Energy consumption and thermal analysis model for a Formula Student electric vehicle

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Abstract. The available range is one of the biggest issues regarding battery electric vehicles. In Formula student competitions, the endurance event requires the vehicle to be able to do 22 laps of a specific 1 km track. The possibility of finishing an endurance event must be analyzed during the development stage of any formula student vehicle to reduce the time needed for prototyping. This paper analyzes the performance of the vehicle during an endurance event using a specific battery configuration. Using theoretical calculations, a model in MATLAB was developed that allows the calculation of the energy consumption and battery temperature on the racetrack, based on the parameters of the battery. Fuel cells present a promising solution for powering the motors and were also considered and analyzed even if current regulations of Formula student prohibit the use of Fuel cells. This analysis can be used in case of a possible conversion to a Fuel cell powered vehicle in case the regulations are changed or to be tested on a prototype.

Keywords: Formula Student, battery vehicles, electric vehicle, fuel cells, energy consumption, thermal analysis

1. Introduction

Energy management is one of the main concerns during the development of a new vehicle. Knowing the energy required of the vehicle dictates the requirements of battery capacity and fuel cell power generation respectively, which are critical in the design phase of the prototype. Computer simulations can help to estimate energy consumption, battery State of Charge (SOC) and H_2 consumption of a fuel cell as well, necessary to achieve the required dynamic performance of a vehicle. Simulation models can be used before the battery or fuel cells are bought, to save money and time on the project side. Energy consumption of a vehicle is mainly influenced by the dynamic loads of the motors that are needed to overcome the road load forces. Also, parameters of the energy storage systems influence energy consumption. The number of cells, configuration of the battery/fuel cell, nominal voltage, internal resistances and the energy demand from the cooling system needed to maintain an optimal operating temperature[1,2]. When energy is released from a battery or fuel cell, it is followed by a heat release that increases their temperature. In the analysis of energy consumption, it is necessary to analyze the temperature evolution of the battery and fuel cells [1–3].

In recent years, different simulation models have been developed to assess the design decisions regarding the energy and thermal management of battery electric vehicles (BEV). Gjengedal et al. [2] developed a second order equivalent circuit model for LiPo battery cells to analyze the dynamic behavior of the battery using laboratory obtained test data. Hemlecki and Fabiś [4] analyzed the different possibilities of battery types and configurations for a Formula Student electric vehicle defining a systematic approach in battery design step. To increase the lifespan of electric vehicles batteries, Afzal et al. [5] used artificial neural network to adapt the droop control loop based on SOC.

Fuel cell vehicles have gained lot of attention recently, but their development is strongly dependent on the availability of hydrogen. Simulation models for fuel cell energy management usually consider the fuel cell stack, anode supply system, cathode (air) supply system, and the cooling of the fuel cells. Biberci et al. [6] developed a dynamic model to analyze the impact of operating pressure on power density. Hwang et al. [7] described the process of developing a lightweight vehicle and validated the decisions using real test data. Different machine learning (ML) algorithms have been used to evaluate the performances of proton exchange membrane fuel cells (PEMFC). Neural networks were used by Chavez-Ramirez et al. [8] to estimate the output voltage and temperature of the fuel cells. To increase the power density of fuel cells Li et al. [9] used a deep belief network to estimate the density of the current. Cell output voltage has been estimated using a convolutional neural network by Huo et al. [10] to reduce the testing of the membrane electrode. Since machine learning algorithms are difficult to implement if not enough data are available about fuel cells, a thermal analysis model was implemented by Liso et al. [3] for a fuel cell stack without using ML methods that can be used for thermal system design for fuel cell vehicles.

In this paper, by using MATLAB, the energy consumption and temperature rise of a High Voltage battery designed for a Formula Student electric vehicle were analyzed for different engine power limitation scenarios on the Most racing track (Czech Republic). After analyzing the battery performance, the vehicle was simulated on the same track using a fuel cell. For the fuel cell simulation, hydrogen consumption and fuel cell heating were analyzed after a full track lap.

2. Methodology

2.1. Battery simulation

The battery stack that equips the Formula Student vehicle was simulated to see how much the temperature rises and what is the SOC after an entire lap. The considered vehicle is equipped with two motors on each drive wheel, each producing a maximum power of 27 kW. The engines load profile is determined using a single mass point quasi-steady state model that the authors developed in their studies.

To analyze energy consumption, the main parameters of battery cells were integrated into the model (Table 1). The battery pack was assembled using 10 parallel connected stacks of 48 battery cells made by Sony/Murata US18650VTC6 [11] connected in series (48s10p).

Tabel 1. Battery cells main parameters [11]

Parameter	Value	Measuring unit
Nominal Voltage	3.6	V
Nominal Capacity	3	Ah
Thermic Capacity	50	J/K
Thermic Resistance	30.8	K/W

If the speed and torque profile is known in any point on the track, then the electric efficiency of the motors can be determined using the efficiency map from Figure 1 [12]. Once the efficiency of the engines is interpolated, the voltage available from the battery can be determined based on the state of charge and the battery cells discharge map (Figure 2). At the beginning of a lap, a predetermined SOC can be set. The assumption that all the cells are being discharged at the same rate was made, so that the discharge rate map could be used for only one cell. For the full stack voltage, it was calculated with the relation [13]:

$$U_b = U_c \cdot n_s \quad (1)$$

where: U_b is the voltage of the battery stack [V]; U_c – voltage of one battery cell [V]; n_s – number of series connections.

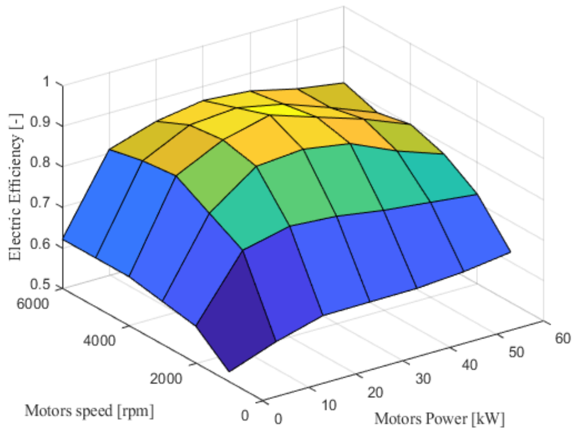

Figure 1. Efficiency map for combined electric motors [12].

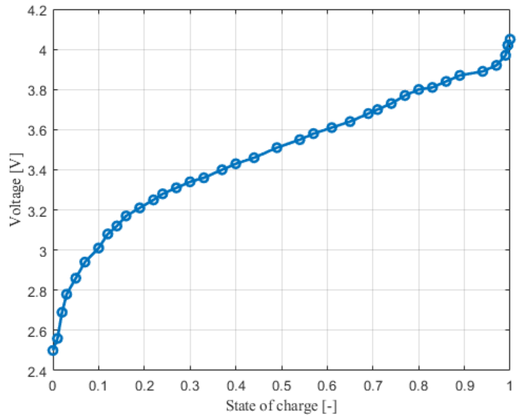

Figure 2. Discharge map of Sony US1865 0VTC6 [11].

The state of charge can be calculated if the electric energy consumed on each segment of the track is known. The electric energy needed (E_e) to power the motors was determined with relation [13]:

$$E_e = \frac{I_c \cdot dt \cdot n_p}{3600} \quad (2)$$

where: I_c is the battery cell intensity [A]; dt – time interval in which the vehicle is on the segment of the track [s]; n_p – number of parallel connections in the battery stack.

The battery cells' intensity (I_c) was calculated using the following relation, as it depends on the number of parallel connections in the battery [13]:

$$I_c = \frac{P_e}{\eta_{el} \cdot U_b \cdot n_p} \quad (3)$$

where: P_e is the engine power [W]; η_{el} – electric efficiency of the engine [-]. Considering that there is no regenerative braking or charging of the battery during a lap, the electric energy needed for each segment is subtracted from the total available energy of the battery. The division between the remaining energy and the total capacity of the battery is the state of charge, and it is updated at the end of each sector until the end of the lap with the following relation [13]:

$$SOC(i) = \frac{E_r(i-1) - E_e}{E_t} \quad (4)$$

where: *SOC* is the state of charge (between 0 and 1) [-]; i – position on track; E_r – remaining available energy in the battery [Ah]; E_t – maximum energy available in the battery [Ah].

The heat flux coming from the battery was calculated for every single cell, and it was assumed that all cells generate the same amount of heat. The main factors influencing heat release are the internal resistance of the battery cells (varies based on SOC (4) and rate of discharge (5)) and the current intensity

[13]. After the calculation of the internal resistance, the heat flux produced by the entire battery can be calculated using relation 6.

$$C_d = \frac{I_c}{C_c} \tag{5}$$

$$Q_p = I_c^{\,2} \cdot r \cdot n_s \cdot n_p \cdot dt \tag{6}$$

where: Q_p is the heat generated by the battery stack during a lap sector [J]; r – internal resistance of the battery [Ω]; C_d – rate of discharge; C_c – nominal battery capacity [Ah] [13].

The final step of the simulation of the battery stack was to calculate the temperature evolution of the stack during a lap. To do this, the following assumptions were made: all battery cells have the same temperature, the starting temperature of the battery is equal to the environmental temperature, the thermic resistance and thermic capacity of the batteries are constant. The temperature evolution of the battery was calculated using the relation [13]:

$$T_i = \frac{dt}{C_{thermal}} \left(\frac{Q_p}{n_s \cdot n_p \cdot dt} + \frac{T_{amb} - T_{i-1}}{R_{thermal}} \right) + T_{i-1} \tag{7}$$

where: T_i is the battery temperature at any point on the track [°C]; $C_{thermal}$ – thermal capacity [J/K]; $R_{thermal}$ – thermal resistance [K/W].

The battery's energy consumption was calculated at different positions on the track with relations (1-4). After the battery's current intensity was determined (3), the battery's temperature variation was calculated on all points of the track with relations (5-7). After one lap, the remaining energy of the battery and the battery's temperature are known.

2.2. Fuel Cell simulation

After simulating the battery stack for the Formula Student vehicle, the same vehicle was simulated using a fuel cell to provide the engines with the necessary energy. To simulate the fuel cell configuration and reduce the model complexity, the model takes into consideration the following assumptions: the load on the fuel cell is the same as for the battery stack configuration; in this simulation model the focus was on stack-level behavior so there is no explicit model for the humidifier, air compressor and back-pressure valve. These assumptions were made because complete fuel cell models require parameters that are not publicly available and may not be available during the development step of creating a fuel cell vehicle for a Formula Student application.

The voltage and intensity of the fuel cell were calculated based on the polarization map, which highlights the correlation between intensity and voltage of the fuel cell. This model does not consider dynamic polarization behavior under transient load, while voltage shows time lag, overshoot and hysteresis. In this model, the assumption was that, based on the load on the fuel cell, the fuel cell can provide the required voltage and intensity without lag. Taking this into consideration, the efficiency of the fuel cell is influenced by temperature and current intensity, and the system efficiency was selected from the fuel cell's efficiency map [1,14,15].

If the voltage, efficiency and current intensity are known, the needed H_2 ($\dot{m}_{H_2}$) to generate the desired power can be obtained using the relation [15]:

$$\dot{m}_{H_2} = \frac{P_e}{\eta_{fc} \cdot \eta_{el} \cdot LHV_{H2}} \tag{8}$$

where: η_{fc} is fuel cell system efficiency [-]; LHV_{H2} – lower heat value of H_2 [J/kg].

In order to evaluate the fuel cell's temperature, different assumptions were taken into consideration: the cooling of the fuel cell stack is done by air convection on the surface of the stack, and the heat generated by the gases in the fuel cell is ignored. Considering these assumptions, the following relation was used to calculate the temperature rate of change with respect to time [3]:

$$\frac{dT}{dt}=\dot{E}_t\text{-}E_{el}\text{-}\dot{q}_{conv} \tag{9}$$

where: $\dot{E}_t$ is the total energy flux generated by the Faraday law [W]; E_{el} – electric energy flux [W]; $\dot{q}_{conv}$ – cooling flux by air convection of the fuel cell [W].

Relation 9 can be rewritten so that fuel cell's temperature was determined as follows [3]:

$$\mathrm{T(i)}=T(\mathrm{i}\text{-}1)+\left(\frac{\mathrm{n_c}\cdot I_{fc}}{2\cdot\mathrm{F}}\cdot\Delta\mathrm{H}\cdot 1000\text{-}I_{fc}\cdot V_{stack}\text{-}\mathrm{k_{conv}}\cdot\mathrm{A_{fc}}\cdot(T(\mathrm{i}\text{-}1)\text{-}\mathrm{T_{amb}})\right)\frac{\mathrm{dt}}{\mathrm{CM_{stack}}} \tag{10}$$

where: i is the current vehicle's position on track; n_c – number of cells; I_{fc} – fuel cell intensity [A]; F – Faraday constant [C/mol]; ΔH – hydrogen enthalpy of combustion [kJ/mol]; V_{stack} – voltage of the fuel cell stack [V]; k_{conv} – convection heat transfer [W/m²K]; A_{fc} – fuel cell stack surface area [m²]; C_{fcth} - thermal capacity of the fuel cell [J/K].

By solving equations 8 and 10 for the entire load profile defined on the track, the temperature variation and the H_2 consumption analysis can be done. A structural approach to fuel cell vehicle modelling is shown in Figure 3.

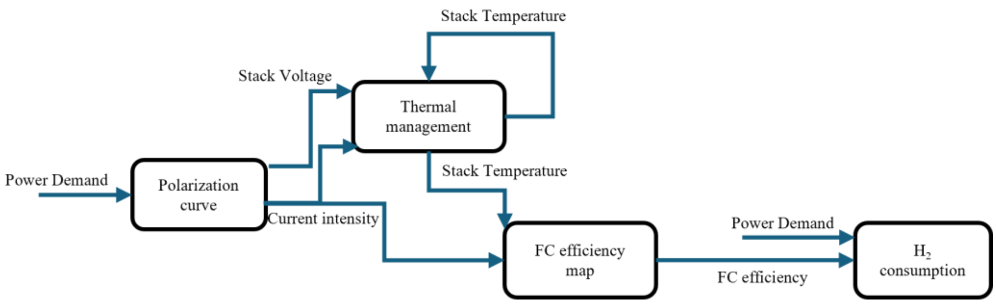

Figure 3. Fuel cell simulation strategy.

3. Simulation test cases

One of the main challenges at Formula Student competitions is the endurance and efficiency event. For an endurance test, it is required to drive the vehicle 22 km [16]. The Most track has a length of 1 km, and it will be assumed that the vehicle will behave the same for all 22 laps. The state of charge was calculated for one lap, and the difference between the SOC at the beginning of a lap and the end of the lap should not be higher than 4.5%. In case the vehicle cannot achieve this performance, the power available from the engines would be limited to different steps (at 25 kW and at 15 kW combined power), until the power demand is found so that the vehicle can achieve a SOC difference lower than 4.5% per lap.

After finding the correct power limitation for the motors. The vehicle was simulated on the same track using a fuel cell to power the engines. The fuel cell stack was modeled using publicly available data [14,15] and its parameters are shown in Table 2. For the fuel cell simulation on the track, H_2 consumption and temperature were analyzed.

Table 2. Fuel cell parameters [14,15]

Parameter	Value	Measuring unit
Number of cells	220	-
Stack active area	333	cm^2
Stack thermal mass	50	kJ/K
Theoretical voltage per cell	1.23	V

4. Results and discussions

The state of charge drop during a full lap is shown in Figure 4. As the power is limited, the energy demand on the battery decreases. When the entire tractive force is available for the engines to use, the SOC drop after one lap is highest, at 93.89% (from 100%). Once the power is limited, the SOC drop decreases, at a power limit of 25 kW the SOC drops after a lap to 94.43% and at 15 kW the SOC drops to 96.7%. The main disadvantage of power limiting is the decrease of acceleration performance and can be monitored in the total time for one lap. From the case where the full power is available to the case with only 15 kW available, the lap time increases by 3.42 s. The lap time increase is not so significant because the vehicle cannot use its entire tractive force on a road with lots of turns. The only configuration that can complete 22 laps is the one with the power limited to 15 kW, even if this will lead to an increased time to finish all laps by 75.24 s. If the SOC drop is the same for all the 22 laps, then the final available SOC after 22 laps will be 5.4%. As expected, the power limitations influence battery temperature (Figure 5) – at lower power availability, the temperature gradient in the battery is lower than the one at full power. If the power demand is not limited, then the temperature of the battery increases to 40.04 °C (considering the starting temperature 30 °C) after one lap. When the power demand is limited at 15 kW the temperature increases to 33.41 °C. In both cases, only natural convection by air is available. For multiple laps, forced cooling systems are necessary.

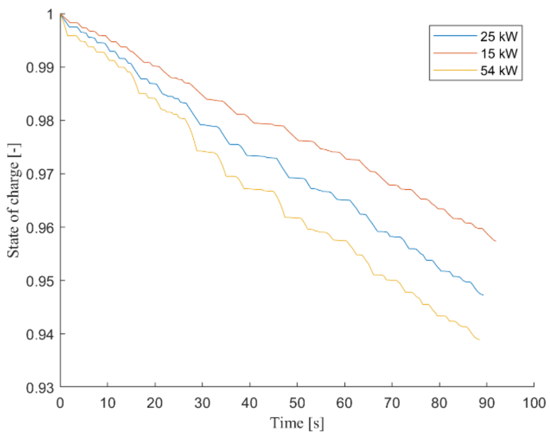

Figure 4. State of charge drop at different power limitations.

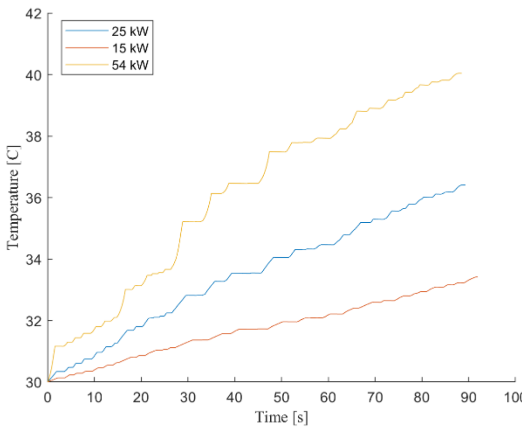

Figure 5. Battery temperature rise at different power limitations.

Because the vehicle cannot use its entire power during an endurance event, the vehicle was simulated with a fuel cell stack instead of a battery. In this case, for the vehicle to do an entire lap, the total needed

H_2 was calculated at 16.4 g (Figure 6). This means that for an entire endurance event, the needed H_2 is around 366 g. To store the H_2 needed to complete an endurance test at a pressure of 700 bars (considering the H_2 density at 700 bars at 42 kg/m^3 [17]), a 10 liters tank would be necessary. For the temperature simulation, the starting temperature of the stack has been set at 65 °C, to simulate the fuel cell in the optimum working domain. During a single lap, the fuel cell stack temperature does not increase above the optimum working range (65 °C to 85 °C), so natural air convection cooling would be enough [3]. For the entire endurance event, the temperature would rise above the optimal temperature range and additional cooling would be needed.

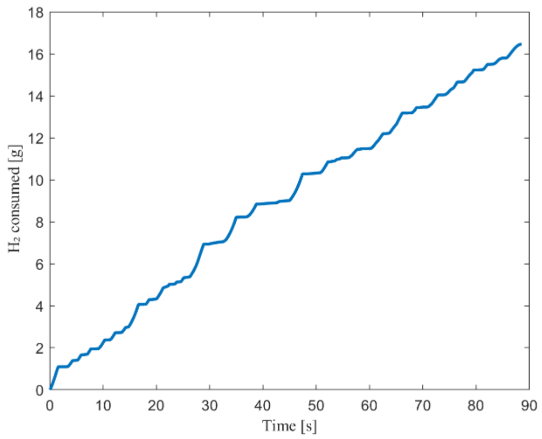

Figure 6. Hydrogen consumption during a lap.

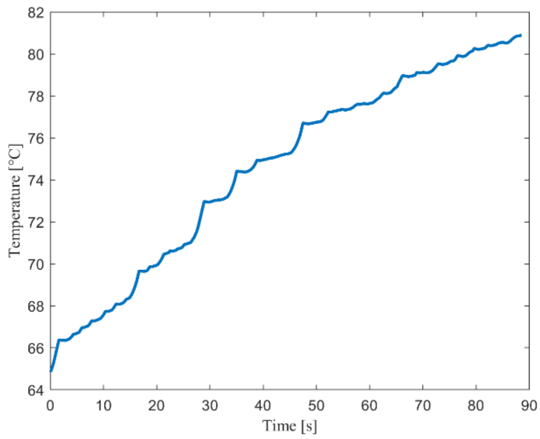

Figure 7. Fuel cell temperature rise during a lap.

5. Conclusion

A battery state of charge and thermal model was implemented for an electric Formula Student vehicle. The battery performances were analyzed at different loads from the two electric engines by limiting the power demand on the battery. Limiting the motors' power, increased the available SOC by 3% compared to the full power model. This increase in available SOC allows the vehicle to finish an endurance event. When the power is limited, the battery does not generate the same amount of heat, so the temperature after one lap decreases by 16.55% compared to the temperature after a lap with all the power available. Even if the power limitation allows the vehicle to finish the endurance event, the total time needed to finish the event will increase by 3.71% and can affect the final score. To allow the entire power of the motors and finish the endurance event, battery cells with a higher density of energy can be used, or the current number of battery cells can be increased.

If only a fuel cell is used instead of a battery to power the two motors, the hydrogen needed to do an endurance test can be stored in a 10 l high pressure hydrogen tank, but the actual fuel consumption can be reduced if a high voltage battery is used in parallel with the fuel cell. The battery's role would be to assist the fuel cell during highly dynamic load scenarios, where the fuel consumption increases.

Both configurations (battery and fuel cell), require additional cooling for an endurance test, natural convection cooling not being enough for more than one lap.

To further develop these type of models, additional cooling methods can be implemented, and hybridization between fuel cells and a lower capacity battery stack can be implemented to analyze the impact on hydrogen consumption.

6. References

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