

26,500km Down the Pan-American Highway in an Electric Vehicle A Battery's Perspective

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ABSTRACT

This paper presents a novel battery degradation model based on empirical data from the Racing Green Endurance project. Using the rainflow-counting algorithm, battery charge and discharge data from an electric vehicle has been studied in order to establish more reliable and more accurate predictions for capacity and power fade of automotive traction batteries than those currently available.

It is shown that for the particular lithium-iron phosphate (LiFePO_4) batteries, capacity fade is 5.8% after 87 cycles. After 3,000 cycles it is estimated to be 32%. Both capacity and power fade strongly depend on cumulative energy throughput, maximum C-rate as well as temperature.

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INTRODUCTION

The members of the Racing Green Endurance project (www.racinggreenendurance.com) designed and built the then longest-range (514km+) road legal electric vehicle (EV) in the world in 2010, and within 87 driving cycles drove it from the Arctic Circle in Alaska down to the southernmost city in the world, Ushuaia in Argentina. In doing so, the Radical SRZero shown in [figure 1](#) was the first electric vehicle to drive the entire length of the Pan-American Highway (26,500km).

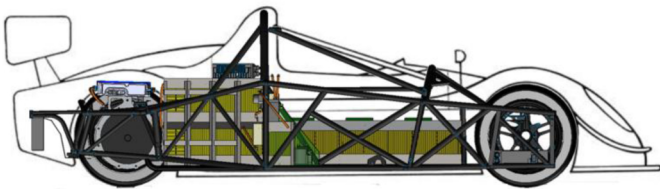


Figure 1. Technical Sideview of SRZero

The vehicle was exposed to extreme atmospheric and very diverse geographical conditions as well as to much varied states of road quality. Consequently, the drive along the Pan-American Highway tested the long-term durability and also the resistance to extreme conditions of this EV. Valuable data from the batteries and the electric powertrain has been collected for detailed analysis.

VEHICLE SPECIFICATIONS

The SRZero is a battery electric vehicle based on the chassis of a Radical SR8. It draws its energy from a 54 kilowatt hour (kWh) lithium-iron phosphate (LiFePO_4) battery pack placed at the back directly behind the driver's and the co-pilot's seat and in the two sidepods of the open-cockpit sportscar. The electrical energy is converted from DC to AC power via two motor controllers in parallel, mounted above the rear axle on top of two three-phase AC permanent magnet motors. These motors also act as generators while the SRZero is recuperating energy from deceleration and/or braking. The supervisory control is carried out by a real-time controller, a CompactRIO. [Figure 2](#) illustrates this powertrain setup.

The vehicle was designed for a very long range in order to cover long distances between built infrastructures in remote areas, where the EV could be recharged. Thus, a highly efficient and robust powertrain was the overriding design priority favouring endurance over speed. It also draws from the high system efficiency that the battery pack voltage was chosen to be relatively high (540V nominal voltage). This reduces heat losses due to high currents. Also, the motor shafts are directly connected to the wheels, making a gear box unnecessary and diminishing friction losses. Additionally, the EV only features the most necessary auxiliaries. These include lighting and radio communication powered by a 12V battery which also serves to start the car. Air conditioning, heating and entertainment systems are

omitted. Detailed technical specifications are listed in [table 1](#) below.

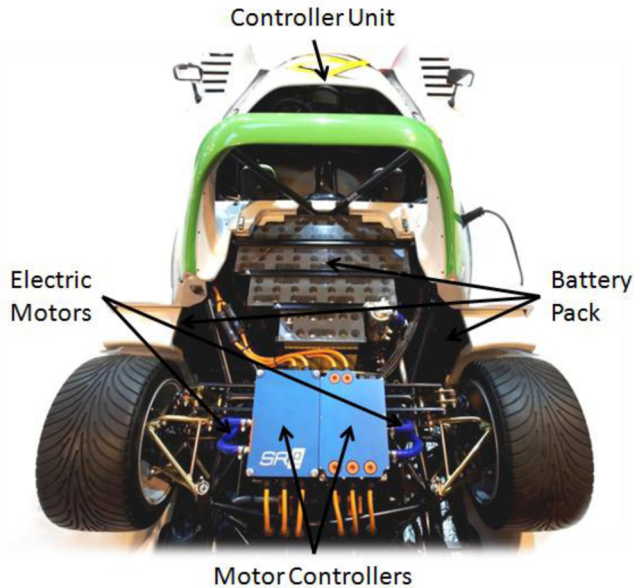


Figure 2. Powertrain Setup of SRZero

Table 1. Specifications of SRZero

Battery Capacity	54 kWh (100Ah)
Battery Type	LiFePO ₄
Number Cells	164
System Voltage	540 V
Battery Pack Weight	574 kg
Motor Type	3-Phase AC Permanent Magnet
Max. Power Output	300 kW (400bhp)
Max. Torque Output	1,300 Nm
Number of Motors	2
Drive System	Rear Wheel Direct Drive
Kerb Weight	1,150 kg
Length	4.2 m
Width	1.8 m
Height	0.8 m
Wheel Diameter	0.6 m
Frontal Area	1.44 m ²
Drag Coefficient C _d	0.38
Rolling Resistance C _r	0.015
Range	514 km+
Top Speed	190 km/h
Acceleration	7 s (0-100 km/h)

DATA ACQUISITION AND DATA ANALYSIS

The CompactRIO simultaneously serving as a real-time controller and also as a field-programmable gate array (FPGA) is used to implement an efficient and robust vehicle

control system. It controls the vehicle's battery management system (BMS) and additionally manages the motor controllers, driver interface and safety systems. [Figure 3](#) shows how the controller is embedded in the vehicle's configuration.

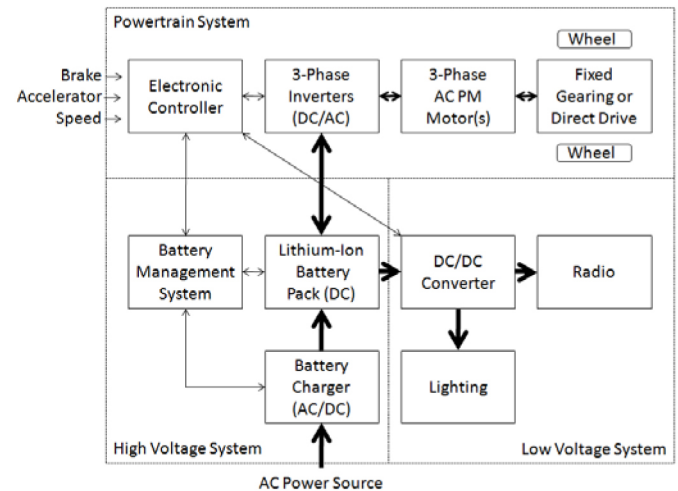


Figure 3. Configuration of SRZero

Most relevant in the context of this paper is the controller's ability to store data in real-time. The data logs sampled at a frequency of 1Hz include analogue and error state data, records from the chargers, the BMS, motor controllers and motors. The following subsections explain how this information has been analysed, first in terms of charge/discharge cycles and secondly in terms of battery characteristics.

CHARGE/DISCHARGE CYCLE ANALYSIS

A complete battery cycle is characterized by a full charge followed by a full discharge. In order to prolong the lifetime of any battery however, deep discharges should be avoided. The recommended depth of discharge (DoD) for the ThunderSky TS-LFP100AHA batteries that have been used for the SRZero is 80% [1]. Consequently, only about 43kWh of battery capacity can effectively be charged and discharged during one cycle. The battery capacity is usually quoted in Ampere-hours (Ah) which is the time integral of the current drawn from the battery pack, also referred to as Coulomb-Counting. An alternative way of expressing the capacity is in terms of energy i.e. in kilowatt hours (kWh). The battery capacity in kWh is determined by the multiplication of the Ampere-hour rating with the nominal system voltage.

It was decided to use existing infrastructure for charging purposes as opposed to a mobile charging unit. Consequently, the available power for charging varied significantly over the course of the test run. The charging power ranged from 1-10kW, averaging at about 3kW usually coming from single phase supplies. [Figure 4](#) displays a typical charging cycle for the SRZero with the relevant DC voltage, current and power

values. For the purpose of this paper energy flows in and out of the battery pack are most relevant, which is why AC circuits are not analysed in detail. Charging efficiency averaged at 93% which agrees with values found in the literature [2]. The particular charge shown in Figure 4 delivered 60Ah or 33kWh of charge capacity. In total, 5695Ah or 3,229kWh of DC charge capacity has been delivered during the 87 driving cycles in the Americas. This means that the average charging demand of the EV is 128Wh/km or 2.5mins of charging time for every kilometre driven from the average AC power source. Together with the average speed of 40km/h this highlights that during any 5mins 2 kilometres could be 'charged' or nearly 3.34km could be 'discharged'. Thus, time management has been very important throughout this lengthy test drive with the car either being charged overnight or being discharged during daytime at any given point in time.

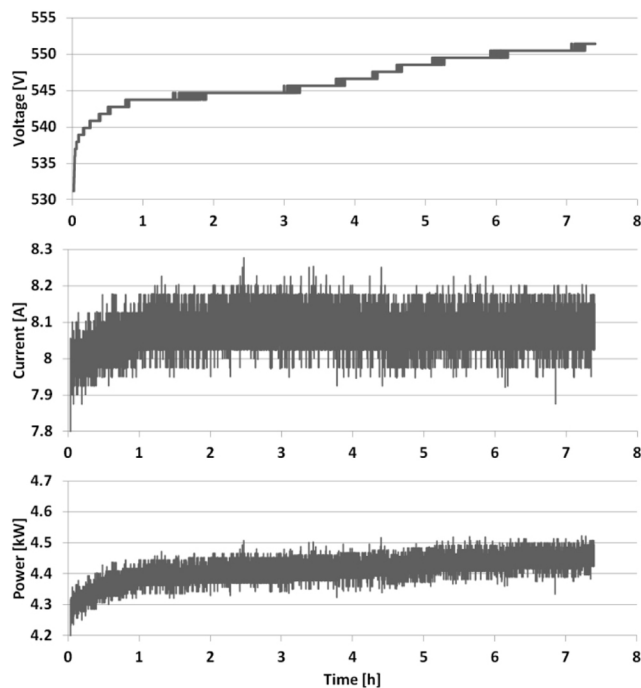


Figure 4. Typical SRZero charge cycle

Like the charging cycle, the typical driving (i.e. discharge) cycle tended to be relatively long as well. Usually, the two tended to last for about the same amount of time. The most relevant features of the discharge again include the data for the DC voltage, currents and power consumption. They are illustrated in Figure 5.

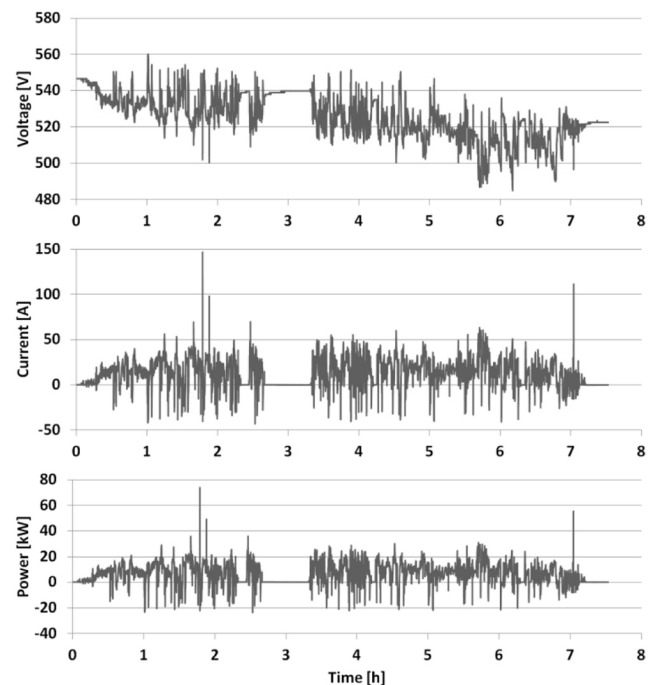


Figure 5. Typical SRZero discharge cycle

During this particular discharge 92Ah or 49kWh of discharge capacity has been used. In total, 5494Ah or 2,913kWh of battery capacity has been consumed along the Pan-American Highway. Thus, for every kilometre driven 110Wh of energy were drawn from the battery pack. This results in a battery efficiency of 90% (Coulombic Efficiency).

BATTERY CHARACTERISTICS ANALYSIS

The following sections are devoted to the analysis of the battery charge and discharge characteristics. First, an introduction as well as a summary of the state of the art into state of charge and battery degradation estimations is given. This is followed by the introduction of a novel battery degradation model.

State of Charge Estimation

Determining the exact and correct state of charge (SOC) is essential for the operation of an EV. The driver of the vehicle at all times needs to know how much energy he or she has left in the battery pack. More precisely he or she needs an accurate prediction of the range that the EV can still cover. So far, research was focused on SOC only, but range estimations based on GPS data and satellite navigation have become increasingly important. Range estimations are functions of SOC, temperature, driver behaviour, congestion, and the slope of the road. Thus, the SOC estimation forms an integral part of the range estimation. Here, it will be addressed in more detail. Fundamentally, there are two different methods of determining SOC: current and voltage based estimations.