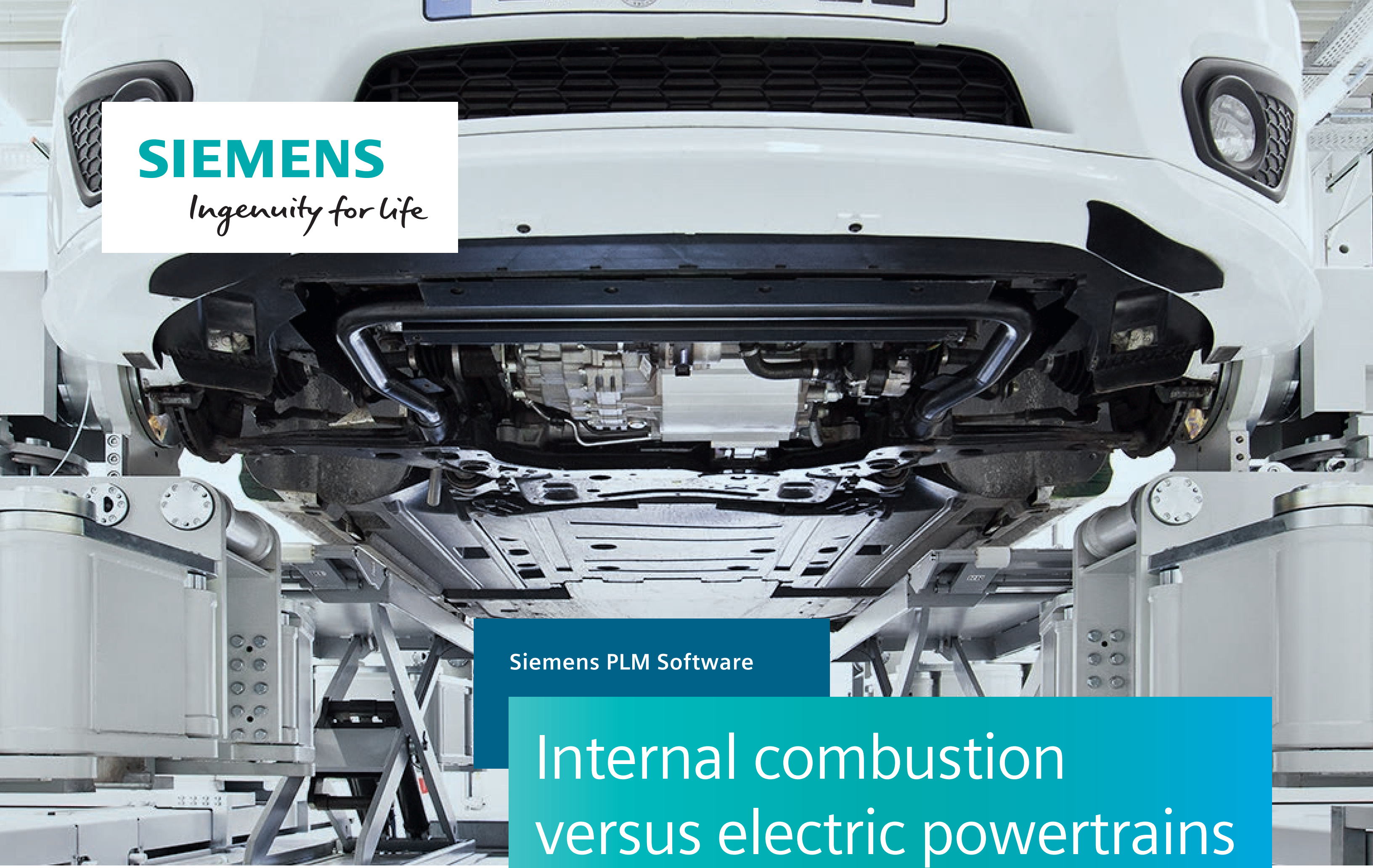

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Internal combustion versus electric powertrains

A comparison of electrical system design in formula student vehicles

Executive summary

TUfast Racing Team – the Formula Student Team of the Technical University of Munich – is one of only a few formula student teams worldwide to build both an internal combustion engine (ICE) and a fully electric race car annually. Thus we are well positioned to make firsthand comparisons between the two types of vehicles. This white paper analyzes the key differences, main challenges and potential of electrical systems for Formula Student Electric (FSE) in comparison to Formula Student Combustion (FSC) cars, using the specific example of the TUfast Racing Team cars. Also described are the various development tools from Siemens which helped significantly in the design and development of efficient electrical systems in our vehicles. Finally, the potential of knowledge transfer from Formula Student to commercial EVs is discussed from the view of a Formula Student engineering student.

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Introduction

Due to declining urban air quality, climate change and consequent legislative changes, demand for environment-friendly mobility is increasing. Accordingly, vehicle electrification has become a very important field of study, especially in the last few years. The internal combustion engine (ICE), around for over a century, is obviously a well understood, mature technology. While there is room for further innovation, improvements will be largely incremental and heavily constrained by cost.

It's worth noting that none other than *The Economist* declared the internal combustion engine to be "Roadkill" on its August 12, 2017 cover. (In case there is any doubt as to the venerable magazine's conclusion, consider the headline to the Leader article that kicks off the issue: "The death of the internal combustion engine. It had a good run. But the end is in sight for the machine that changed the world.")

In contrast, electric vehicles yield the potential for completely new concepts and innovative solutions. The electrical system plays a key role in the process of electrification, involving some risks but also considerable potential.

TUfast Racing Team – the Formula Student Team of the Technical University of Munich – is one of only a few student teams worldwide to build both an ICE and a fully electric race car every year, thus allowing us to compare electric and ICE cars first-hand.

This paper analyzes the key differences, main challenges and potential of electrical systems for Formula Student Electric (FSE) in comparison to Formula Student Combustion (FSC) cars, using the example of the TUfast Racing Team cars. Furthermore, CAE development tools from Siemens PLM Software, are presented which help significantly in the design and development of efficient electrical systems in vehicles. Finally, we explore the potential of knowledge transfer from Formula Student to commercial EVs.

Figure 1: 2016 Formula Student Germany event.

About Formula Student

Formula Student, with over 500 international teams, is the biggest design competition for students worldwide. To compete, students form a team at their school and within a year, design and build a race car following the international Formula Student rules.

The first part of a season is committed to concept development and designing the car. This involves state of the art computer automated design (CAD) and simulation. Students develop and manufacture almost every part of the vehicle on their own. Project planning, along with financial and team management, are essential parts of the process. Next comes a testing phase in which the team improves the car's setup and reliability. Finally, entries from international teams compete against each other during events, in disciplines such as acceleration, cornering speed (skidpad), sprint (autocross), endurance testing and efficiency. During the events, teams are also judged on their business plans and cost reports.

Competitions for combustion engine cars started in 1981. FSE, an additional class featuring pure electric powertrain (but with identical mechanical rules), was introduced in 2010. Since then, performance of FSE race cars has developed rapidly and the electric cars are now able to race at the same level as their combustion counterparts. As figure 2 shows, even in their first-year appearance in 2010, FSE cars outpaced FSC cars in acceleration and since then have extended their lead year by year. The bottom line is that Formula Student has emerged as a very interesting field for studying vehicle electrification and has proven to be a perfect environment for young engineers to find innovative solutions in designing electric powertrains and electrical systems.

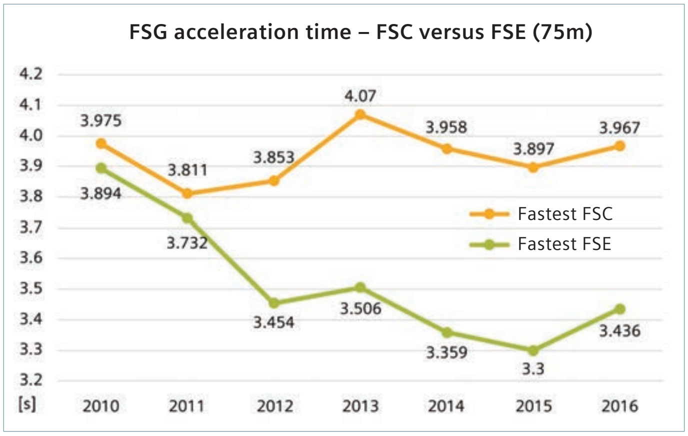


Figure 2: FSE cars widen gap in terms of acceleration.

Driven by the safety- and innovation-focused Formula Student rules, the race cars are designed to compete on narrow, curved race tracks. As a result, the cars incorporate cutting-edge, lightweight technology and also use advanced aerodynamic devices to increase cornering speeds. The 2016 TUfast cars, for example, weighed just 162kg (FSC) and 178kg (FSE) and achieved up to 2.8G in lateral acceleration, which puts them in a class with Deutsche Tourenwagen Masters (DTM) racing cars[1]). A modified version of the 2014 car "grimsel" of the Formula Student Team "AMZ" from the University of Zürich beat the world record for acceleration (0-100km/h) for electric vehicles. In fact, various Formula Student teams have repeatedly beat this prestigious record culminating in AMZ's performance in 2016 of 1.513s[4]. Achieving such a performance means pushing design limits for components and systems throughout the vehicle – especially the electrical system that's the core of both ICE and electric vehicles.

General differences in FSE and FSC car design

Figure 3 shows the TUfast racing team together with their two 2016 TUfast race cars "nb016" (FSC) and "eb016" (FSE) on which the following comparison is based. On the face of it, both cars look almost identical. This is because FSC and FSE cars are subject to almost identical rules, excluding the powertrain. There are multiple carryover parts between nb016 and eb016 with respect to the mechanical structure. Both cars have identical aerodynamic packages, very similar carbon fiber monocoques (structural skin) that only differ in the rear due to the different powertrains, as well as suspensions based on the same concept but adapted to the specific powertrains. Consequently, within the TUfast team there are sub-teams for chassis, aerodynamics and suspension that work across domains and are responsible for both cars. In contrast, there are two separate teams for ICE and electrical powertrain, due to the inherently different mechanical and electrical structures.

For FSC cars, the main restrictions are the usage of a maximum 610cc four-stroke piston engine, with an air restrictor also limiting the power [FSAE rules 2016]. Hybrid powertrains, such as those using electric motors running off stored energy, are prohibited. The nb016 uses a naturally aspirated KTM 570cc single-cylinder engine, with a focus on being lightweight and efficient. Other common Formula Student engines are naturally aspirated two- and four-cylinder engines, also turbo charged engines.

For FSE cars the main restriction is the 80kW cap for power drawn from the battery as well as a maximum voltage level of 600V[2]. Naturally, only electric motors are allowed, but there is no limitation to the number of motors used. Therefore, the eb016 is four-wheel driven with an electrical machine at each wheel supplied by a self-developed 7.6 kWh capacity lithium battery pack. To optimize weight and minimize the influence on aerodynamics, the machines are integrated as a wheel hub drive, using self-developed uprights with integrated planetary gears. In summary, the powertrain only modestly influences work on aerodynamics, chassis and suspension. On the other hand, the electrical system is highly adapted to the different powertrains.

Figure 3: TUfast racing team with its ICE and electric entries for the 2016 competition.

Differences in electrical design

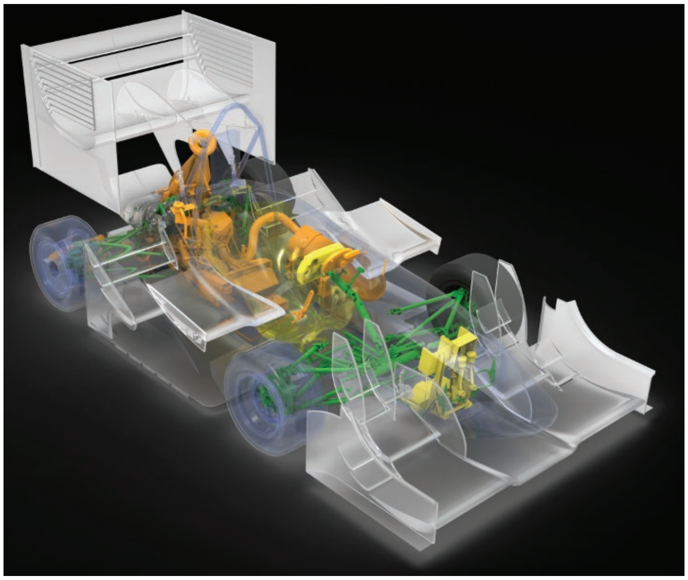


Figure 4: Formula Student combustion car (nb016).

Overall, there are four major differences between the FSC and FSE electrical systems.

First, there is a much higher level of mechanical stress for FSC cars. Vibrations for the combustion engine cars are intense, and this is especially true with the nb016 single-cylinder engine in which drivers have even reported problems with breathing at certain engine speeds. Moreover, screws and entire components that are not secured properly tend to become loose within minutes of starting to drive. These stresses of course also influence the whole electric system and must be considered during the design process.

The same stresses are not apparent in the electric car with its smooth-running powertrain. However, it has a different internal enemy to cope with – electromagnetic interference. Due to high (nominal) voltage (HV), high currents and high switching frequencies of the inverters with the electrical system packed tight in a small space, the FSE teams have to focus their design on electromagnetic compatibility (EMC). FSC cars maximum voltage level is restricted by the rules to 60V DC. Additionally, apart from the ignition system, there are normally no high frequency currents in FSC cars. Therefore, without major design errors, especially in the harness, interference can only come from outside the vehicle.

The third big difference is the total computing power needed for FSC and FSE cars. To calculate the optimal torque for each wheel of the electric four-wheel drive system, in every driving situation, a powerful on-board control unit is necessary. Furthermore, in contrast to the case in combustion engine vehicles, these electric vehicle control units can also be used for controlled braking in so-called regeneration (regen), and in assisted cornering in the form of torque vectoring. This is no small computing task as the torque demands for every motor must be calculated in real time while simultaneously processing a high volume of sensor data.

Finally, there is also a big difference in safety issues between the electrical systems due to the FSE car using high voltage components, which will be discussed later in this paper.

The following sections with run through a series of comparisons between the electrical systems of the two vehicles.

Power supply

The main difference between the two vehicles is the high voltage (HV) battery pack in the electric eb016. The battery is based on a lithium-ion chemistry and provides 600V nominal DC voltage, 7.6kWh capacity, 129.6A peak charge current and 158.4A peak discharge current. Using a higher voltage reduces the current needed to provide a given amount of power to the traction motors, enabling the cross-sectional area of the cables to be reduced. This reduces both wiring harness weight and electrical losses. However, a higher voltage DC bus requires more stringent safety considerations and teams are required to implement various systems to ensure acceptable system safety.

One example is the mandatory battery management system (BMS) which protects against over-/under-voltage and over-current protection, as well providing thermal management. There also are systems to guarantee electrical separation of the HV system (the so called "traction system") and the grounded low voltage (LV) system. This separation ensures correct system function and reliability, while also preventing any harm to people operating or working on the vehicle.

The LV system supplies sensors, actuators and control units at a voltage level of 12V, the current standard in the automotive environment and where most compatible commercial parts are available. In case of the eb016, the LV system is supplied by a DCDC converter (600V to 12V), which makes it very stable electrically. Using an additional LV battery is also possible as shown by other FSE teams. FSC cars normally use a small lithium battery sometimes supported by an alternator.

Usually the LV network of the FSC cars oscillates considerably more than that of electric cars, due to the higher load sensitivity of the LV-battery compared to the DCDC-converter, as well as to pulsing loads such as spark plugs and the starter motor. Therefore, the proof voltage is more important while designing PCBs for the combustion car (in comparison to electrics).

Another big difference is the battery pack's influence on the packaging of the FSE car's monocoque design and weight distribution. The eb016's battery pack weighs around 49kg while the nb016 battery weighs just 2kg (a difference explained by the fact that two packs fulfil such radically different tasks). The thermal management of the eb016 electric vehicle powertrain is also a major design consideration. Overheating battery packs are common in Formula Student vehicles, so an approach to cooling is needed for the HV-battery and the inverters. At the same time, the electric motors also need to be cooled, while FSC cars usually need to manage only the engine temperature. Managing temperatures of three individual components, all working in different temperature ranges, while minimizing the influence of the cooling system on aerodynamics, is a major challenge. However, due to significantly reduced losses in electric powertrains, the influence on aerodynamics can be considerably lower for FSE cars as the comparison between TUfast's nb016 and eb016 shows: With 18kW heat to dissipate, the nb016 needs a 50 percent bigger cooling system compared to the 12kW to be dissipated by the cooling system of the eb016's electric powertrain.

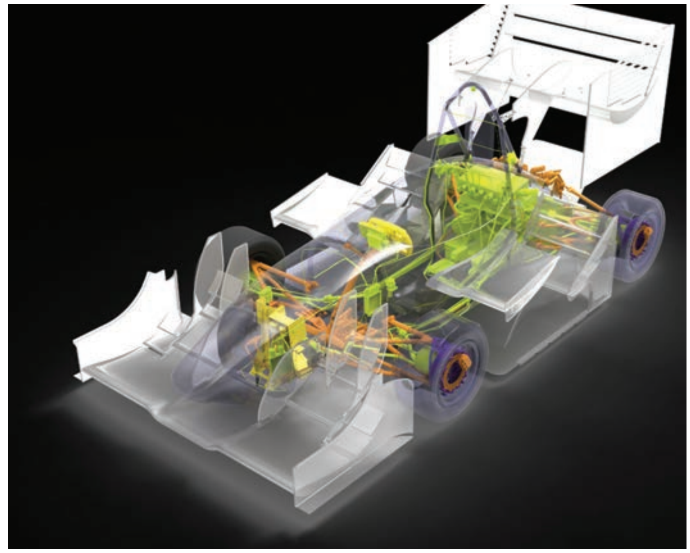


Figure 5: Formula Student electric car (eb016).

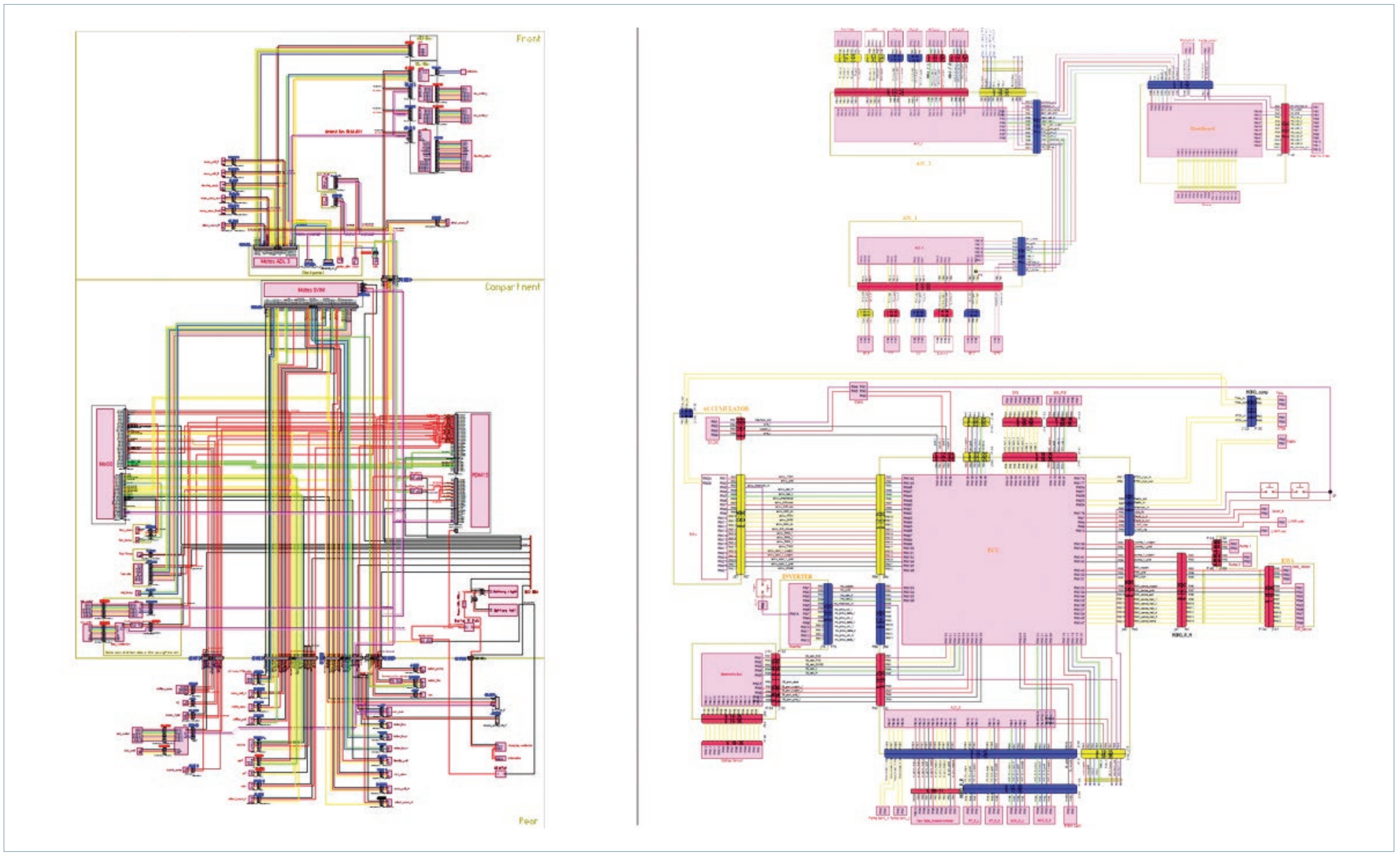


Figure 6: Formula Student low voltage electrical distribution system (FSC left, FSE right).

Electrical sensors and actuators

Regarding LV sensors and actuators, the main differences between nb016 and eb016 are related to the powertrains. The combustion engine needs various sensor parameters to operate correctly, such as air box pressure over fuel temperature and pressure, as well as exhaust gas parameters like the lambda value. The in-wheel, four-wheel drive electric powertrain, on the other hand, needs a different set of vehicle control sensors, such as an optical sensor to determine the exact speed and moving direction of the car (the Correvit). And for the four-wheel drive vehicle, wheel speeds cannot be used to determine the correct ground speed. Due to the slip of all wheels at the same time, the ground speed cannot be measured via the front wheel speeds as done in the rear wheel drive nb016. Additionally, gyro- and accelerometer sensors at each wheel are needed for adaptive control.

Safety relevant sensor data (for example, all driver inputs) need to be collected by redundant sensors for FSE cars, as stated by the rules. Sensors not connected to the powertrain are common for both cars, like suspension and aero sensors. The same applies to all other actuators in the LV system which are not connected to the powertrain; examples include an electrically actuated drag reduction system (DRS) and an electric rear wheel steering system.

Mechanical stress (for the combustion car) and EMC (for the electric car) proved to be big influences on the selection of specific sensors and actuators. Analog sensors with low output voltage, like 3V, are more likely to suffer electromagnetic interference. Therefore, sensors with a direct digital output like CAN bus, were preferred.

Topology and bus system

Digital communication networks like the CAN bus are utilized for internal vehicle communication. Their electrical robustness and lightweight nature make them very popular in combustion cars and now they are also used in FSE cars.

While there is just one CAN bus used for internal communication in the nb016, there are four in the eb016. The reason is due to significant higher overall data load for the eb016 with data from numerous sensors needed for real-time, safety-critical applications. For the FSC car, it is convenient to use just one CAN bus as all functions that are independent from the engine can be outsourced as standalone PCBs, while a commercially available engine control unit (ECU) takes care of injection and ignition.

This decentralization of LV subsystems is also possible for FSE cars, but not in same manner as in the FSC car. Due to the various safety functions and the complex vehicle-dynamics control functions, a central control unit is needed that acts as a master to all subsystems.

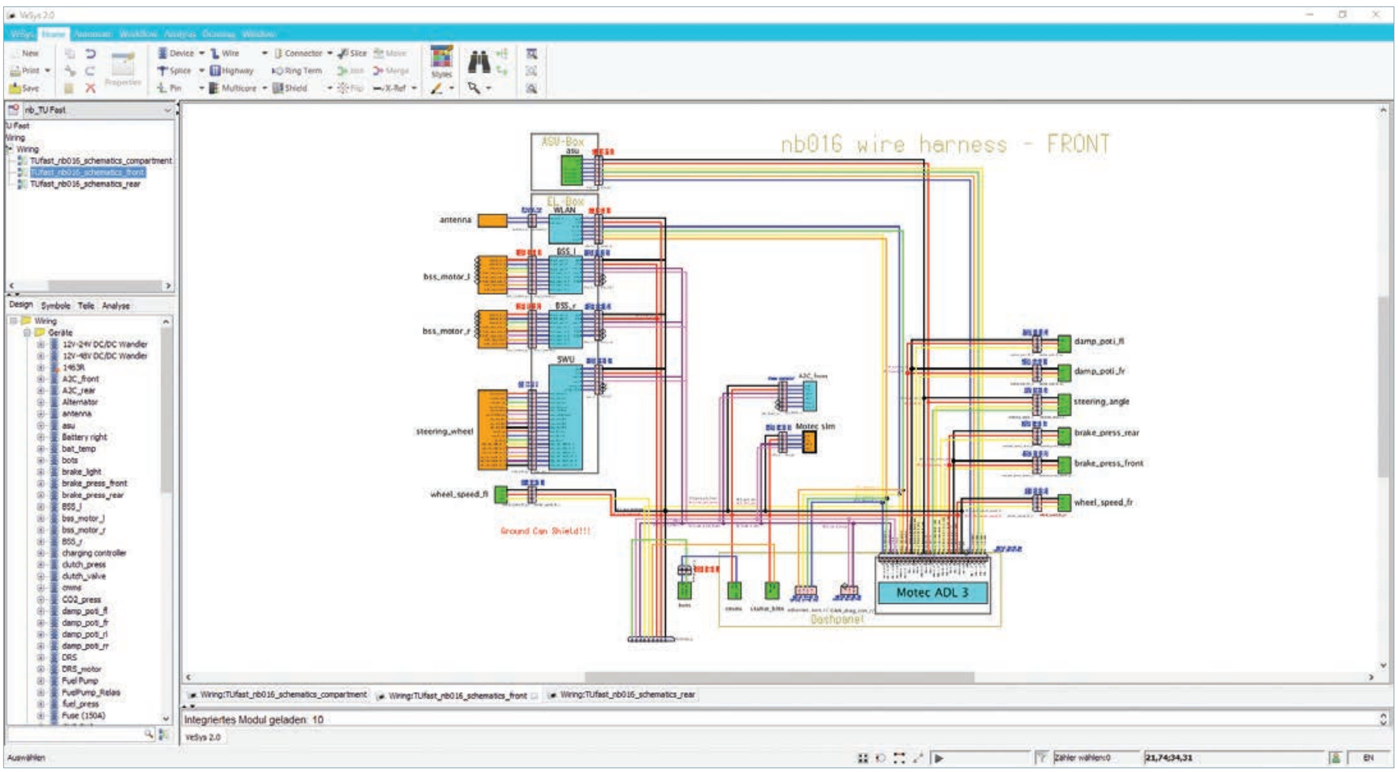


Figure 7: VeSys tool used for electrical system design.

Control units

As already stated, the FSE cars need a more powerful supervisory central control unit (CCU). This often self-designed or customized main control unit is completely different than ordinary commercial ECUs for combustion engines. The nb016 uses a MoTec ECU, for which popular architectures have been available for decades. Control units for FSE cars must be able to run code generated from analytical and simulation tools like MATLAB, Simulink or LabVIEW in real time to enable functional vehicle dynamics control. At the same time, software as well as hardware for FSE cars must be absolutely reliable as they are highly safety-relevant. In the case of the eb016, the CCU is in the rear of the car, tightly packed together with the battery pack and the inverters. Therefore, EMC is a crucial parameter during the design of the CCU.

With the help of Siemens PLM Software PADS PCB design software, TUfast Racing Team built a 240g (including cooling), tightly packed CCU, integrating USB, Ethernet and CAN interfaces, as well as the entire LV power supply. The PADS feature of impedance controlled layout helped in integrating the differential bus systems on the board. Furthermore, the PADS "Autorouter" feature made possible time-efficient integration of a complex processing unit. The unit, which combined dual core processor and field programmable gate arrays (FPGAs), could be fitted in a space-saving six-layer board.

Currently there is no trend towards a specific solution for central control units. Therefore, designing control units for FSE cars is in general a very promising field of study. Besides the CCU and the ECU, independent subsystems like the already mentioned DRS and rear axle steering are usually controlled by self-designed, CAN compatible, low voltage PCBs containing a micro controller.

Safety

Let's come back to the relevance of CCUs to safety in electric vehicles. A primary reason is the CCU's responsibility to calculate torque demand for each wheel. Differences in wheel torques lead to yaw moments making the car turn. This effect is used intentionally in the case of torque vectoring, however it can be very dangerous in case of an error, leading to an uncontrollable vehicle. With only one engine driving the rear wheels and without an active differential, FSC cars normally don't have the risk of unintentional yaw. Overall, the technology in FSE cars is significantly more safety-critical.

The HV system itself and a malfunction of the battery pack pose a danger for drivers and engineers. This leads to the requirement for numerous safety systems in electric vehicles. The only common safety functions for FSE and FSC cars are the cockpit-mounted master switch – an emergency switch for the driver – and the brake over-travel switch, which is triggered in case of a brake system fault. They are the only electrical safety features in the combustion engine cars' shutdown circuit, which controls power for the ignition and fuel pump.

The safety system in FSE cars must include multiple additional components such as an insulation monitoring device (IMD) to guarantee separation of HV and LV system, tractive system active light (TSAL) and the ready-to-drive sound to show the car is active to drive. In addition, there are interlocks in the shutdown circuit to shut down the tractive system in case of a mechanical failure. Further safety functions are provided by tractive system monitoring. Overall there are just two pages of rules for the electrical systems of FSC cars but 21 for FSE, which shows the significantly increased safety focus[2].

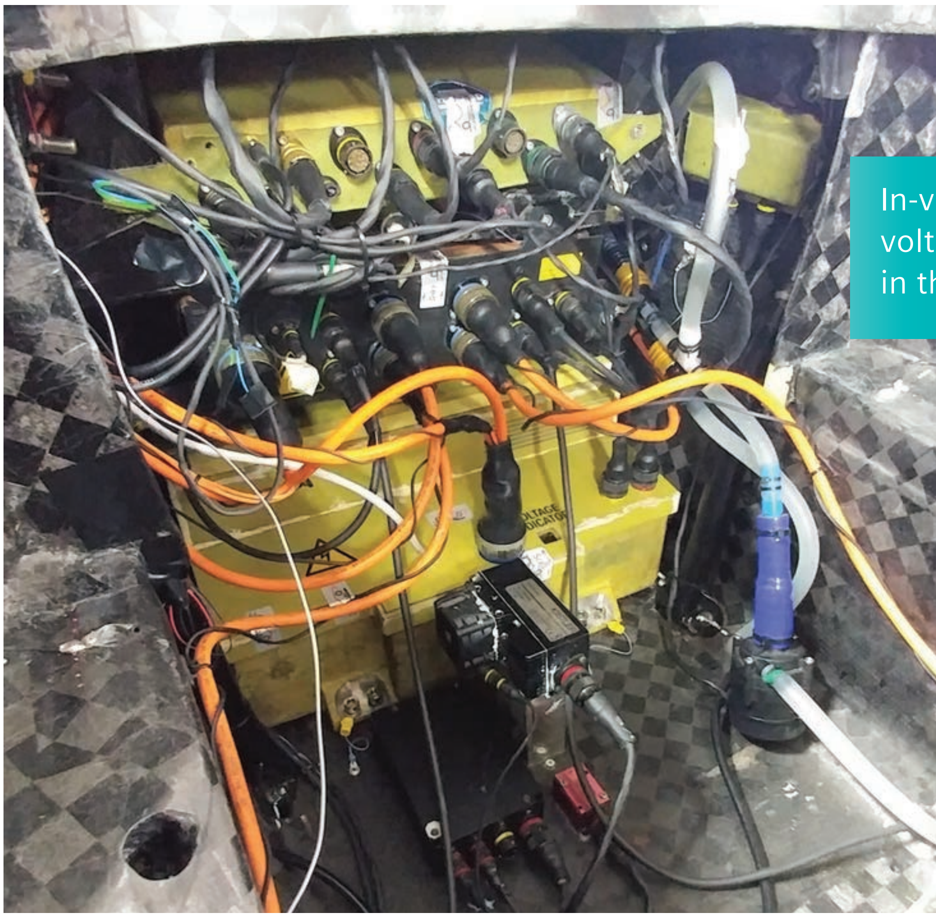
Wire harness

Due to the dissimilar topology and subsystems, the eb016 and nb016s wire harnesses are completely different in terms of layout. Some of the key differences are the self-built and therefore custom design control units in the eb016 and the addition of a HV distribution system. It is necessary to design a simple, straightforward wire harness with hardly any branches. The HV creates EMC challenges that must be mitigated, mostly by shielding of wires. On the contrary, mechanical stress played the main role during the nb016s harness design process. The reason for this lies in frequent maintenance of the combustion engine, high temperatures of the exhaust system as well as corrosive oil and fuel contamination. But the main culprit is the violent vibrations of the single cylinder engine. Therefore, building an electrical system that can withstand the mechanical stress over a long term was the biggest challenge for the combustion car.

Experience from previous seasons showed that cables not properly protected are destroyed within a couple of minutes during driving. Therefore, a lot of effort was invested to reduce the number of branch points, ensure easy maintenance as well as a smooth path to high quality manufacturing. Due to the less centralized topology and multiple commercial control units such as the

ECU, the complexity of the nb016s harness significantly exceeds that of eb016. With over 70 connectors and nearly 400 individual wires to connect them, a powerful but as easy to use design tool was essential.

Here, VeSys wire harness design tool was successfully used for both cars for the first time. A simplified version of the powerful Capital electrical systems design tool, VeSys included automatic creation of wire lists and documentation, which helped speed the manufacturing process. Most important, it was easy to use, with the support of online training, enabling us to complete the short design phase of Formula Student teams, despite being first-time users.



In-vehicle high voltage harnessing in the FSE car.

Conclusion

In summary, there are fundamentally different challenges in developing electrical systems for FSC and FSE race cars. On the one hand, mechanical stress, caused by vibration, heat and chemical corrosion is a large factor for FSC cars. On the other hand, EMC, computational power and safety are essential considerations for FSE cars. The problems FSE cars face will also be a challenge for commercial electric vehicles. Besides potential EMC considerations, due to the HV system of the electric powertrain, EVs provide the opportunity for innovations in the electrical system, specifically HV wire harness, control unit, battery pack and safety.

The different approaches in these fields in the Formula Student competition show that there are no uniform solutions. What is true is that powerful development tools are needed to find new, innovative and economic solutions. Additionally, FSE is a showcase for new capabilities in precise vehicle control, due to the excellent controllability of electric motors as well as the possibility of multiple motors. In FSE race cars, these vehicle control capabilities are used to improve lap times (for example, by torque vectoring). For commercially available vehicles, especially for sports cars, vehicle control can also be used to improve driving enjoyment.

Walter Röhrl, one of the most famous rally drivers who raced in the infamous “Group B”, once said after test driving the fully electrical “Mercedes SLS E Cell”: “The steering of the car is amazing. Unbelievable, really. As soon as you touch the throttle, the vehicle shoots forward – incredible! You can only dream of such driving dynamics. Breath taking, simply outstanding! No question, these are totally new dimensions of driving that I haven’t experienced within the last 45 years. Very nice. I’m really happy to have had the chance to experience this.”[3]. Furthermore, the fast and precise controlability of electrical powertrains allows for improved vehicle control safety functions, that could help to further decrease the risk of accidents.

Formula Student demonstrates that, when it comes to electrification, it’s not only necessary to make small adaptations of the electric system for the new powertrain, but in fact what’s required is a complete reinvention of the whole system, its subsystems and architecture. Developing system architectures satisfying safety and reliability will also be essential for future autonomous vehicles. Formula Student Germany is a pioneer in this regard, by hosting the first “Formula Student Driverless” (FSD) competition in this year’s 2017 FSG competition in Hockenheim. Therefore, for the first time the TUfast Racing Team will be competing with three different vehicles – an electric vehicle, an ICE vehicle and a driverless race car at the same time.

About the Higher Education Program

Founded in 1985, the Higher Education Program further develops skilled engineers within the electronics industry. The program provides colleges and universities with leading edge design tools for classroom instruction and academic research to help ensure that engineering graduates enter into industry proficient with state-of-the-art tools and techniques.

For more information, please see: mentor.com/company/higher_ed/.

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