shows a comparison of the two cycles:

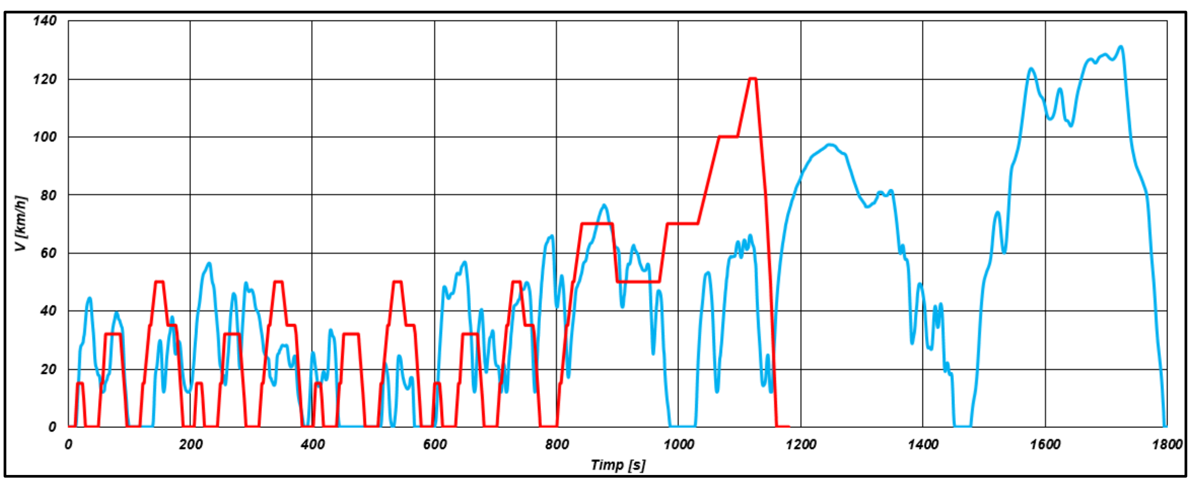

Figura 3.9. Comparison between profiles NEDC – WLTC.

For the study proposed in this subsection, it was necessary to implement the two speed profiles of the cycles in the simulation model. The set of values being much narrower, the „RepeatingSequence” block allowed profiles to be imported from the .xlsx file into Simulink. For WLTC the dataset was extracted from [8], and for NEDC using data from [7].

The comparative study of the results obtained:

In this case, the comparative analysis of the results obtained from the simulations on the two considered cycles is followed, respectively in relation to the information provided by the official websites or by the manufacturer regarding the reference values indicated by them for the two cycles. Figure 3.51 compares the variation of simulated energy consumption on the two cycles:

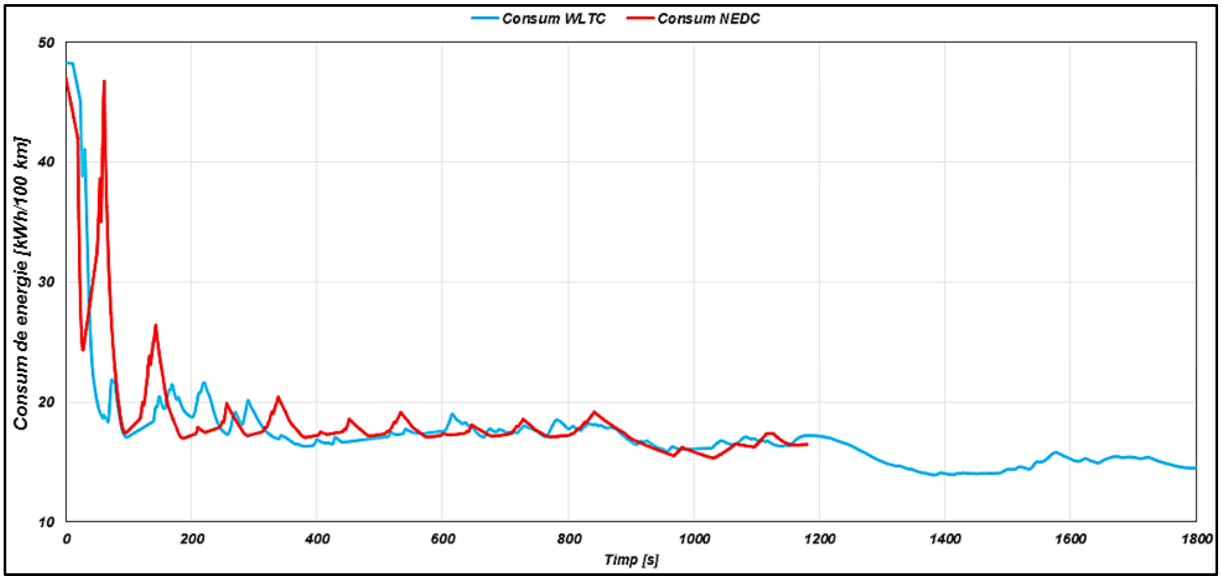

Figura 3.10. Energy consumption from the simulation – comparison between NEDC and WLTC.

The comparison of the results obtained by simulation for the two cycles will be presented in table 3.2:

Tabel 3.2. Comparison of simulation results for NEDC and WLTC cycles.

	NEDC	***WLTC***
Abatere viteză [km/h]	***+0,112/-0,09***	***+0,015/-0,021***
Turație maximă [rot/min]	***~11635***	***~12720***
Accelerație maximă [m/s^2]	***1,694***	***1,189***
Stare de încărcare [%]	***97,82***	***95,95***
Energie totală consumată [kWh]	***1,82***	***3,36***
Energie consumată – sisteme auxiliare [kWh]	***0,23***	***0,35***
Consum de energie [kWh/100 km]	***16,45***	***14,49***
Autonomie [km]	***389***	***512***

Taking into account the information provided by the manufacturer [6, 9] regarding energy consumption and autonomy, table 3.3 presents the comparison between the results obtained by simulation and the real values:

Tabel 3.3. Comparison between simulation results and values for NEDC and WLTC cycles.

	Simulat		***Real***			***Eroare***		
	NEDC	***WLTC***	***NEDC***	***WLTC, [6]***	***WLTC, [9]***	***NEDC***	***WLTC, [6]***	***WLTC, [9]***
Consum de energie [kWh/100 km]	***16,45***	***14,49***	***15,8***	***15,2***	***14,1…15,3***	***4,12%***	***4,67%***	***2,77…5,3%***
Autonomie [km]	***389***	***512***	***-***	***537***	***502...548***	***-***	***4,65%***	***1,99...6,56%***

Study of the influence of two-speed transmission on the performance of an electric utility vehicle using the simulation model

For the two-speed transmission model, a „Switch” type block has been added to allow switching between the two values of the transmission ratio, thus basically commanding the change of gears. In order to command the gear change, it was necessary to determine the value of the speed at which the change between the two gears should take place. In this sense, a series of simulations of the starting performance of the chosen vehicle were carried out using the basic model equipped with the single-speed transmission in which the two calculated values of the transmission ratios were implemented in turn, after which the signals results were extracted using the „ToWorkspace” command and processed in excel, so that the acceleration variation was obtained according to the travel speed, for it1 and it2, and the two graphs were superimposed so as to determine the first point of intersection of the two accelerations from which the speed of 35 km/h was identified, a value that will represent the point of exchange of the two gears.

The graph for determining the gear change speed is presented in figure 3.11:

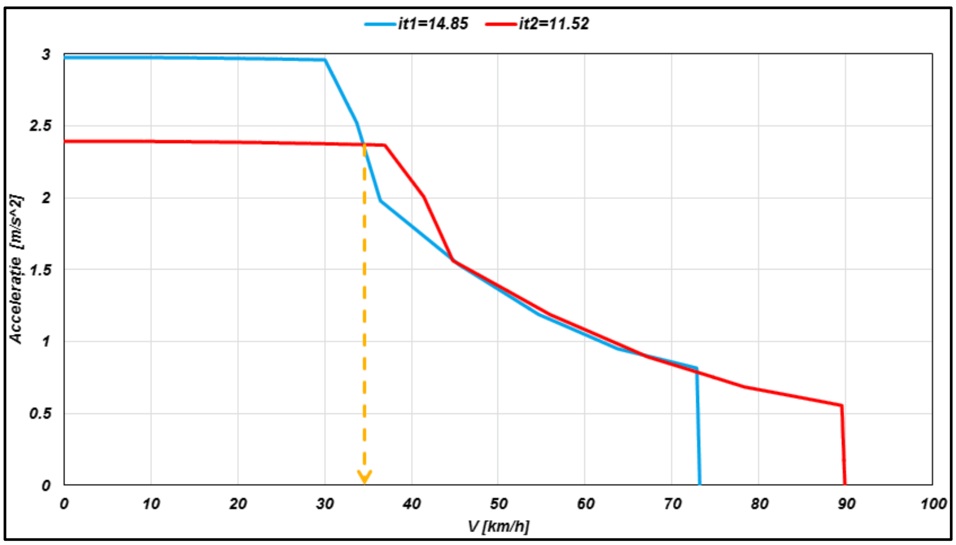

Figura 3.11. Variation of acceleration for it_1 and it_2.

Once these conditions were established, it was implemented in the two-stage transmission model (figure 3.12).

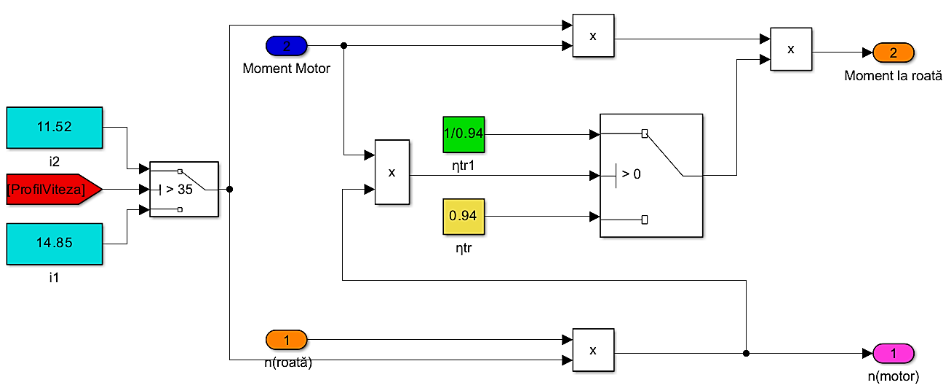

Figura 3.12. Two-speed transmission model.

The „Switch” block analyzes the reference signal represented by the speed profile of the driving cycle to which the model is subjected, and at the moment when the driving speed exceeds the value of 35 km/h, the block changes the gear going from it1 to it2 and obviously the phenomenon also happens in the opposite direction, when the speed on the cycle is equal or falls below the reference value, it changes to 1st gear.

The „RepeatingSequence” block was also used to implement the two portions of the standardized cycles, while the „SignalBuilder” block was used for the two phases of the real cycle. In terms of model baselines, 1 s step was used for the standardized cycles, with a duration of 1022 s for WLTC (end of medium phase, [8]) and 1054 s for NEDC. In the case of the real cycle, the step was set to 0.7 s according to the measurement period with which the cycle was obtained, and the duration of 4516 s representing the moment of finishing the part of the extra-urban cycle and entering the highway. The solver used was still „ode45Dormand-Prince” along with the „powergui” block that sets the simulation type and parameters, the option set being „Continuous”.

The results obtained for the three portions of the chosen cycles will be presented graphically and tabularly, the quantities of interest being: the energy consumed per cycle, the specific consumption, the state of charge, the autonomy and the degree of use of the two steps implemented.

Comparative analysis of the results obtained for the three driving cycles (real, WLTC, NEDC):

This part of the thesis aims at the detailed presentation of the results obtained from the simulations in order to be able to identify the main advantages of using the two-speed transmission on the chosen vehicle and not only, as well as identifying the limitations that can influence the experimental results obtained through the simulation. Table 3.5 summarizes the results obtained for the three cycles, in the case of the one-speed transmission and in the case of the two-speed transmission.

Tabel 3.4. Results obtained regarding the performance of the vehicle in relation to the three considered cycles.

	1-speed			2-speed		
	Real cycle	WLTC	NEDC	Real cycle	WLTC	NEDC
SOC [%]	***79,78***	***96,11***	***96,68***	***80***	***96,18***	***96,73***
Total energy [kWh]	***8***	***1,57***	***1,372***	***7,924***	***1,55***	***1,356***
Energy consumed – aux. systems [kWh]	***0,76***	***0,18***	***0,18***	***0,76***	***0,18***	***0,18***
Energy consumption [kWh/100 km]	***19,57***	***20,13***	***16,41***	***19,34***	***19,81***	***16,61***
Distance [km]	***40,92***	***7,82***	***8,3***	***40,92***	***7,82***	***8,3***
Autonomy [km]	***162***	***161***	***199***	***164***	***164***	***201***

Based on table 3.4, the resulting differences between the two cases could also be calculated to clearly observe and underline the gain of implementing the two-speed transmission. It can also be seen that the distance traveled and the energy consumed by the auxiliary systems are not influenced in any way by the transmission change. Table 3.5 shows the resulting differences:

Tabel 3.5. Comparative analysis of the obtained results.

	Max. error [%]		
	Real cycle	WLTC	NEDC
SOC [%]	***0,27***	***0,07***	***0,05***
Total energy [kWh]	***0,95***	***1,27***	***1,17***
Energy consumption [kWh/100 km]	***1,18***	***1,6***	***1,22***
Autonomy [km]	***1,24***	***1,86***	***1***

A very important aspect that must be emphasized in this study is the degree of use of each step for each speed profile used, thus the values from the model were exported in excel to be able to use the counting function "COUNTIF" through which it was possible track and later calculate, as a percentage, the degree of use of the two steps (in table 3.6).

Tabel 3.6. Degree of use of the two steps compared for the three considered cycles.

	First gear (i_{t1}=14,85)	*Second gear (i_{t2}=11,52)*	*Total*
Real cycle	*53%*	*46%*	*100 %*
WLTC	*62,5%*	*37,5%*	
NEDC	*68,2%*	*31,8%*	

It can be seen from the table above that gear I was predominantly used, with a percentage of over 50%, which is obviously validated by the fact that the cycle portions chosen are characterized by low travel speeds, predominantly below the reference value of 35 km/h , so it was identified following the study, the main advantage of the implementation of the two-speed transmission related to the start-up performance that can be presented by the variation of acceleration over time, which experienced a significant increase in the maximum value with the use of two speeds, obviously value influenced by the transmission ratio in the first stage compared to the standard case (figure 3.13).

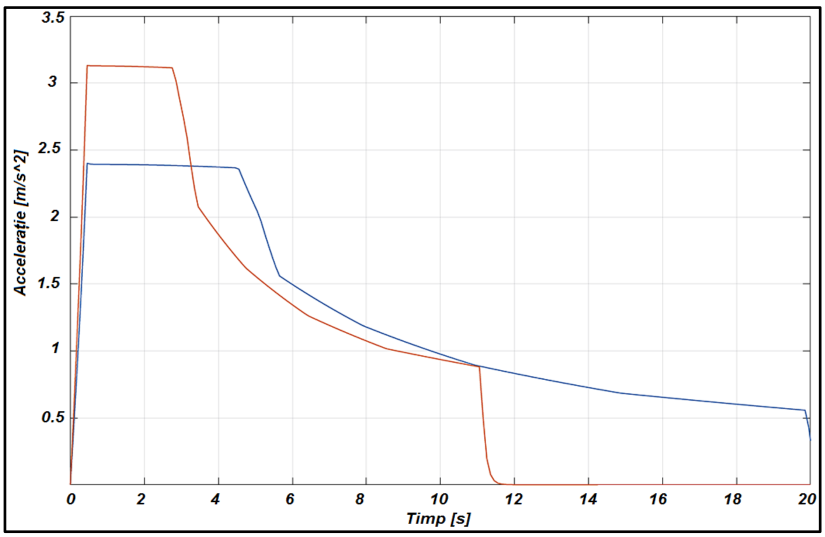

Figura 3.13. Variation of acceleration for one gear (blue line) and two gears (red line), [10].

Analyzing the accelerations, it can be seen that for the single-speed transmission, the maximum acceleration was 2.4 m/s2, and for two-speed it was 3.1 m/s2, which means an increase of 0.7 m/ s2 respectively 22.6%. The values were obtained for an acceleration from 0 to 90 km/h, with a simulation duration set to 30 s, resulting in a start time of 20 s for the first case and ~11.5 s for the second case which means by implementing the two-speed transmission, starting performance has improved considerably.

It can therefore be concluded that for the vehicle chosen in the study it is preferable to use a two-speed transmission considering that the average speed with which it moves is below 50 km/h, and the need to increase the starting performance by increasing the maximum acceleration, therefore implicitly and through the use of maximum torque, it is an important advantage especially in the case of a vehicle intended for the transport of goods.

Solutions for optimizing the performance of electric vehicles using the simulation model

For this study, using the simulation model along with the dynamic and energy characteristics of the reference vehicle, a series of researches were carried out on how certain quantities or coefficients can influence the energy performance of the vehicle. The influences are studied and determined using the proposed real cycle, in accordance with the initial conditions imposed and the simplifying assumptions considered from the beginning of the modeling and simulation using the variation of the quantities considered in different intervals.

The parameters analyzed were the following: rolling resistance coefficient f, vehicle mass ma, [kg] and ambient temperature t, [°C].

The coefficient of rolling resistance

Following the simulations related to each value of f0, the following were determined: the energy consumed per cycle, the specific energy consumption, the state of charge of the battery and the autonomy of the reference vehicle when running on the real cycle as shown in table 3.7:

Tabel 3.7. Variation of the energy performance of the reference vehicle in relation to the variation of f0.

No.	f_0 [-]	f [-]	Energy [kWh]	Energy consumption [kWh/100km]	SOC [%]		Autonomy [km]
					Final	Down	
1	**0,005**	0,005…0,0102	14,13	18,36	84,36	15,64	427
2	**0,006**	0,006…0,0112	14,5	18,83	83,96	16,04	415
3	**0,007**	0,007…0,0122	14,87	19,31	83,55	16,45	404
4	**0,008**	0,008…0,0132	15,24	19,79	83,14	16,86	393
5	**0,009**	0,009…0,0142	15,61	20,28	82,72	17,28	383
6	**0,01**	0,01…0,0152	15,99	20,76	82,31	17,69	374
7	**0,011**	0,011…0,0162	16,36	21,25	81,9	18,1	364
8	**0,012**	0,012…0,0172	16,74	21,74	81,48	18,52	356
9	**0,013**	0,013…0,0182	17,11	22,23	81,07	18,93	347
10	**0,014**	0,014…0,0192	17,49	22,71	80,65	19,35	339
11	**0,015**	0,015…0,0202	17,87	23,2	80,23	19,77	332

Table 3.7 shows that with the increase in f, both the electricity and the specific consumption acquire a linear increasing trend, and for the global interval obtained from figure 3.64, namely 0.005...0.02, a variation of the consumption was obtained between 18.36...23.2 kWh/100 km, and the energy contained in the range 14.13...17.87 kWh. The state of charge resulting from the real cycle simulations varied in the range of 84.36...80.23% with an average reduction of 17.7% and a range of 15.64...19.77%.

The range of autonomy obtained is between 332...427 km, so a global reduction of 95 km between a minimum coefficient of 0.005 and the maximum obtained of 0.02.

Vehicle mass

Table 3.8 recorded the results obtained from the simulations by changing the mass of the vehicle under the conditions of the proposed real cycle:

Tabel 3.8. Variația performanțelor energetice ale autovehiculului de referință în raport cu masa.

No.	$m_{simulare}$ [kg]		Energy [kWh]	Energy consumption [kWh/100km]	SOC [%]		Autonomy [km]
	Formula	Value			Final	Down	
1	m_0+75	2150	15,18	19,71	83,21	16,79	395
2	$m_0+75+75$	2225	15,53	20,16	82,82	17,18	385
3	$m_0+75+2*75$	2300	15,87	20,61	82,47	17,53	377
4	**Masa de încercare**	**2325**	15,99	20,76	82,31	17,69	374
5	$m_0+75+3*75$	2375	16,22	21,06	82,05	17,95	368
6	$m_0+75+4*75$	2450	16,57	21,51	81,67	18,33	360
7	m_0+m_{un}	2540	16,98	22,02	81,21	18,79	350

This resulted in a variation in energy between 15.18...16.98 kWh, limit values corresponding to the minimum mass in driving conditions (own mass + driver's mass) and the maximum mass corresponding to the total mass of the vehicle according to the manufacturer, so the energy consumed per cycle the proposed real increases globally by 1.8 kWh with the progressive increase in mass. The energy consumption obtained varies between 19.71...22.02 kWh/100 km, so a global increase of 2.31 kWh/100 km. The state of charge has decreased from the initial value of 100% by 16.79...18.79%, so a global reduction in relation to the mass variation of 2%.

The range decreases from 395 km when ma is equal to 2150 kg to 350 km when the maximum value according to the manufacturer is reached.

Ambient temperature

To carry out the tests, the WLTC cycle according to the work [15] was used, together with the real cycle obtained experimentally. For this type of simulation, the stopping times were set to 1800 s for the WLTC and 5676 s for the real cycle, but according to the suggestions of the examples in Simulink for this type of tests where the demand on the model is quite high, the solver was modified the discrete type being used, namely „ode23tb(stiff/TR-BDF2)”. The model used to implement the thermal effect consists of two "Battery" blocks, one without any influence from the point of view of temperature, and another to which the input signal "Ta" has been added which represents the ambient temperature which can be a constant or a thermal cycle. In addition to these changes, the batteries are connected to a current source of the „Controlled Current Source” type that receives as an input signal the variation of the discharge current calculated and implemented in the model so that the system in figure 3.14 was obtained:

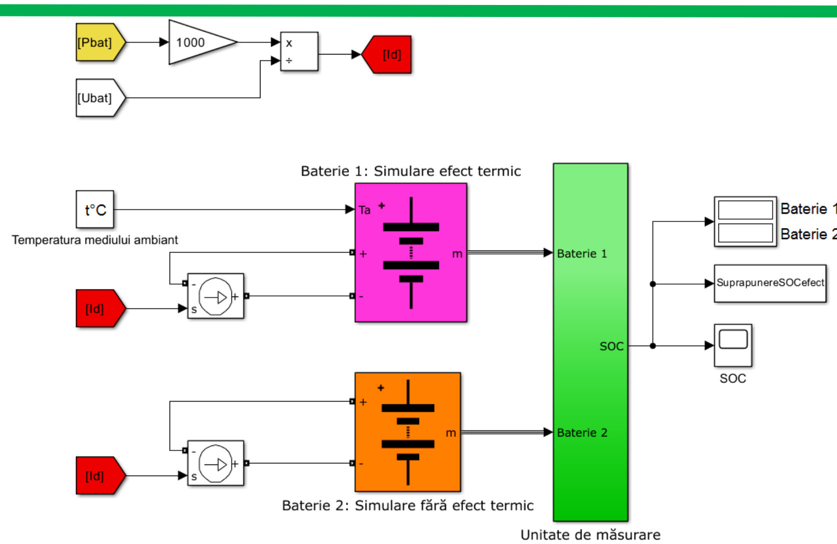

Figura 3.14. Thermal effect battery simulation model implemented.

The model also contains a „Scope” block for viewing the results graphically, a „Display” operator to record the final values obtained, and a „ToWorkspace” command to be able to further process the obtained signals. Table 3.9 shows the results of the simulations for the two mentioned cycles in relation to the temperature values of the proposed thermal cycle:

Tabel 3.9. SOC variation of the battery in relation to the ambient temperature.

		-20°C	-15°C	0°C	15°C	25°C	35°C	45°C
SOC [%]	WLTC	*82,69*	*85,52*	*90,29*	*92,69*	*93,73*	*94,51*	*95,11*
	Real cycle	*36,25*	*46,67*	*64,23*	*73,09*	*76,9*	*79,77*	*82*

In table 3.10, the autonomy values for the temperatures used in the simulation are presented in relation to the two cycles:

Tabel 3.10. Variation of autonomy in relation to ambient temperature.

		-20°C	-15°C	0°C	15°C	25°C	35°C	45°C
Autonomy [km]	WLTC	*108*	*129*	*192*	*255*	*297*	*340*	*381*
	Real cycle	*97*	*116*	*172*	*229*	*267*	*304*	*342*

The variation of the state of charge in relation to the ambient temperature is presented in figure 3.15:

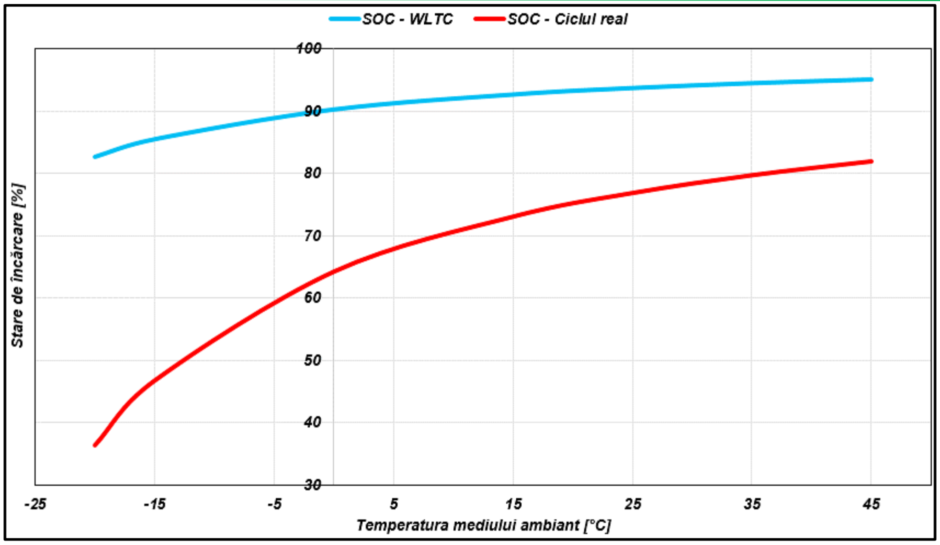

Figura 3.15. Variation of state of charge according to ambient temperatures.

The variations of the battery state of charge were also extracted from the simulation for the two cycles depending on the proposed thermal cycle from which the related curves resulted compared to the situation where the battery does not take into account the thermal effect (figures 3.16 and 3.17).

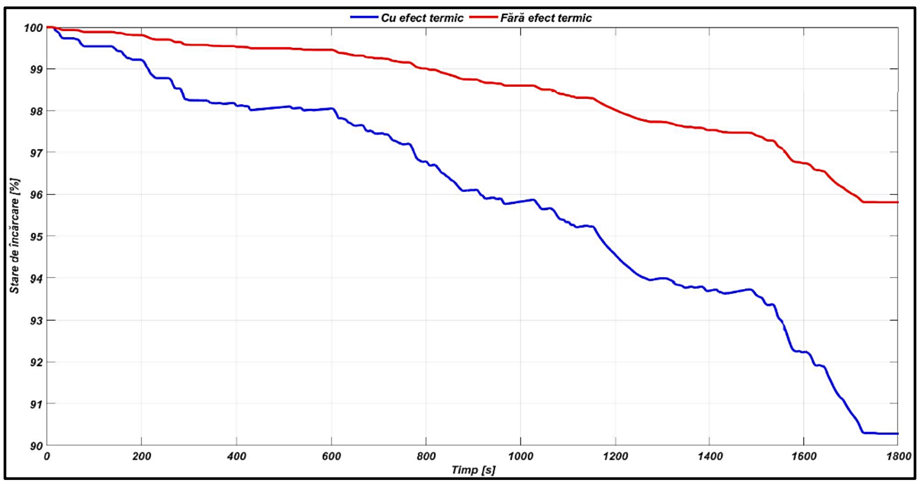

Figura 3.16. Variation of the state of charge according to the implemented thermal cycle - WLTC.

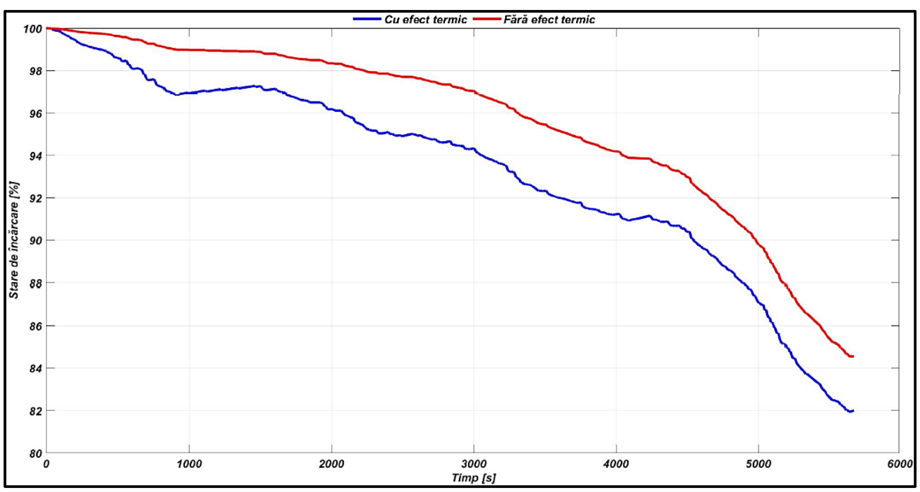

Figura 3.17. Variation of the state of charge according to the implemented thermal cycle – real cycle.

FINAL SIMULATION MODEL:

The results obtained through the simulation presented in the previous subsections, the final structure of the basic model that uses the characteristics of the Eniaq iV80 reference vehicle, the one through which the proposed experimental tests were carried out in real driving conditions, is represented in figure 3.18. The model can be optimized according to the requirements applied to it and new subsystems can be added to it for various tests and trials that can be extended to the processing of internal phenomena within the components of the electric propulsion system. The proposed model started from a series of extremely valuable, well-structured and detailed information by the author in the work [2], a work that was one of the basic pillars for expanding the knowledge related to the MatLAB - Simulink modeling and simulation environment.

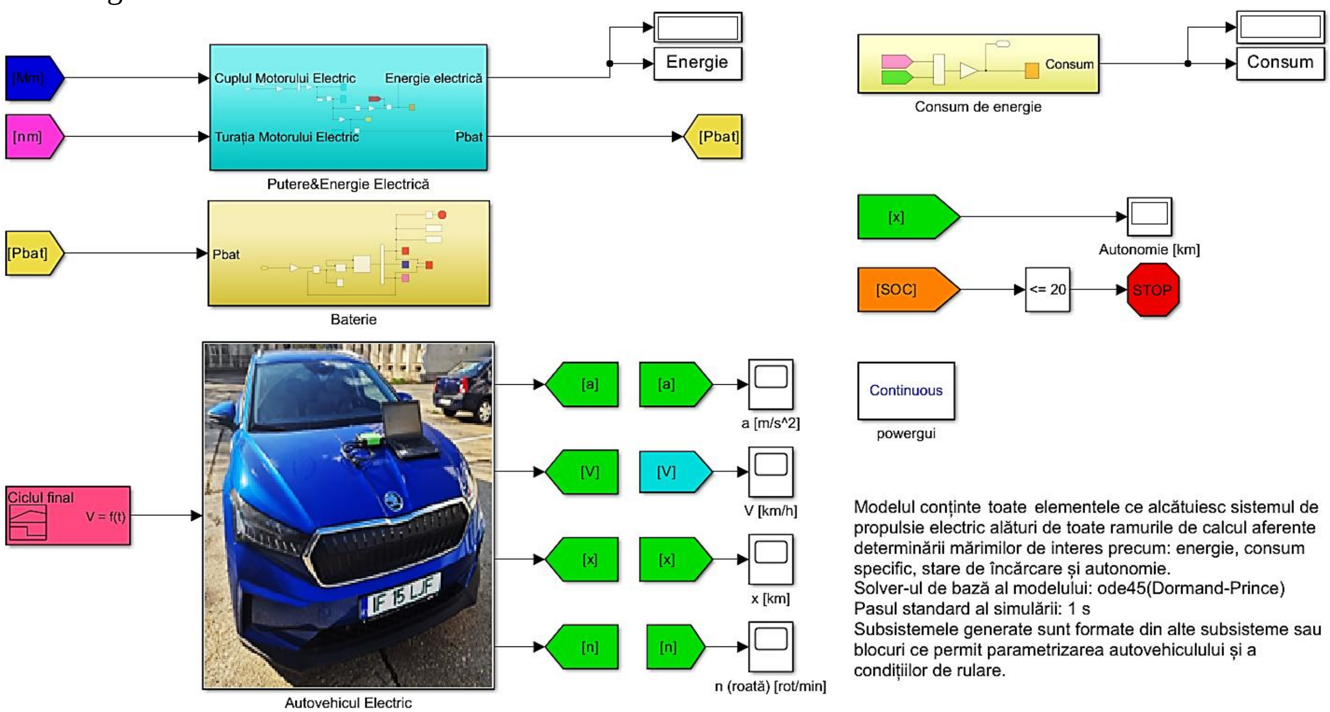

Figura 3.18. The final structure of the simulation model.

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CHAPTER IV. EXPERIMENTAL RESEARCH OF AN ELECTRIC VEHICLE

General considerations

Experimental research in the case of a motor vehicle generally consists of determining certain dimensions and characteristics of it when running on a set test cycle or in real driving conditions on a predetermined route. In order to carry out measurements on a test cycle (e.g. WLTC, UDDS, FTP) it is necessary to use a dynamometric stand that can simulate the running conditions and allow the determination of experimental results as soon as possible and more correct, which allow the optimization of performances of a motor vehicle or its approval. For conventional vehicles, the aforementioned cycles are used to determine fuel consumption and the level of pollutant emissions in order to approve them; for electric vehicles, it is no longer a question of polluting emissions but of electricity consumption and the autonomy of the vehicle under the conditions imposed by the cycle used. The measurement in real driving conditions is based on the RDE (Real Driving Emissions) standard for conventional vehicles, which determines the pollutant emissions produced by a vehicle in real driving conditions using portable equipment that allows this (eg PEMS). For an electric vehicle, as already specified, polluting emissions are non-existent, so the measurement on a real cycle is reduced to the determination of electricity consumption, autonomy, as well as other quantities of interest that highlight the dynamic and energetic performance of these vehicles.

In order to study the behavior of an electric vehicle and to take into account all the existing influencing factors, this paper approaches the determination of the performance in real driving conditions for an electric vehicle, with the aim of identifying all the advantages as well as the disadvantages of using an electric vehicle in different driving areas (e.g. urban, extra-urban or motorway). The main purpose of the experimental measurements is the detailed analysis of the variation of electricity consumption on a predetermined route and the variation of autonomy, taking into account internal and external factors that influence these quantities and why not, the subsequent analysis of sustainable solutions to optimize dynamic and energetic performance of an electric vehicle.

Another fundamental aim of the experimental research is the verification and validation of the simulation model made in Chapter III, through which other vehicles can be modeled and simulated in the situation of running on a real predetermined cycle without the need for detailed measurements beforehand.

Although the determination of pollutant emissions is not aimed at as there is no logical basis for this for an electric propulsion system, some hardware and software equipment is still needed to facilitate communication with the vehicle and allow the recording of some data of interest that can later be used in the validation of the realized simulation model, such as for example the speed profile of the real cycle, the obtained energy consumption and the autonomy of the vehicle.

In order to achieve all these points and to comply with some basic conditions regarding the measurement on a real cycle, the existing regulations in the European regulations (EU) 2017/1151 and (EU) 2018/1832 as amended will be analyzed and used. The basic conditions also apply to an electric vehicle when determining its energy consumption and range.

In the following sub-chapters we will analyze in turn: the structure of the vehicle used for the experimental research, the conditions that were taken into account in accordance with the mentioned regulations and the experimental results obtained in comparison with those resulting from modeling and simulation.

The structure of the propulsion system equipping the electric vehicle used for testing

The Skoda ENIAQ iV 80 model, which is the first electric vehicle produced by Skoda, was chosen for the experimental tests taking into account the requirements for running in all areas mentioned in regulation (EU) 2018/1832. The constructive peculiarity of this vehicle is related to the platform on which the propulsion system is mounted called MEB (Modularer E-Antriebs-Bauksten) [1], in translation a modular kit that allows the implementation of an electric propulsion system. This platform is common in the VAG group and has the advantage that it can be used on several models of electric vehicles.

The ENIAQ model is produced in several constructive variants that depend on the size of the battery, so on the energy storage capacity. These are: the 50 model with a 55 kWh battery, the 60 model with a 62 kWh battery and the 80, 80x and RS models with the 82 kWh battery, [1]. Also, standard overall layout regardless of model is "all rear", which uses an electric drive via a permanent magnet synchronous motor and a single-speed transmission. With this solution, there is also the possibility of configuring the solution with all-wheel drive by adding an asynchronous motor to the front axle.

In experimental research, the model used is the one organized according to the "everything behind" solution. The traction battery is the largest of the three variants, the 82 kWh one, being mounted in the central area of the vehicle between the two decks and measuring approx. 500 kg. Figure 4.1 shows the electric propulsion system for the Skoda ENIAQ iV 80:

Figura 4.1. Electric propulsion system of the Skoda Enyaq iV 80 vehicle, [1]:
1 – Air conditioning compressor, 2 – DC/DC 12 V voltage converter, 3 – High voltage heating system, 4 – High voltage battery, 5 – Speed variator-electric motor-transmission assembly, 6 – Power unit charging, 7 – Charging port.

Conditions imposed for experimental research

ANNEX III A of Regulation (EU) 2018/1832 presents several types of requirements and conditions that must be taken into account when carrying out RDE homologation tests. Given that this work strictly addresses vehicles equipped with an electric propulsion system, only a part of the respective conditions that apply regardless of the type of fuel or propulsion system used were extracted for the tests. These conditions were tracked and taken into account in the experimental measurements in this thesis.

Equipment used in carrying out experimental tests

Considering the fact that the experimental tests are based on running on a real predetermined cycle, in order to be able to make the necessary data acquisition, an equipment from the laboratories was used, namely the Bosch KTS 590 module from ESI[tronic] with cable connection with OBD II socket. This device allows a quick and efficient connection between the vehicle and a laptop by means of a cable that connects through the OBD socket and allows communication with the vehicle's computer. KTS is part of the category of multi-brand devices with the possibility of connecting to most vehicles on the market and is a module that deals with the diagnosis of control units.

Using the connection with the vehicle's computer through the OBD socket and the communication with the CAN network, the KTS module allows the measurement of several characteristic quantities in real time, on the set driving cycle, and in addition to this, it also allows saving the graphs obtained as a function of time and later conversion of files in the form of which they are automatically saved in the device's memory, into .xlsx type files that allow fast processing of the measured data and help in the detailed analysis of the obtained experimental results.

Figure 4.2 shows a schematic diagram of how to connect the KTS module to the vehicle's OBD socket alongside the laptop used as an interface for module command and control and data acquisition.

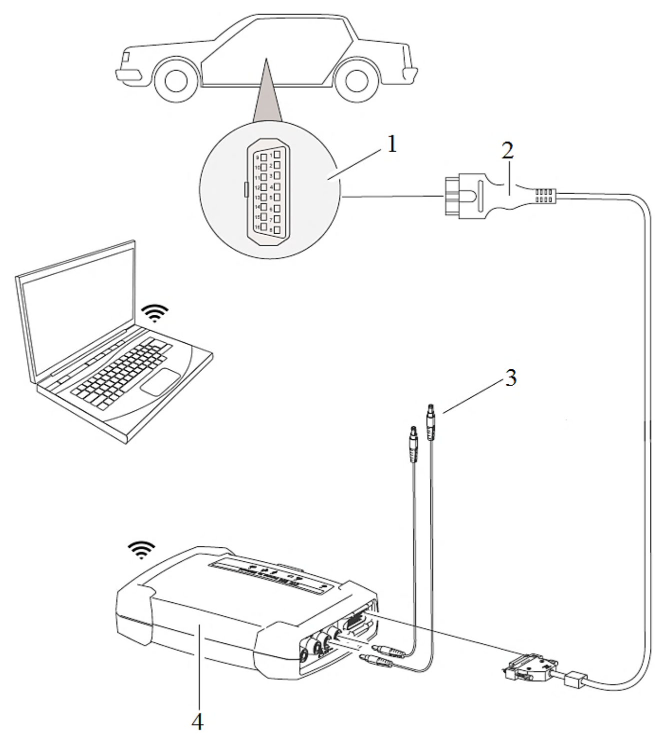

Figura 4.2. Schematic diagram of the connection plan for KTS 560/590, [4]:
1 – OBD connection on board the vehicle; 2 – OBD connection cable; 3 – Measuring cables; 4 – KTS mode.

Carrying out the tests

Choosing the route and preparing the vehicle

Once the vehicle used for the tests was established, it was necessary to choose and establish a route that combines and fulfills as best as possible the respective conditions extracted in subchapter 4.3. The tests were carried out in Bucharest and outside, in its vicinity, and the starting point was in the inner yard of the Faculty of Transport, in the laboratory area of the Department of Road Vehicles where the vehicle was charged at a 11 kW/32A station and where its instrumentation was carried out. Then, in order to avoid changing the slope of the road, the direct exit through Iuliu Maniu Boulevard was avoided and the area from Doinea Cornea Boulevard was chosen, after which the route followed its course towards Virtuții Road through Iuliu Maniu Boulevard, then on Splaiul Independeței towards the Railway Station from the North and finally on Calea Griviței towards the exit from Bucharest towards Chitila. This portion constituted the running part in the urban area, until the exit on the Bucharest Ring Road. Then, the route continued on the belt until the entrance to the A3 Bucuresti-Ploiești Highway, a portion considered the extra-urban cycle, and finally a part of the Highway was traveled to complete the cycle. Obviously, through the higher speeds required to achieve the extra-urban cycle and the one on the highway, they determined the increase in the distance traveled so that the time is proportional to that in the urban environment.

The route is presented in figure 4.3 through points of interest that helped shape it:

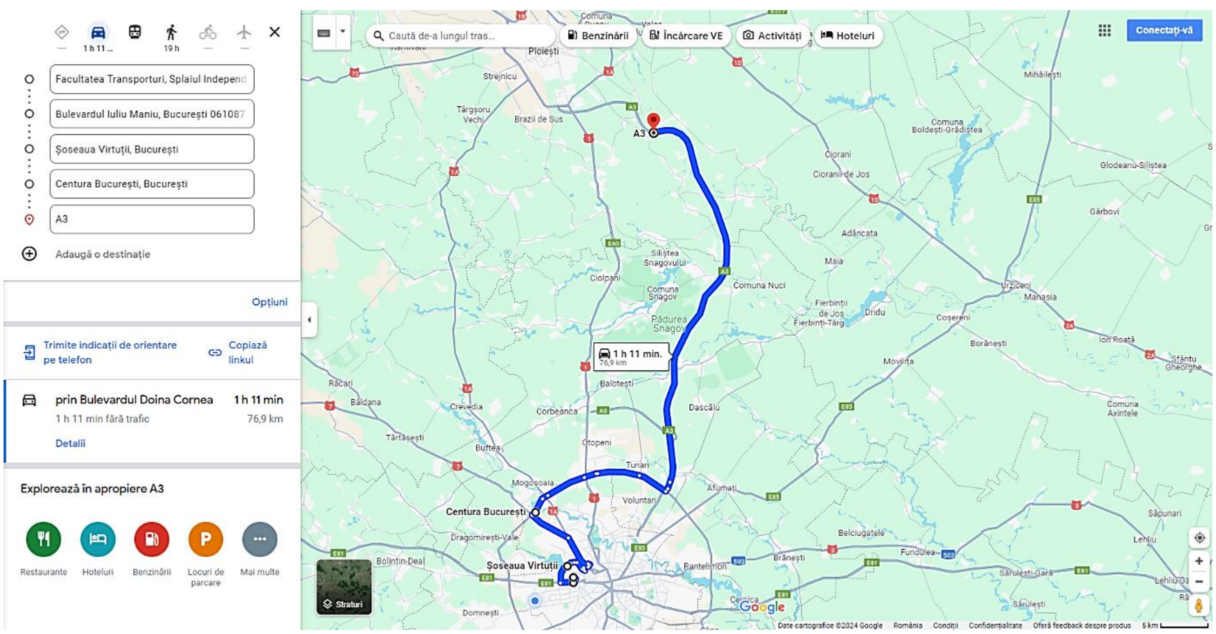

Figura 4.3. Map of the route established for research, [8].

Fig. 4.4 shows an image from the experimental tests in the urban environment next to the Skoda Eniaq iV80:

Figura 4.4. Image during experimental trials (left) / the Skod Eniaq iV 80 vehicle (right).

Communication through the GLOBAL OBD II menu allows simultaneous real-time monitoring of up to eight quantities selected from the list, and this was a limitation for testing because more parameters had to be monitored. In this regard, a "Y" connection with two female and one male OBD plugs was used to connect in parallel a second measuring device through which other parameters of interest could be stored. The device of choice was the ELM327 module with Bluetooth connection along with the "CarScannerPro" smartphone app. Thus, using the mobile phone and the ELM327 mode, they were extracted through the double connection using the "Y" connector and other important quantities in the basic study of the present paper. The following quantities were extracted through the KTS module:

- *Vehcile speed over time*
- *Variation of the electric motor speed over time*
- *Electric motor torque – driver option*
- *State of charge of the battery over time*
- *Variation of the working voltage of the traction battery*
- *Variation in the intensity of the electric current absorbed by the inverter from the traction battery*
- *Energy consumed on the actual cycle performed [kWh]*
- *Energy consumption on the real cycle achieved [kWh/100 km]*

Through the ELM327 module, other quantities of interest for the study proposed in this work were extracted, namely:*Puterea consumată de sistemele auxiliare aflate în funcționare pe parcursul rulării:*

- *The energy consumed by the auxiliary systems in operation during the run*
- *Ambient temperature variation over time*
- *Variation of internal battery temperature over time*

Experimental results obtained

According to the experimental measurements, the real cycle completed had a duration of 5676 seconds, so approximately 95 minutes, and the total distance covered on the established route was 77 km. The average speed in the urban environment was 19.7 km/h, and the maximum speed reached on the highway was 131 km/h in accordance with the legislation in force. By complying with all the traffic rules and adapting the driving speed according to the traffic conditions, the following real driving cycle based on the conditions specified in the regulation (EU) 1832/2018, Annex III, presented in figure 4.5, was obtained:

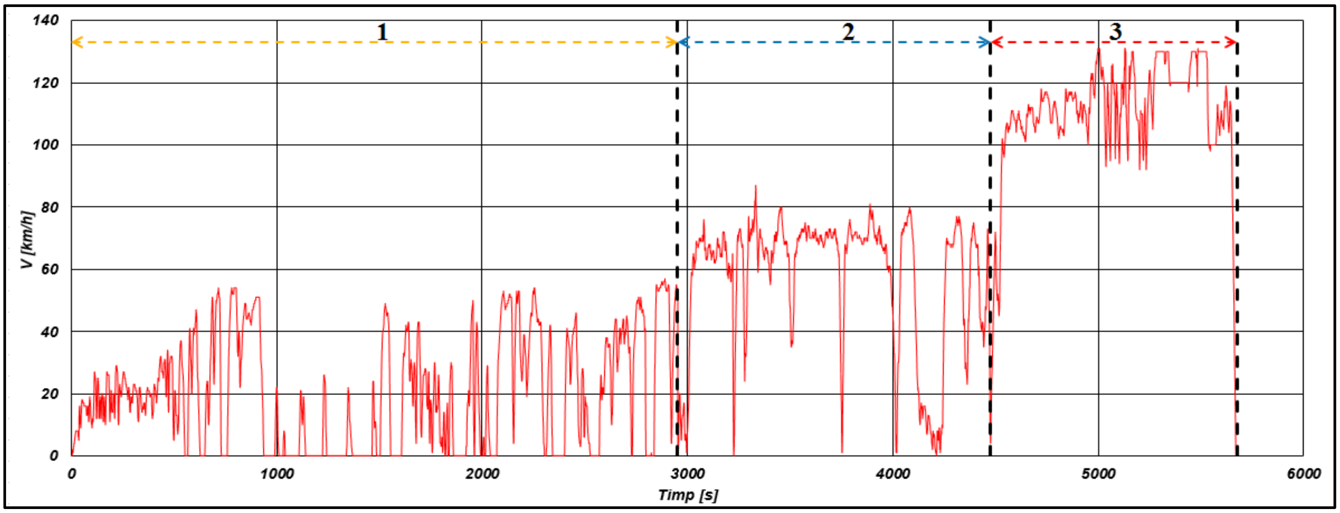

Figura 4.5. The real cycle obtained from experimental measurements: 1 – Urban; 2 – Extra-urban (rural); 3 – Motorway.

Processing the data in Excel also allowed the determination of other quantities of interest that characterize the performance of the tested vehicle, namely the acceleration and the distance traveled on the proposed cycle (4.6 and 4.7):

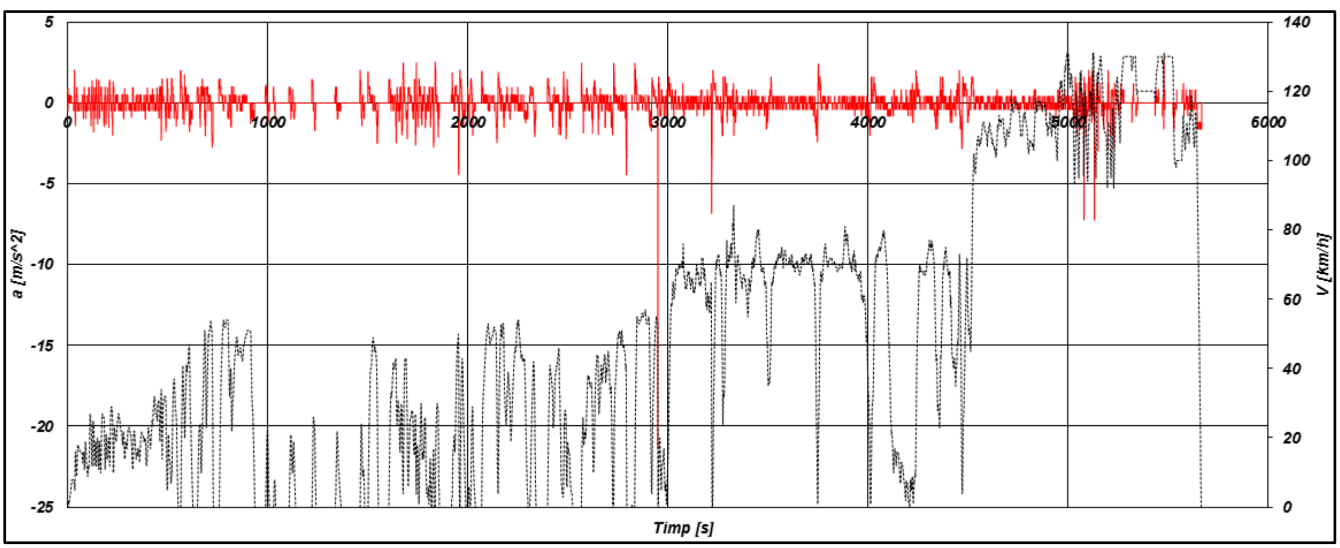

Figura 4.6. Variation of acceleration during the proposed cycle.

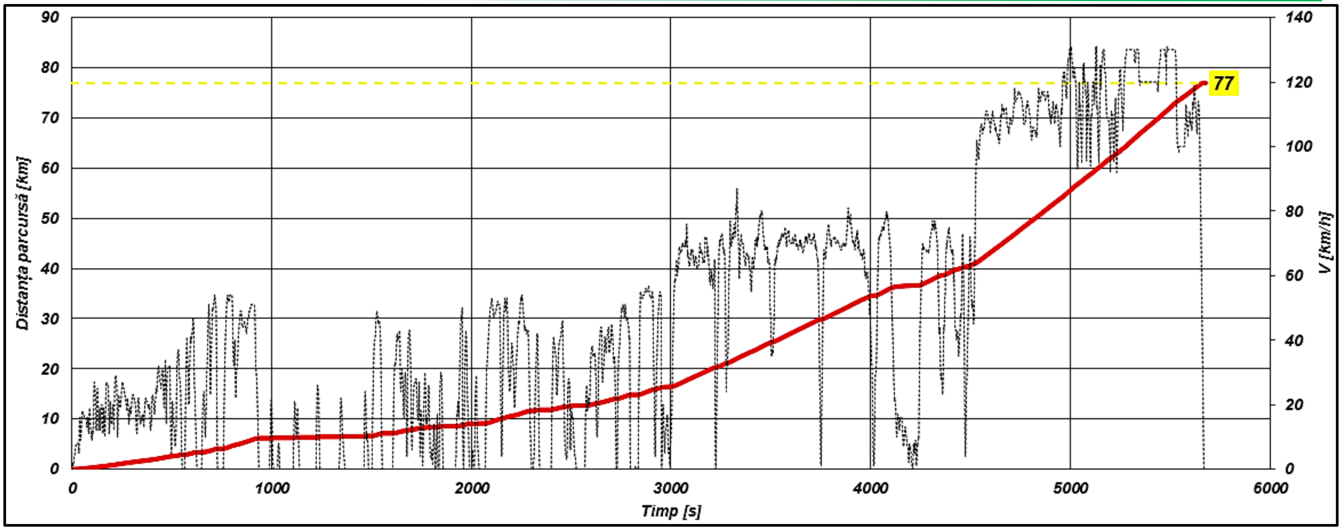

Figura 4.7. Distance traveled during the cycle.

The distance traveled on the established route was 77 km, and the maximum acceleration reached was 2.81 m/s2, while the maximum deceleration was -21.32 m/s2, the latter being influenced by the appearance of a pedestrian in - an area with reduced visibility which required a sudden and strong brake.

After processing the obtained results, the speed corresponding to the speed of 100 km/h was identified around the value of 9620 rpm and the maximum value reached on this cycle of ~12690 rpm which corresponds to the speed of 131 km/h.

It is also observed that the torque requirement was higher in the urban environment where the driving speed was low, the accelerations had high values, and the speed values did not exceed by much the value of 4500 rpm, a value that represents the basic speed in the characteristic mechanics of the electric motor.

In addition to the specific dimensions of the electric motor, the main characteristics of the traction battery were measured, namely: state of charge, working voltage and discharge current:

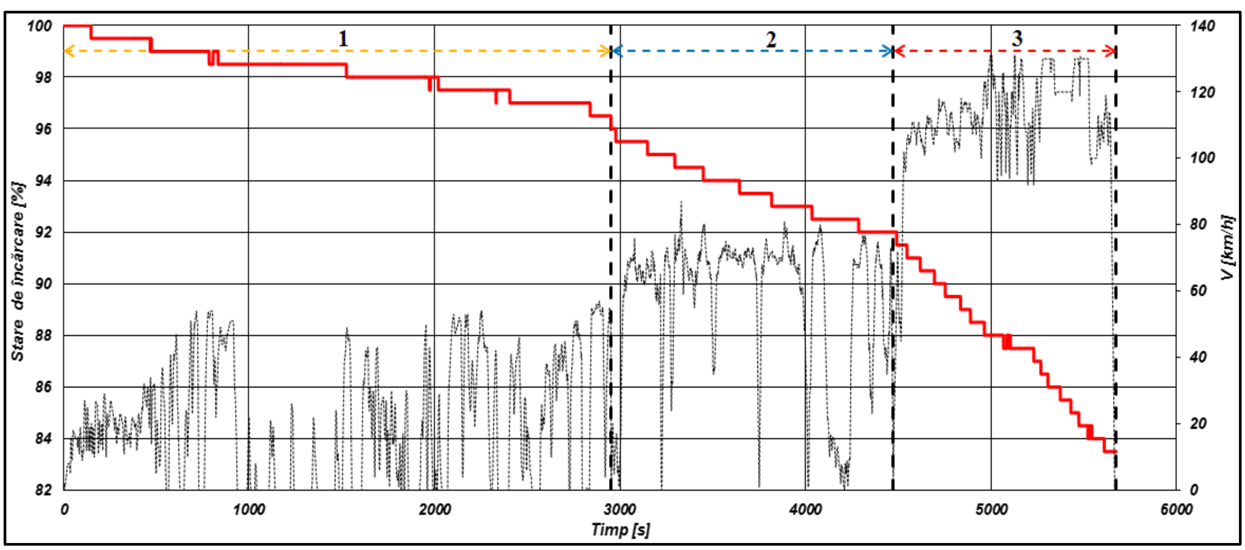

Figura 4.8. SOC variation of the battery.

The state of charge of the battery at the start of the driving cycle was 100%, after a controlled charge and sufficient time for stabilization. On the urban driving portion, the state of charge decreased by 3.5%, so it reached 96.5%, after which on the extra-urban driving portion it decreased by another 4.5%, thus meaning 92 % and finally on the portion of driving in highway mode, where the speeds were higher, the state of charge dropped to 83.5%, so with another 8.5% when the vehicle was stopped and the measurements ended. Thus, on the chosen route, the state of charge of the battery decreased by a total of 16.5% (figure 4.8).

The total energy consumed during the driving cycle was another quantity measured and recorded, and its variation is represented in figure 4.9. After traveling the route and completing the measurement cycle, the value of 16.77 kWh was obtained, the energy consumed to travel the 77 km.

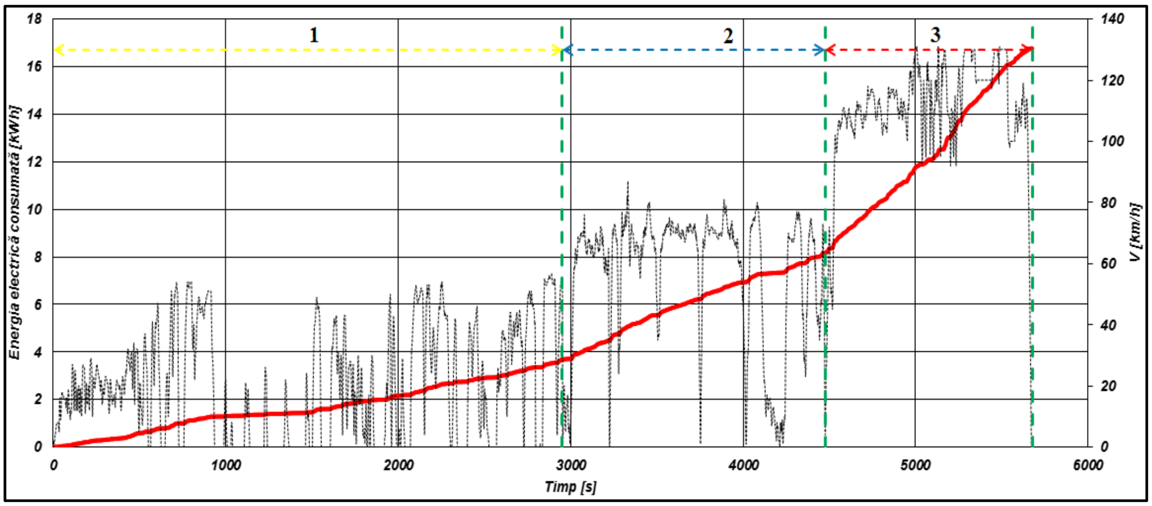

Figura 4.9. Variation of total energy consumed.

At the same time, the variation of energy consumption on the established route was recorded, and the value obtained was 21.78 kWh/100 km. The variation in electricity consumption can be seen in fig. 4.10:

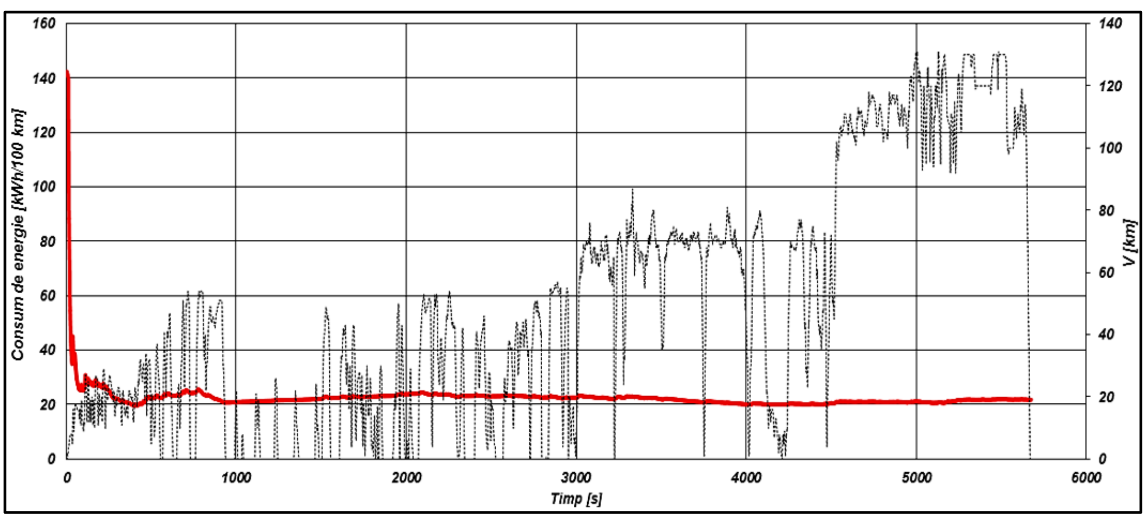

Figura 4.10. Variation of the energy consumption.

For a more detailed study of consumption performances, another extremely important parameter that was measured during the cycle was the power absorbed by the auxiliary consumers. During the drive cycle, daytime running lights were used and the climate system set to a temperature of 22°C and the fan set to „position 2”. The audio system, as well as other consumers, were not put into operation during this period. Thus, the variation of the power consumed by the auxiliary systems is shown in fig. 4.11:

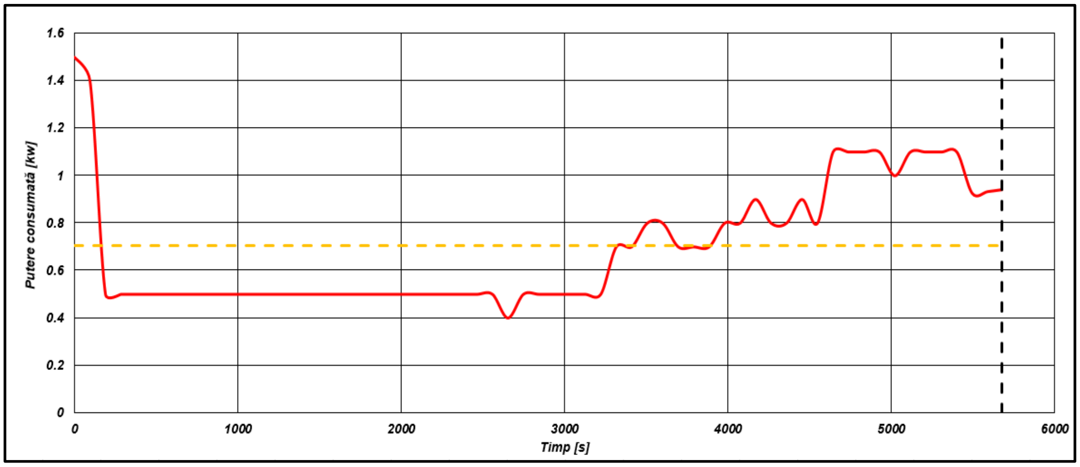

Figura 4.11. Power absorbed by auxiliary consumers.

The average value of the power consumed by the auxiliary systems in operation during the driving cycle was 0.7 kW resulting in an energy of 1.103 kWh. An important advantage to mention by acquiring these values is the fact that the developed simulation model can be optimized and this energy loss due to auxiliary consumers will be taken into account in the modeling and simulation of energy performances.

Comparison between experimental measurements and results obtained by modeling and simulation

The main parameter of interest is the speed of the vehicle along the proposed cycle. Figure 4.12 shows the comparison between the two profiles, the real (measured) and the simulated one:

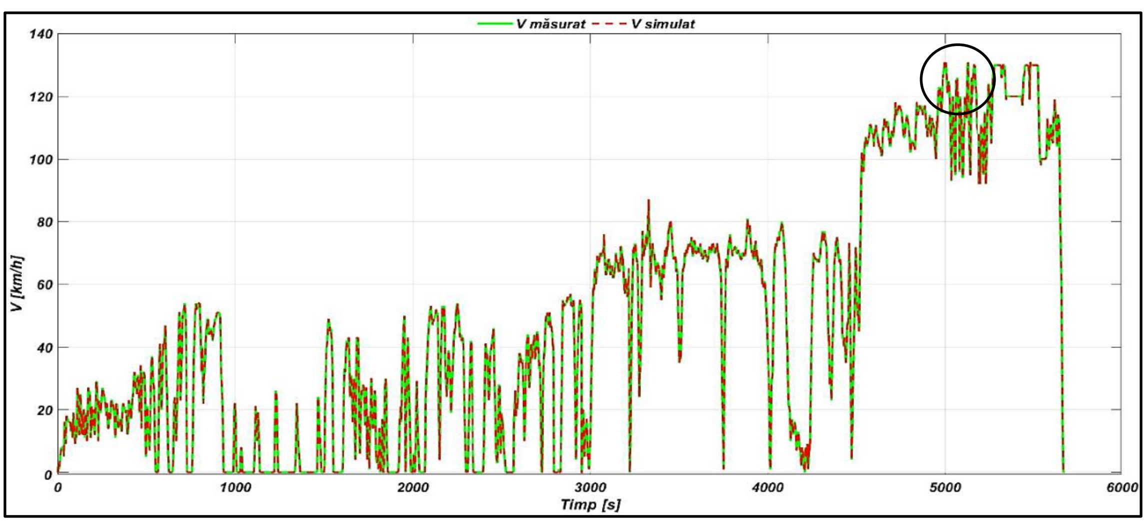

Figura 4.12. Superposition of vehicle speed profiles.

According to [3] a deviation of the vehicle speed profile with respect to the reference one with a margin of ±2 km/h is admitted and accepted. In this sense, the verification of this deviation was followed in several points of the diagram in figure 4.12 and an area was identified where the maximum deviation was + 0.15 km/h, and the minimum was - 0.2 km/h, values that respect the interval in the regulation. Figure 4.13 shows the detail regarding the deviation of the two speed profiles:

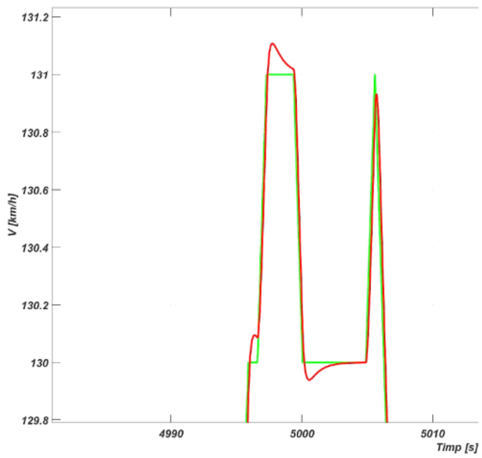

Figura 4.13. Detail of the deviation between the two vehicle speed profiles.

It was found that the simulated acceleration follows the points of the real profile very well except for some areas that represent approx. 5% of the graph, namely the moment of maximum deceleration on the real cycle, when there was an unforeseen situation and the pilot had to act on the pedal promptly and strongly, and in the case of simulation, the response time of the „Driver” subsystem via the PID controller generated that inadvertence by producing a deceleration of ~ -12.5m/s^2, respectively the speed increase points on the actual cycle, where the maximum and minimum value settings of the „Saturation” block in the engine command limited the acceleration.

In the case of the real profile, the maximum motor speed was 12689 rpm, and the simulation resulted in a value of 12696 rpm, which means an error of 0.06%, also generated and influenced by the settings related to the „Driver” subsystem in electric motor control area.

The comparative study for the state of charge of the battery and for the variation of the energy consumed during the cycle are presented in figures 4.14 and 4.15:

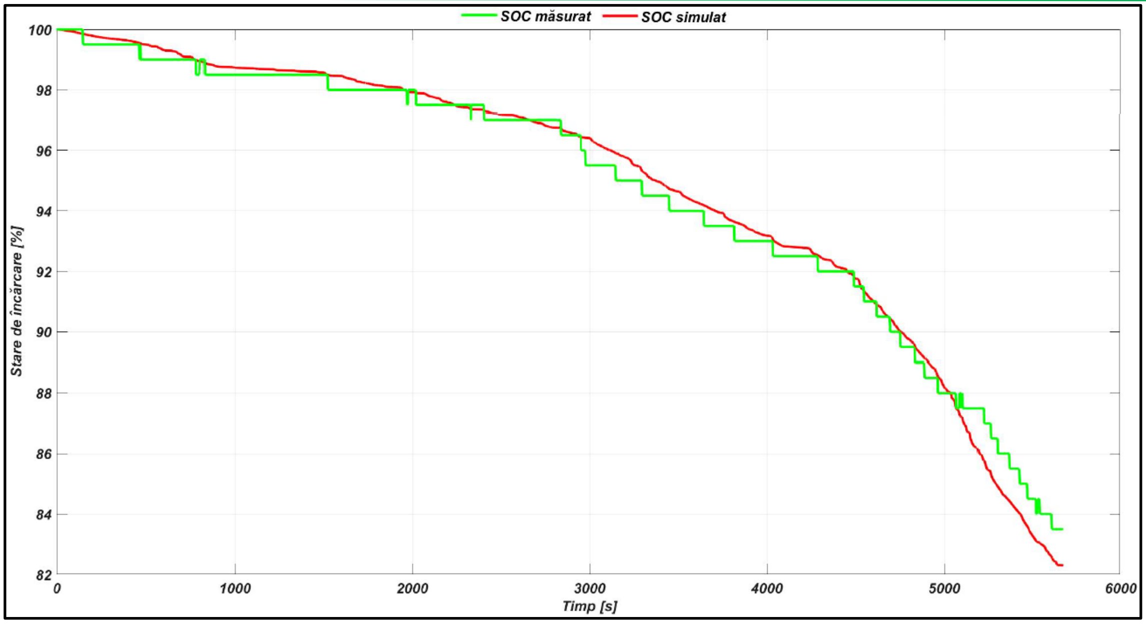

Figura 4.14. State of Charge Overlap.

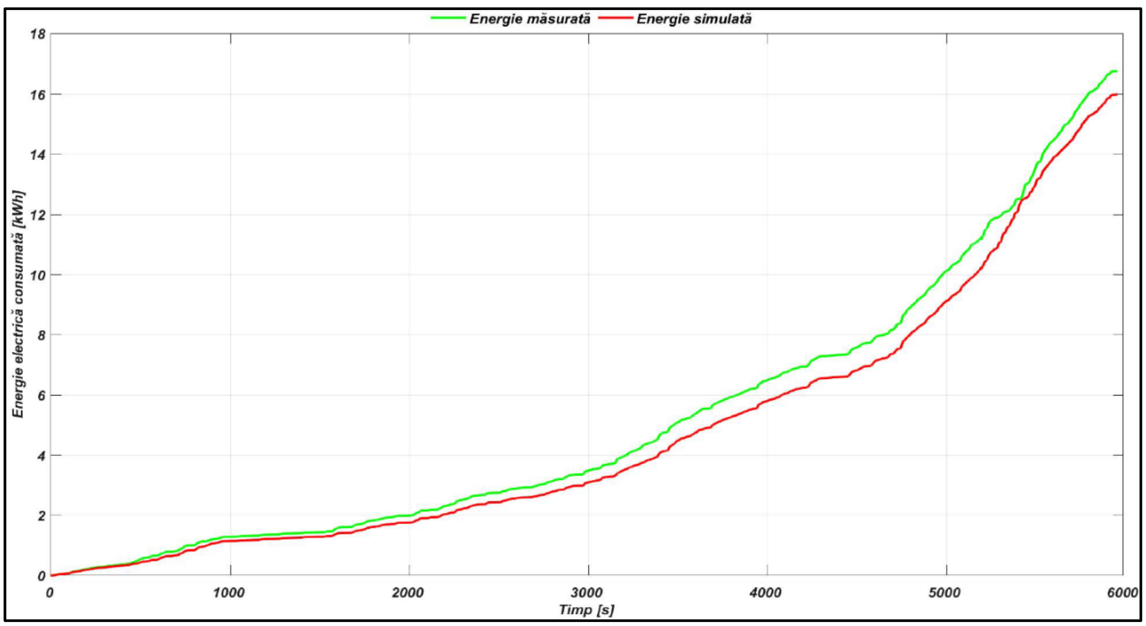

Figura 4.15. Overlap of consumed energy.

Regarding the state of charge of the battery, the final values obtained by both measurement and simulation are extremely close: 83.5% - real (measured) and 82.31% - from simulation. In terms of energy consumed during the driving cycle, the measured value according to the time variation was 16.77 kWh, while the simulation resulted in 15.99 kWh, so a difference of 0.78 kWh between real case and simulation resulting in an error of 4.65%.

Also, a comparison was made between the specific consumption measured and the one resulting from the simulation, from which the following values were obtained: 21.78 kWh/100km - real (measured) and 20.76 kWh/100km - from the simulation, a situation in which an error of 4.68% resulted. The comparative variation of energy consumption is shown in figure 4.39:

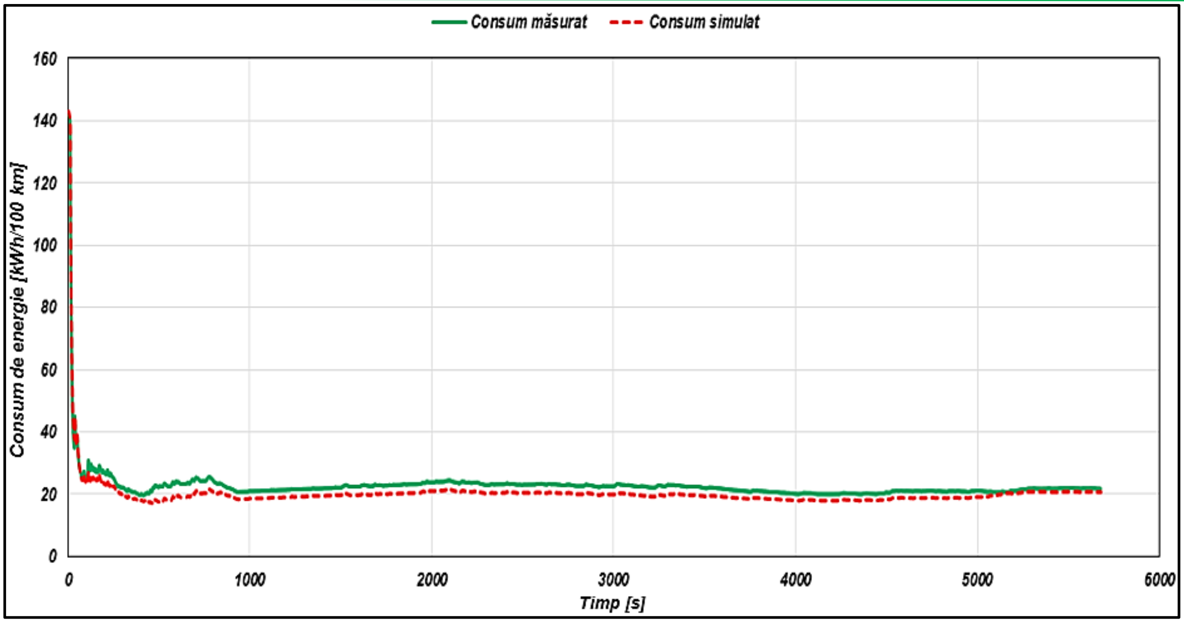

Figura 4.16. Overlapping consumption.

In [7], where the consumption values are presented depending on the driving regime and the zone, an average of the electricity consumption between driving in the city (urban environment), extra-urban and highway is 22.9 kWh/100km, thus resulting in a difference of 1.12 kWh/100km between the reference value presented in that analysis and the cycle proposed in this paper, which also covered all three driving zones, and the consumption obtained was: 21.78 kWh/100km - real (measured), thus resulting in a difference of 4.89%.

So, according to the results obtained from the simulation, compared to the measured ones, the resulting errors are below 5%, and the model sizes follow the real values very well, with small inadvertences obviously generated by the precision of the developed subsystems, by certain settings in the program options regarding the chosen step , to the type of solver, as well as certain conditions that cannot be physically modeled or simulated similar to the traffic reality.

The model created can thus constitute a tool for studying the dynamic and energetic performance of electric vehicles, especially in the case of cars and small utility vehicles.

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CHAPTER V. FINAL CONCLUSIONS. PERSONAL CONTRIBUTIONS. DISSEMINATION OF RESULTS

Final conclusions

The main conclusions resulting from the theoretical and experimental research within the doctoral thesis are:

- ❖ Current trends show a global increase in the number of electric vehicles, and negative factors such as infrastructure, charging time or autonomy are beginning to be resolved to allow the electric vehicle to spread strongly, especially at the passenger car level (category M1) and light vans (category N1);
- ❖ Through the detailed analysis of the current models of electric vehicles, a great architectural flexibility was found that allows the development of a wide range of solutions for their organization;
- ❖ The proposed real cycle was used in a period with low temperatures, an aspect that constituted a negative influencing factor on energy performances;
- ❖ The speed profile obtained experimentally was influenced by the pilot's driving style and also by the portions chosen for the cycle, but especially the speed limits in force according to Romanian law;
- ❖ In the extra-urban area, namely the ring road of the capital, the northern part where the speed limits allowed the realization of the second phase of the cycle where the driving speed could be maintained in the range of 60...90 km/ h, there were still sections where it was necessary to decelerate to very low speeds, or sometimes even to a stop where pedestrian crossings or roundabouts were encountered;
- ❖ As a result of the experimental measurements, it was found that when driving in the urban environment, on approx. 18 km traveled battery state of charge decreased by 3.5%;
- ❖ When traveling at speeds below 60 km/h, with an average speed of 19.7 km/h and short and frequent braking due to the existence of traffic lights and busy intersections, the state of charge experienced slight increases generated by regenerative braking, which demonstrates from a practical point of view, the fact that an electric vehicle lends itself extremely well to driving in the urban environment;
- ❖ Driving on the highway at high speed produced an 8.5% reduction in the state of charge, i.e. 2.5 times higher than in the urban environment, which demonstrates the fact that the speed of travel is a main influencing factor on the energy performance of electric vehicles;
- ❖ Through the comparative analysis between the results obtained experimentally and those from the simulation, errors between 0...5 % resulted, which gives the simulation model a high degree of confidence in its use for other more complex studies;

- The differences between the values obtained experimentally and those from the simulation using the real speed profile are generated by the fact that certain conditions and situations encountered in reality cannot be 100% implemented in a mathematical simulation model;
- By implementing the two-speed transmission in the case of a utility electric vehicle, a maximum 2% reduction in energy consumption resulted compared to the case of a single-speed transmission;
- It was highlighted that the implementation of the two-speed transmission generates a significant improvement in dynamic performance;
- The research carried out in the framework of the thesis regarding the influence of the rolling resistance coefficient on energy performance highlighted the significant impact it has on energy consumption and on the autonomy of the vehicle;
- Through the simulation, it was highlighted that the loading of the vehicle influences the energy performance and the autonomy during the driving cycle. In the example presented in the thesis, a 10.5% increase in energy consumption and a 12.85% decrease in autonomy were integrated;
- Experimental research on the variation of the thermal regime compared to the case where it was considered constant, revealed the fact that the state of charge of the battery decreased on the WLTC cycle by 5.32%, and on the real cycle by 2.56%;
- As a result of experimental research, as well as simulations, it emerged that the operating mode of an electric vehicle considerably influences its real autonomy;

Personal contributions

The theoretical research carried out through modeling-simulation and the experimental research highlight a series of personal contributions of the author, among which are mentioned:

- Carrying out a complex study on the current and future trends related to the evolution of electric vehicles worldwide correlated with the main limitations existing at the moment and the possible solutions for their elimination.
- A detailed presentation of the current solutions existing on the electric vehicle market worldwide correlated with the innovative solutions proposed by manufacturers for the near future.
- Analysis of the architectural flexibility and constructive diversity available to electric vehicles at the moment.
- Realization of principle constructive schemes that reflect the general organization solutions of an electric vehicle.
- Choice and implementation of a route consisting of three phases: urban, extra-urban and highway for the realization of experimental research, which respects the conditions imposed by the regulation in force.

- Experimental determination of the dynamic and energetic performance of an SUV-type electric vehicle in real conditions using equipment specialized in the diagnosis of a vehicle.
- Development of an original mathematical model using the modeling-simulation program MATLab-Simulink that allows the analysis of the dynamic and energetic performances of an electric vehicle, especially from the M1 and N1 categories using a real driving cycle or a standardized one (in this paper: WLTC and NEDC).
- Validation of the developed model through the comparative analysis of the results obtained through simulation with those obtained experimentally in real conditions.
- Highlighting the main possibilities and advantages offered by the model developed for the MATLab-Simulink modeling-simulation program and the usefulness of this methodology for the optimization and development of electric vehicles.
- Elaboration of a study using the simulation model regarding the main influencing factors on the dynamic and energetic performances of electric vehicles and the identification of optimization solutions applicable in practice.
- Comparative analysis by simulation of the dynamic and energy performance of an electric SUV when running on a real cycle and on different standardized test cycles.
- Through the multitude of results obtained using the simulation model in accordance with certain internal and external factors of influence, a tool for researching the performance of electric vehicles has been developed that can be used by specialists in the field to develop future studies with the role of optimization or development of vehicles electrical.

Dissemination of results

During the three years devoted to doctoral studies, several papers presented at various national and international conferences, respectively in specialized magazines, were developed on the performance of electric vehicles, as well as on the stages of the development of the designed simulation model. Of these papers, 6 were done as first author, and 3 as co-author as follows:

1. Danciu, Gr., **Ancuța, A.A.** *„Optimisation Analysis of the Hybrid Vehicles Powertrain”* – Congresul EV2019. Publicată în IEEE Xplore la 11.11.2019 – Cod 19136028, accesibilă la https://doi.org/10.1109/EV.2019.8893117.

2. **Ancuța, A.A.**, Danciu, Gr., Frățilă G. *„Modeling and simulation of an electric propulsion system equipped with Fuel Cell”* – Conferința AITS 2021, Universitatea Thenică din Chișinău. Publicată în *IOP Conf. Ser.: Mater. Sci. Eng. 1220 012011,* DOI 10.1088/1757-899X/1220/1/012011.

3. **Ancuța, A.A.**, Voloacă, Ș., Danciu, Gr., Frățilă G. *„Modeling the characteristics of an electric propulsion system for a small electric vehicle”* – Congresul ICOME, Universitatea din Craiova, Facultatea de Mecanică, 2022.

4. **Ancuța, A.A.**, Voloacă, Ș., Danciu, Gr., Frățilă G. *„Simulation of the Parameteres of a Lithium-ion Battery thay Equips an Electric Vehicle”* – Congresul EAEC-MVT, Universitatea din Timișoara, 2022.

5. Mînzatu, C., Nișulescu, V., Bancă, G., Toma, M., Rențea, C., **Ancuța, A.A.** *„Research Regarding The Simulation Of The Autonomy For The Electric Vehicles In The Case Of The WLTC Test Cycle”* – Congresul EAEC-MVT, Universitatea din Timișoara, 2022.

6. Voloacă, Ș., Toma, M., **Ancuța, A.A.** – *„The Optimization of a Cost-Effective Journey Data Recorder Used in te Automotive Industry”* – publicată în Revista Ingineria Automobilului Nr.66, martie 2023, ISSN 1842-4074, WOS:001156834100007.

7. **Ancuța , A.A.** „*Analysis of Thermal Influence on the Operation of a Li-Ion Battery Used by an Electric Vehicle*” – 46th International Spring Seminar on Electronic Technology (ISSE, 10-14 Mai 2023, Timișoara, Romania) publicată în IEEE Xplore, DOI: https://doi.org/10.1109/ISSE57496.2023.10168455, ISBN 979-8-3503-3484-5, ISSN 2161-2536.

8. **Ancuța, A.A.**, Voloacă, Ș., Frățilă G., Danciu, Gr. *„Analysis of Energetic and Traction Performances for an Electric Vehicle in Real Driving Conditions”* – Congresul EAEC-ESFA, Universitatea Națională de Știință și Tehnologie POLITEHNICA București, Noiembrie 2023. Publicată în *IOP Conf. Ser.: Mater. Sci. Eng. 1303 012006*, DOI 10.1088/1757-899X/1303/1/012006.

9. **Ancuța, A.A.**, Rențea, C.A. *„The Influence Of The Two-Speed Transmission On The Performances Of An Commercial Electric Vehicle”* – publicată în Revista Ingineria Automobilului Nr. 70, martie 2024, ISSN 1842-4074.

Participation in various activities with links in the field:

- Speaker at the "Green Vehicles" conference within the POLI AUTOFest 2022 festival with the presentation "Current Status and Trends Regarding the Evolution and Development of Electric Vehicles".
- Speaker in the "Electric Vehicle" debate within the POLI AUTOFest festival, May 19, 2023, with the current situation and the future perspective regarding the spread of electric vehicles.
- Group coordinator, specialist in the field of electric vehicles during the participation in the study visit of the TESLA factory: Giga Factory Berlin – May 2023.