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# Electromobility concept for racing cars based on lithium-ion batteries and supercapacitors

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ABSTRACT

For the construction of an all-electric race car, all aspects from engineering design over cost estimation up to the road capability are illuminated. From the most promising batteries for electric vehicle propulsion, the state-of-the art and commercial availability of lithium-ion secondary batteries is critically discussed with respect to cycle-life and unfavorable charge–discharge conditions. A market-overview is given with respect to a small electric car. Different combinations of electric motors and a recuperation system have been investigated. Weight aspects of central drive systems were considered and compared with decentralized wheel-hub drives. As a result, a centralized high-speed drive train based on a permanent-magnet synchronous engine with high-energy magnets seems to be superior due to limited space for assembly.


## 1. Introduction

The Formula Student competition among the universities all over the world pursues the construction of a prototype racecar. A group of students at the UAS in Amberg has been handling all aspects from engineering design over cost estimation up to the road capability of an electric car. There are three major challenges.

(1) *Design and construction.* The ambitious performance specifications of the all-electric vehicle require intensive experience in building and manufacturing, as well as considering new materials and the economic aspects of the automotive industry. The racecar must provide excellent driving characteristics such as acceleration, braking and handling. And it must be produced at a minimum of cost.
(2) *Drive train.* Different combinations of electric motors (such as induction, brushed and brushless DC or reluctance machines, gears and frequency inverters) must meet the demand of high driving performance. Weight aspects and performance of central drive systems have to be compared with decentralized wheel-hub drives. Although a recuperation system could reduce electric energy consumption, the additional equipment and weight might be considered critically.
(3) *Secondary battery.* The most promising batteries for electric vehicle propulsion have to be selected. Special attention is required by the performance data and cycle-life of lithium-ion batteries under more or less uncontrolled charge–discharge conditions.

Due to limited space for assembly, as shown in Fig. 1, a high-voltage permanent-magnet synchronous machine with high-energy magnets might be advantageous. Centralized high-speed drive trains seem to be superior at high voltages and low currents.

## 2. Battery concept

### 2.1. Challenges for the battery package

The battery package must meet the demands of different driving disciplines: Whereas skid pad, acceleration, and autocross require high electric power over short distances below 1 km, the endurance test across a 22 km distance forces a high energy battery.

The typical load profile of the endurance testing cycle is shown in Fig. 2. Average speed equals about 52.4 km $h^{-1}$ during the acceleration periods, and 44.3 km $h^{-1}$ during the deceleration processes. Whereas top speed was at 85.5 km $h^{-1}$, the most frequent velocities range between 30 km $h^{-1}$ and 60 km $h^{-1}$. Maximum acceleration reaches roughly 19 m $s^{-2}$ (about 2 g). To accelerate the vehicle, instantaneous specific power, $P_s(t) = a(t)\cdot v(t)/m$, culminates at 126 W $kg^{-1}$, and the average specific power of 40 W $kg^{-1}$ is required. To move a car weighing 365 kg, this corresponds to an average drive power of 14.6 kW, and an energy demand of 6 kWh for a 25 min endurance race. Air drag and rolling resistance are discussed in Section 2.3.

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**Nomenclature**

| | |
|---|---|
| $A$ | equivalent frontal area of the vehicle ($m^2$), specific electric loading ($A\,m^{-1}$) |
| $B_\delta$ | magnetic flux density in air gap (T) |
| $C$ | capacitance (F) |
| $c_w$ | aerodynamic drag coefficient (–) |
| DoD | depth of discharge (%) |
| $F_L$ | Lorentz force (N) |
| $g$ | gravitational acceleration: $9.81\,m\,s^{-2}$ |
| $I$ | electric current, winding current (A) |
| $l$ | magnetically active machine length (m) |
| $m$ | mass of the vehicle (kg) |
| $n_N$ | nominal speed, number of revolutions per minute ($min^{-1}$) |
| $P$ | electric power (W) |
| $P_N$ | nominal power (W) |
| $p$ | number of machine poles (–) |
| $R$ | resistance (Ω) |
| $r$ | bore radius (m) |
| $T_N$ | nominal torque (Nm) |
| $T_E$ | electromechanical torque (Nm) |
| $U$ | electric voltage (V) |
| $v$ | vehicle velocity ($m\,s^{-1}$) |
| $x$ | flat projection: $x = r\,\theta$ (m) |
| $W$ | energy (J) |
| $z$ | total number of conductors (–) |
| $\alpha$ | gradient angle of the road (deg) |
| $\theta$ | angle (rad) |
| $\mu$ | rolling resistance coefficient (–) |
| $\psi$ | flux linkage (V s) |
| $\rho$ | air density ($g\,m^{-3}$) |
| $\tau_p$ | pole pitch (m) |
| $\omega$ | angular frequency ($rad\,s^{-1}$) |

Motorcars consume 3–4 l gasoline for this performance, as we know from our earlier racing experience. With the heating value of fuel, and an overall efficiency of the internal combustion engine of roughly 30%, the fuel consumption corresponds to an energy demand for the race of about

$42{,}500\,J\,g^{-1} \cdot 0.74\,g\,cm^{-3} \cdot 3500\,cm^3 \cdot 30\% \approx 9.2\,kWh.$

Supposing an electrical efficiency of the traction system of close to 90%, and a realistic voltage drop of battery voltage of 20% during discharge, the battery requires a stored energy of about 12 kWh, corresponding to, e.g., 600 V and not more than 20 Ah.

The battery package, according to Fig. 3, consists of a series combination of several battery modules, in which a number of single batteries is connected in parallel. The series combination supplies the required voltage for the electric engine. The parallel combination improves battery capacity to meet the requirements of the endurance race. A constant peak performance of 580 V, and 100 A for a duration of 25 min, requires an unrealistically big battery (24.2 Wh, 41.7 Ah). Based on 260 commercial 22.2 V/4 Ah lithium-ion modules ($n$ = 26 in series, $z$ = 10 in parallel), this 40 Ah battery pack would weigh 172 kg at a volume of 89 l, except connections and cables.

### 2.2. Cell chemistry

The secondary battery must meet the following requirements:

- General safety during operation and handling
- High specific energy and efficiency
- Maximum discharge current of 100 A, and high current density for recuperation
- Small voltage drop under current load
- Low cost

The regulations recommend that each accumulator is monitored by a battery management system during charge and discharge, which monitors the cell voltage of every cell to keep the cells inside at the allowed minimum or maximum cell voltage. Continuous temperature measurement shall prevent the accumulator from thermal runaway.

#### 2.2.1. Battery type

Table 1 compiles the specific characteristics of current battery systems for an application in a small electric car. With respect to specific energy and power, current battery technology recommends lithium-ion batteries (about $100\,Wh\,kg^{-1}$ at $500\,W\,kg^{-1}$ for 1000 s), followed by nickel–metal hydride. Nickel–cadmium technology involves environmental concerns, lead-acid batteries are far too heavy (about $10\,Wh\,kg^{-1}$ at $500\,W\,kg^{-1}$ for 100 s). Volume and weight play the most important role for the electric racing car, whereas cycle life and shelf life are less important.

#### 2.2.2. Lithium-ion technology

Unfortunately, appropriate low-cost lithium-ion batteries for electrotraction are hardly available on the market. In Table 2, a market overview of current secondary batteries of various manufacturers is given with respect to suitability for the E-car project. Cylindrical cells are good at maintaining a high mechanical pressure and stability. Prismatic housings allow large formats cells and high surface area, especially pouch-type cells (coffee-bag design). Market prices per single lithium-ion cell range between about $1.30\,EUR\,Ah^{-1}$ and $11\,EUR\,Ah^{-1}$.

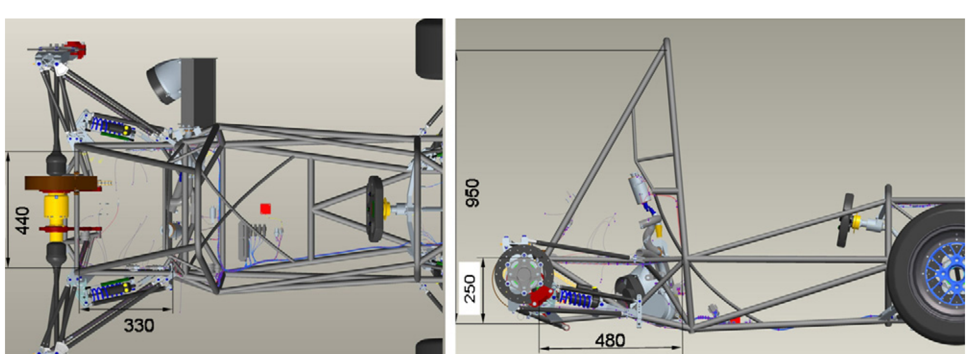


**Fig. 1.** Limited space for the electric propulsion system.