Analysis Platform for Energy Efficiency Enhancement in Hybrid and Full Electric Vehicles

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***Abstract*—The current paper presents a new virtual analysis method that is applied both on hybrid and electric vehicle architectures with the purpose of contributing to the improvement of energy efficiency. The study is based on Matlab modeling and simulation. A set of parameters are considered in order to assess the system performance. The benefit is given by the comparative overview obtained after the completed analysis. The effectiveness of the analysis method is confirmed by a sequence of simulation results combined in several case studies. The impulse of the research is given by the fact that the automotive market is focusing on wider simulation techniques and better control strategies that lead to more efficient vehicles. Applying the proposed method during design would improve the battery management and controls strategy. The advantage of this method is that the system behavior with regards to energy efficiency can be evaluated from an early concept phase. The results contribute to the actual necessity of driving more efficient and more environmental friendly vehicles.**

***Index Terms*—batteries, data analysis, energy efficiency, electric vehicles, modeling.**

I. Introduction

Hybrid vehicles are more complex comparing to classic vehicles mainly from software perspective. The software has almost double complexity, and the hardware is considered to be 25% more complex [1]. Electric vehicles are less sophisticated than hybrid vehicles with regards to hardware, but have similar level of software density. One of the biggest technical challenges with regards to hybrid and electric vehicles (HEV) is the level of energy efficiency. Electric traction is one of the most promising technologies that can improve the vehicle performance [2].

In order to mitigate the risk of failures and to create a robust design the automotive sector relies, in the last years, on simulation performed in the concept phase. Mathematical modeling and simulation tools became more advanced and the concept of simulation evolved into an actual design tool. Accurate battery models have a high contribution in the development [3]. Research activities are focusing on improving the energy management in order to minimize the fuel consumption and emission, and to increase the driving range [4]. Fuel consumption depends on the driving patterns [5].

Improvements in the energy efficiency area can be obtained through a rigorous battery management. Battery management systems in vehicles contains sensors, actuators, controllers which have various algorithms and signal wires. The main scope is to assure that the batteries operate within the proper voltage and temperature interval, and guarantee that the batteries could fulfill the vehicles requirements [6]. Power split between energy sources is very important to minimize the fuel consumption without affecting the vehicle speed. [7].

The proposed paper presents a set of simulation and analysis methods for modeled hybrid vehicle architecture and for modeled electric vehicle architecture [8-13]. A set of parameters are varied and analyzed with the scope of improving the energy efficiency. Several parameters are taken in consideration and varied in specific case studies in order to find solutions that would improve the vehicle performance. The scope is to increase the range that hybrid vehicles drive on electric power and extended the full range achieved by electric vehicles. Improvements can be done through a better parameterization and by selecting the appropriate configuration for the expected performance. A precise setup can be developed when enough research data are available. In the study, parameters like battery state of charge, battery power, battery current, vehicle mass, battery type, fuel consumption, driving cycle, motor power, and propulsion change threshold are varied and evaluated for a complete system overview. The result is a new perspective over the design of hybrid and electric vehicles with regards to the area of energy efficiency enhancement.

II. Hybrid Architecture Assessment

The model block diagram used in simulation is shown in Fig. 1 [8]. It consists of one block for control simulation, one for engine simulation, a power split device and a block dedicated to the electrical part of the architecture.

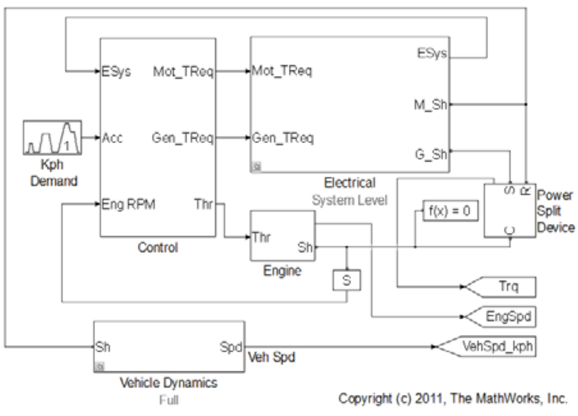

Figure 1. Hybrid vehicle architecture – block diagram

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The electric part is most relevant for this paper since it focuses on simulating the motor and generator, the DC-DC converter and the configurable battery models. Power electronics is indispensable in hybrid vehicle [9]. Development of power electronics for EVs needs to evolve in order to fulfill the market needs [14].In the analysis of the hybrid vehicle architecture a transient symmetric driving cycle is used in order to obtain a valuable understanding of the system behavior in terms of energy efficiency [15]. The battery state of charge (SOC) and the fuel consumption are analyzed in different configurations.

The change between electric motor and internal combustion engine (ICE) is possible at different motor speeds with a direct impact on the vehicle performance. Six different thresholds between 600 and 1100 rpm are taken in consideration in the proposed analysis method. Considering the modeled architecture and the vehicle dynamics, the enable of the internal combustion engine is considered to be done between 20 and 45 km/h. The impact of the RPM threshold value on the battery state of charge is presented in Fig. 2. The plot is linked to an architecture consisting of a 200 V Lithium Ion battery type. The same simulation and data analysis are repeated for other 2 battery types: Nickel Cadmium and Nickel Metal Hydride.

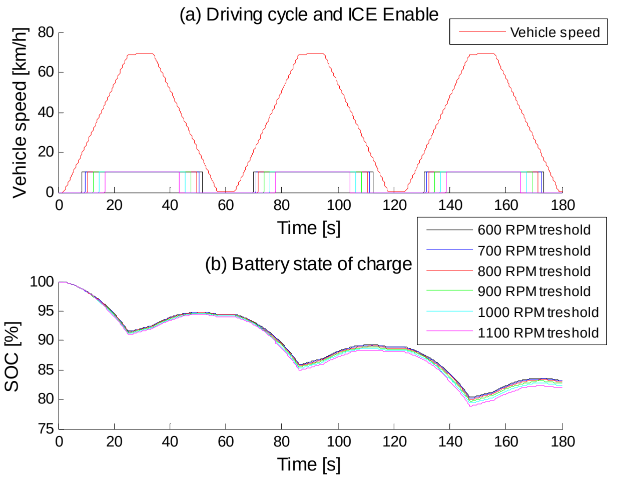

Figure 2. Battery state of charge – hybrid vehicle

A comparative analysis is presented further in the paper. In Fig. 2, it is visible how the battery state of charge is evolving in relation to the driving cycle. Moreover, in the upper side of the figure together with the vehicle speed it is visible when the ICE is enabled in each particular case. It is shown that if the RPM threshold is higher, the final value of the battery state of charge at the end of the driving cycle will be lower. If the threshold of switching to the internal combustion engine is higher than the electric motor will require more energy from the battery.

The scope of this paper is to identify the most efficient point for a certain setup and to help in making a conscious decision when designing a certain product. It is important to assess the impact of the RPM threshold on the energy efficiency from an early concept phase in order to adjust the design and the control strategy in an effective manner. The evolution of the battery state of charge is influenced by the specific driving cycle and to the specific battery type. Performing the same simulation on a driving cycle with different acceleration and deceleration gradients or on a modal driving cycle, it can be observed that the battery state of charge will evolve in a different manner. The impact of the RPM threshold will still have a linear influence.

More electric driving requires more efficient batteries, with the advantage that it consumes less fuel and has fewer emissions. The same simulation approach and the analysis technique were extended to different battery types in order to identify if the system behaves in a different manner. An overview of the performed case studies is presented in Table I. For each battery type there is a variation of the RPM threshold and the value of the battery state of charge at the end of the driving cycle is presented.

TABLE I. BATTERY STATE OF CHARGE - HYBRID

Battery type	**ICE enable threshold [rpm]**	**SOC [%]**
Li-ion	600	83.2463
Li-ion	700	83.1274
Li-ion	800	82.9502
Li-ion	900	82.707
Li-ion	1000	82.3675
Li-ion	1100	81.9186
NiCd	600	83.9047
NiCd	700	83.778
NiCd	800	83.5903
NiCd	900	83.3236
NiCd	1000	82.9384
NiCd	1100	82.3753
NiMH	600	84.1281
NiMH	700	84.0108
NiMH	800	83.8386
NiMH	900	83.5955
NiMH	1000	83.2561
NiMH	1100	82.7979

It is demonstrated through the end results presented in Table I, the fact that the value of the state of charge after a certain driving cycle can vary from one threshold to another and can be compensated by adjusting the proper battery type to the design. It can be observed in Fig. 3 that the value of the battery state of charge is similar in case of a threshold of 800 RPM with a Lithium Ion battery, and a threshold of 1000 RPM with a Nickel Cadmium battery. It is more efficient to change to ICE propulsion at 1100 RPM with a Nickel Metal Hydride battery that at 900 RPM with a Lithium Ion battery. Driving more on electric propulsion, the vehicle will burn less fuel and will be more environmental friendly. Through the applied simulation and analysis method, a comparative overview is generated. A conscious decision can be made in terms of what architecture is more appropriate for the final product.

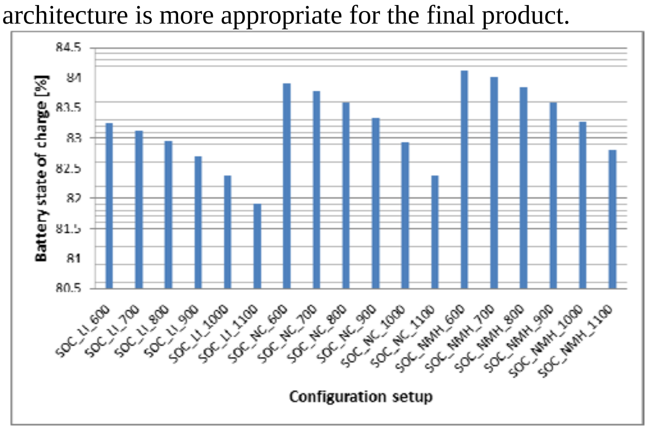

Figure 3. Battery state of charge comparative overview – hybrid vehicle

A similar comparative overview obtained from a set of simulations is presented in Fig.4. In Fig. 4b there is a zoom on the Y axis between 0 and 3 l/100km. This zoom is chosen for a better visibility. The battery state of charge is replaced with the fuel consumption in the graph. It is analyzed how the fuel consumption evolves during the driving cycle for each RPM threshold. It is visible that the vehicle burns less fuel if it drives more on electric power. The presented simulation results are valid for a Lithium Ion battery but simulation data for further analysis were generated with additional battery types.

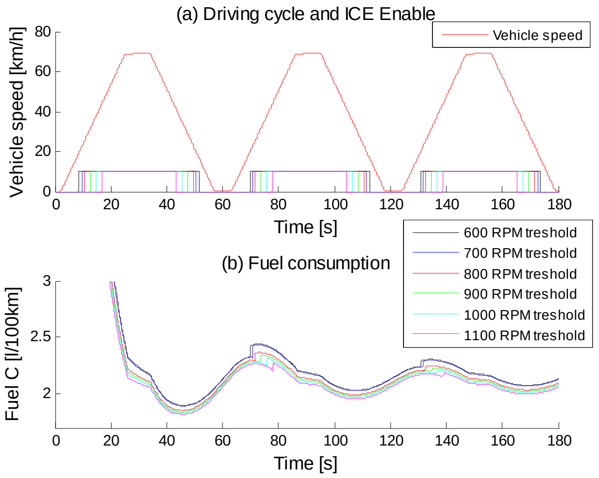

Figure 4. Fuel consumption for the analyzed configurations

An overview of the performed simulations and resumed results are presented in Table II. The lowest fuel consumption was obtained with a Lithium Ion battery type that runs on electric engine up to 1100 rpm, approximately 45 km/h. This configuration had the lowest value of the battery state of charge at the end of the driving cycle.

TABLE II. FUEL CONSUMPTION

Battery type	ICE enable threshold [rpm]	Fuel consumption [l/100km]
Li-ion	600	2.473
Li-ion	700	2.4
Li-ion	800	2.3278
Li-ion	900	2.1717
Li-ion	1000	2.1411
Li-ion	1100	2.0784
NiCd	600	2.3112
NiCd	700	2.4402
NiCd	800	2.2639
NiCd	900	2.2444
NiCd	1000	2.1625
NiCd	1100	2.1142
NiMH	600	2.5481
NiMH	700	2.3383
NiMH	800	2.232
NiMH	900	2.2676
NiMH	1000	2.1225
NiMH	1100	2.1025

A graphical representation of the analyzed data is presented in Fig. 5. The results are presented both in tables and graphs due to the fact that the obtained values are very close to each other. This helps to clearly distinguish the values up to the 3rd decimal. It is visible that the value of the fuel consumption varies from one set of data to another. In order to improve the energy efficiency, a wide amount of data can be generated and both battery state of charge and fuel consumption need to be taken in consideration. This proposed simulation and analysis method makes it possible to generate a high number of results that will support a good overview. In order to have an effective and reliable design, it is important to identify the key point on both aspects: battery efficiency and fuel efficiency. The designer can easily choose what is more important at a certain moment and where is better to compromise.

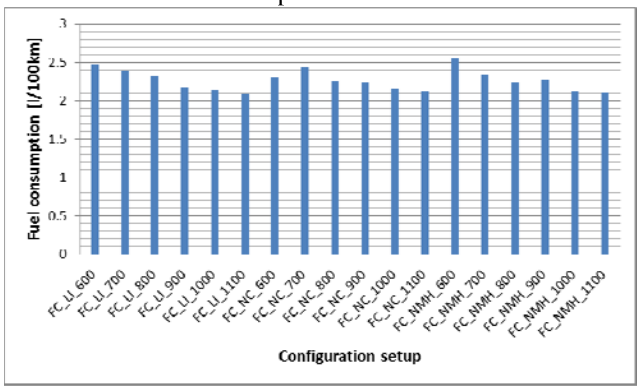

Figure 5. Fuel consumption comparative overview – hybrid vehicle

Battery current and battery power are also aspects that need to be taken in consideration. In Fig. 6 it is presented the progress of the battery current and power through the driving cycle under analysis. The simulation result is valid for a Lithium Ion battery type and the impact of the RPM threshold is analyzed. There is a current spike visible when the propulsion changes from electric engine to internal combustion engine that is also translated into a spike in the battery power. This event is shifted to the right and the amplitude increases once the RPM threshold increases.

When considering the impact on Lithium Ion battery current and power, the system responds in a linear manner to the increased threshold. Again, this linearity can be compensated by using different battery types with the right level of parameterization.

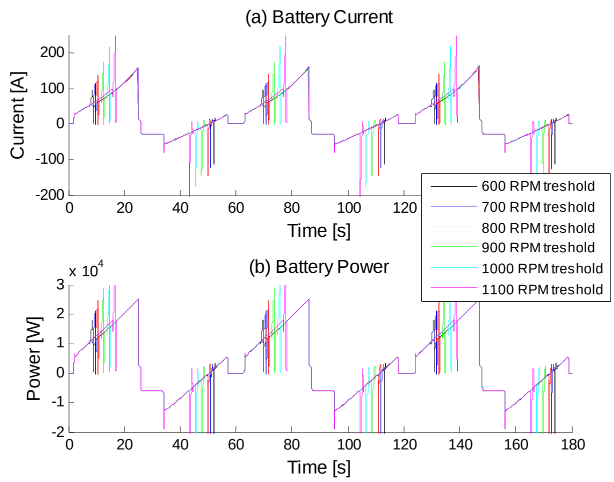

Figure 6. Battery current and battery power for the analyzed configurations

The scope of the previous analysis is to support the transformation of the actual hybrid vehicles towards more electric drives. Driving in a hybrid manner has certain advantages but increasing the electric propulsion would certainly decrease the level of fuel consumption and the level of emissions in the atmosphere. Saving 0.1 litters of fuel for 100 km on an entire vehicle fleet equals with the amount of CO2 that is absorbed by millions of tress in one year [9]. It is better to design a hybrid vehicle that drives up to 50 km an hour on electric power since this is mainly the maximum speed for driving in the city.

III. From Hybrid to Electric

One of the major technical challenges for electric vehicles is represented by the autonomy range. This aspect can be improved by a better parameterization, a better control strategy and a better battery management. In order to support these aspects, improved simulation techniques need to be developed. Starting from the hybrid architecture model presented in Fig. 1, a full electric architecture was developed in order to support research in the area of energy efficiency for electric drives. The block diagram of the electric architecture model is presented in Fig. 7 [8]. It consists of a controls strategy block, an electrical block and vehicle dynamics block. An internal combustion engine is not part of the simulation anymore.

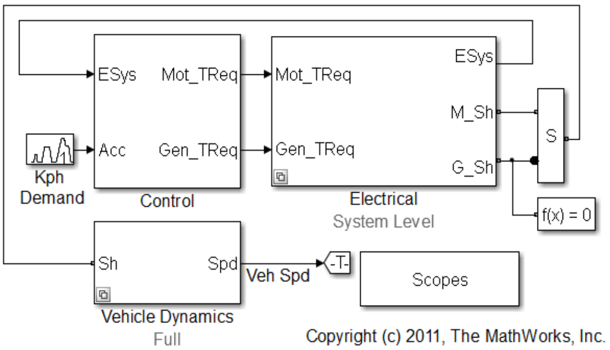

Figure 7. Electric vehicle architecture – block diagram

A parallel representation of a hybrid and an electric architecture results, on a specific driving cycle, is presented in Fig. 8. For the hybrid architecture simulation, it is visible that the ICE is enabled above 800 rpm and this has an impact to the Lithium-Ion battery power.

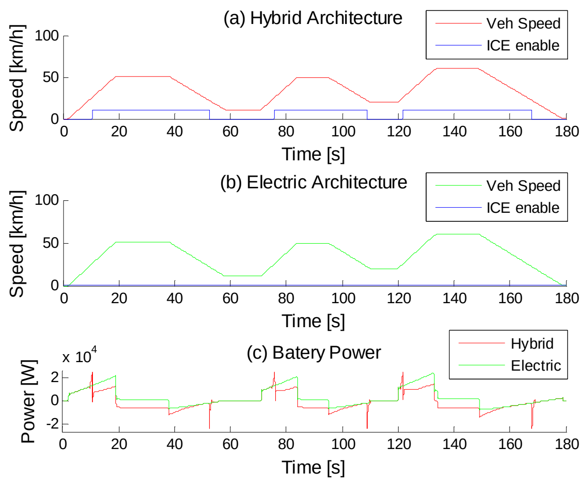

Figure 8. Battery power comparison – hybrid and electric vehicle

Once the speed rises and the ICE starts powering the vehicle the battery needs to provide less power. Whereas driving at constant speed the battery is charged in a hybrid configuration, however in an electric configuration the battery power is still above 0. During breaking the battery is charged more efficient in the hybrid configuration. The impact on the battery state of charge for both architectures under study is presented in Fig. 9. In Fig. 9 is visible that the battery state of charge for the hybrid architecture is maintained to the maximum value during this driving cycle by the contribution of the ICE.

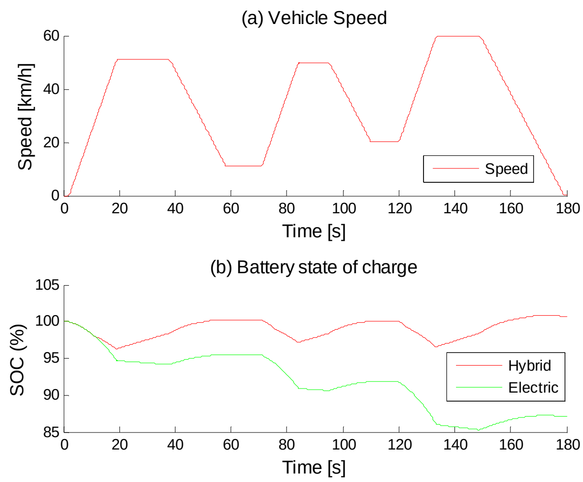

Figure 9. Battery state of charge – hybrid and electric vehicle

For the electric configuration, even if some energy is recovered through the regenerative breaking, the state of charge is decreasing. It is important to have a good estimate of the battery state of charge for hybrid electric vehicles in order to improve the energy efficiency. The importance of energy management systems in HEV is continuously increasing [16]. The simulation results from Fig. 8 and Fig. 9 were obtained with the same battery configuration: 200V Lithium Ion. The analyzed results show that an electric vehicle needs a different battery configuration compared to a hybrid vehicle to compensate the absence of the ICE and increase the driving range. The battery needs to have a higher voltage and a higher capacity but the vehicle will be less heavy due to the absence of the ICE, clutch and other parts specific to a classic or hybrid vehicle. In principle, an electric vehicle is less complex comparing to a hybrid vehicle. It has the benefit of being lighter and this brings an improvement to the driving range.

IV. Electric Architecture Assessment

With regards to the battery setup, the current paper proposes the usage of multiple rechargeable battery cells to create the electric vehicle battery. Multiple cells can be arranged in series and parallel in order to obtain the desired voltage and capacity. This approach offers a certain degree of independence when designing the battery. The proposed battery cell type is a NCR18650B from Panasonic. The rated capacity is 3.2 Ah, nominal voltage 3.6 V, height of 64.93 mm, diameter of 18.2 mm and weight of 47.5 g, as described in the corresponding datasheet. A proposal of arrangement for the battery cells is listed in Table III.

TABLE III. Battery configuration

Series	Series pack in Parallel	Total battery cells	Voltage [V]	Capacity [Ah]
100	10	1000	360	32
105	11	1155	378	35.2
110	12	1320	396	38.4
110	13	1430	396	41.6
110	15	1650	396	48

For example, 100 cells are connected in series and the resulted set is connected in parallel 10 times. This will result in a voltage of 360 V and a capacity of 32 Ah. The weight will be 47.5 Kg and the battery will have a volume of around 0.21 m3. The same calculation can be done for the other proposed configuration in Table III. Having a high degree of liberty in configuring the battery characteristics the right battery parameterization can be selected towards the designed vehicle architecture. EVs must make optimum use of the energy stored in the battery [17].

An accurate simulation technique can contribute to an exact assessment from an early design phase. In this paper, a set of simulations and corresponding data analysis are performed for the proposed values in Table III. The vehicle mass is furthermore consider in the case studies in order to extend the analysis scope and obtain a broader overview of the battery state of charge in different condition. An overview of the driving cycle used in the energy efficiency assessment of an electric vehicle is presented in Fig. 10.

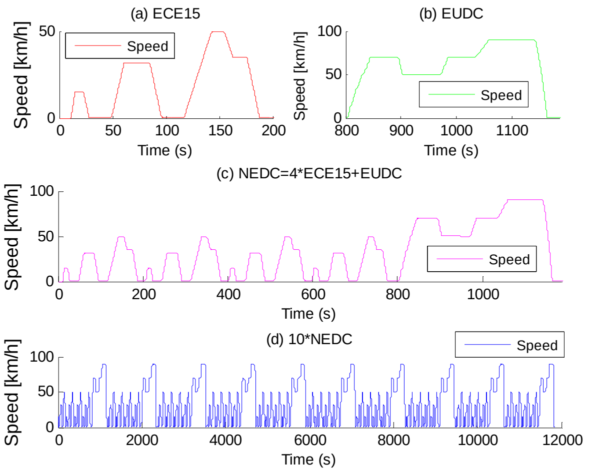

Figure 10. Driving cycle definition

The ECE15 is an urban driving cycle and is intended to represent city driving conditions. It is characterized by low vehicle speed and low engine load. The Extra Urban Driving Cycle (EUDC) has been designed to represent more aggressive driving modes [18]. The variant presented in this paper is an alternative EUDC cycle for low-powered vehicles. Four repetition of ECE15 followed by one EUDC represent the New European Driving Cycle (NEDC). The distance of an NEDC is 10.9314 Km in a time frame of 1180 seconds. The simulation in the present paper was performed over 10 NEDCs in a row having in this way an estimate after 109 km drive. The scope is to assess the value of the battery state of charge at the end of the driving session. The simulation of 11850 seconds assures a high amount of recorded data that supports a good assessment of the battery state of charge and electric vehicle autonomy. Different battery voltage, battery capacity and vehicle mass values were combined in a set of 25 case studies.

The battery characteristics were derived in line with the previous proposal of using battery cells. The simulation results are intended to assess the impact of these values on the vehicle performance and to validate the suggested setup. The evolution of the battery state of charge over the entire driving range is presented in Fig. 11. It is visible that the battery state of charge is influenced by the battery voltage, battery capacity and vehicle mass. A relative indication of the results for each case study sorted by the value of the battery state of charge is presented in Table IV. It is obvious that finding the proper input values in the design process the energy efficiency can be improved. Using the proposed approach of small battery cells and applying the analysis method, the efficiency of the design will increase.

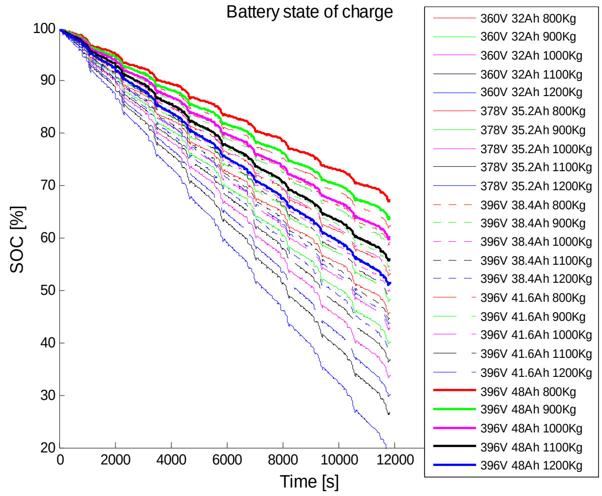

Figure 11. Battery state of charge – electric vehicle

During designing a battery pack, some cells can be swapped from series to parallel or from parallel to series. This will change the voltage or capacity. Rerunning the simulation with the updated values and considering the vehicle mass, the battery state of charge and vehicle autonomy can be estimated.

TABLE IV. STATE OF CHARGE - ELECTRIC

Battery voltage [V]	Battery capacity [Ah]	Vehicle mass [Kg]	SOC [%]
396	48	800	67.3205
396	48	900	63.9198
396	41.6	800	62.2455
396	48	1000	60.1268
396	38.4	800	59.0657
396	41.6	900	58.3103
396	48	1100	55.942
396	38.4	900	54.7941
396	41.6	1000	53.919
378	35.2	800	53.1425
396	48	1200	51.3656
396	38.4	1000	50.0258
396	41.6	1100	49.0712
378	35.2	900	48.2405
360	32	800	45.7608
396	38.4	1100	44.7587
396	41.6	1200	43.7649
378	35.2	1000	42.7632
360	32	900	40.063
396	38.4	1200	38.989
378	35.2	1100	36.7042
360	32	1000	33.6839
378	35.2	1200	30.0503
360	32	1100	26.6015
360	32	1200	18.7616

It is not always needed to use high values. It is important to use exactly what is needed at a certain moment in time. The simulation environment generates enough data, in order to make a conscious decision in terms of performance, cost, size and weight. A virtuous comparative overview leads to a robust design. The distribution of battery state of charge for the analyzed configurations is presented in Fig. 12. It is presented the last value of SOC at the end of the driving range. After 109 km, this value is between 67.3 % and 18.7

%, depending on the setup configuration. The simulation can be easily extended and additional data can be generated.

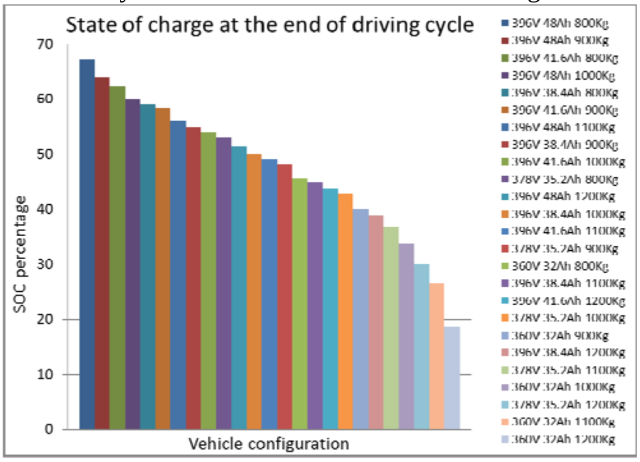

Figure 12. Battery state of charge assessment – electric vehicle

V. Conclusion

The proposed paper focused on developing simulation and analysis techniques, with the scope of improving the energy efficiency in hybrid and electric vehicles. Hybrid vehicle architecture was analyzed with regards to the battery state of charge and fuel consumption. The speed threshold representing when the vehicle changes from electric propulsion to ICE propulsion was taken in consideration and varied for different battery types in order to assess the impact on the energy efficiency. A comparative overview was generated and possibilities of making hybrid vehicles more electric were identified. The focus is to drive more on electric power, decrease the fuel consumption and emission level. The research was extended towards full electric vehicle architecture. Both hybrid and electric architectures were compared with regards to battery performance. Options to increase the driving range of an electric vehicle were identified. Another analysis method was proposed for estimating the performance of electric vehicles with regards to driving range. A proposal for battery architecture was offered together with simulation results and data analysis. A variation of battery voltage, battery capacity and vehicle mass was performed and the result was a relative summary of several electric vehicle configurations. The battery state of charge was assessed after a driving session of approximately 3.2 h. The most efficient configuration was identified (396V, 48Ah, 800Kg) and the applicability of the analysis was underlined. The present study offered a set of methods for simulation and data analysis intended to be used for prototyping purpose in the field of hybrid and electric vehicles. This approach would offer valuable performance estimation from an early concept phase. The scope is to support designing more efficient and competitive hybrid electric vehicles. The proposed method can be applied also on Hardware-in-the-Loop (HIL) systems. If HIL is applied the performance can be evaluated without actually installing that component in real vehicles [19]. HIL decreases the development cycle and the cost of vehicle controller [20].

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