Sizing of motor and battery pack for an automotive electric vehicle given a specific route

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Sizing of Motor and Battery Pack for an Automotive Electric Vehicle Given a Specific Route

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Abstract— **This paper presents a strategy for sizing both an electric motor and battery pack for an automotive electric vehicle, given a specific route and function. In this case, the vehicle will be used to gather recyclable material on the Campus Darcy Ribeiro, University of Brasilia, Brazil, covering a course given by the location of the collection containers. To apply this strategy, a load and inclination study is used to set the torque and power needed from the electric motor. Then, a length and condition survey is made of the course, along with other data acquired from it, to set the necessary vehicle travel range, which will be supplied by the battery pack, thus, completing the electric motor and battery pack sizing.**

Keywords— **Electric motors, Brushless motors, Batteries, Electric vehicles, optimization methods, Battery pack sizing**

I. NOMENCLATURE

Utilized Notation:

m - mass [kg]
v - speed [m/s]
a - acceleration [m/s^2]
g – gravity acceleration [m/s^2]
 $g = 9.81$ m/s^2
r_{wheel} – wheel radius [m]
A_{front} – vehicle frontal area [m^2]
ρ_{air} – air density [kg/m^3]
 $\rho_{\text{air}} = 1.095$ kg/m^3
η_{motor} – motor efficiency [%]
c_{re} – rolling resistance coefficient
c_{d} – drag coefficient
 $c_{\text{d}} = 0.5$
θ – ramp angle [°]
P_1 – power one [W]
P_2 – power two [W]
P_{motor} – demanded motor power [W]
F_{roll} - rolling resistance force [N]
F_{drag} – drag force [N] [1]
F_{accel} – vehicle acceleration force [N]
F_{ramp} – weight force in a θ degrees ramp [N]
F_{trac} – tractive force [N]
T_{wheel} - torque on the wheel [Nm]
G - gear ratio
E - energy [J]

II. INTRODUCTION

Following the world tendency in the search for renewable energy sources and considering environmental awareness, the Project Ciclar, from the University of Brasília (UnB), carried out by professors and students from several engineering and design areas, propose the making of an automotive electric vehicle for recyclable material gathering on UnB’s Darcy Ribeiro campus. The vehicle will run only with electrical energy, using an electric motor to move and a battery pack as the power supply.

For the electric motor sizing, a demanded power and torque study is necessary. The vehicle will be used to collect and carry large amounts of recyclable material along a route with many ramps and imperfections, thus requiring definition of possible critical situations and worse case scenarios, so that the sizing calculations may be accurate.

It will be necessary to size a battery pack that is compatible with both the electric motor and the given route. So, all possible collection courses, their slopes, conditions and load variations due to collected material, must be considered. These data are needed to determine the necessary vehicle travel range that will be defined in the battery pack project.

Worldwide, several types of battery cells and electric motors are already available. Brushed DC Motors, induction Motors, Synchronous electric motors, Brushless DC Motors, and others. The same is true for battery cells, with Lead-Acid, Nickel-Cadmium, Lithium-Ion, and many more. In this paper, the advantages and disadvantages of each electric motor and battery cell available are considered, leading to the most suitable choice for the project.

Section III presents the complete study of the Electric Vehicle given route, showing the variables and information needed for the calculation done in sections IV and V, about electric motor sizing and battery pack sizing, respectively. Furthermore, the suitable choice for electric motor and battery cells for the project is shown in section VI. Section VII brings a brief explanation to a better known sizing method [8], followed by a result comparison of both results. Finally, section VIII sums up all the results and concludes the work.

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Data:

"Table I" presents pre-defined data for the electric vehicle:

TABLE I
PRE-DEFINED VEHICLE DATA

Unloaded Vehicle Mass	700 kg
Maximum Vehicle Load	600 kg
Loaded Vehicle Mass	1300 kg
Drag Coefficient	0.013
Vehicle Frontal Area	3 m^2
Losses between motor shaft and wheel	20%
Tire Diameter	0.52 m
Motor Efficiency	80%
Gear Ratio	1

III. VEHICLE ROUTE STUDY

The electric motor and battery pack sizing method, shown in this work, is based on the vehicle's given route and function.

Therefore, a complete and detailed study of this route was made. This study is important both to define the critical situations where the most will be demanded of the motor, in order to determine the travel range supplied by the battery pack.

The project Ciclar electric car will perform the selective waste collection within UnB's Darcy Ribeiro campus. Each university container holds up to 850 liters of recyclable material, arranged in close to 20 sacks of 3.53 kg, on average. So, each container provides up to 70.5 kg. Therefore, during the course, the vehicle load will increase gradually.

Four groups of containers were defined, named as A, B, C and D. For each group, there is a certain amount of containers and a given path. According to tables II and III, a distribution of scheduled collections was defined, based on the collection needs of each group.

TABLE II
PATH DETAILS

Path	Distance Traveled [km]
A	11,43
B	14,91
C	11,32
D	25,07

TABLE III
WEEKLY COURSE ORGANIZATION

Day of the week	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**
paths	AB	AC	AD	AB	AC	AC

Now, it's it is possible to calculate the travel range necessary for the vehicle. For that, the following must be considered:

The day with the longest paths is Wednesday, with a total of 36.5 km. Adding 20% safety margin, we have 43.8 km.

However, there may be a day when more than two paths are taken, due to any eventuality. Considering the worst case, in which the three largest ones are selected, and adding the 20% safety margin, we have a total of 57.38 km. Situations where more than these three paths are taken are not viable, due to overload or excessive time.

Therefore, the vehicle must have autonomy of at least, 57.38 km. Considering this course, we can set the ideal route out of many possible ones. However, the driver, for whatever reason, may decide his own course to collect the containers. So, the longest possible way, defined as worst route, was the base for the energy calculations.

These routes, both best and worst, are shown in Figure 1:

Fig. 1. Worst Route (red) and Best Route (blue).

The differences between the best and worst routes are basically, length, ramps and stops, which demand more torque and power from the electric motor and more autonomy from the battery pack. Over the worst route, the vehicle will be exposed to several speed, acceleration and ramp situations. The maximum ramp angle is 18º, with an average angle of 2º. The vehicle will also be made for a 60 km/h top speed.

Four common and four critical situations faced by the vehicle were defined, based on the total mass (given by the sum of the vehicle mass and the load mass), speed, acceleration and ramp angle, θ. Tables IV and V show these situations:

TABLE IV
COMMON SITUATIONS

Mass [kg]	**Speed [km/h]**	**Acceleration [m/s²]**	**θ [º]**
700	60	0.5	2
700	40	1.7	2
1100	40	1.2	2
1100	20	2.8	2

TABLE V
CRITICAL SITUATIONS

Mass [kg]	**Speed [km/h]**	**Acceleration [m/s²]**	**θ [º]**
1300	10	0.5	18
1300	15	0.5	18
1300	20	0	18
1300	0	1	18

The next sections will show the methods used to size the electric motor and battery pack, based on the given route studied.

IV. ELECTRIC MOTOR SIZING

In this section, the mathematical formulation, based on the data shown in Tables IV and V, for the calculation of the electric motor power and torque will be presented. To determine the power and torque, the calculation of applied forces on the vehicle will be needed, considering drag resistances, rolling resistances and vehicle total weight. The four main forces present will be considered: rolling resistance force, drag resistance, weight force on a θ degrees ramp and dynamic force [1].

Equating:

The four main forces present on the vehicle are defined bellow, form (1) to (4) [1].

$$F_{\text{roll}} = m.g.\ c_{\text{re}} \tag{1}$$

$$F_{\text{drag}} = \tfrac{1}{2}.\ \rho_{\text{air}}.\ A_{\text{front}}\ .c_{\text{d}}\ .v^2 \tag{2}$$

$$F_{\text{accel}} = m.a \tag{3}$$

$$F_{\text{ramp}} = m.g.sin(\theta\ .\ \pi/180°) \tag{4}$$

The potency is given by the force and the speed. In this case, it is given by (5).

$$P_1 = v.(F_{\text{roll}} + F_{\text{drag}} + F_{\text{accel}} + F_{\text{ramp}}) \tag{5}$$

For the motor power calculation, its efficiency must be considered:

$$P_{\text{motor}} = \frac{P_1}{\eta_{\text{motor}}} \cdot 100 \tag{6}$$

The vehicle wheel torque is given by (7).

$$T_{\text{wheel}} = (F_{\text{roll}} + F_{\text{drag}} + F_{\text{accel}} + F_{\text{ramp}}).\ \ r_{\text{wheel}} \tag{7}$$

Analysis and Results:

The power and torque calculations were made for the set of situations shown in Tables IV and V. First, the common situations will be analyzed. The demanded electric motor power and the wheel torque were calculated. The graphics below show the results for motor power, in kW, and torque, in Nm, for each situation according to the motor rotation, in RPM:

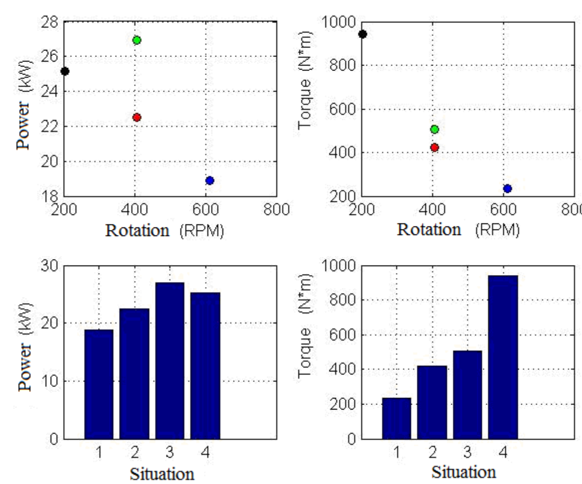

Fig. 2. Demanded torque and power graphics in each common situation.

Reading:

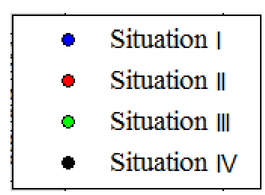

Table VI presents the demanded motor power and torque values for the common situations:

TABLE VI
TORQUE AND POWER VALUES FOR COMMON SITUATIONS

Situation	Power [kW]	Torque [N.m]
I	18.88	235.75
II	22.49	421.19
III	26.91	503.81
IV	25.15	941.64
Average	23.36	525.6

In the common situations, the average power and torque were 26.36 kW and 525.6 Nm, respectively. The greatest demanded power was 25.15 kW, which occurred when the vehicle had a load of 1100 kg, 20 km/h speed and a 2.8 m/s^2 acceleration.

Next the critical situations will be analyzed. The same calculations for the common situations were made resulting in the graphics below. They show the results of motor power, in kW, and torque, in Nm, for each situation according to the motor rotation, in RPM:

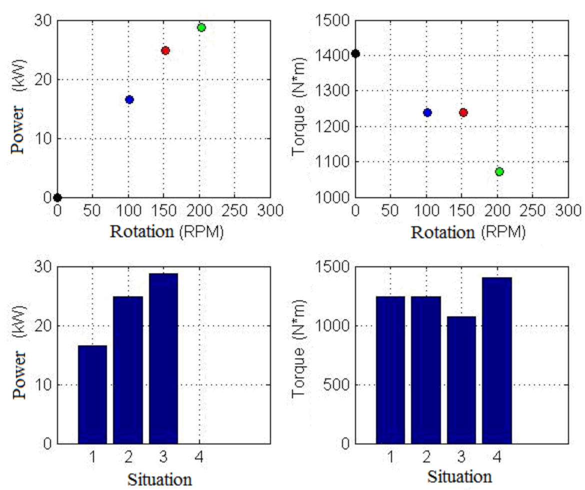

Fig. 3. Demanded torque and power graphics in each critical situation.
Reading:

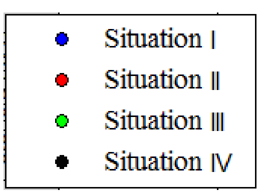

Table VII presents the demanded motor power and torque values for the critical situations.

TABLE VII
TORQUE AND POWER VALUES FOR CRITICAL SITUATIONS

Situation	Power [kW]	Torque [N.m]
I	16.52	1237.29
II	24.83	1239.36
III	28.67	1073.24
IV	0	1404.65

The greatest demanded motor power comes from situation III, with 28.67 kW power and 1073.24 Nm torque. Another important critical situation is IV, with no power demanded, but with a 1404.65 Nm torque. The no-power situations must be analyzed with the vehicle in low speed, and they are important for further sizing of the vehicle gear, since they show demanded torque.

There are several other situations that could be analyzed for more data but, for this paper's objective, the exposed data is enough. With the values obtained, it is possible to define the main characteristics of the electric motor.

From the common situations, there is an average demanded power of 23.36 kW. The maximum power in the critical situations was 28.67 kW. Based on the lowest and greatest demanded power, which are the common situation I and critical situation III, respectively, we can set that a nominal power for the motor would be at least 18.88 kW and the maximum power above 28.67 kW.

The greatest torque demanded by the motor was 1404.65 Nm, in critical situation IV. However, as will be seen in section V, there are no motors with such a high torque. So, a gear reduction system will be needed to adjust this value [5].

V. BATTERY PACK SIZING

The battery pack sizing for an electric vehicle with specific route and function is based on the study of the possible courses that will be taken. It will be necessary to determine the energy spent by the vehicle to run the worst possible route. This route has the largest course and the heaviest material load to collect, aside from other situations that increase energy consumption, such as more frequent stops and ramps. All this information is shown in section II, about the complete vehicle route studied.

Therefore, after determining the necessary energy, all that is needed is a battery pack that has an equal or almost equal amount of energy stored in it.

The battery pack sizing method developed consists of determining the speed variation during the given route. An experiment was made on the worst route, which consisted of:

I. Using a car with characteristics similar to the electric vehicle (700 kg mass and motor power of 20 kW);
II. Running the course, simulating the material collection, using an attached tow to increase the load.
III. Measuring the speed at each moment, using a GPS, not going over the electric vehicle limit of 60 km/h

The experiment result was a speed versus time graphic, shown in the picture below, using the software MATLAB:

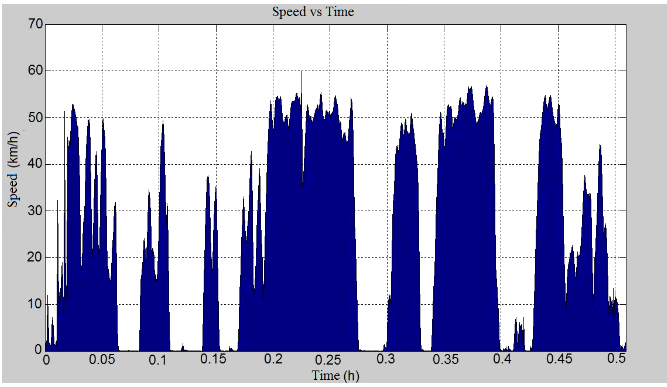

Fig. 4. Speed versus time graphic

From the speed versus time measures obtained, and considering traction forces, it is possible to obtain the power at each moment. Integrating this power results in the energy spent during the route, which is used to select the battery pack. This power is calculated in (8).

$$P_2 = v.\, F_{\text{trac}} \tag{8}$$

P_2 is the power and F_{trac} is the traction force and v is the speed. F_{trac} is given by (9) [1].

$$F_{\text{trac}} = F_{\text{roll}} + F_{\text{drag}} + F_{\text{accel}} \tag{9}$$

So,

$$P_2 = v.(F_{\text{roll}} + F_{\text{drag}} + F_{\text{accel}}) \tag{10}$$

Note that P_2 is different from P_1 by the term F_{ramp}. This term is disregarded here because, during the route, the ramp inclinations are already included in the speed versus time data.

The torque, also used, is defined as:

$$\mathrm{T} = (F_{\text{trac.}}\, r_{\text{wheel}})/\mathrm{G} \tag{11}$$

with T as torque, r_{wheel} the wheel radius and G the gear ratio.

Finally, the energy spent is given by:

$$E = \int P_2 \cdot dt \tag{12}$$

Where E is the energy in Wh. It can be calculated as the area below the Power versus Time Graphic.

Using the speed versus time data and the equations shown previously, a MATLAB routine was created to determine the energy needed to feed the electric vehicle.

The MATLAB routine consists of using the given data and traction forces to set the power at each moment. From that, a power versus time graphic is obtained, as shown below:

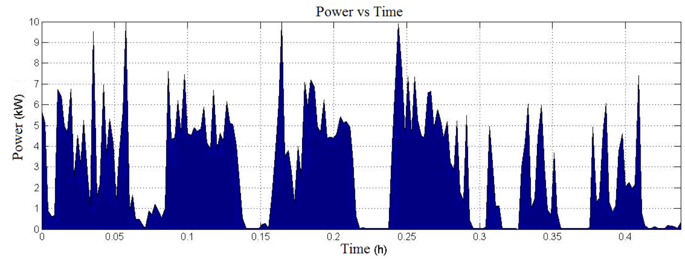

Fig. 5. Power versus Time graphic

Therefore, the area below the graphic, or the function integral, as shown in (12), can be used to determine the energy spent during the route. The results of these calculations show that the energy needed to run the route is 6.6742 kWh, resulting in a travel range of 54.05 km. These values consider the use of the whole battery pack charge. However, the battery pack charge must always be above 20%. Adding a 10% safety margin, we have a total of 9.5345 kWh.

With all the sizing data in hand, regarding both electric motor and battery pack, the next section, section V, shows a possible choice considering these elements.

VI. Electric Motor and Battery Pack Choice

The data obtained for the electric motor and battery pack sizing are: 18.88 kW nominal power and 26.67 kW maximum power, and a 1404.65 maximum torque, for the motor. For the battery pack, a total energy amount of 9.5345 kWh is needed.

The adequate choice for the electric motor to be used in the vehicle is based on the three main types of electric motors available: Brushed DC motors (BDC), Brushless DC motors (BLDC) and Induction Motors (IM) [4][5].

Based on the power and torque study, research on the possible motors was done. There is no motor that could reach the torque needed in the common and critical situations. So, we chose a motor with a high torque, but one inferior to that needed, so as to analyze the necessary gear reduction. Also, it is necessary to calculate the motor maximum rotation needed in order to define if a gear box will be used.

The electric motor was then chosen to meet some minimum specifications:

- Nominal Power >18.88kW / 23,11hp
- Maximum Power > 28.67kW
- Maximum Weight = 150 kg

The BDC achieves high torque values at low speeds. But it was discarded for low efficiency and excessive maintenance [4][5]. The IM, possessing low cost and easy maintenance, was also discarded due to the high complexity in transforming the battery pack DC voltage in to a three-phase voltage and for the high controller's cost [4][5]. The BLDC demands a high precision controller, for the activation of several coils must be made in regions that are very near Even though this sophisticated control raises the motor and controller prices, they hold some operational advantages over the BDC, like heat dissipation on the outer region of the motor, enabling smaller motors to be made [4][5]. Such advantages are important to the project, for the vehicle space is limited, and a motor with the lowest weight possible is needed [3].

From the motor comparison of the motors, it was stated that the electric motor which shows the best conditions and adaptability to the project was the BLDC. Below, we present the approximate specifications, in Table VIII, of the chosen motor that better satisfies the project's needs, aside from other advantages, as shown in the torque and power versus speed graphic on figure 6:

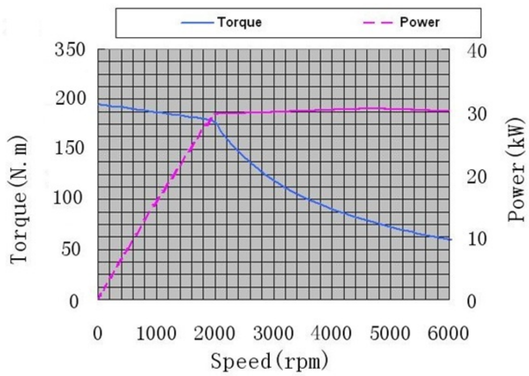

Fig. 6. Approximate curves of power and torque versus rpm of the chosen motor

TABLE VIII
CHOSEN MOTOR DATA

Nominal voltage	Nominal power	Max. power	Nominal torque	Max. torque	Efficiency
200 V	20 kW	30 kW	75 N.m	200 N.m	95 %

The chosen electric motor possesses both maximum and nominal power within the minimum specification desired. A gear reduction study was made since the vehicle demanded maximum torque greater than the maximum torque offered by the motor. For the gear reduction calculation, we must divide the demanded wheel torque by the torque offered by the motor [2], as shown in (13).

$$\text{Reduction} = T_{\text{wheel}}/\text{T}_{\text{motor}} \tag{13}$$

The maximum torque on the wheel is 1404.65 Nm. The motor has a nominal torque of 75 Nm and a maximum of 200 Nm. For the reduction calculation, a 170 Nm value is acceptable, not needing the maximum torque. Therefore, the gear reduction value found is 8.26. This is the value of the reduction G [2].

Also, the maximum rotation demanded by the motor must be calculated to evaluate the need for a gear box. An approximate 610 rotating speed will be needed on the wheel for the 60 km/h top speed. Using 650 for safety, the multiplication of this value by the reduction G gives us the motor maximum rotation, as shown in (14):

$$\text{Rotation} = \text{reduction x } 650 \tag{14}$$

The result was a value of 5370.7 RPM for the maximum rotation. Since the chosen electric motor has a maximum speed of 5600 RPM, there will be no need for a gear box.

With an electric motor selected, and having in hand its characteristics, we continue on to the battery pack selection, which will be used to feed the motor.

With all the data obtained, it is only necessary to select a type of battery that fits the vehicle and motor requirements. In this case, the project Ciclar, the electric car needs a high efficiency, long life, high energy density, security, and no battery memory effect. Table IX shows some types of battery cells and some characteristics, in averages, to justify the choice made.

TABLE IX
BATTERY TYPES AND CHARACTERISTICS

Battery	Lead acid	Nickel Cadmium	Ni-Mh	Nickel iron	$LiCoO_2$	$LiFePO_4$
Energy per kg [Wh/kg]	30-40	40-60	30-80	100	120	100
Cycles	500-800	2000	1500	200	1500	2000
Op. temp. [°C]	-20|50	-40|60	-20|60	-20|60	-20|60	-20|60
Cost [$/kW]	150	400-800	250	150-200	300	400
DOD	20%	20%	50%	20%	80%	80%
Observations	Toxic	Memory effect	High self discharge	Corrosion	Risk of explosion	No memory effect

According to Table IX, the battery type that best fits in the mentioned requirements is the LiFePO4 battery, since it has no memory effect and high energy density, aside from being considered the most promissory rechargeable battery from the weight reduction point of view [7].

However, the disadvantage of this type of battery is the need for a sophisticated monitoring system during the recharging process [6].

Within this universe of batteries, five well-known producers were studied, three of them Chinese and two North American. From the websites and phone calls, the data acquired from these producers are summed up in Table X:

TABLE X
MANUFACTURERS BATTERIES

Manufacturer	Weight	Variety	Shape	Energy density	Price	Controller price	Controller efficiency	N º of Cycles
1	III	I	II	III	II	I	IV	2000 to 3000
2	III	II	II	III	II	I	IV	2000
3	I	II	I	II	I	IV	I	2000
4	II	IV	IV	III	IV	I	IV	2000
5	I	III	II	I	III	III	IV	1500

Reading:

I. Very Good
II. Good
III. Regular
IV. Bad

Using data from Table X, the decision was made in favor of manufacturer three (3). They have characteristics closer to the ones required: size, weight and, of course, energy density.

To meet the demand of 9.5345 kWh, with an approximate voltage of 200 V, a battery pack of 47.6 Ah is needed. Therefore, battery cells of 50 Ah were chosen, each with a 3.2 V voltage. That way, 60 LiFePO4 cells are needed to complete the battery pack. This results in a voltage of 192 V. To achieve the 200 V voltage needed, a DC/DC converter could be used. But it would mean losses in efficiency and more complexity in the system. Therefore, adding 3 cells also fixes the problem, resulting in: 201.6 V voltage, 119.07 kg, 10.08 kWh, supplying a 58.65 km nominal travel range.

This 58.65 km range indicates that, when the battery pack reaches 20% of its total charge, it must be recharged. However, there is still energy to be used. Therefore, the maximum vehicle autonomy, which uses 100% of the battery pack charge, is a little above 73 km.

VII. COMPARISON WITH ANOTHER METHOD

The most common method of battery pack sizing [8] is based on the conversion of normal combustion motor cars in electrical vehicles.

Since these vehicles possesses no specific route or function, an over sizing is necessary to assure the vehicle works correctly in various different situations.

The application of this method is based on an average of energy consumption per kilometer. Given in kWh/km this average, for vehicles with a mass close to 700kg, 24 hp power and 60 km/h average speed is of 0.19 kWh/ km [8]. For the travel range of the project Ciclar vehicle, 57.43 km, and already considering the 80% maximum discharge and 10% safety margin, plus the 200 V motor voltage, we have the following calculation:

$$Ah = \frac{(0{,}19kWh \cdot 57{,}43km)}{0{,}7 \cdot 200V} = 77{,}94Ah \qquad (14)$$

Therefore, a battery cell of 78 Ah would be needed, or to connect cells with lower values in parallel. Considering a single cell voltage of 3.2 V, it would be 62 cells of 78 Ah. The total energy of this battery pack would be of 15.72 kWh. If applied to the project Ciclar's vehicle, it would result in 98.25 km nominal travel range or almost 140 km of maximum autonomy. We can see that theses values are extremely oversized, considering a daily route of 57.38 km, and this would mean extra costs that could be avoided using the method shown in this paper.

VIII. CONCLUSION

Considering the strategy described, it is possible to make the sizing of the traction system for an electric vehicle (electric motor and battery pack), with reduced capacity loss, given the specific function and route.

This strategy can be very useful in load transportation vehicles, as with the Project Ciclar's electric car, but also in public functions, such as electric buses, street-cleaning vehicles and others. The sizing method application in these cases is made easier, since the functions and routes of such vehicles are very specific, almost without daily changes.

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X. BIOGRAPHIES

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