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On the potential of regenerative braking of electric buses as a function of their itinerary

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Abstract

This paper proposes a mathematical model for an electric bus powertrain, implemented in a simulation platform. We intend to analyze the consumption of energy according to the route specifications and other performance measures. The potential for regenerative braking will be evaluated for different routes, since it depends significantly on them. It is expected that a "pattern" can be observed in that concerning the potential of the system to recover back some of the energy spent in its operation. Moreover, the use of supercapacitors to make this braking energy absorption is investigated.

Keywords: Electric Bus Performance; Regenerative Braking; Mathematical Modeling; Lithium-Ion Batteries; Supercapacitors

1. Introduction

The well-being of growing urban metropolitan regions is intimately connected to the provision of adequate and appropriate transportation systems, as it has a great influence and impact on regional patterns of development, economic viability, environmental issues, and on maintaining socially acceptable levels of quality of life (Murray & Stimson, 1998). However, in larger cities travel times are increasing at a high pace and one of the main reasons for that is the fast growth of vehicle registrations. This factor can be observed in Fig. 1, which shows the increase in number of cars per thousand habitants in the European Union (EU) along time, on the basis of increased

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populations, increased wealth and increased commercial penetration. Generally speaking, urban vehicular trips in such cities are made around 75% by transit, which means that making public transport work has high priority (Gakenheimer, 1999) as well as increasing investments on this sector.

Another factor that goes against a sustainable urban development is the impact of private cars on the consumption of land in space/time terms (land consumption in square meters per hour) (Camagni, 2002). Research carried out in the Paris region showed that the private car, which accounts for 33% of total trips, consumes 94% of road space/ hour, whereas the bus, with 19% of total trips consumes only 2.3%; in other words, a bus in movement consumes 24 times less space per passenger than a single car (Servant, 1996).

Another well-known disadvantage associated with the the large spread use of automobiles relates to Green House Gas (GHG) emissions. According to NASA, motor vehicles are the largest net contributor to global warming pollution, followed by the burning of household biofuels (i.e. wood and animal dung) and raising livestock (Unger et al., 2010). Besides, GHG emissions have negative effects on the earth's ecosystems as a whole; studies prove that by reducing the air pollution (namely fine-particulate) in 10 μg per cubic meter, an overall increase in life expectancy of 15% is observed (Pope, Ezzati, & Dockery, 2009).

In this sense, incentives and investment on conventional city buses – equipped with internal combustion engine – do not seem alone to be an adequate attempt at solving all the aforementioned issues. On the other hand, electric buses emerge as a more comprehensive solution to solve both the air pollution issue - due to the absence of tailpipe emissions - as well as the "urban chaos" problem.

Fig. 1. Number of cars per thousand habitants along time for the EU (Eurostat, 2011)

Electric buses also have plenty of other positive aspects. The electric engine causes far less vibration throughout the vehicle, which increases the life and reduces maintenance requirements of the bus, making it a cost-effective option for operators (Unger et al., 2010).Another quality associated with electric buses is their reduced noise. They are quieter than regular internal combustion engine buses, promoting higher comfort for those onboard. Although the initial introduction of an electric transport system and fleet can be costly, as a long-term mode of public transport they are surprisingly cost-effective (Unger et al., 2010).

Nowadays, there are already some electric buses in operation around the world. The Portuguese company *CaetanoBus* has launched its electric bus powered by lithium-ion batteries in 2011 for a 3-month test phase in Portugal. This company has also supplied one of these models for Offenbach, a German city where it will operate under regular service and which makes also part of the testing phase.

Sinautec Automobile Technologies (Sinautec, 2011) and its Chinese partner, *Shanghai Aowei Technology Development Company*, have spent the past three years demonstrating their supercapacitor bus model in China without any incident or failure. *BYD* (BYD - Build Your Dreams, 2012), a Chinese company and the largest supplier of rechargeable batteries worldwide, has also its own electric bus model – eBUS-12 – which started operations in Shenzhen and Changsha, China, in January 2011. The Fe battery (a technology of the company BYD) used on eBUS-12 is non-polluting, and the chemical materials contained in the battery can be recycled. The solar cells installed on top of eBUS-12 can supply more power to supplement the Fe battery. Another company that has developed its own electric bus using lithium-titanate *Altairnano* (Altairnano, 2011) batteries is *Proterra* (Proterra, 2011), which launched its newest model EcoRide BE35™ in California in 2010, for a testing phase.

There is a lack of appropriate tools to assess the regenerative braking abilities of electric buses. This is an important issue once electric buses have advantages regarding this matter, such as high weight, predicted routes and many stop-and-go episodes. Thus this paper will focus on the investigation of the amount of energy required to complete certain standard driving cycles, in order to evaluate the amount of energy that can be recovered by regenerative braking and observe whether there exists a pattern regarding this amount. This will be done through the application of a mathematical model developed exclusively for this purpose, as a way to simulate the behavior of an electric bus on an urban environment. The ability of the batteries to absorb the regenerative braking energy will also be analyzed, as well as the possibility of using supercapacitors for this purpose.

The remaining part of this paper is organized as follows: Section 2 approaches to the related work concerning the main subject of this paper: regenerative braking. Section 3 introduces the proposed approach to the problem and Section 4 defines the variables to be used on the mathematical model. Section 5 describes the experimental setup made for the simulations and section 6 concludes with final remarks and future work.

2. Related Work

It is easy to qualitatively describe the benefits from regenerative braking of vehicles, but a much more difficult analysis is required to quantify these benefits. Such an analysis requires determining a vehicles power requirements as a function of the driving cycle, establishing a realistic representation of the driving cycle and the characteristics of the regenerative braking system to be used in terms of control system, the algorithm to determine under what conditions the storage should be charged or discharged, along with establishing any possible decrease in the maximum power requirement from the primary engine or electric drive system that can result from the storage capability (Wicks & Donnelly, 1997). This statement resumes the difficulty we had in finding related work in what concerns the quantification of the benefits of regenerative braking.

Wicks & Donnelly (1997) analyze the upper limit of the benefit of regenerative braking on a municipal bus, which is a heavy hybrid vehicle with a certain driving cycle. They assume an ideal regenerative braking system in the form of a flywheel, which can be defined as having a 100% charge/discharge efficiency and no additional weight on the vehicle. The paper shows how the power for the cycle was calculated, but the methodology they used to quantify the potential energy to be recovered from regenerative braking is quite unclear.

Other papers that have regenerative braking as the main subject are focused on how to obtain the optimal efficiency of energy regeneration, once this is a very difficult matter, due to complex road conditions and the high sensibility of the converter to lose power. (Huang, Yang, Liang, & Gai, 2008) state that different control strategies, such as maximum regenerative power control, maximum regenerative efficiency control, constant regenerating current control, and so on, are usually put forward. However, there is the need for optimizing the control strategy so as to improve the entire vehicle efficiency. Thus they propose a solution to overcome this issue, namely the definition of a control strategy with algorithms, but the amount of energy that can be recovered on braking episodes is not calculated.

(Cikanek & Bailey, 2002) also propose a detailed description of the regenerative braking algorithm along with simulation results from a dynamic model of a hybrid vehicle, exhibiting the regenerative braking performance. Again, the focus is on the efficiency with which the vehicle is capable of absorbing the energy from braking, and not on the quantification of this amount.

(Lin et al., 2001) propose an integrated simulation tool of a hybrid vehicle and its further use for energy management control algorithms. They use a commercial simulator for simulating the dynamics of the vehicle and integrate it with Simulink for the further development of the control algorithms. Hence, the focus is primarily on the energy management control algorithms, such as in (Grbovi, Member, Delarue, Le, & Member, 2010) who discussed modeling and control aspects of the regenerative controlled electric drive using the supercapacitor as energy storage and emergency power supply device.

3. The proposed approach

A mathematical model of the electric bus performance was implemented in *MATLAB Simulink*. This model has several subsystems, which are used to calculate specific parameters. One of these subsystems represents the vehicle powertrain, taking into account the forces that work against its movement and the gear ratios involved. An output of this subsystem computes the amount of required energy for a driving cycle to be completed. There is a third subsystem that calculates the amount of energy that may be possibly recovered from the regenerative braking, taking into account the kinetic energy of the vehicle. The two other subsystems are related to the batteries and the supercapacitors, evaluating whether they are capable of absorbing the energy from the braking. The high-level scheme for this model structure can be observed in Fig. 2.

The calculation starts with the choice of the driving cycle, specified as an array of vehicle velocity versus time (at intervals of one second) (Malcolm A. Weiss, John B. Heywood & Andreas Schafer, 2000). This information is used to calculate the torque needed to operate the vehicle at each moment, considering tire rolling resistance, aerodynamic drag, climbing grade and vehicle inertia effects. Those effects combined compose what is called the tractive force, which is basically the force propelling the vehicle forward, transmitted to the wheels. The next section describes each of these forces and presents their mathematical equations.

Fig. 2. High-level model structure

3.1. Tractive Force

This force must overcome the vehicle resistance to the movement, which is composed by the sum of the different forces that act against its movement (Ehsani, Rahman, & Toliyat, 1997). This tractive effort has to accomplish the following (Larminie & Lowry, 2003):

- overcome the rolling resistance;
- overcome the aerodynamic drag;
- provide the force needed to overcome the component of the vehicle's weight acting down the slope;

- accelerate the vehicle, if the velocity is not constant.

The rolling resistance force, F_{ro}, is due primarily to the friction of the vehicle tire on the road, but friction in bearings and on the gearing system must also be considered. The aerodynamic force F_l is consequence of the friction of the vehicle body moving through the air. The hill climbing force F_{st} is the force needed to drive the vehicle up a slope. It may have a negative impact on the movement of the vehicle, acting indeed as a resistance force but also a positive impact, if the vehicle is going down a hill. A force has to be applied in addition to the forces already mentioned if the velocity of the vehicle is changing, to overcome it is inertia. The acceleration force F_{ta} will provide the linear acceleration of the vehicle (Ehsani et al., 1997; Larminie & Lowry, 2003; Malcolm A. Weiss, John B. Heywood & Andreas Schafer, 2000). The mathematical equations that define all those forces are listed below. The total tractive force F_{te} is the sum of the abovementioned forces.

- Rolling Resistance (Gillespie, 1992):

$$F_{ro} = f.m.g \tag{1}$$
$$f = (0.0041 + 0.000041.v.2.24).C_h$$

- Aerodynamic Drag:

$$F_l = 0.5.\xi.C_W.A.(v^2) \tag{2}$$

- Hill Climbing Force:

$$F_{st} = m.g.\sin\alpha \tag{3}$$

- Acceleration Force:

$$F_{ta} = m.a \tag{4}$$

Where:
f = rolling resistance coefficient
m = mass of the vehicle (kg)
g = gravitational acceleration (m/s^2)
v = linear speed (m/s)
C_h = road surface coefficient
ξ = air density (kg/m^3)
C_W = aerodynamic drag coefficient
A = vehicle frontal area (m^2)
v = vehicle speed (m/s)
α = grade angle

3.2. Torque, power and motor speed

The torque can be expressed by $F_{te}.r$, where *r* is the radius of the tire, and F_{te} is the tractive effort delivered by the powertrain. Assuming *G* as the gear ratio of the transmission system connecting the motor to the axle, and *T* the motor torque (Larminie & Lowry, 2003), it can be calculated according to:

$$T = \frac{F_{te}.r}{G} \tag{5}$$

After calculating the tractive force, it is necessary to know the amount of power required for each instant of the driving cycle. This power can be calculated as a function of the vehicle torque and motor speed, according to (Ehsani et al., 1997):

$$P = \frac{T.v_m.2.\pi}{60000.\eta_m.\eta_c} \tag{6}$$

Where:
$P = Power\ (kW)$
$T = Torque\ (N.m)$

$v_m = Motor\ Speed\ (rpm)$
$\eta_c = Controller\ Efficiency$
$\eta_m = Motor\ Efficiency$

The motor speed v_m in revolutions per minute can be calculated taking into account the linear speed, the perimeter of the wheel and the transmission gear ratio:

$$v_m = \frac{v.60.G}{2.\pi.r} \tag{7}$$

3.3. Kinetic energy

The next step is to define the kinetic energy of the vehicle, once it is known that the effect of the vehicle mass when accelerating and stopping the vehicle in urban conditions has considerable influence on vehicle performance. Basically when a vehicle of mass m (in kg) is travelling at velocity v (in m/s) its kinetic energy is given by the half of the mass multiplied by the square speed. If the vehicle brakes, this kinetic energy is converted into heat at the braking disks. When regenerative braking is used a certain amount of the energy is recovered. The kinetic energy is being used in this model for calculating the amount of energy dissipated in braking, considering the tires and air resistance and the climbing grade.

3.4. Variables definition

The data used hereafter is taken from an actual *CaetanoBus* electric bus, currently under its testing phase in Portugal. This electric bus has a brushless permanent magnetic motor, with a 650 N.m peak torque, 150 kW peak power also capable of working as a generator to allow regenerative braking. Motor efficiency data was extracted from the supplier's plot of motor efficiency versus motor speed and that can be represented by the equation bellow. The necessary parameters to calculate the tractive force can be observed in Table 1.

$$\eta_m = -3.(10^{-8}).(v_m^2) + 0.0002.v_m + 0.638 \tag{8}$$

Table 1- Variables Definition

Variable	**Value**
Tire Radius (r)	0.5 m
Road Surface Coefficient (C_h)	1.2
Vehicle Frontal Area (A)	10 m^2
Gravitational Acceleration (g)	9.8 m/s^2
Climbing Grade	0° (ground level)
Aerodynamic Drag Coefficient (C_w)	1.17
Air Density (ξ)	1.2 kg/m^3
Vehicle Mass (m)	17,048 kg
Controller Efficiency (η_c)	92%
Gear Ratio (G)	First Gear: 1:3 Second Gear: 1:1 Differential: 8.83

3.5. Battery data

One of the main assessments to be performed is whether the lithium-ion batteries are able to absorb the burst of energy that a braking can cause. Usually, this energy is converted into heat and dissipated through the brake system. Therefore, the question is how much allowance does the battery system gives for taking some of the work from the common braking system into the motor/generator and therefore recovering it back to the system and into the batteries. To proceed with the calculations, some relevant battery data has to be defined.

The battery selected for analysis was taken from the same *CaetanoBus* electric bus model as referred above. The most relevant battery data is presented in Table 2 (a).

It can be observed that there are both batteries in series and in parallel. In this case, there are 112 cells in series with a maximum charging voltage of 3.65 V each, which gives a maximum voltage of 408.8 V for the system. Analogously, batteries in parallels have their current capability multiplied by the number of cells in parallel. For this specific case the maximum charging current is 1 CA - 1 times the nominal current capacity of the cell, 3 Ah - totaling 420 A of maximum current capacity for the entire battery system.

However, due to charging characteristics of these batteries, the controller limits the current transference, and the amount of regenerative braking current allowed by it is 200 A, which is the value used for the calculations.

3.6. Supercapacitors data

In order to investigate whether supercapacitors are able of absorbing regenerative braking energy, some data should be defined to be used on the calculations. Due to their higher power density, it is expected a higher value for the amount of energy they can absorb when compared to batteries. The chosen model to be analyzed was from Maxwell Technologies (Maxwell Technologies, 2011), model *BMOD0063 P125 B03*, since this model is specific for heavy-duty vehicle application. Some important data of this supercapacitor is presented in Table 2 (b).

Table 2: (a) Battery data; (b) Supercapacitors data

(a)

Variable	**Value**
Type of Battery	LiFePO4
Nominal Capacity	3 Ah
Maximum Charging Current	1 CA
Maximum Charging Voltage	3.65 V
Number of Cells in Parallel	140
Number of Cells in Series	112
Weight	90 g
Total battery pack weight	1,411 kg
Total battery pack storage capacity	172 kWh

(b)

Variable	**Value**
Type of Capacitor	Supercapacitors Module
Rated Capacitance	63 F
Rated Voltage	128 V
Resistance	18 μΩ
Maximum Continuous Current (@40°C)	240 A
Peak Current, during 1 second	1,900 A
Weight	60.5 kg

4. Experimental setup

One of the most critical components of the simulation of a vehicle dynamics is the driving cycle on which all the vehicle calculations are based (Malcolm A. Weiss, John B. Heywood & Andreas Schafer, 2000). For this study, two standard driving cycles were chosen, in order to investigate the potential of energy recovery through regenerative braking, and evaluate whether there is a pattern on it. These driving cycles have in common the fact that represents an urban operation of a vehicle, with constant stops and low average speeds. One of them is the New York City Cycle (NYCC), as it has been developed to simulate low speed urban driving with frequent stops. The average speed of this cycle is 11.4 km/h and the distance covered is 1.89 km. The other one is the Urban Dynamometer Driving Schedule (UDDS) and simulates an urban route of 12.07 km with frequent stops, with an average speed is 31.5 km/h. As it can be observed, the distance travelled is quite different for each cycle. However, it does not represent an issue once the expected outcome of the simulations will be the percentage of the energy of the cycle that can be recovered through regenerative braking.

Fig. 3 shows in graphs both of these cycles.

The source of all calculations in the simulation program is the driving cycle. One file with the extension .mat was created for each driving cycle, as a way to make Simulink understand this data. From the data contained in this file, the program calculates the resistance forces, which are those that act against its movement, as already explained. Then, according to the speed with which the vehicle is running, the gear ratio is automatically chosen. This has direct impact in the calculation of the torque and consequently in the calculation of the power for each second of each cycle. Furthermore, based on the calculations previously described, the energy to complete a whole cycle is calculated by applying the integral of the power along time.

In parallel in the simulation program, the kinetic energy is calculated, and a routine was created in order to isolate the points where the vehicle brakes, so that it is possible to evaluate the kinetic energy at the moments of most importance for this work. Similar routine was developed to isolate the braking points on the resistances forces energy graph.

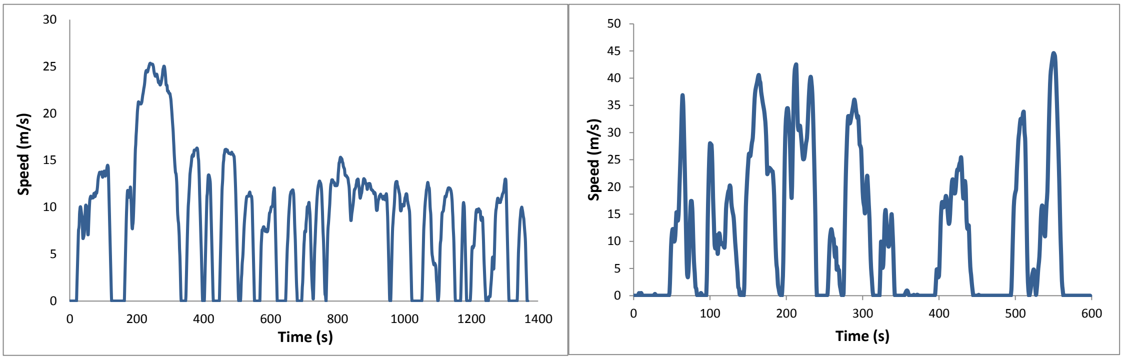

Fig. 3. (a) New York City Cycle (NYCC); (b) Urban Dynamometer Driving Schedule (UDDS)

A third part of the simulation program evaluates the performance of the batteries, applying the parameters previously defined in Table 2 (a). Similarly, an evaluation of the performance of supercapacitors, based on the parameters presented on Table 2 (b), is also carried out.

5. Preliminary results analysis

After running the simulation program, it was possible to calculate the amount of energy that each driving cycle requires for being completed, which is approximately 3.25 kWh for NYCC and 16.41 kWh for the UDDS (Fig. 4).

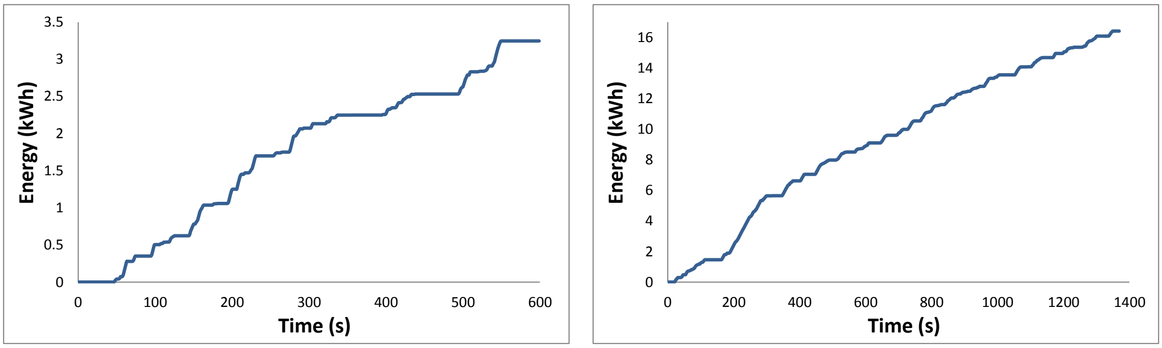

Fig. 4. (a) NYCC total energy; (b) UDDS total energy

The next step was to verify how much of this energy can be recovered through regenerative braking. In order to accomplish that, the kinetic energy was calculated for each point of the driving cycle that has a braking episode and as final speed 0 km/h. The resistance forces for each of these points were also calculated, transformed into energy and discounted from the master value of kinetic energy.

At this point, it is important to consider the efficiency of the motor when working as a generator, which is what happens during regenerative braking. By the supplier's datasheet, it can be observed that the worst-case scenario for efficiency in this case is 65% and this is the number considered for the calculation of the potential of recovering braking energy. Thus, the amount of energy that can be recovered through regenerative braking for the NYCC is 0.69 kWh, which represents around 21% of the total energy of the cycle. Regarding the UDDS, the amount of energy that can be recovered is 4.06 kWh, which corresponds to approximately 24% of the total energy necessary to accomplish the cycle.

It is important to state that, so far, it was considered the battery pack could absorb all the energy in every braking episode, which is not entirely true, as it can be observed in the next steps.

5.1. Battery analysis

In order to assess the potential of the batteries to absorb the energy dissipated on braking episodes, a specific analysis was carried out. Each chosen driving cycle has its own characteristics, such as duration of the braking episodes and amount of energy that each braking episode dissipates – once it has direct relation to the speed. Therefore, as a study case, a specific braking episode was picked up to be analyzed for each driving cycle. These braking episodes were chosen based on a worst-case scenario: the highest amount of dissipated energy in a short period of time. For the NYCC, it happens between instant 232 s and 240 s, an 8-second braking episode. In this case, through simulation analysis, 0.255 kWh of energy is dissipated. For the UDDS, we picked the 612 s to 620 s time period, also an 8-second braking episode, which dissipated 0.3 kWh. The performance of the batteries will be analyzed for an 8-second period and the ability of them to absorb energy will be observed.

By using the battery block from Simulink (in the absence of experimental data to perform an accurate battery performance model), and applying all the parameters of this block taking into consideration the amount of batteries in parallel and in series that the system has, the charging of the batteries for eight seconds was simulated, assuming an initial state of charge (SOC) of 50% and a constant current of 200 A (maximum allowed current for the regenerative braking). The outcome of this model is the evolution of the SOC and the voltage. By applying Eq. 11, it is possible to determine the amount of energy (in kWh) that the batteries were able to absorb in this period of time (Larminie & Lowry, 2003), as it can be checked in Fig. 5. (a).

$$E_b = \left(\int_0^7 (i.V)\right).3.6.10^{-6} \tag{9}$$

By analyzing the graph, it is possible to observe that the batteries are able of absorbing 0.17 kWh in 8 seconds. This value represents approximately 67% of the amount of energy that is dissipated while braking for the NYCC and 57% for the UDDS, values that can be considered quite significant. However, it is important to state that in a real system, this value would be lower, as the batteries efficiency should be considered.

5.2. Supercapacitors analysis

At this point, it is important to hold a study on the ability of supercapacitors of absorbing energy from braking episodes, and as a way of comparing to the performance of the batteries. As already stated, supercapacitors are known for their higher power density, a fact that leads to an important ability of absorbing a high amount of energy in a short period of time. On the other hand, they usually have a lower energy density when compared to batteries, which means that batteries are able of storing a higher amount of energy.

For this case study, it was considered the use of two modules in series. Therefore, the total rated voltage would be 256V and 31.5 F of capacitance. In order to know how much energy this system of supercapacitors can absorb, the first step is to calculate the amount of electric charge (C) it absorbs in time through the following equation (Brian E. Conway, 1999):

$$Q = C.V.(1 - e^{-t/RC}) \tag{10}$$

The time constant (RC) is expressed by the multiplication of resistance (in Ω - Ohm) and capacitance (in F - Farad). The next step is to calculate the energy (in kJ) from the information of electric charge, using:

$$E = \frac{1}{2000}.\frac{Q^2}{C} \tag{11}$$

Assuming the same simulation conditions used for the batteries, the equations presented related to supercapacitors were modeled in Simulink and the simulation was carried out. The graph presenting the energy versus time that these supercapacitors can absorb is showed in Fig. 5. (b).

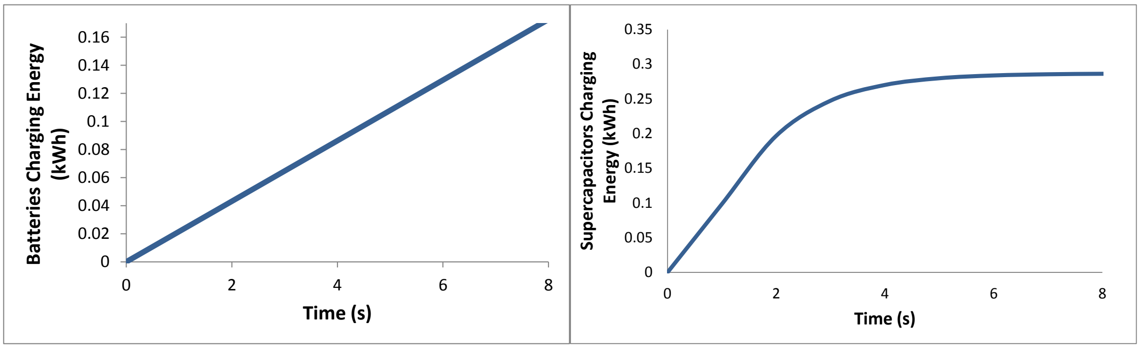

Fig. 5. (a) Batteries Charging Curve; (b) Supercapacitors Charging Curve

After running the simulation program, it could be noticed that they are able of absorbing 0.29 kWh of energy, which compared to the value of 0.255 kWh of the regenerative braking energy potential for the NYCC, makes them suitable for this application. In the case of the UDDS cycle, the amount of energy that the supercapacitors are able of absorbing represents 97% of the total dissipated energy on the braking, which is a much better number when compared to the batteries performance. This implies that the supercapacitors have a better performance than the batteries concerning the regenerative braking energy absorption.

6. Conclusions and future work

This work presents a mathematical model that was developed in order to calculate the required energy for completing two standard driving cycles (the New York City Cycle and the Urban Dynamometer Driving Schedule). This model was extended to account for the investigation of the ability of lithium-ion batteries and supercapacitors of absorbing bursts of energy originated in electric bus braking. It could be confirmed through the simulation model devised in this work that supercapacitors are able of absorbing much more energy than the batteries in such episodes, managing to absorb 100% of the chosen braking episode of NYCC and 97% of the one from UDDS.

It is important to mention that all calculations were performed taking into consideration the most critical scenario: the bus is circulating with full capacity of passengers. Another relevant fact is that the whole analysis was carried out considering specific braking episodes. If the braking episode had occurred in a longer time interval, batteries performance would be probably better, once they charge slowly. However, although the degree to which batteries could be better is not known, it is expected that supercapacitors would excel batteries for this sort of application, since the occurrence of braking episodes are usually short in time.

The results herein presented serve as an initial step for future further analysis, such as the possibility of replacing part of the battery pack of an electric bus by supercapacitors, which would lead to the decrease on the bus weight and the use of other energy storage device technologies dedicated to the braking energy absorption and their comparison to supercapacitors performance. By this time, other factors must be investigated and considered, such as changes in the autonomy of the bus, and the possibility of having partial charges at bus stops.

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