Modeling of battery pack sizing for electric vehicles

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ABSTRACT

The paper presents the mathematical modeling for battery pack sizing to evaluate the vehicle energy consumption by using the derivation from Parametric Analytical Model of Vehicle Energy Consumption (PAMVEC) by Simpson in R Studio. The assess of storage batteries for electric vehicles (EVs) application is presented in this paper. The main source of power in EVs are batteries and to properly optimize their use in them, a parametric vehicle dynamic model is created and factors like battery mass, energy needed for the EV etc. are predicted using inputs such as battery specific energy, range etc. An assessment of output parameters is performed by using different batteries and compared to determine best battery for EV application.

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NOMENCLATURE

a	Acceleration	a	Vehicle acceleration (m/s^2)
g	Acceleration due to gravity	ρ	Density of air (~ 1.2 kg/m^3)
m	Mass of vehicle	C_d	Aerodynamic drag coefficient
A_f	Frontal area (m^2)	C_{rr}	Rolling resistance coefficient
C_{cell}	Cell capacity	g	Gravitational acceleration (9.81 m/s^2)
C_{rate}	Discharge rate of cell	z	Road gradient (%)
V_c	Cell voltage	k_m	Factor to account for the rotational inertia of the power train (k_m = 1.1 or 1.2)
f	Ratio between total cell weight to battery weight	T	Total journey time
V_{grade}	Gradient of vehicle with respect to road	v_{rmc}	Root mean cubed velocities
v	Voltage	v_{avg}	Average velocity
P_{road}	Road load power (W)	z	Gradient component
v	Vehicle speed (m/s)		

1. INTRODUCTION

Renewable energy resources (RERs) plays a very significant role in planning and operation due to no emissions and clean electricity production. During the last few years, a wide installation of RERs has been promoted to the power system. The energy production from these RERs is the leading solution towards the decarbonization of the society and the security of energy supply. However, various issues of intermittency of

RERs and the constraints for the connection of electric vehicles (EVs) should be effectively addressed [1]. Energy storage could be one option to handle the uncertainty of RERs. More efficient operation of market is required to accommodate flexible demand and electric vehicle (EV) charging and discharging. EV is a type of vehicle that uses electricity to run. There are three main components in EVs, i.e., electric motor, battery pack and a non-conventional transmission that transfers the motor power to the wheels. While driving, the battery power is used and depleting its supply. The batteries in EVs need to be charged regularly. The battery EVs offer about (100-150) km driving range before needing to be recharged [2]. But actual driving range depends on the driving style, speed driven, climate control usage and weather. EVs use low drag aerodynamic shapes, use highly advanced technology, reduced weight and fuel costs and zero emissions [3].

EVs are considered as an important technology to reduce fossil fuel consumption, emissions and energy consumption. But, the EVs require larger battery packs to reach acceptable range levels. The development of new batteries with higher specific energy could reduce the mass and the cost of EVs and increase their driving range [4]. The design and optimization of the battery pack in an EV is essential for the integration of EVs into global market [5]. EVs can also be used to smooth out the varying fluctuations in the energy profile of output energy generated by the sources. Energy storage from electric vehicles' batteries can act as a network of mobile storage systems, which can also help to support the grid by providing real backup power and improving the energy profile by providing reactive power compensation. Therefore, batteries are considered one of the widely used energy storage systems [6]. EVs are cheaper to run compared to conventional petrol/diesel vehicles, they are eco-friendly, cheaper to maintain, and can be charged from RERs such as solar, wind and geothermal, etc.

The batteries used for EVs are lead-acid, nickel-based, and lithium-ion. Lead-acid batteries were used in EVs in early generation [7]. The present trend for electric mobility is towards using lithium-ion battery. As lead-acid batteries are of low cost but they have low specific energy and have more weight. Nickel-metal hydride batteries were also prominence for the use of EVs, but lithium-ion batteries are more prominence towards the use of electric and hybrid EVs [8].

A battery-powered EV model along with a simple simulation-based iterative method of battery sizing is proposed in [9]. Reference [10] proposes a new battery cooling system for hydrogen fueled hybrid EVs that achieves more efficient cooling and driving, which increases vehicle driving range and enhances vehicle safety by maintaining the batteries at optimum operating conditions. A customer adaption cost that decreases with battery energy capacity is proposed in reference [11]. Reference [12] provides a basic guideline for cell selection and integration of cell for the EVs battery pack. An effective battery thermal management system solution is presented in reference [13]. Various EV battery technologies are presented in [14]. Modeling and simulation of battery EVs has shown in reference [15] that the choice of battery technology has a high impact on vehicle performance. Reference [16] proposes a mathematic model for the simulation of battery packs based on element wise calculations of matrices. The study and modeling of a lithium-ion battery cell is presented in reference [17].

For construction of future scenarios, trends in energy storage technologies were discussed in this paper. A simulation model which takes vehicle parameters and cell parameters (specific energy, voltage, discharge rate etc.) as inputs and provides estimates the energy storage requirement for the vehicle is developed [18]. It is observed that for likely future scenarios of battery technology, there could be significant positive impact on the cost and/ or performance of EVs. In this work, it is assumed that there is no change in the vehicle design or component sizing. The vehicle is assumed to remain same as in its present form, except the fact that the battery pack is constructed with cells of emerging technologies. Therefore, it is possible to have higher benefits as compared to the results shown in the present work. The application of these batteries for EVs is presented in this paper. The main source of power in EVs are batteries and to properly optimize their use in them, a parametric vehicle dynamic model is created and factors such as battery mass, energy needed for an EV are predicted by using inputs like battery specific energy, range etc [19]. An assessment of output parameters is performed by using different batteries, and compared to determine best battery for EV application.

The remainder of this paper is organized as follows: Section 2 presents the detailed mathematical modeling of battery pack sizing. Simulation results and discussion is presented in Section 3. Finally, the contributions with concluding remarks are presented in Section 4.

2. MATHEMATICAL MODELING OF BATTERY PACK SIZING

The prediction of range and performance of electric vehicles (EVs) is important. Three important parameters in this regard are range per charge of battery, maximum speed and acceleration. Development of a mathematical model to estimate these performance parameters for various hypothetical future batteries will require consideration of fundamental equations of the vehicle dynamics. The performance of a given vehicle depends to a large extent on the driving cycle it follows. A driving cycle is time vs speed profile of the vehicle. Since there are infinite number of possibilities for such driving pattern in real life, typically a standard time vs speed profile is defined based on statistical analyses and such a standard driving cycle is accepted for various regulatory purposes [20]. Modified Indian Driving Cycle (MIDC) is the driving cycle accepted in India. The fuel economy of vehicles are tested with respect to this driving cycle. Vehicle manufacturers in India report mileage/fuel economy with respect to this MIDC driving cycle. Similarly, standard driving cycles are available in other countries such as United States of America, Europe, and Japan etc. By using standard mathematical equations and spreadsheets, the simulation can be done in MATLAB and Excel sheets. Inputs to model are various vehicle attributes such as mass of the vehicle, its dimensions, gear ratio, wheel base speed, motor power etc., and it is necessary to have a good performance of the vehicle so that it can achieve the target of a current IC engine vehicle. Another important aspect for EVs is its range [21-22]. A mathematical model is developed to calculate the range of vehicle based on the type of battery and its capacity. Figure 1 depicts the road load equations of EV.

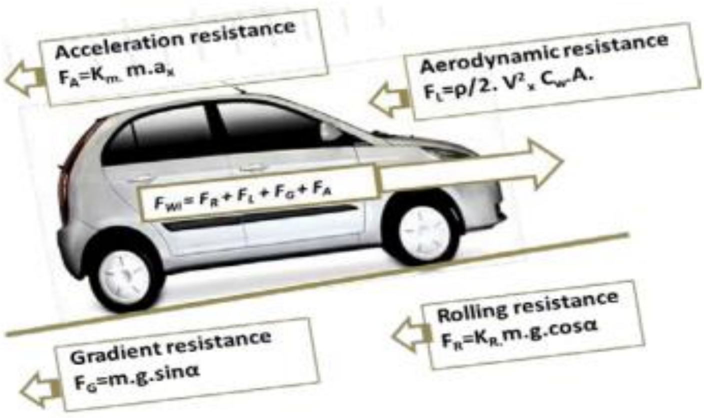

Figure 1. Flow chart of cuckoo search algorithm.

2.1. Power consumption by a vehicle

While running, a vehicle needs to overcome four forces opposing, they are motion - aerodynamic drag, rolling resistance, a component of its weight depending on the gradient, and its inertia. Since the power consumption is obtained by multiplying the force with velocity, and since the velocity of the vehicle changes continuously during its movement. Typically, simulators are used to estimate power consumption at each simulation steps. The energy consumption is obtained by integrating the power consumption values over time [23].

However, a parametric approach for estimating vehicle energy consumption has been introduced by Simpson et al. in reference [24]. The model developed by them is known as Parametric Analytical Vehicle Energy Consumption (PAMVEC). The fundamental concept of this approach is to de-couple the total tractive forces into two separate categories. First one comprises the aerodynamic drag and rolling resistance, which are non-recoverable. The other one comprises the gradient related force and inertia, which result in change in potential or kinetic energy of the vehicle, and can be recovered. Simpson et al. have shown that a driving cycle can be represented by four parameters: average speed, root mean cubed velocity, velocity ratio, and characteristic acceleration [25].

2.2. Average road load power

The modeling of vehicle energy consumption is approached by the parametric description of following road load equations [26],

$$P_{road} = P_{aero} + P_{roll} + P_{accel} + P_{grad} \tag{1}$$
$$P_{road} = \frac{1}{2}\rho C_d A v^3 + C_{rr} m_{total} g v + k_m m_{total} a v + m_{total} g z v \tag{2}$$

Equation (1) is the average road load power equation, and it consists of four components. P_{aero} and P_{roll} are irreversible power losses due to aerodynamic and rolling drag, whereas P_{accel} and P_{grad} are the power for vehicle acceleration and hill-climbing, representing the potential and kinetic energy, and they are recoverable [27]. This assumption makes P_{accel} and P_{grad} equal to zero, i.e.,

$$\int_0^T P_{accel} = 0 \; and \; \int_0^T P_{grad} = 0 \tag{3}$$

In order to parameterize the road load equation, it is assumed that a vehicle's journey is defined as including the return trip to its point of departure [28]. Similarly,

$$\int_0^T K_m m_{total} av \, dt = 0 \; and \; \int_0^T m_{total} gzv \, dt = 0 \tag{4}$$

These are valid as the net change in speed and elevation is zero. Since, the vehicle returns over the journey to its point of departure, the elevation and net change in speed is zero.

$$P_{road} = \frac{1}{2}\rho C_d A v_{rmc}^3 + C_{rr} m_{total} g v_{avg} \tag{5}$$

where $v_{avg} = \frac{1}{T}\int_0^T v \, dt$ and $v_{rmc} = \sqrt[3]{\frac{1}{T}\int_0^T v^3 \, dt}$. The driving pattern velocity ratio (Λ) is defined as the ratio of v_{rmc} to v_{avg}. From this, the average road load power is expressed as [29],

$$P_{road} = \frac{1}{2}\rho C_d A \Lambda^3 v_{rmc}^3 + C_{rr} m_{total} g v_{avg} \tag{6}$$

Equations (5) and (6) accounts for gravitational energy and inertial losses as a part of vehicle road load. These two losses are due to inefficient mechanisms in vehicle power train.

2.3. Average braking losses

The friction brakes dissipates the gravitational energy and kinetic energy stored within the inertia of the vehicle [30]. The average rate of energy stored is determined within the inertia of a vehicle. Therefore, to derive the average rate of energy storage, the following equation is considered.

$$P_{recoverable} = m_{total}(k_m a + \; gz)v \tag{7}$$

Let $a_e = k_m a + \; gz$. The gradient component and acceleration both can be represented by single acceleration term. The average rate of energy storage in vehicle inertia ($P_{inertia}$) is written by assuming the gradient of zero, i.e.,

$$P_{inertia} = \frac{1}{T}\int_0^T k_m m_{total} av|_{a\geq 0} \tag{8}$$

Here, to substitute a parametric equation, positive acceleration kinetic energy per unit distance (PKE) is introduced, which is a measure of acceleration work required in a driving pattern. PKE is the sum of distances between the squares of the final and initial velocities in successive acceleration, dividing by total trip distance. It is expressed by using [31],

$$PKE = \frac{\Sigma\left(v_{final}^2 - v_{initial}^2\right)}{D} = \frac{\Sigma\left(v_{final}^2 - v_{initial}^2\right)}{\int_0^T v \, dt} \tag{9}$$

The average rate of kinetic energy (KE) storage [32] in a vehicle during driving cycle is represented by,

$$PKE \times v_{avg} = \frac{\Sigma\left(v_{final}^2 - v_{initial}^2\right)}{T} \tag{10}$$

The average rate of KE storage in a vehicle mass during a driving pattern is expressed as,

$$P_{inertia} = \frac{\Sigma\left(\frac{1}{2}k_m m_{total} v_{final}^2 - \frac{1}{2}k_m m_{total} v_{initial}^2\right)}{T} \tag{11}$$

The equation for energy storage within vehicle inertia is given by,

$$P_{inertia} = \frac{1}{2} k_m m_{total} v_{avg} PKE \tag{12}$$

The above equation is a parametric expression for the average rate of energy storage, which is a consistent form of P_{accel} in equation (1). Therefore, the characteristic acceleration (ã) can be expressed as,

$$\tilde{a} = \frac{1}{2}\mathrm{PKE} = \frac{1}{2}\frac{\Sigma\left(v_{final}^2 - v_{initial}^2\right)}{\mathrm{v_{avg}T}} \tag{13}$$

The average rate of energy storage in the vehicle inertia over a driving cycle, assuming a flat road is given by,

$$P_{inertia} = k_m m_{total} v_{avg} (\tilde{a}) \tag{14}$$

The average braking losses can be defined by using the regenerative braking fraction (k_{regen}), and it can be expressed as,

$$P_{braking} = \left(1 - k_{regen}\right) \tag{15}$$

Then, the $P_{inertia}$ can be expressed as,

$$P_{inertia} = \left(1 - k_{regen}\right) k_m m_{total} (\tilde{a})\, v_{avg} \tag{16}$$

The equations (6) and (16) can be combined to get the average power requirement at the output on the driven axle of a vehicle, i.e., power at drive shaft is equal to power due to road load and power due to braking [33], and it can be expressed as,

$$P_{drive-out} = \frac{1}{2}\rho C_d A v^3 v_{avg}^3 + C_{rr} m_{total} g v + \left(1 - k_{regen}\right) k_m m_{total} (\tilde{a})\, v_{avg} \tag{17}$$

As k_{regen} tends to 1, braking losses tend to become zero, the potential and kinetic energy is returned for recapture of the power train. If there would be 100% efficiency of storage mechanism and energy recapture, no energy consumption would affect due to gravitation and inertia.

3. RESULTS AND DISCUSSION

In this paper, a spreadsheet model is developed to calculate the parameters of the Modified Indian Driving Cycle (MIDC), namely, average velocity, root mean cubed velocity, velocity ratio and characteristic acceleration**.** To model the impact of battery technology, it is important to predict the performance of a vehicle based in terms of criteria's, such as: top speed, i.e., maximum speed of the vehicle (km/h), driving range, and acceleration time, i.e., time taken for the vehicle to reach from minimum speed to maximum speed(s) (Table 1). The model considers input vehicle specifications and some details about the energy storage technology used are specific energy, specific power, cell voltage etc. The main outputs obtained are the maximum speed, range and acceleration time. After extracting the vehicle parameters form the specifications table, then the tyre outer diameter and motor base speed can be calculated.

The Indian driving cycle, i.e., speed vs time graph is depicted in Figure 2. The parameters of Indian driving cycle taken from spreadsheet calculation are as follows: total time is 196s, total distance < -1022.67km, $v_{avg} < -5.22$, $v_{rmc} < -3.26$, $A_{ch} < -0.27$ and velocity ratio < -0.62. Various constants considered in this paper are ρ is 1.225, g is 9.81, C_d is 0.3, C_{rr} is 0.01, k is 1.1, k_r is 0.3. Once the vehicle attributes are obtained, the motor and transmission efficiencies are assumed, and other such constants. The necessary values of v_{rmc} and v_{avg} are calculated from the velocities obtained from the drive cycles. And other parameters such as initial cell mass and maximum acceleration are also calculated.

The vehicle dynamics equations are now evaluated and the battery mass is optimized. The equations for mathematical model is taken from Parametric Analytical Model of Vehicle Energy Consumption (PAMVEC) by Simpson. It explains the energy consumption model which predicts the total energy consumed by the vehicle, by parametric driving cycle and vehicle attributes as an input. The derivation outlines the parametric formulation of road load equation.

The obtained results by using the proposed approach are: battery power is 17920W, battery energy is 12185.6Wh, maximum speed is 101.09 m/s, motor base speed is 9554.14rpm, acceleration time is 20.63s and energy consumption per km is 160.87Wh.

Table 1. Technical vehicle specification of Mahindra's e2O Plus electric vehicle.

Parameter	Value	Parameter	Value
Top speed	85 km/h	Grade speed	10 kmph
Target range	140 km	Overall gear	10.83
Acceleration minimum speed	0 kmph	Wheel diameter	14 inch
Acceleration maximum speed	60 kmph	Side wall height	99 mm
Acceleration time	9.5 s	Motor power	19 kW
Glider mass	1257 kg	Motor torque	70 Nm
Passenger weight	320 kg	Consumption	88 Wh/km
Cell specific energy	170 Wh/kg	Battery capacity	280 Ah
Gradient PC	18%	Number of modules	16
Frontal area	2.496 m^2	Number of cells	64
Pack voltage	72 V	Battery kWh	15 kWh
Cell capacity	70 Ah	Battery weight	112 kg
Discharge rate	0.5 C	Cell specific power	200 W/kg
Cell voltage	3.2 v	Grade speed	10 kmph
Cell to battery weight	0.8	Overall gear	10.83

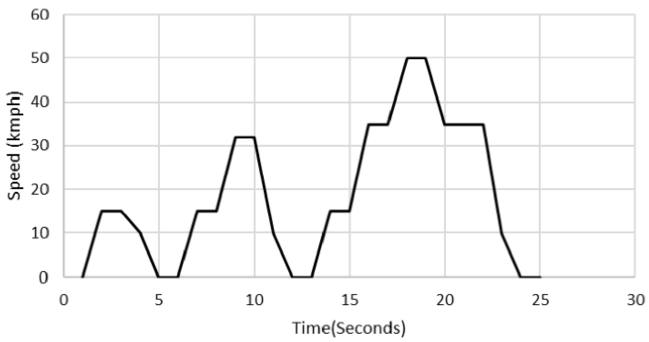

Figure 2. Indian driving cycle.

3.1. Impacts of future developments in energy storage technologies on EVs

Range/mileage: The mileage of vehicle can be improved if the specific energy of the battery increases. This results in longer driving range for the same battery mass. Hence, one will need lesser stops for charging, also leading to lesser impact on the grid. The goal is to achieve the range in an EV equal to what is seen in a petroleum based vehicles for the same amount of fuel (to achieve specific power close to that of gasoline/diesel in batteries).

Battery mass reduction for same power: If the power is kept same and the specific energy increased, then the mass can be reduced due to increase in energy output per kg weight. This in-turn effects the load of the vehicle and decreases the energy consumed per km, adding to the increase in range.

Lifecycle improvement: Development in batteries could also potentially affect the increase in lifecycles of the battery, leading to longer battery lifetimes, and hence increasing the life of the battery.

Faster charging: Development in batteries could potentially lead to faster charging (with same charging power) from the electrochemical change in the batteries.

4. CONCLUSIONS

This paper has analyzed the possible future improvements in energy storage technologies that have various applications such as electric vehicles (EVs). Modeling of battery pack sizing for EVs has been presented in this work. The objective of this paper is to conduct and analyze the impacts of futuristic/emerging battery technologies. It is not possible to consider detailed battery characteristics such as its charge-discharge characteristics etc., as such data are not available for the emerging battery chemistry. Such issues are typically considered at the time of actual design of the vehicle battery pack. However, this work does not require a detailed design of vehicle battery pack. The future work can be focused on flow batteries and their use in EVs and their impacts on EVs. As the flow batteries are also more efficient than the rechargeable batteries, but the disadvantage is of its structure. Therefore, more concentration on reducing the structure and weight of the flow batteries can be done.

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