Numerical analysis of the SOC factor variations' influence on the autonomy of an electric vehicle

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Abstract. Electric vehicles are considered to be the immediate solution to drastically reduce the pollutant emissions from the road transport sector. However, one of the barriers of the massive penetration of the automotive market by electric vehicles is related to consumer/driver anxiety linked to the autonomy of electric vehicles. Autonomy depends directly on the battery technology that equips the electric vehicle, and from this point of view, the technology based on Li-Ion electrochemistry is the most accepted. This article presents a study by numerical simulation methods on the functional performance (autonomy) of an electric vehicle equipped with three different types of batteries (LiCoO2, LiFePO4, and a classic Acid-lead), as they have a low battery energetic charge. The obtained results showed that there are differences between the various technologies considered, the most efficient one being the LiCoO2 battery type.

1. Introduction

It is widely accepted that the development and use of electric vehicles (EV) is the long-term solution for reducing today's transport pollution. EVs are already produced as passenger cars and buses for passenger transport, and shortly an electric propulsion group solution will be developed for freight transport vehicles.

However, the widespread integration of EV into transport systems involves overcoming current market barriers generally defined as [1-3]: Range satisfaction (autonomy); Sustainable technology; Vehicle's purchase price; Reduced greenhouse gas emissions; Costs of exploitation and maintenance.

It is noticed that one of the critical barriers in accepting EV by consumers is the one related to the autonomy of an EV. The autonomy of an EV depends on three main factors of influence: Vehicle design, Driver, and Exploitation environment [4]. In turn, these factors may be direct or indirect and are characterized by parameters such as: the vehicle's geometric dimensions, passenger capacity, body type, rolling train and tires, specific front area, tires, type of heating, ventilation and air conditioning systems, the behavior of the driver, climate conditions, traffic, route, road infrastructure, state of charge (SOC), state of health (SOH), battery type and energy capacity etc.

The most crucial role in the autonomy (range) of an EV, the largest is the amount of energy stored in the energy source (battery) estimated by the SOC parameter and evaluated by different researchers as being 50-60% from total [4].

The SOC parameter represents/defines the amount of instantaneous energy in the battery, available to be supplied to the electric propulsion group, being a parameter characteristic for each electrochemistry used in the construction of the batteries' cells.

The battery's SOC is calculated using Peukert's Law as [5]:

$$SOC_t = SOC_0 - 100 \cdot \int_0^t \frac{1}{C_{nom}} \cdot I \left(\frac{I}{I_{nom}}\right)^{k-1} dt \quad (1)$$

where: SOC_0 is the battery's initial state of charge, C_{nom} is the nominal capacity of the battery measured for the nominal electric current I_{nom}, I the electric current, k is Peukert's constant and t is time. Because Peukert's constant has a specific value for each type of battery cell (electrochemistry), the SOC value/variation will be different for different electrochemistry of cells. At present there are several types of batteries used as energy sources for EV (Li-ion, NiMH, Zebra, Li-Air etc.), each of which has different features in terms of energy performance, but Li-Ion technology has proven to be the fully-accepted solution for EV batteries, due to the immediate advantages it offers: high life (8 to 15 years), life cycles (2000 ... 5000) and high operating temperature range (-20 ... + 60oC) [6-8].

Lithium based battery technology also offers many functional advantages as the high potential of an electrode, high operating voltage, high discharge rate, the possibility of fast charging, low self-discharge rate, and no memory effect. Table 1 presents several features of the different technologies used in the construction of Li-ion batteries for EV, and Figure 1 is presented the performance of Li-ion batteries compared to other battery technologies [9].

Table 1. Characteristics of different Li-ion battery technologies (source [6-8])

Type	Energetic mass density	Energetic volumetric density	Charge/ discharge cycles	Price	Electric power	The maximal temperature of functioning	Cell's electric potential	The optimal range of operating temperature
	(Wh/kg)	(Wh/l)	-	(USD /Wh)	(C)	(°C)	(V)	(°C)
$LiCoO_2$	170-185	450-900	500	0.31-0.46	1C	170	3.6	-20…+60
$LiFePO_4$	90 -125	130-300	2000	0.30-0.60	5-10C	270	3.2	-20…+60
NMC	150-190	270-330	1500	0.50-0.90	2-5C	215	3.7	-20…+60
Li-Ti	65 -100	118-200	12000	1.00-1.70	10-20C	-	2.5	-50…+75
Li-Mn	90 -110	280	>1000	0.45-0.55	3-5C	255	3.8	-20...+50

Based on the above considerations, the paper aims to identify the effect of different SOC variation curves (specific to each type of battery considered) on the functional performance of an EV (autonomy). Both the functional parameters and the constructive parameters (Wh/kg) for each battery considered in the study were taken into account. SOC variation curves were experimentally determined within the experimental activities of the URBIVEL project.

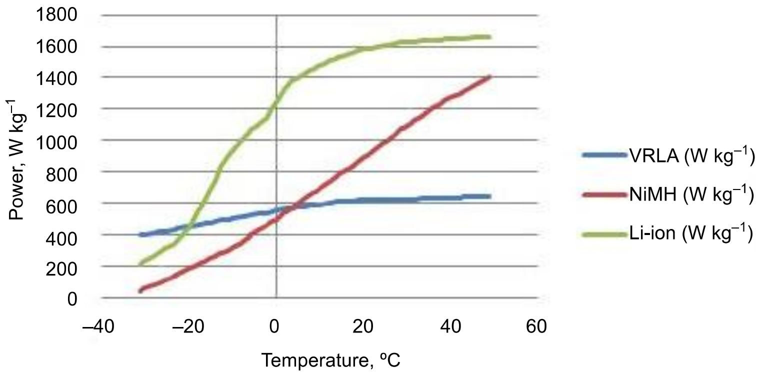

Figure 1. Energy performance of different battery types (technologies) depending on the operating temperature (VRLA - acid-lead accumulator) [9]

2. Methods

Numerical simulation methods (IPG CarMaker software) have been used, and the typical EV model considered was the Tesla Model S.

The Tesla Model S was chosen because it is a validated model in IPG CarMaker software, and the WLTC (Worldwide harmonized Light vehicles Test Cycle) was implemented, and the driver has to follow the velocity variation. The driver behavior was selected as a “normal” driver, meaning that the driver can go with a maximum velocity of 150 km/h, maximum longitudinal acceleration 3 m/s^2, maximum longitudinal deceleration -4 m/s^2, maximum lateral acceleration 4 m/s^2. The road was a straight line with no elevation, as required for the WLTC test cycle. The maneuvers were implemented as velocity requirements for the driver to follow.

The battery types that were considered in the present study were $LiCoO_2$, $LiFePO_4$, and a classic Acid-lead battery (APb). The significant difference between the chosen batteries is the SOC influence factor to idle voltage variation specific for each battery’s chemistry, as shown in figure 2. For each battery type simulations were done with the initial charge of the battery at 10%, 20%, 40%, 60, 80% and 100% respectively. The most important output factors that were followed were the vehicle’s autonomy (range), the vehicle velocity, and the variation of SOC of each considered battery.

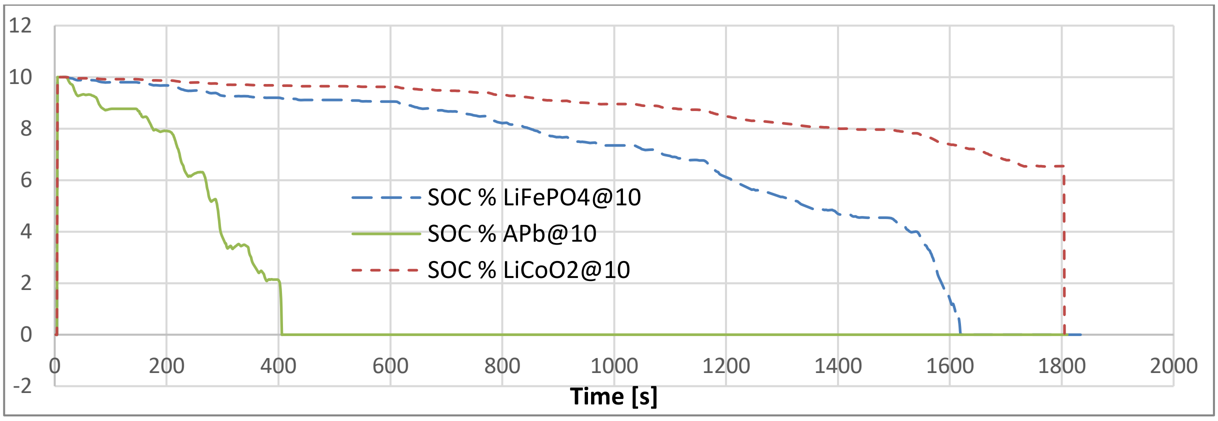

Figure 2. SOC for batteries starting with 10% initial charge

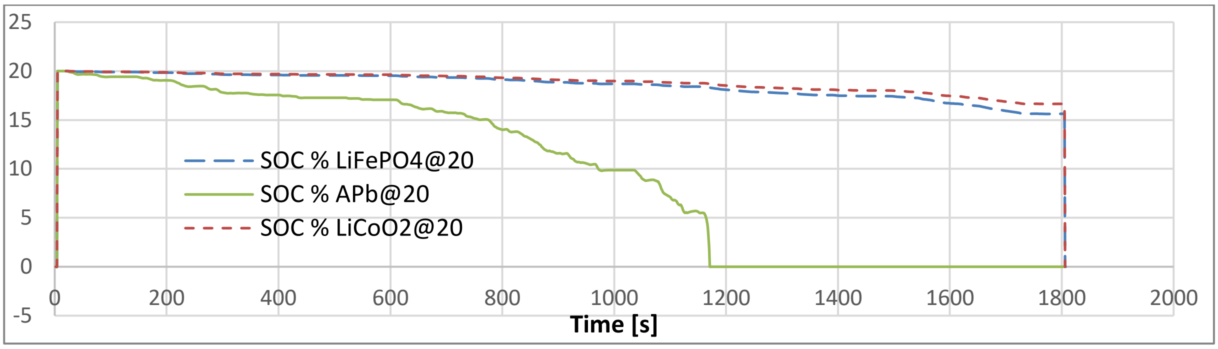

Figure 3. SOC for batteries starting with 20% initial charge

3. Results

The results of the simulation were extracted from IPG Control Data Window and exported to MS Excel to be further analyzed and interpreted. Figure 2 presents the variation of SOC parameter for the $LiCoO_2$, $LiFePO_4$, and Acid-lead battery, in the case when the vehicle starts on the WLTC test cycle with 10% of battery charge. Since the differences were significant, figure 3 underlines the SOC for all the batteries at an initial charge of 20%. Since the consumption of the batteries was small on the WLTC, the results for the 60%, 80%, and 100% battery charge are very similar and therefore not shown.

The typical evolution of the car distance when using the $LiCoO_2$ battery and the small difference when using the $LiFePO_4$ battery, with a considerable reduction in autonomy when using Acid-lead batteries which are not an energetic efficient solution for EVs, especially for low charging conditions (3127 m compared with 24078 m for $LiCoO_2$ and 19788 m for $LiFePO_4$).

4. Discussions

The analysis of the influence of the different types of batteries that can equip an electric vehicle is necessary because one of the major barriers that impede the massive penetration of the car market by the electric vehicle is the consumer's (the driver's) anxiety of being left with no energy. From this point of view, when designing and building an electric vehicle, it is necessary to take into account the battery's ability to provide the required energy for as long as possible.

From the numerical analysis, we can see that there are major differences regarding the autonomy that can be achieved both between the types of batteries used and the initial loading condition (considered as the initial moment of simulations). If the $LiCoO_2$ battery has reached the distance of 24078 m for an initial charge of 10%, the $LiFePO_4$ battery has been reached 19788 m and for the Acid-lead technology the result was only 3127 m. In the case of Acid-lead batteries, it can be argued that obtaining such a reduced distance was also due to the heavy weight of the battery pack, the weight that was taken into account in the numerical analysis performed. Therefore, it can be said that the best results (for each case considered) are the battery based on $LiCoO_2$ technology, the battery considered to be the second generation of Li-Ion batteries. The $LiFePO_4$ battery has lower performance than the $LiCoO_2$ battery but offers the advantage of having a much lower (approx. 15%) production price, which justifies the presence of this type of battery in the equipment of many electric vehicles (both passenger cars and buses). The $LiCoO_2$ battery has higher energy efficiency in that the maximum speed achieved is 134 km / h compared to 120 km / h for the $LiFePO_4$ battery.

All of these data lead to the primary conclusion that the $LiCoO_2$ battery offers the best performance in terms of efficient operation of an electric vehicle, especially when the battery has a low energetic potential.

5. Conclusions

The paper presents a comparative study of the energy potential of different technologies used in the construction of batteries for electric vehicles. Numerical analysis methods (IPG CarMaker software) were applied on a Tesla S electric vehicle, where three types of batteries were used.

The study highlighted the behavior of the electric vehicle in terms of its functional performance (the autonomy/distance that can be reached under different battery charging conditions), as the battery is relatively low at 10, 20 and 40% respectively from total charge capacity. For higher battery charge values ranging from 60 to 100%, there were no major differences about the achieved distance/autonomy between the batteries considered in the study. This difference arose for the special conditions under which batteries are discharged and when the electric vehicle systems need to provide accurate information about the remaining autonomy of EV. The most efficient batteries in this respect were those using $LiCoO_2$ technology, the worst results being the Acid-lead batteries.

It should be noted that the future hardware and software solutions developed for the SOC estimation must also take into account the electrochemistry of the cells from which the battery that equips the electric vehicles is formed.

Acknowledgments

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