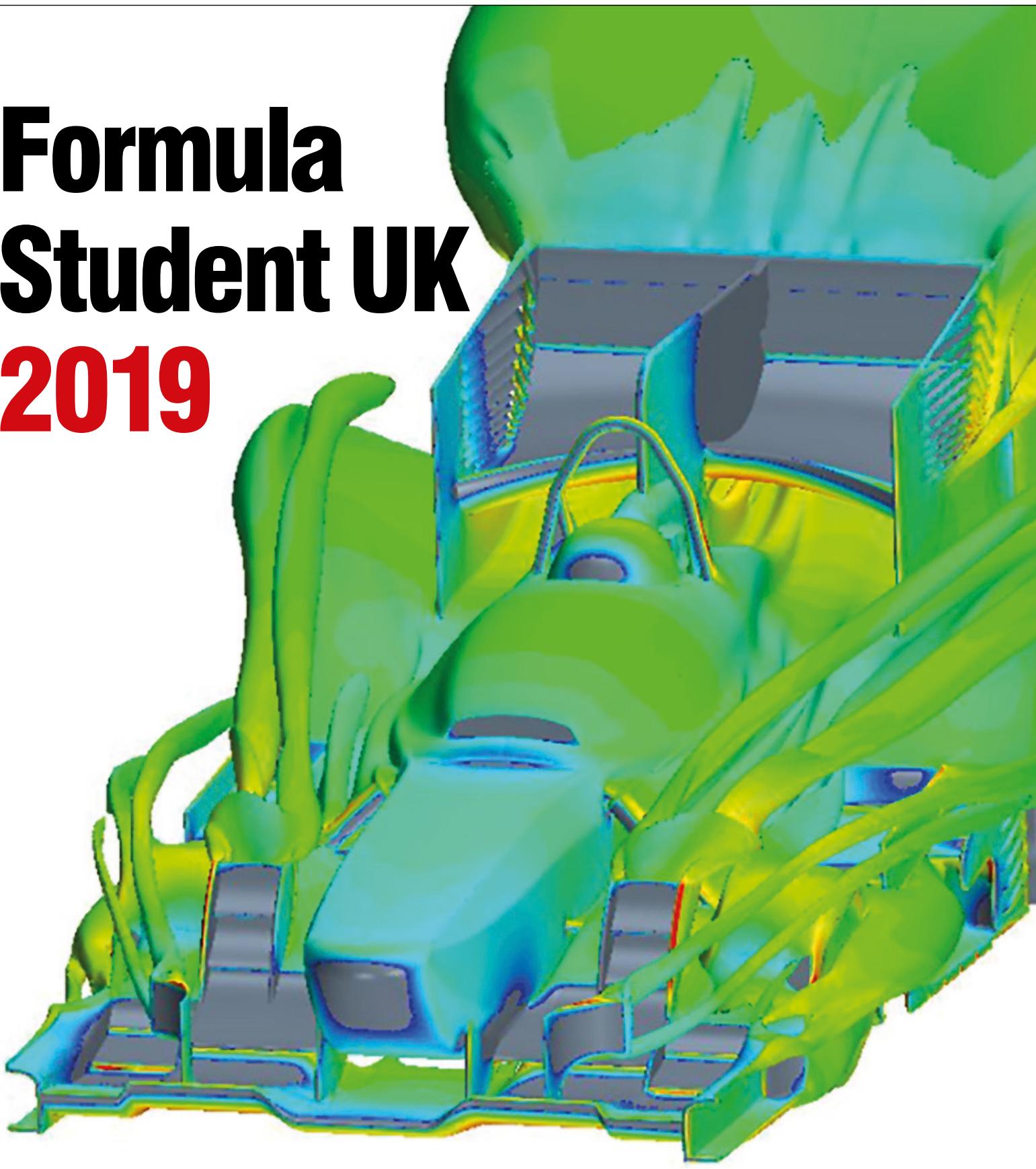


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This year's FSUK event saw a deserved win for the Modena Racing team, which elected to take the lightweight approach to the competition, shaving around 10 per cent from the overall weight of its 2018 car. It was heartening to see that the winner of the UK event did not need to go electric, in keeping with the political trends, but instead focussed on increasing efficiency. It was interesting to note that the team also had an engine development programme, but a failure in bench testing meant that it had to revert to a smaller, less powerful unit. So this will be an interesting contender again next year.

Of course, there was the usual mix of electric and ICE engines, and huge aero designs against other teams that opted for mechanical grip, which helps to keep the competition lively. There is nothing worse than spec formula racing, or anything that is too prescriptive, and it is always enjoyable to see variety and experimentation. That's what makes racing interesting.

However, it cannot be ignored that the governing bodies of racing are currently pursuing a path of conformity, with limited numbers of manufacturers bidding to provide spec parts, be it chassis, gearboxes, brakes or whole car. At that point the

emphasis changes to making the most of your package. The theory is that the racing will become closer and emphasis will switch from the car and technology to the team and the driver. This will, apparently, save costs and make racing more sustainable, although we are well aware that this is the wrong tree up which to bark.

The FS grids better represent real life than the current international racing scene. The future of motoring will include a variety of powertrain solutions, including electric, gasoline and (whisper it) diesel. For the young engineers to be experimenting with at least two of the three possibilities, plus moveable aero devices, will benefit the wider industry. It now falls to further advancements, such as active suspension, to feature. Peter Wright has written in *Racecar Engineering* about his first attempt at active suspension in F1 while at Lotus in the early 1980s. His opinion is that, had the system not been banned, such technology would now be commonplace and a cheap way to gain performance. I'm sure that the technology is now reliable and robust enough to support such a programme, should an FS team pursue this path.

ANDREW COTTON

Editor, *Racecar Engineering*

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Taking charge

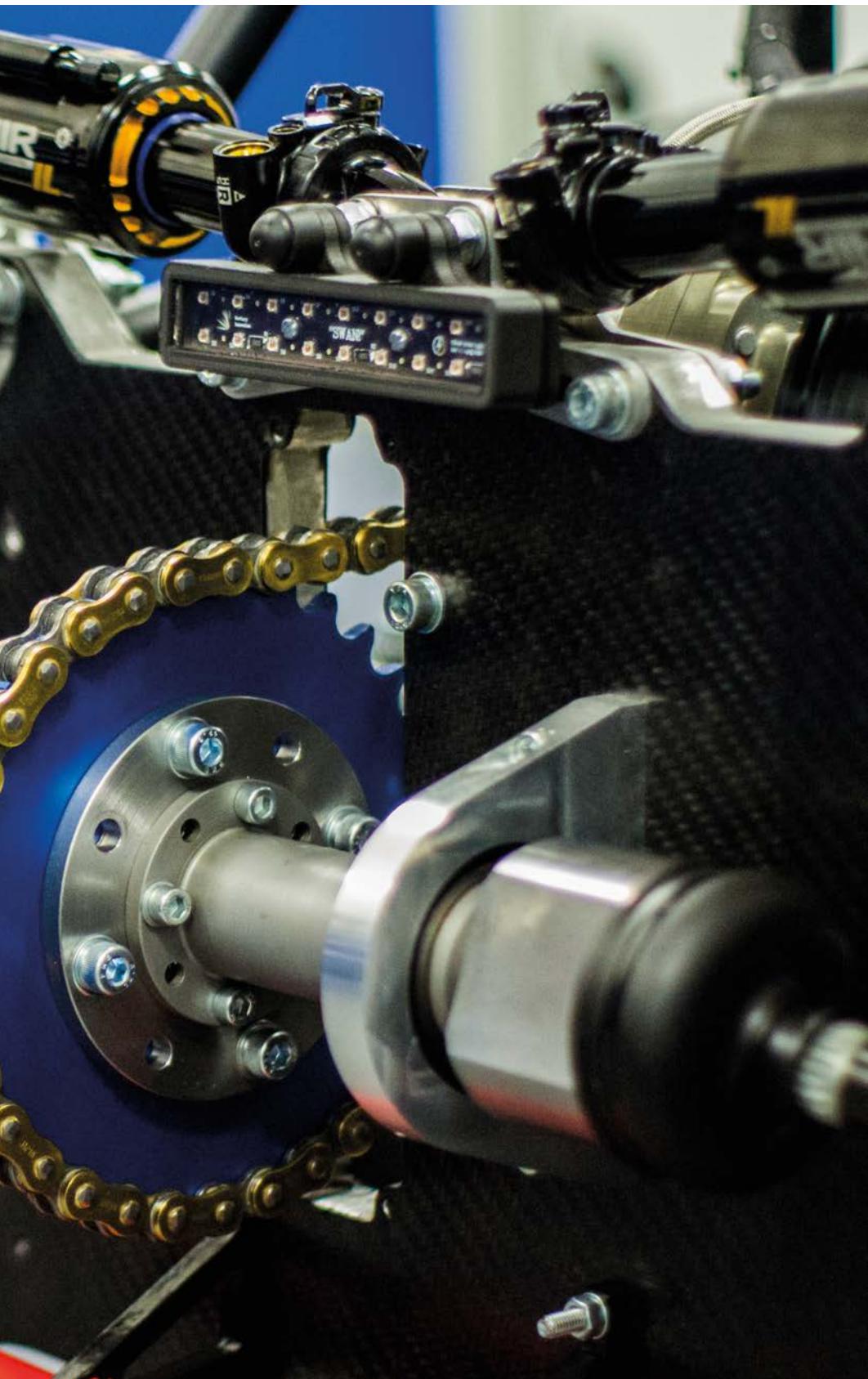
Electric racecars competed at FSUK way back in 2007 – four years before Formula E was even conceived



The Team Bath Racing car makes use of a chain drive solid spool axle, which is a common approach on Formula Student designs that are running with a single electric motor

A large and ever-increasing number of Formula Student cars are now electrically-motivated but, as *Racecar* discovered, developing such a machine presents teams with a whole host of complications and technical challenges

By GEMMA HATTON



Formula Student may be an engineering competition for universities, but the innovations showcased by these racecars are often a step ahead of the motorsport industry. For example, autonomous cars are now fully integrated into the competition and the first electric racecars competed at FSUK way back in 2007 – four years before Formula E was even conceived.

In fact, in 2016 the electric FS car from AMZ racing set a world record for the fastest-accelerating electric vehicle, achieving 0-100km/h in just 1.513s, which still stands today. In comparison the new generation of Formula E cars accelerate from 0-100km/h in 2.8s. Although this is not an entirely fair comparison as Formula E and electric FS are designed to a completely different rule set, it does highlight the incredible standard of engineering within these FS cars.

Today, over 32 per cent of FSUK teams are now electric, with 39 teams also competing in the electric category of Formula Student Germany. It is no longer just the well-resourced outfits that are taking on the electric challenge, but the smaller teams are too.

Plugging in

As with any racecar, the first port of call is the rulebook, and for electric Formula Student cars complying with the rules is extremely tough. 'One of the most important things to realise when competing in electric FS is that you have to go through two sets of entirely different scrutineering at competition,' says Ben Carretta, technical manager at Team Bath Racing Electric. 'As well as the standard scrutineering you also have to go through an accumulator [battery] scrutineering and a full electrical scrutineering. It feels like the rules are trying to make you jump through a lot of unnecessary hoops, but when you start building the car, the rules are actually quite a sensible guidebook on how to design a safe electric racecar.'

'For an electric FS team starting up I would say that the most fundamental thing is to have a simple and reliable system, one that you know is going to work, and then pay close attention to the rules,' Carretta adds.

With this in mind, most teams opt for a two-year approach when starting an electric project. The first year is spent designing, with the final versions of the virtual car submitted into Class 2 of the competition. Judges then analyse their progress throughout the Design, Cost and Business Plan events. The second year

is then used to build and test the real car, ready to compete in Class 1. To help further kick-start the electric team, many universities will continue to run their combustion car, which aids the transfer of mechanical know-how to the electric team. This was the strategy that Oxford Brookes took with its new electric team, competing in Class 2 this year.

'Aside from our accumulator lead engineer, pretty much everyone in the team is new to electric vehicles and the challenges that they bring,' says Deepak Selvan, chief engineer of Oxford Brookes Racing Electric. 'So having the Class 2 and then Class 1 structure has been probably the most important aspect for making the switch to electric achievable. The biggest challenge so far has been moving decisions forward in such an open and unknown problem space. With an electric car there is a big phase of research and learning and what we struggled with most was defining where we cut that off and actually start making decisions. It wasn't actually an electrical challenge but more a project management one.'

Skills audit

A team also needs to decide which components will be developed in-house and which will be bought in and this depends on the expertise within the team. 'It's about looking at who you've got within the team and what knowledge you have within the university and figuring out what you are capable of doing,' says Carretta. 'It's easy to look at individual systems

'With regards to the batteries and motors, we are not a road car and we are not a racecar'

and say "this is feasible" but it's bringing all those systems together to create a reliable package which is most difficult. We had people who were interested in battery technology, so that has been an area that we've dived into ourselves, with the help of our sponsors. It wasn't necessarily an area that we decided we could make a massive improvement on. Formula Student is a learning experience and if you had people in your team who loved motor design then that might be what you try and develop.'

'At the end of the day Formula Student is an engineering competition and in general you have to ask yourself whether it is sensible to take the time and resource to develop something, or are you trying to reinvent the wheel, in which case it may be better to buy something in,' says Natalie Kyprianou, the accumulator lead at Team Bath Racing Electric. 'We're building a prototype car and the requirements are very different to what you can buy off the shelf. With regards to the batteries and motors, we are not a road car and we are not a racecar. We don't race the

distances they do in Formula 3 or Formula E and we don't have the speed requirement that these series have either. Also, we need to consider the rules. We could buy or produce an extremely powerful motor but that would be unnecessary mass as the electric Formula Student cars are power limited. Furthermore, as the power increases the struggle of putting that power down to the wheels would be greater due to the limit of traction. We decided to build our own battery because we wanted to fully understand what was inside it.'

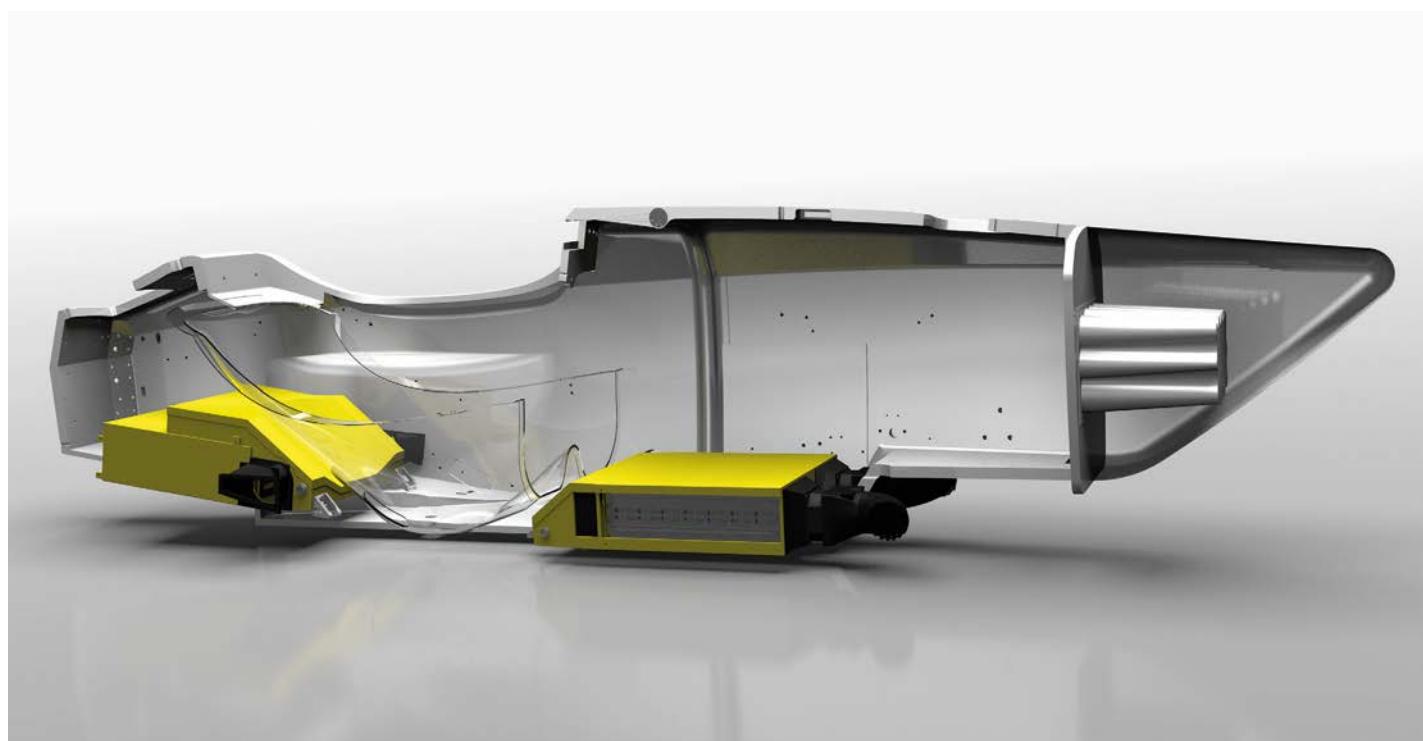
Batteries included

With off-the-shelf batteries often heavy and not customised for Formula Student, this is an area where teams can make significant performance gains. 'In our 2017 car the battery weighed approximately 120kg; 2018 was the first time we developed a truly custom design which dropped the weight down to 67kg,' says Carretta. 'We continued developing the BMS [Battery Monitoring System] and other battery ancillaries and dropped the weight down again to 48kg for this year's car. Compared to off-the-shelf solutions which can be around 70 to 75kg, this is a huge weight saving.'

Once the overall approach has been defined the next stage is to develop a concept, and again there are several schools of thought here. There are two parts to a car's electrical system. Firstly there is the high voltage, which is all the components with an electrical connection to the accumulator (effectively the powertrain).



'Having the Class 2 and Class 1 structure has probably been the most important aspect for making the switch to electric achievable'



The location of the battery modules within the chassis can affect the weight distribution and CoG, which can change the vehicle's dynamic behaviour. AMZ Racing's design pictured



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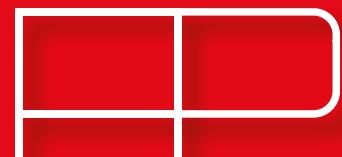
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Secondly there is low voltage, which is all the safety and data logging systems.

An electric car works through an accumulator or battery providing power, but this is often in the form of direct current (DC). An inverter then uses a transistor switching arrangement to convert this to three phase alternating current (AC). This then powers a motor which essentially rotates a magnet (rotor) surrounded by copper coils (stator) and the resulting oscillating magnetic field is used to generate rotational motion which is then mechanically coupled to the wheels.

Current thinking

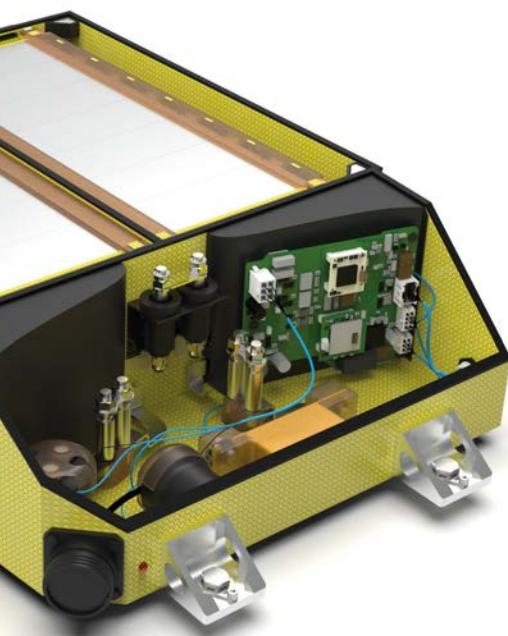
The most simplistic concept is a single motor on a fixed rear axle and to increase traction during cornering a mechanical differential or a chain driven solid spool axle can also be incorporated. To achieve further control of the vehicle dynamics, a second motor can be added to drive the two rear wheels separately, along with a chain drive single gear reduction or a planetary gearbox. However, the most effective method to maximise traction and dynamic control is to have independent motors driving each wheel. This four-wheel drive approach is costly, but it does give the teams using it the opportunity to explore the benefits of technologies such as torque vectoring.

There are many different approaches to designing an electric powertrain. But for FS usually the first stage is to decide between 2WD and 4WD and whether the motors are inboard or outboard, which then determines the maximum power requirement. This is dictated by the rules which stipulate a maximum power of 80kW for 2WD and 60kW for 4WD. The motors

Teams can choose between batteries with high power density or high energy density. Because of the distances raced and the demands placed on the battery high energy cells are often more suitable

can then be selected, with teams aiming to match the torque and speed characteristics of the motor to suit Formula Student style competition. The operational voltage of the chosen motors and inverters then dictates the maximum voltage required from the battery.

'We started with having a target voltage that we wanted to be at, based on the motor package we are running on to try and keep it in the efficiency band we wanted,' explains Selvan. 'From there we looked at a range of cells with different voltages and capacities along with data from our lap time sims on what our energy needs were for endurance.



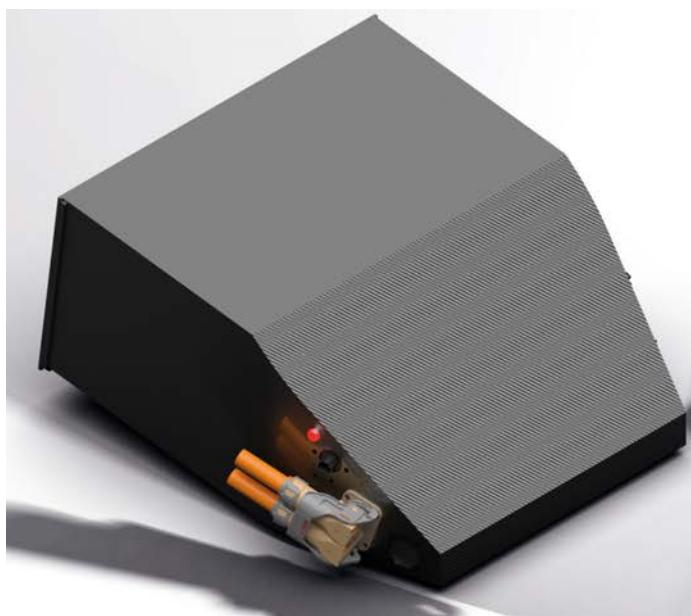
'We did also look at how much of a buffer we would need if we don't get regenerative braking working or aren't able to keep the motors in their efficiency band,' Selvan adds. 'We ended up working down from about 26 different battery configurations to a short-list of three before deciding on our final battery design.'

Energy limits

'You are only allowed a specific amount of energy in every compartment, so this limits the maximum number of cells of each module,' explains Andreas Horat, chief technical officer at AMZ Racing. 'The maximum voltage of the



The most effective method to maximise traction and dynamic control is to have independent motors driving each wheel



Putting more cells in series increases battery voltage, while putting more cells in parallel increases current. Batteries need to be designed to meet specific current and voltage targets

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accumulator is on one side limited by rules, which allow a maximum of 600V, but in our case it was also driven from the inverter. The inverter used in previous years specified the maximum battery voltage which then leads to the number of cells in series. Together with the estimated necessary energy, the number of cells in parallel is fixed. We have 130 cells in series. We then look at the current draw at maximum as well as the maximum charging current when recuperating [energy]. In the end the number of cells is adjusted to fit them in a convenient way within the box. The cooling is also considered during the cell placement.'

Motor specs

An alternative approach to determine the motor spec is to focus on the desired tyre performance. 'Calculations including mass transfer, speed-sensitive aerodynamic loads and tyre data in combination with our self-developed lap time simulation as well as mass sensitivities derived from post-season tests were used to find the event-point optimal key parameters for the motor design,' says Horat. 'A top speed of 115km/h and a maximum wheel torque of 395Nm yield the highest score prediction. Briefly said, the motor design is driven from the tyre side so we can reach the optimum performance of the tyres and the accumulator is driven from the capacity side to ensure we have enough energy for the whole endurance.'

The next stage is to determine the amount of energy and therefore the capacity that the battery must carry throughout one single discharge to complete endurance. For this, often a Matlab script called Lapsim is used. This

programme takes an aerial-view image of a track with a known pixel-to-physical-distance ratio and then runs a theoretical vehicle through a lap of the circuit. The physical characteristics of the vehicle (weight and gravity etc) as well as vehicle dynamic parameters (downforce, roll, pitch etc.) are considered along with safety factors, an aggressive set-up and all parasitic losses at 100 per cent to simulate the worst case scenario. This model identifies the energy required from the accumulator during one lap, and therefore the energy that is required for the entire endurance race as well as all the other dynamic events at competition.

The accuracy of this simulation can be further developed by incorporating more reliable data such as that from tyre tests. Also, the script itself can be extended to calculate the performance of different powertrain concepts to determine the potential number of points each concept could achieve at competition.

'We only have to complete 22km for the endurance and we are limited to a max of 80kW for rear-wheel drive cars and 60kW for four-wheel drive cars, so this already creates your window of both power and energy,' says Garretta. 'We looked at the average power and speeds of previous cars to get an energy requirement in kWh and size our battery. We then identified the power draw at each individual point to see how much we would stress our batteries which then gave us an ideal power and energy requirement so we could look for cells that matched that and start building up the battery pack from there.'

Choosing the 'perfect' cells for the battery is by no means an easy task. Not only are

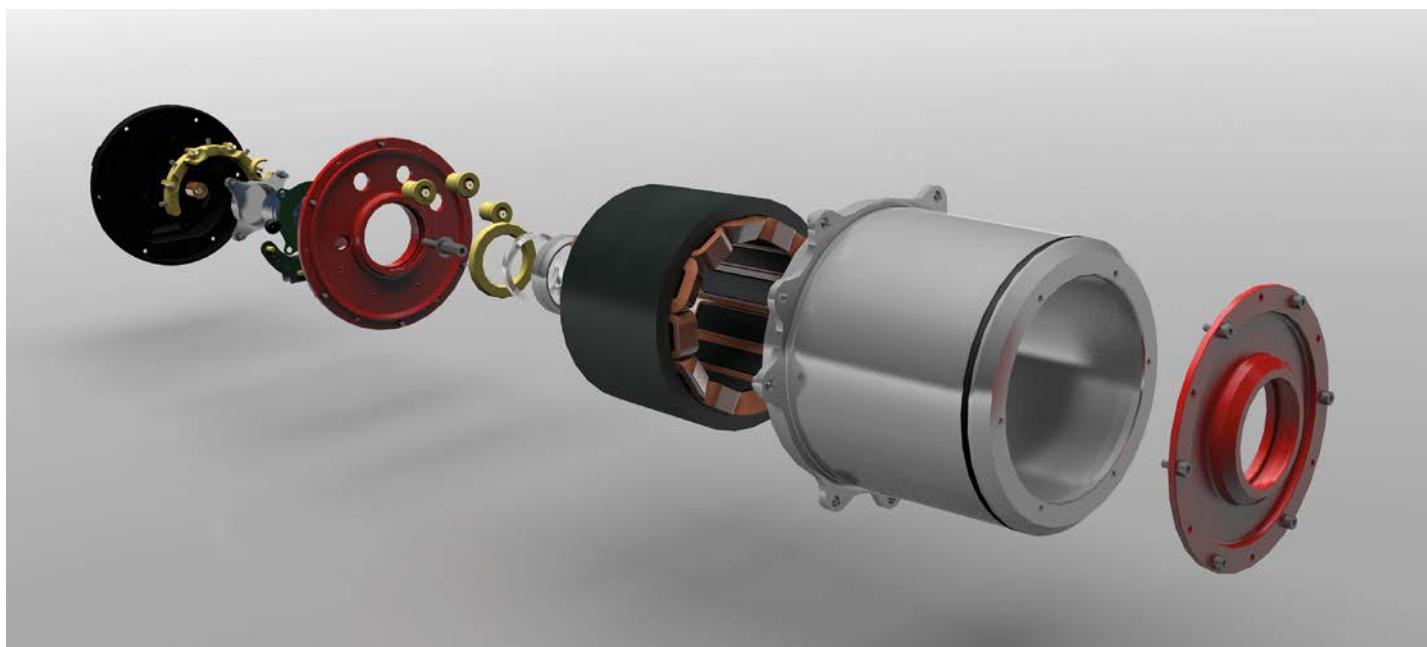
there different chemistries, but there are also different types to consider, such as pouches or cylindricals, with each cell offering different power and energy density combinations.

Perfect chemistry

Most motorsport batteries are lithium ion chemistries, with different cathode (positive electrode) materials. Selecting the optimum chemistry is a balancing act between achieving the desired energy and power densities whilst maximising safety. 'Li-ion cells with iron phosphate or manganese-based cathodes are intrinsically safer than any of the primarily cobalt based lithium ion cells,' says Dr Dennis Doerffel, chief technology officer at REAP Systems, which supplies battery components to Formula Student teams. 'This is because their cathode spinel structure doesn't collapse if it is completely depleted at the end of charging and the anode cannot be overcharged because li-ions from the cathode are depleted. The spinel structure does not collapse and the cells do not provide oxygen in case of thermal runaway. So they are safer but often heavier.'

'Most cathodes are a mix of nickel, cobalt and manganese these days in order to balance the advantages and disadvantages,' Doerffel adds. 'Cells which have a high manganese content – similar to li-ion phosphate cells – can't produce [their] own oxygen, if the cells overheat. So, they can be more easily extinguished with CO₂. These manganese-based cells have higher voltages than iron phosphates which is why they have a higher energy density and the current is a little lower so power densities are quite similar. If you want higher

'Battery packs must be designed in such a way that a thermal runaway in one of the cells cannot propagate to the next one'



The AMZ car uses four 37kW motors with a refined rotor and stator design; these drive a wheel each and give it good traction out of the many tight turns that are typical on FS events

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power and energy densities then you can go for more cobalt content and less manganese, but the higher cobalt and nickel content means that if the cell catches fire it will be virtually impossible to extinguish. Battery packs must be designed in such a way that a thermal runaway in one cell cannot propagate to the next.'

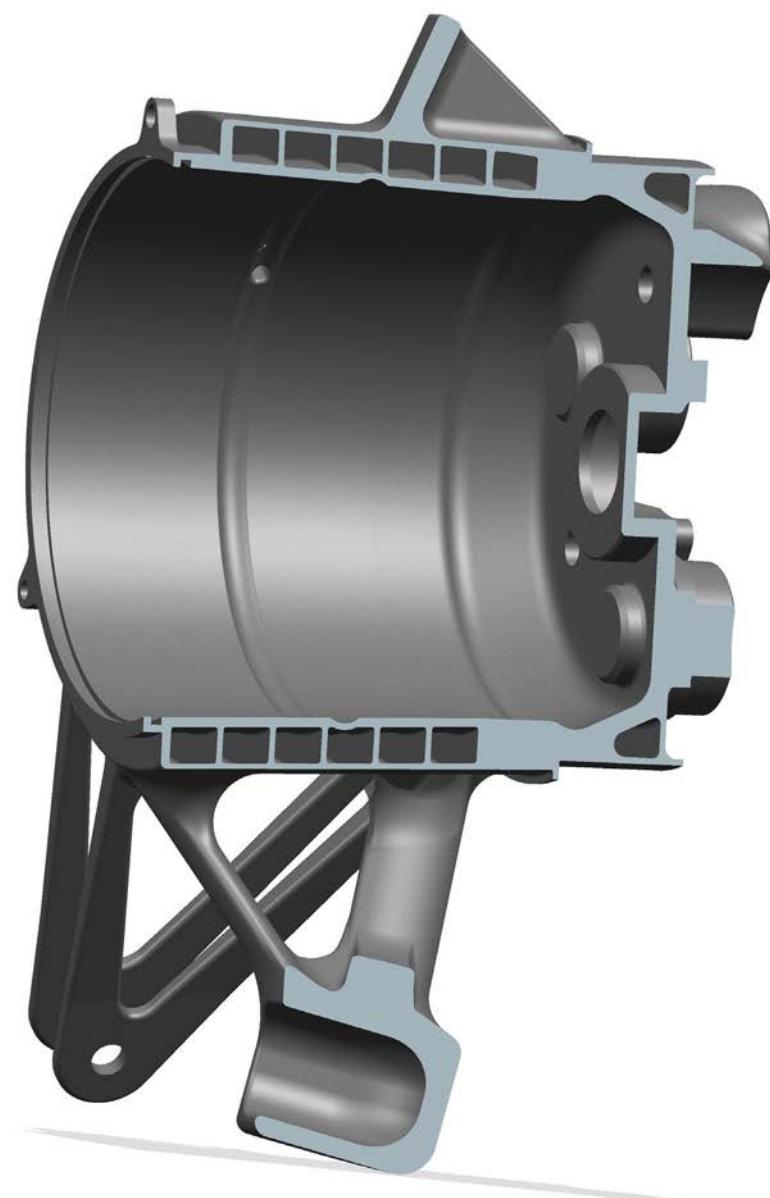
To get our heads around these power and energy densities let's look at other high voltage motorsport batteries. In F1, the ERS (Energy Recovery System) battery is discharged and recharged multiple times per lap as the energy from braking is stored in the battery which can then be utilised later as additional boost. Therefore, to achieve the power required for that boost within the smallest F1-style package available, these cells have high power densities of approximately 10-17kW/kg, with lower energy densities of around 90-120Wh/kg.

On the opposite end of the spectrum is Formula E, where the battery has one single discharge over the entire race and teams only have a fixed number of joules of energy to play with. Therefore, the batteries are designed to contain as much stored energy as possible, whilst the car is optimised to use this energy efficiently. This is why Formula E batteries have lower power densities of roughly 2.2kW/kg but much higher energy densities of around 232Wh/kg, compared to Formula 1.

High energy

'The longest race in Formula Student is endurance which is usually half an hour or so which requires high energy cells, rather than high power cells,' says Doerffel. 'A high energy cell can fully discharge in about 20 minutes, whereas a high power cell can discharge in six minutes with ultra high power cells discharging within three minutes or faster. The problem is that in a high energy cell there is more internal resistance, so although it may have a higher amp hour capacity rating, the watt hour rating may significantly reduce if you discharge with higher current. Also, regenerative braking with high energy cells can be difficult as usually they charge at 1C [coulomb, a unit of electrical charge] so you can't push as much power back into the battery when compared to a high power cell.'

'Another interesting consideration is the cell manufacturer's data sheet,' Doerffel adds. 'As manufacturers have to ensure their cells can provide the life cycles they specify, you can usually push the cells more than what the data sheets say because racing usually doesn't require the stated cycle life of 3000 or so cycles. However, it is difficult to find out how much more you can push them safely because



AMZ Racing cools its motors by using water-cooling channels that are integrated within its 3D printed aluminium uprights

manufacturers won't tell you. This is why FS is so interesting, because the teams can choose either high energy or high power cells but they really need to identify the overall benefits and that is a question that can't be answered without developing accurate simulation tools or without testing cells and packs.'

Cell selection also depends on how the cells are packaged within the battery box as this can affect the overall performance characteristics. The number of cells in series determines the voltage, while the number of cells in parallel determines the current and capacity. Therefore, the more cells in parallel, the higher the current and the more cells in series, the higher the voltage. High voltages results in low currents which is beneficial for the motors and inverters,

but not the battery. Furthermore, the rules stipulate that the battery has to be split into isolated modules, each limited to 120V, 6MJ of energy and a maximum weight of 12kg. Therefore, a high voltage battery would have to be split into several modules, each accompanied by a positive and negative high current connection, BMS, fuse, contactors and other ancillaries – all adding weight to the overall battery box. Alternatively, teams can choose lower voltage batteries and save weight but take the hit on motor and inverter performance.

'The Formula Student rules require you to take the battery out of the car when charging for safety reasons, which is a big design limitation as it means we can't make the battery structural like you can on other electric racecars,'

'The Formula Student rules require you to take the battery out of the car when charging for safety reasons, which is a big design limitation'

The cells need to be arranged in such a way that the air can effectively flow in between them and through the battery

says Kyprianou. 'So then you think "we will split the battery in two", but the rules specify that each module has to be identical so not only does it double the electronics, switches and mass, but also the risk of failure as you're effectively building two batteries.'

Cool running

Cooling the cells is another vital consideration that needs to be thought about early on in the design process. Most Formula Student batteries are air cooled, with a fan circulating the air. Therefore, the cells need to be arranged in such a way that this air can effectively flow in between the cells and through the battery.

'Our research showed that for what an FS car has to endure, with the hottest and longest cycle being the endurance, active air cooling was suitable,' says Kyprianou. 'We have fans inside the battery and pass air though the cells rather than liquid. Liquid cooling adds a lot of risk and there's a lot more work involved.'

It's not just the battery that requires cooling, often the motors do too, as is the case with AMZ Racing's car. 'We started nine years ago to

design our motors ourselves and although we have continued to optimise the rotor and stator design, the main design concept remained the same for the past few years which allowed us to continuously improve our motor every iteration, reaching 22Nm and 38kW at a weight of 2kg in the 2019 season,' says Horat. 'Cooling of the motors is really important, so for this year's car we have integrated the motor cooling inside the upright so that the motor needs no additional cooling casing. So we effectively cool our upright which in turn cools the motors. This allowed us to design a lighter and stiffer upright.'

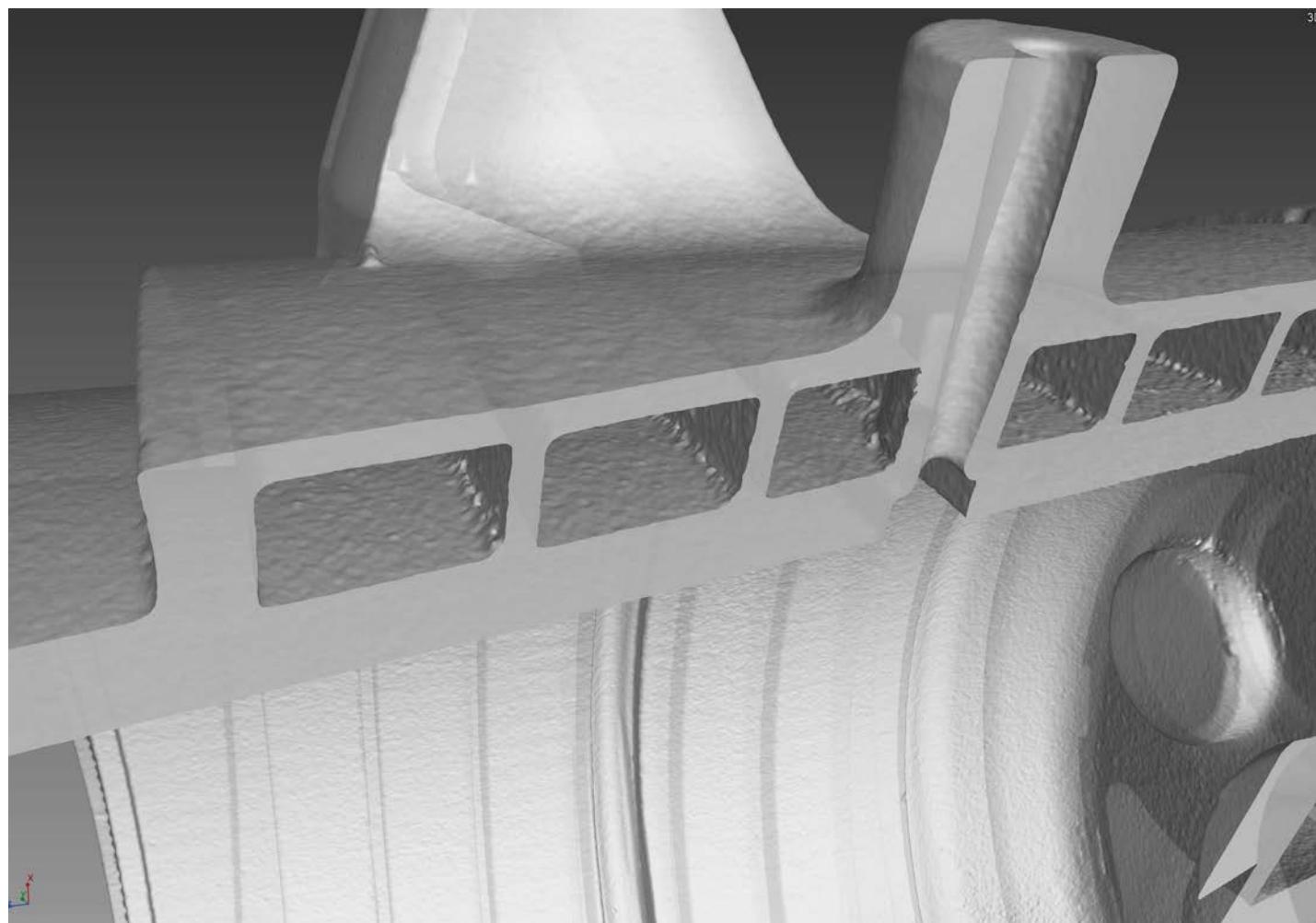
Safety systems

Once the motors, inverters and cells have been selected and the battery configuration has been optimised, the next challenge is to integrate the BMS and other safety systems. 'We have our predominant shutdown system which is a single loop that goes around the car and it has various systems such as emergency stop buttons, [in] the BMS or the ECU that can break that electrical line which then causes the car to shut down,' says Kyprianou. 'So, if anything goes wrong

the shutdown line is broken and therefore the battery isolates itself completely, so you have a really robust and simple safety system.'

Although some teams develop their own BMS, the majority buy off-the-shelf tried and tested systems. However, this still requires some level of engineering from the teams. 'Our BMS is not specifically designed for Formula Student, so the teams still have to understand how it works and do a lot of engineering,' says Doerffel. 'There is a lot of electro-chemistry inside batteries that engineers are still understanding and I think one of the biggest concerns is that batteries are very quiet. They sit there and they look quite peaceful, and students can underestimate the safety risks of them.'

Overall, there are a huge number of factors to consider when developing an electric powertrain, and a whole host of additional factors to design a high performance one. But with competitions such as Formula Student encouraging students to face these challenges early in their careers, the next generation of engineers will be able to solve the mysteries of electric technology much faster.



The geometry of the water cooling channels on the AMZ Racing uprights can be seen here in this CT scan. This approach had a knock-on effect of improving the upright's design

Schools of thought

Formula Student UK and Formula Student Germany were once again hotbeds of innovation this year with inspiring and intriguing solutions on show at both. Here's our review of the most fascinating technology and trends to come out of the 2019 competitions

By JAHEE CAMPBELL-BRENNAN

With concepts ranging from single-cylinder combustion cars to 4WD electric drivetrains, this year's Formula Student UK (FSUK) and Formula Student Germany (FSG) events were once again great adverts for the ability and ingenuity of student engineers, and there was very much of interest on show at both Silverstone and Hockenheim.

Starting with the suspension, in general the overall design approach to this across the paddock has more or less converged to a common format. Springs and dampers are positioned inboard of the wheels and the chassis is actuated via pushrod and bell-crank assemblies. This year's UCL car, however, featured an innovative and novel approach to suspension design in the form of flexures. In the context of control arms, flexures are an alternative mounting technology to the traditional spherical bearing configuration. Traditionally, control arms are fastened to the chassis via bolts in double-shear with articulation to allow for wheel displacement provided by spherical bearings. The idea of

a flexure is that the control arm is mounted to the chassis without a spherical bearing and instead uses a flexible section of material bonded and fastened to the arm. The benefits of this arrangement include reduced weight and friction in wheel articulation, as well as a finer control of kinematic and compliance effects within the system.

Flexible approach

It was at first a little surprising to see flexures on a Formula Student car due to the fairly large wheel travel requirement (a combined 50mm of bump and droop), whilst the control arms are relatively short so there is a typically large range of angle required for wheel articulation.

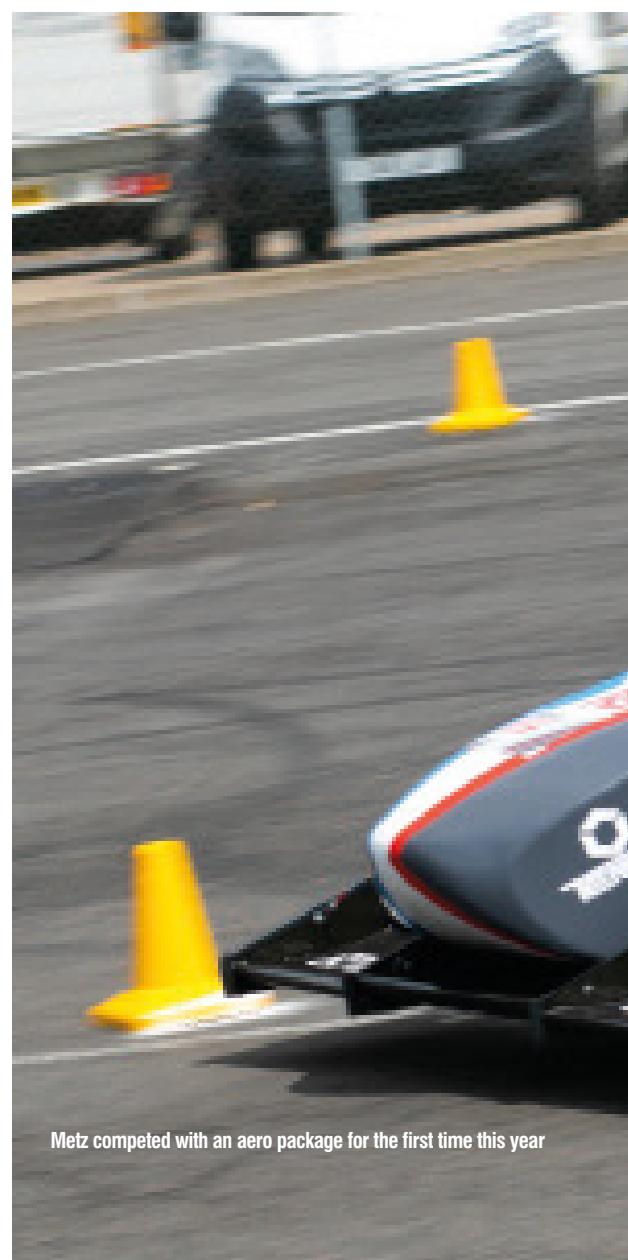
'The entire approach to this FS car was towards mechanical grip rather than that of aerodynamic grip' says Pete Weston, who played a key role in the development of this feature. 'With the suspension we saw the opportunity to try something a little different and so have used flexures on the control arms. We initially began the project with the intention of using torsion springs to reduce the friction

and stiction of the system, although that idea didn't make it on to the finished car.'

The car featured no downforce generating bodywork; the entirety of grip generated was mechanical and so the team at UCL focused on creating a chassis that worked the tyres efficiently, generating heat and maximising grip. 'We initially performed a study into which suspension parameters had the largest influence on tyre temperature and incorporated



Flexures, seen here on the UCL control arms, are an alternative to the traditional spherical bearing approach



Metz competed with an aero package for the first time this year

the results from that study into our design,' Weston says. 'We did extensive FEA on the flexures. The solution was driven through a combination of [using] x-section and the length, and is designed to be flat at static ride height so the nominal deflection is defined by a maximum of 25mm of travel at the wheel either side of this to equally load it in bump and droop. Material selection was a big factor in defining a safe flexure and we settled on SAE 4130, which is a high UTS steel with a good fatigue life.'

Aero smiths

Despite aerodynamic appendages now being a common sight in FS, the philosophies around the paddock are far from converged. Depending on the resources available to each team some opt for wingless configurations with simple fairings to reduce drag while the more well-resourced teams have developed complex and extremely aggressive aero packages in the search for downforce, with large chord and high camber wings, dual tier rear wings with two or three elements and high gradient diffusers.

Despite the low speeds of the competition's dynamic events with maximum speeds only around 75mph/120km/h, the overall results



Just two students were responsible for designing the Metz aero package and the team has only nine members

do suggest that the additional weight and drag penalties of an aerodynamic package are outweighed by performance gain.

Metz arrived at FSUK this year with its first attempt at an aero package, despite competing in FS for the last nine years. FS aero packages tend to be very aggressive in design due to the low speeds that result from the design of the

track and Metz's package wasn't any different in this respect. But the really impressive thing about it was its complexity, despite there being just nine members in the team. In fact, just two students developed the entire aerodynamic package from a blank sheet of paper.

'Our aim with the aerodynamics of the car was to build a solid and efficient foundation,'



The more well-resourced teams have developed complex and extremely aggressive aero packages in the search for downforce

says Alexandre Leys, team manager at Metz. 'We didn't initially search for ultimate downforce figures but we wanted to be safe and incorporate adjustability from which to create an aerodynamically balanced platform. We wanted our centre of pressure just behind the centre of gravity and we accomplished this with a 53 per cent rearward aerodynamic balance to our 50:50 weight split, generating a total of around 45kg of downforce at 60km/h.'

This was achieved using a relatively simple tiered front wing which directs the air over the front wheels to reduce lift and subsequent downstream turbulence, with an outer dual element tier and vertical end plates. The rear wing was again not revolutionary but of a sound and concise design; featuring three elements along with an upper tier. The lowermost aerofoil of the three-element assembly featured a very long chord length. Presumably this is aimed at maximising the potential of the extremely turbulent and low energy air that has travelled over the driver, main roll-hoop and engine intake. This results in a more efficient flow on to the upper tier, which also featured a neat Gurney flap to aid flow attachment.

Go with the flow

The underbody aero also featured a high gradient diffuser to promote mass flow. 'Our two aerodynamicists worked for the first six months solely on design and simulation and often had simulations running 24 hours a day,' says Leys. 'Our sponsors, Safran, assisted with the manufacture of the wings, with a foam core used for the aerofoil sections. The profiles were cut by us with a wire-cutter but without the experience and help of Safran we wouldn't have been able to manufacture them in time.'

Metz's implementation of sound aerodynamic theory coupled with its maturity in not attempting the unachievable was impressive and should be commended, especially when achieved with relatively small resource. Often it's better to keep things simple and do them well, rather than overcomplicating the task and running into issues.

Another neat aero innovation was the front wing design of the Strathclyde car. Regulations necessitate a jacking point at the rear of the car which when used will rotate the front wing into contact with the ground and therefore damage it. This usually means that the teams design wings that are mounted relatively high and therefore are clear of any potential ground effect performance gains. However, to work around this, Strathclyde installed gas struts and a pivot point where the front wing is mounted to the nose. So as the rear of the car is jacked up, the front wing contacts the ground, compressing the gas struts which consequently prevents any damage. 'Mounting the front wing in this way meant we could utilise ground effect; reducing our drag and increasing the downforce,' says Iain Lowther, the team's technical director. 'This then

'The entire approach to this car was towards mechanical grip rather than aerodynamic grip'



The ingenious use of gas struts on the Strathclyde FSUK entry allowed the front wing to run in ground effect

allowed us to use a more aggressive rear wing package and consequently increase the car's overall downforce numbers.'

To make its aero package Strathclyde used a simplistic but effective carbon fibre lay-up technique. 'We have a pretty simple lay-up technique which means we could manufacture the entire aero package within two weeks but it's also pretty lightweight, at only 7kg,' says Lowther. 'We had to stretch the limits on what we could technically get away with, but it resulted in the second lightest aero package of the [FSUK] competition, so we are proud of that.'

Joint effort

Occasionally, universities work with each other to develop an FS car and one such collaboration for 2019 was that of Ain Shams University in Egypt and the University of Sussex in the UK. In all forms of motorsport, technical collaborations

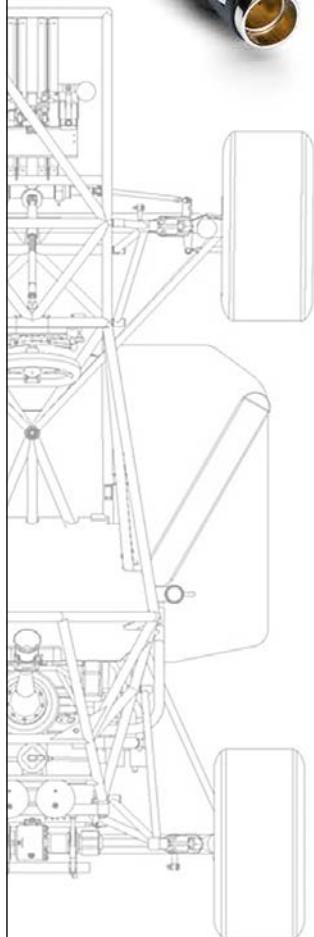
are prominent, teams outsource engineering solutions due to time, budget and expertise limitations. In this collaboration Ain Shams produced the chassis, suspension and bodywork whilst the University of Sussex developed the electric powertrain and other electrical systems.

'From the start of the project, anticipating future complications, both teams agreed that we would keep the car as simple as possible for our first venture, with reliability at the forefront,' says Serdar Cicek, team leader of the project. 'As ever, there were plenty of obstacles to overcome. For example, the chassis was manufactured in Egypt so when we received it, we found there were some tolerances in the manufacture that were larger than expected, which resulted in some issues which we had to overcome, so we learnt valuable lessons there. The chassis didn't arrive until early May for various reasons so we only had around five



Imperial's car features a largely self-designed electric powertrain

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CD34

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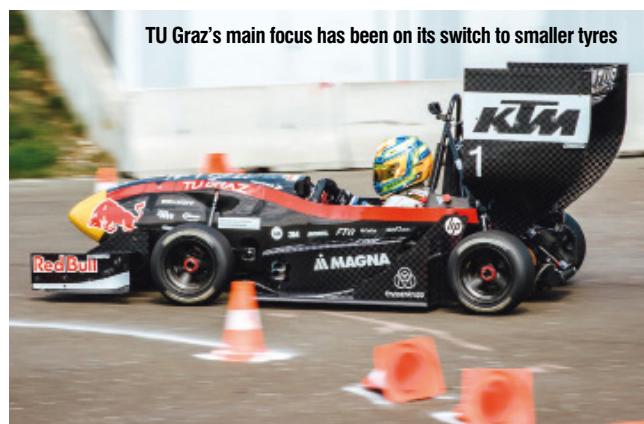
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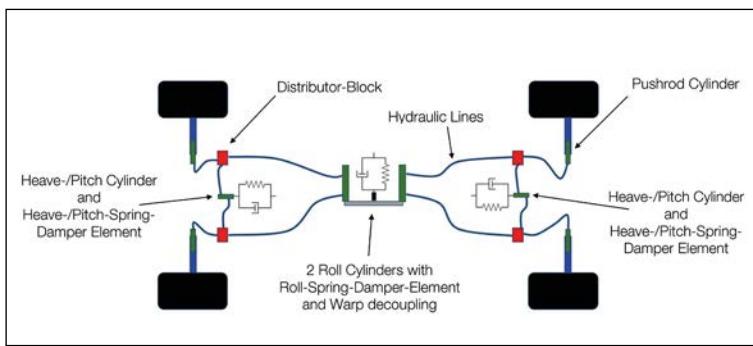
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TU Graz rear wheel steering system; the toe control arms are actuated by the motor assembly



TU Graz's main focus has been on its switch to smaller tyres



AMZ's mode decoupling suspension is similar to the FRIC system on the Porsche 919 LMP1 car



The remarkably light AMZ car features four 37kW wheel-mounted electric motors

weeks before our car launch to prepare the car and mate all the systems together. Therefore, we effectively only had nine weeks to complete a running car, but never the less we managed to get our car ready for competition.'

Imperial measured

Imperial University entered FSUK with its first Class 1 entry, having previously only entered the competition in Class 2, which is where teams are judged on their designs alone. The team developed a car with an electric powertrain but the ingenuity with this project was its battery solution. The battery was designed and manufactured entirely in house and is air cooled. While that may not be revolutionary in itself (see page 72), the battery is cooled using passive airflow travelling underneath the car, rather than the more conventional method of active air cooling which utilises fans.

A team of four students worked on the battery and used cells from an external supplier. These were then used to build up the battery modules, which were mounted underneath the chassis rather than in the more common location of behind the driver. This is not only a clever way of reducing complexity and cost, but it also has further dynamic benefits such as lower weight and improved weight distribution. 'Some of our challenges were with the manufacture, in order to fit the cell packs in the tight space under the chassis as opposed to in the sidepods or behind the driver,' says Harry Thompson, who developed the batteries at the Imperial team. 'We had to employ some very tight packaging tolerances so tolerancing and machining were our main hurdles.'

Many forms of electric vehicle battery packs require liquid cooling to keep the lithium-ion cells within a very narrow temperature window, sensitive to $\pm 1\text{degC}$, to optimise performance. But with this solution the rate of cooling is dependent on vehicle speed and therefore the level of heat rejection. 'With our cooling solution, the positive is that when the car is moving slowly and there is low air speed, we don't need to reject a large amount of heat,' explains Thompson. 'At the times where the cells are generating a lot of heat under acceleration, the air speed is high, so it works well in that sense. We have also done some analysis in terms of both computer simulation and within a battery oven at our expected worst case conditions, and while there is always the possibility that the cells get a little too hot in unexpected conditions we have safety measures that will shut the car down to avoid unsafe conditions escalating. Our battery can release the full 80kW limited by regulations and the pack has a capacity of 7kWh which will last the whole endurance event, so we feel we have produced a successful design.'

Graz routes

TU Graz entered the 2019 FS season with an impressive history; three world records and two overall wins in recent years. Its main objective for this year was therefore to continue this success by evolving the technology and designs

of the car. Much of the 2019 car comprises of incremental changes compared to previous years, with particular focus on weight reduction; it achieved one of the lightest FS cars seen at FSG, weighing in at an impressive 150kg.

One of the most substantial changes this year was the switch to a smaller diameter tyre developed by Hoosier. 'We noticed that a lot of the teams were putting substantial work into their aerodynamic development and seeing positive results. So this year our main focus has been on the smaller tyres and how to optimise the car's behaviour with those, whilst also increasing our aerodynamic performance,' explains team leader Jodok Hammerle.

Dropping from 18in to 16in outer diameter tyres, the smaller tyre not only reduces weight, but also the polar moment of the car and rotational mass, complimenting vehicle dynamics. This change also required some modifications to the kinematics of the suspension to capitalise on these advantages, allowing the team to feature some additional aerodynamic elements around the wheel to improve aerodynamic efficiency.

A new rear wheel steering (RWS) developed by the students also featured on the TU Graz car this year. RWS systems are used to influence the yaw responses of a vehicle through actively controlling toe at the rear wheels during cornering to reach optimum slip angles and maximum cornering grip. TU Graz's system uses

TU Graz achieved one of the lightest cars seen at FSG, weighing in at an impressive 150kg

inputs from steering wheel angle, vehicle speed and a gyroscope to create a map of steering input to the rear wheels for best performance. 'In testing we were showing to be one to two seconds faster around the circuit with the system enabled, even gaining 0.3 of a second in one hairpin alone, so it's a great addition for us,' Hammerle says. 'We currently use it for all events aside from the skid-pad as our drivers reported it was very difficult to drive [with it] on that particular course layout. The total weight for the system is 1.4kg so we are not incurring much of a weight penalty with this.'

Going TU Fast

Another one of the best German heavyweight teams is that of TU Fast from the Munich Technical University. Having unfortunately been disqualified for a software issue after effectively winning the FSG competition last year, it was determined to set the record straight this year. So, having already identified the formula to build a competition winning car, the 2019 entry was an evolution of the 2018 racer, with incremental changes and updates, but largely the same technical package.

That said, aerodynamics were a focus for improvement for this year's TU Fast car, with the new aero package being 10 per cent more efficient than last year. 'Our extra aero efficiency was due to a larger rear diffuser and underbody modifications,' says Gregori Garyuk, technical director at the team. 'Most of the effort was focused there and this then meant we had to make adjustments to our front wing to maintain the correct aerodynamic balance, so we added additional flaps to help this.'

Speaking to various Formula Student teams, it seems the vast majority of those running a 10inch wheel have this year moved to the newly available Hoosier 16in tyre. TU Fast also took this opportunity, leading to a revision of its suspension kinematics, which is a pretty standard change. However, it also chose to take this opportunity further and it has downsized its reduction gearboxes too, with the new configuration now reducing the torque reacted in the gearbox, while this alteration also gave it a small weight advantage.

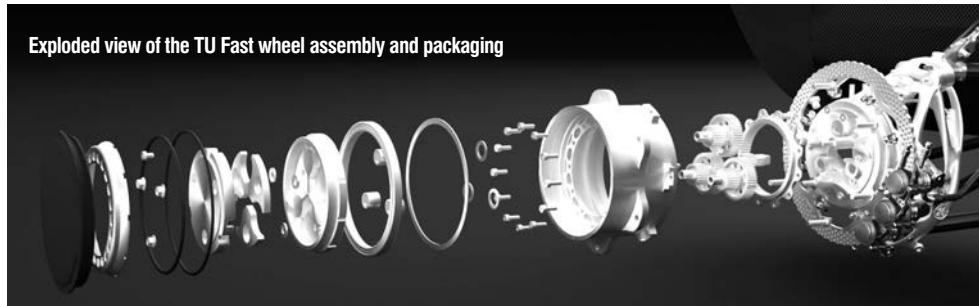
TU Fast also attributes some of its speed on track to a completely (aside from the motors, that is) in-house powertrain design. 'We have developed the ECU, accumulator and inverter in house,' Garyuk explains. 'This year we also changed our communication protocols between the ECU and the inverter which required a little work, but we have a great inverter solution and none of the issues with EMI [electro-magnetic interference] that we have seen other teams have. The combination of ECU, inverter and accumulator is very well adapted to the requirements of our car.'

Electromagnetic interference can occur from components like power inverters when they are not correctly shielded from the behaviour of

CAD rendering of the TU Fast team's car, the eb019



Exploded view of the TU Fast wheel assembly and packaging



The vast majority of the teams running a 10in wheel have moved to the new Hoosier 16in tyre

the electromagnetic field. If not under control it can affect CANBUS communications creating malfunctions of the control systems on the car and can also damage the inverter itself.

Swiss watch

Powertrain development was also a theme at AMZ Racing, the Zurich team. Its 2019 contender is an evolution of last year's car, with the same basic concept. This features four 37kW wheel mounted electric motors delivering wheel torque to a remarkably light 158kg body and a well-developed aerodynamic package and suspension system. Where the 2019 powertrain differs to last year on the Zurich car is the switch from two electrical accumulators to one. This consequently changed the aero concept around and necessitated a smaller rear air diffuser due to package redistribution behind the driver. This allowed the sidepod area to be used for aerodynamics rather than pump and electrical equipment packaging.

Development of its in-house inverters has also continued. The current design is half of the weight of last year's design and was achieved through moving from four single inverters to two double inverters, allowing further packaging and weight distribution freedom.

The tech that really shone on this car, though, was that of the suspension system which featured active wheel control. 'Last year we had a hydraulic active suspension concept actuating each wheel individually, but we ran into major issues which meant we had to run

the system passively, which was not ideal,' says Oliver Haselbach, chief technical officer of the mechanical aspects of the car. 'This year we simplified the suspension system to utilise three spring and damper elements with one element at each of the front and rear axles acting to decouple heave/pitch modes, plus one central element for roll and warp mode decoupling.'

This system is an evolution of an initial concept introduced at AMZ three years ago and from a vehicle dynamics perspective it gives a great amount of control and precision of reaction to input in multiple degrees of freedom, ensuring an optimal dynamic response in a range of conditions. This ultimately leads to a reduction in the variation of contact pressure between tyre and track surface and a set-up that produces maximum mechanical grip. This is similar to systems that have been used in high level motorsport, such as the Porsche 919 LMP1 car's FRIC system, and it will always benefit the car's performance throughout dynamic events, which AMZ has always excelled at anyway.

Lastly, there is also a new wheel upright and motor assembly packaging that was influenced by a move to smaller wheels this year. 'We have a new smaller tyre from Hoosier which meant a change to the wheel packaging,' says Haselbach. 'We are now using SLM 3D printed aluminium uprights which have integrated water-cooling channels for the motors, so it's very complex and we are proud of that. In total we saved 6kg with this packaging update.'



Class of the field

This year's Formula Student UK event at Silverstone threw up some interesting technical solutions, as always, but there was no amount of tech trickery that could deny MoRe Modena Racing (MMR) of its well-deserved victory. Racecar took a close look at the Italian team's clever little M-19L racer

By JAHEE CAMPBELL-BRENNAN

The 2019 FSUK winner, MoRe Modena Racing (MMR), took the competition by storm, with a 119-point advantage over its closest rival, Oxford Brookes.

MMR is based at the University of Modena and Reggio Emilia and its Formula Student journey began back in 2003, when it was run out of a small workshop at a car showroom. Today, the team fields three cars out of a dedicated university workshop and comprises approximately 80 mechanical, mechatronics, electrical and management students.

The 2019 FSUK winning car, the M-19L featured a carbon fibre monocoque for the fifth year running, a longitudinally mounted gearbox and a full aero package. 'The main focus for 2019 was to optimise concepts and solutions from the 2018 car,' says Gianmarco Carbonieri, team leader at MMR. 'There were some components that had reliability issues, for example the DRS system in 2018 did not work correctly, so we made sure that was fixed this year.'

That's a MoRe

Weight was also a strong focus and by optimising component development the team managed to lighten the car significantly, contributing to its dynamic performance targets. 'We had a design objective to reduce individual component weight over the whole car by six per cent from last year, and actually we overachieved this and lost nearly 10 per cent of weight from last year's car – we're currently weighing in at 196kg,' Carbonieri says.

The Formula Student regulations recently changed to allow an increased maximum displacement of 710cc. MMR took full advantage of this and therefore up-sized this year's engine to a 708cc Suzuki GSXR, something it predicted would generate more power over a wider speed range than the previous 600cc GSXR unit. 'The original idea was to use a 708cc Suzuki GSXR engine derived from a 750cc stock unit,' Carbonieri says. 'We modified the crankshaft



The MMR team has worked hard to eradicate an aero imbalance it had with last year's car while also improving the cooling

and connecting rods to reduce displacement to 708cc, but unfortunately on the bench we had a crankshaft failure due to a manufacturing defect. We lost that engine and so had to revert back to the standard 600cc engine. We lost around 7bhp by using this, but we're still managing around 99bhp, so we reached our specific power target of 2kg per bhp.'

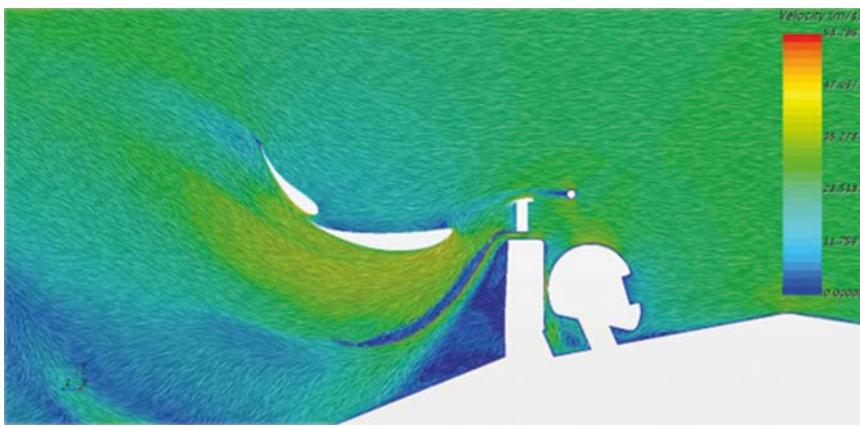
The engine is mounted longitudinally, which is an unusual approach for a Formula Student team, as they usually opt for transverse. 'We are one of the only teams to use the longitudinal engine mounting,' says Carbonieri. 'This brings advantages in terms of space for accessories, it also moves the heat from the exhaust further away from the driver, fuel tank and electronic components. The bevel gear transmission we are now able to use is more efficient in the driveline. We only used gears two to five in this

gearbox, so we removed ratios one and six. This saves us some space and weight that we take advantage of it with a custom gearbox casing.'

MMR's carbon fibre chassis concept is an evolution on previous years' cars and is a slightly different approach to the fully moulded monocoques more regularly seen amongst the winning teams. 'We are using the cut and fold technique without moulds for our monocoque, primarily to reduce costs,' explains Carbonieri. 'Traditional carbon fibre monocoques were costing around €50,000 for the mould and another €10-15,000 for the part. Finished, our chassis is around €10-12,000 total.'

Using this method, carbon fibre and aluminium honeycomb panels are constructed in 2D and 'cut and folded' to form 3D shapes, creating a somewhat geometric appearance to the monocoque. Panels are then bonded

'We are using the cut and fold technique without moulds for our monocoque, this is primarily to reduce the costs'



CFD plot taken along the longitudinal centreline showing the velocity distribution around the car's rear wing

to form the finished part (see V28N9 for the full method). The final chassis is lightweight, weighing under 17kg, and has a high torsional rigidity, which improves vehicle dynamics.

One interesting feature of the MMR car is the driver operated DRS (Drag Reduction System). Used in F1, the concept behind this technology is to reduce the angle of attack of the uppermost wing element (with the largest frontal area), reducing drag significantly where downforce is not needed. 'We use a motor and wire operated element, all the wires are integrated into the main-plane and endplates so it is a neat solution,' says Carbonieri. 'Packaging the wiring was a little difficult initially as we had some problems with the flap cutting the wire, but we have addressed those now. The motors and associated hardware are weighing nearly 500g and are mounted quite high [1m] on the car, but we made the judgement that the effect on CoG was negated by advantages on the straight section of the track.'

One of MMR's key objectives for 2019 was to reduce unsprung mass as much as possible. This is why it aimed to bring new 10in carbon fibre wheels to FSUK. 'We made a prototype but unfortunately we had a problem with the supplier for this part so we only made one wheel. With each wheel weighing just over 1kg this is a 3kg saving across the whole car so we're certainly aiming to implement this design in the future,' says Carbonieri. 'We use M46J CF and unidirectional reinforcements around the centre. It's a 10in diameter with three spokes, of hollow construction. We are using aluminium inserts to be certain that there is an evenly distributed load from the hub into the wheel as carbon fibre is quite fragile in that respect.'

For 2019 MMR had two main aims which drove the design of the car's aero package. The first was to solve the aerodynamic balance which was too rear biased on the 2018 car, and the second was to improve the cooling efficiency, which meant modifying the sidepods. 'We developed the aero package this year to address an understeer issue we had with the 2018 car, so we looked at more aggressive aero on the front wing to solve this,' says Carbonieri. 'A lot of work went into our end plates and

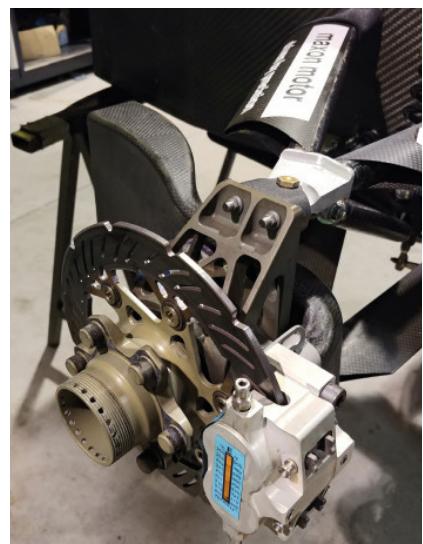
we got to a 58 per cent front balance which works better for us. Last year we had separate radiators for our water and oil but this year we implemented a single air-water heat exchanger for the water and used a water-oil heat exchanger to cool the engine oil.'

'Last year the radiators were fairly big so we have reduced the dimensions of the radiators by 40 to 50 per cent. We have two coolers in parallel and a larger pump with PWM [pulse width modulation],' Carbonieri adds. 'We found this to be more efficient in terms of thermal exchange. This configuration also gained us about 2-3kg of weight saving with smaller radiators, less water and smaller sidepods, with the latter also allowing us to rework the aerodynamic performance and reduce drag.'

Test of time

Testing and verification is an interesting challenge within FS. With only one year for design and manufacture as well as limited resources, development work continues right up until very close to the event. In FS terms, MMR actually had a fairly significant amount of test resource, both analytical and physical, which played a key role in its success. With the powertrain, MMR used analytical tools for the majority of its development and calibration. 'We ran powertrain simulations using 1D sim tools such as Simulink and used a dyno to gather measured data,' Carbonieri says. 'We would correlate all of the 1D sim outputs on the bench to ensure they were producing accurate data which allowed us to trust what we were doing.' Using this approach saves both time and money, allowing iterative concepts to be proven and verified in a short time frame.

Physical testing is not always possible, and definitely not to the extent that teams would like. This is particularly true with aerodynamics, where testing in controlled environments such as wind tunnels is often not available. Therefore, to correlate its CFD data, MMR used a different strategy. 'For our aero package we relied largely on CFD as we had no access to a wind tunnel, but we did try to correlate our CFD using a method of attaching string to the aerodynamic surfaces during track testing to



The M-19's very neat brake and upright assembly

monitor the airflow patterns, and we had quite good success with that,' says Carbonieri. 'We also had displacement sensors on our dampers so we used the data from those during track testing to monitor compression of our springs due to aerodynamic load, this gave us a little correlation to the CFD simulations. We also used this to fine tune the aerodynamic balance.'

Vehicle dynamics simulation was another crucial aspect of the car's development as it allowed the defining of suspension geometries and critical dimensions. It also enables the optimisation of parameters such as spring and damper rates, anti-roll bar stiffnesses as well as understanding the influence and sensitivity of the car to CoG location with regards to weight transfer and the moments generated on track.

'We used ADAMS to design our suspension layout and kinematics and then used VI Grade to run lap time simulations to figure out where last year's car was and where we could improve on this,' says Carbonieri. 'For example, modifying the CoG to see if we had any performance advantages or simulating a lighter car to see how the lap times improved. This was very useful for our development process. We also used MatLab to understand the brake power requirements and the heat produced during simulated braking events, we used this to design the brake ducts and the discs. Last year we had overheating in our brake fluid which led the driver to lose confidence in the car, so we wanted to get that under control this year.'

In terms of physical testing, the team had access to three test tracks encompassing areas for acceleration and brake tests, plus a skid-pad and an autocross track to replicate what it would face in the competition. MMR managed around 150km of testing in the months leading up to the FSUK event, using the time to optimise the aero and vehicle dynamics set-up.

Overall, MMR built on previous experience, and with a solid approach it designed, produced and raced a car that was very worthy of its impressive victory at FSUK in 2019.

Winning formula

Our resident number cruncher presents his must-read master-class on the fundamentals of effective racecar engineering

By DANNY NOWLAN

A DTM BMW on the limit at Brands Hatch. Grip and balance are the properties of a racecar that race engineers will find themselves dealing with the most



One of the most challenging things when we come to engineering a racecar can be how do you actually go about it? I realise that this, for a lot of motorsport professionals, is the question that dare not be asked, on account you might seem silly. However, a couple of weeks ago I was invited by Altair Engineering to be a keynote speaker at its inaugural Australian FSAE technical conference. I figured this was a fantastic opportunity to address this question.

What I will be discussing here is the text version of the presentation I gave. The goal was to give the budding engineers a road map on how to go about engineering a car. In particular, what you need to be thinking about in terms of hand calculations and when you bring in tools such as ChassisSim. All this allows you to make informed engineering decisions as opposed to just mindlessly using a CAE tool or sticking your finger in the air and hoping for the best.

Also, to set the scene, I will be tying together quite a few elements I have previously discussed. For brevity I will reference these as needed, because what we are about to discuss is quite literally a two-day seminar in its own right.

Grip and balance

To kick things off, if we think about the race engineering problem – that is, making a car go as fast as possible – our two main currencies are grip and balance. I should also add to that if you are in an unconstrained formula engine power as well. However, as race engineers we deal with the first two points the most. Make no mistake, if you are serious about having a car that is fast it must have grip and it must have balance. The ultimate incarnation of this, to paraphrase one of my fellow contributors Peter Wright, is not a racecar, but an aircraft, the Spitfire. It was said you didn't fly the Spitfire, the Spitfire flew you. That's the Holy Grail of what we are after as race engineers.

So the critical question is, how do we put numbers to all this? Grip is the easy part of the equation. For a given set-up, bare minimum you can get a very good estimation of the forces the tyres can produce. However, handling is a different ball game entirely.

To nail down handling your best friend is the stability index (see V28N2). What the stability index measures is the moment arm between the centre of the lateral forces of the car and the centre of gravity. This is illustrated in **Figure 1** and just to refresh everyone's memory the stability index (*stb*) is calculated by **Equation 1**.

So, a quick recap of what the stability index numbers mean. If the number is less than zero the car is stable, so it will level itself off when an input is applied. When it is zero you give it an input and it just keeps going. If it's greater than zero you give it an input and it spins. The number the stability index returns is the moment arm between the centre of gravity and the centre

Figure 1: An illustration of the stability index

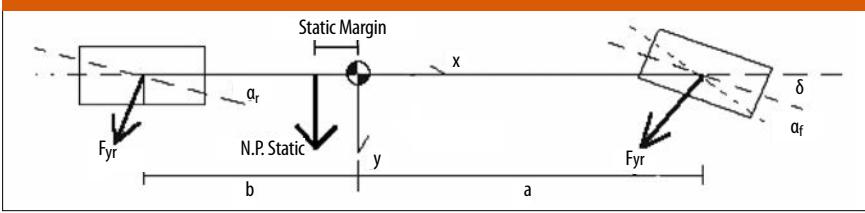


Figure 3: Visualisation of the meaning of a second order tyre model

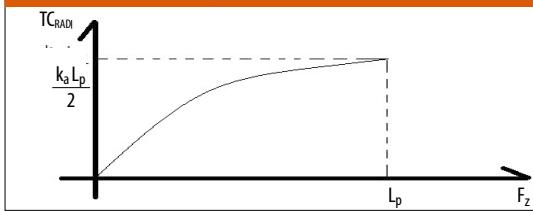
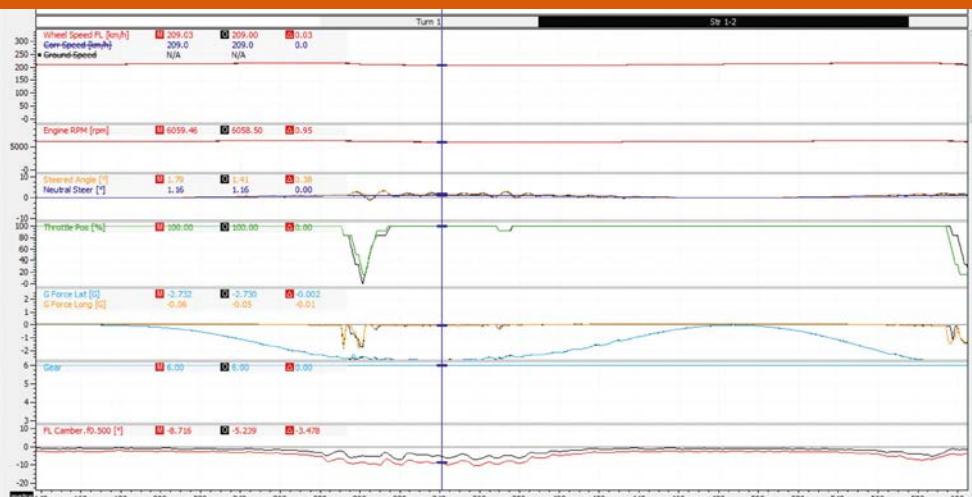


Figure 2: Simulated F3 front wing change



EQUATIONS

EQUATION 1

$$C_f = \frac{\partial C_f}{\partial \alpha_f} \Big|_{\alpha=\alpha_f} \cdot (F_{m1} + F_{m2})$$

$$C_r = \frac{\partial C_r}{\partial \alpha_r} \Big|_{\alpha=\alpha_r} \cdot (F_{m3} + F_{m4})$$

$$C_T = C_f + C_r$$

$$stbi \approx \frac{a \cdot C_f - b \cdot C_r}{C_T \cdot wb}$$

Where:

$\partial C/\partial a(\alpha)$ slope of normalised slip angle function for the front tyre

$\partial C/\partial a(\alpha)$ slope of normalised slip angle function for the rear tyre

$F_m(L_i)$ traction circle radius for the left front (N)

$F_m(L_2)$ traction circle radius for the right front (N)

$F_m(L_3)$ traction circle radius for the left rear (N)

$F_m(L_4)$ traction circle radius for the right rear (N)

EQUATION 2

$$TC_{RAD} = k_a (1 - k_b \cdot F_z) \cdot F_z$$

Where

TC_{RAD} traction circle radius (N)

k_a initial coefficient of friction

k_b drop off of coefficient with load

F_z load on the tyre (N)

EQUATION 3

$$rcm = rcf + wdr*(rcr - rcf);$$

EQUATION 4

$$hsm = h - rcm;$$

EQUATION 5

$$rsf = (krbf + kfa)*ktf/(kfa + krbf + ktf);$$

EQUATION 6

$$rsr = (kfb + krbr)*ktr/(kfb + krbr + ktr);$$

EQUATION 7

$$prm = rsf/(rsr + rsf);$$

EQUATION 8

$$prr = (wdf*rcf + prm*hsm)/h;$$

Where:

rcm mean roll centre (measured in metres)

rcf front roll centre height (measured in metres)

rcr rear roll centre height (measured in metres)

wdr weight distribution at the rear of the car

wdf weight distribution at the front of the car

h centre of gravity height of the car (measured in metres)

rsf wheel spring rate in roll for the front (N/m)

rsr wheel spring rate in roll for the rear (N/m)

ktf front tyre spring rate (N/m)

ktr rear tyre spring rate (N/m)

kfa spring rate of the front coil, acting at the wheel (N/m)

kfb spring rate of the rear coil, acting at the wheel (N/m)

$krbr$ rear roll bar rate (N/m)

prm lateral load transfer through the sprung mass

prr lateral load transfer distribution at the front

tm mean track of the vehicle

of the lateral forces divided by the racecar's wheelbase. As rough rules of thumb you want to be aiming for mid corner values of 0.05 with the occasional venture to 0.1 on turn-in. However these are *rough* rules of thumb.

The reason the stability index is so useful is it succinctly quantifies what the car's handling is doing. The plot of a Formula 3 front wing change in **Figure 2** is a perfect case in point.

The coloured plot is the baseline, the black is the aero balance moved forward by five per cent. As can be seen, the speed, steering and throttle do not change by drastic amounts. The reason for this comes down to the nature of the tyre model and how simulators are like *The Terminator*. They know no fear, they have no concept of mercy and their only goal is speed. However, what has changed quite markedly is the stability index which is shown in the final plot. The baseline has a stability index value of -8.5 per cent and the change is -5.3 per cent. Consequently this forms a valuable tool for nailing down car handling.

Tyre models

So how do we quantify all this? Well the first step is to get yourself a tyre model. Now most people at this stage of the game will just throw their toys out of the pram and say it simply can't be done. But remember a previous article of mine on how to create tyre models from scratch (V26N2)? If so you'll know the key to any tyre model is nailing down the traction circle radius vs load characteristic. Its basic building block is shown in **Equation 2**. What this means in plain English is that any tyre model can be broken down into the visualisation shown in **Figure 3** (L_p is peak load).

So what this all means is that any tyre model can be described by its peak load and force. So if you know what your peak tyre loads are and what grip you're expecting you can get a representative tyre model very easily.

The way we tie this up through our set-up is the lateral load transfer distribution at the front. This is sometimes referred to as the 'magic number'. While this doesn't really have any magical characteristics it's a great tool to help us nail down our tyre load for a given mechanical and aero set-up. A quick summary of where this comes from is shown in **Equations 3 to 8**.

The real significance of the lateral load transfer distribution is that it gives us a first cut

To nail down a racecar's handling your best friend is the stability index

EQUATIONS

EQUATION 9

$$L1 = (wdf * mt * g + Faero_f) / 2 + prr * (mt * ay) * h / tm + \text{other terms}$$

EQUATION 10

$$L2 = (wdf * mt * g + Faero_f) / 2 - prr * (mt * ay) * h / tm + \text{other terms}$$

EQUATION 11

$$L3 = (wdr * mt * g + Faero_r) / 2 + (1 - prr) * (mt * ay) * h / tm + \text{other terms}$$

EQUATION 12

$$L4 = (wdr * mt * g + Faero_r) / 2 - (1 - prr) * (mt * ay) * h / tm + \text{other terms}$$

of what to expect with tyre loads. This is illustrated in **Equations 9 through to 12** – where mt is car total mass (kg); g is acceleration due to gravity; and $Faero$ is total aerodynamic force (N). I go into much more depth on this in my article on tyre load analysis, so I would refer you to that to chase down the details (V28N1).

Even though this is all pseudo static approximations we now have a tool with which we can calculate both grip and stability index. I discussed this in depth in my article on the magic number (V26N9) but the end results of this are illustrated here in **Figure 4** and **Figure 5**.

This is very powerful because for a given set of tyres it will tell you where you need to be for a given lateral load transfer distribution to generate the peak grip and what this will do for car stability. You ignore these figures at your peril.

The next step in the race engineering process is determining springs, roll centres and pitch centres and hot running tyre pressures. All of this determines the core temperatures/pressures the tyre needs to run at. The springs will be dictated by the aero and getting the core heating in the tyres you need. Also, the relationship between springs and suspension geometry will have a massive impact. There are two ways this can be facilitated. Firstly testing, which is pretty self explanatory, then the other method is using track replay facilities, like in ChassisSim, with the internal tyre temp flag turned on.

Quarter car model

Once you have determined your base spring rate your next port of call is damping. Your best friend in this regard is the quarter car model. While it is not the most exact thing out there the beauty of the quarter car is it allows you to articulate mathematically what your dampers are doing. The core sums you will have to get your head around are **Equations 13 and 14**. The key take away from this is the damper guide, as illustrated in **Figure 6**. The thing about this is it is a first cut, but it gets you in the ballpark.

Once you have done all of this you are now ready to turn on the simulator and your first port of call is the shaker rig simulation. The outputs of the shaker rig simulation are shown in **Figure 7**. The power of the shaker rig simulation is that it allows you to look at the car in the frequency domain and through the contact patch load (CPL) variation it gives you a really good gauge of tyre grip.

Simulation in action

In my 2014 article on simulation in action (V24N5) I described in depth how my Australian dealer Pat Cahill used this to engineer the Maranello Motorsport Ferrari F458 to victory in the 2014 Bathurst 12 hours. To summarise the first part of the process, you play with springs and large damper adjustments to minimise CPL. What will happen is you will get into a zone where the CPL will hit a minimum and actually won't vary too much. Once you hit this you start playing with minor spring and damper changes to get the shape of the frequency response that you want. It's actually that simple. This results in a marked improvement in mechanical grip without compromising driver feel. The other key thing to highlight again is that you choose a corner speed and input velocity that is appropriate for a particular corner you want to analyse.

Once you are done with the shaker rig simulation this is when you move on to the lap time simulation. What the lap time simulation does is it allows you to dial in ride heights, gear ratios, wing levels and in the transient simulation

Figure 4: Grip vs lateral load transfer distribution at the front

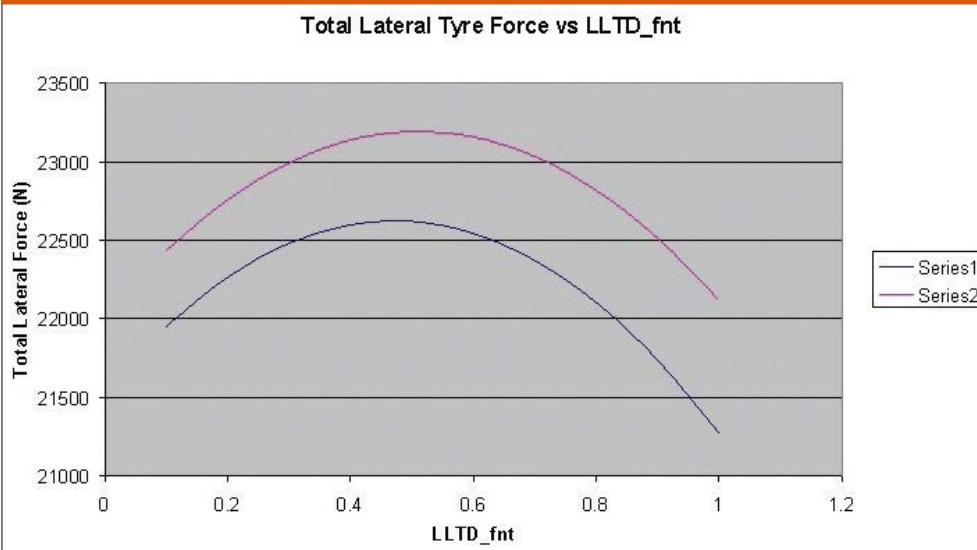
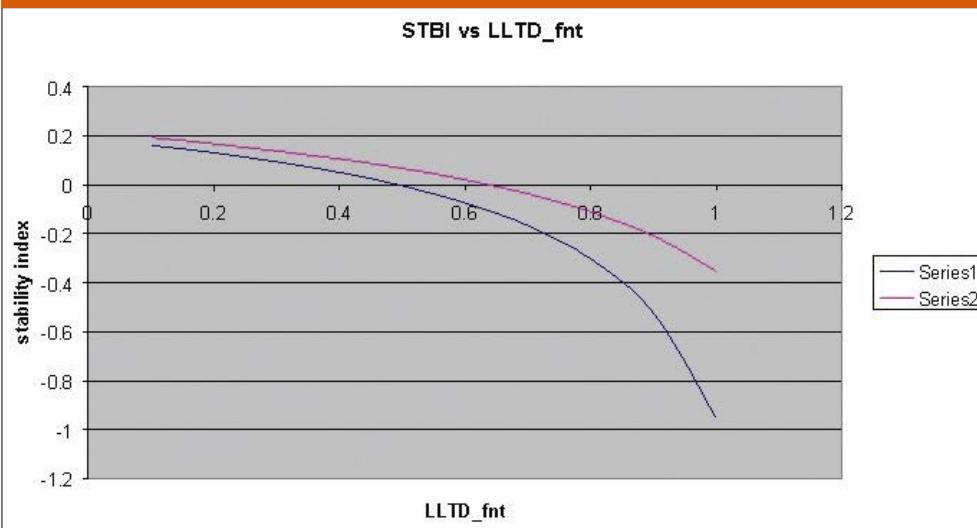


Figure 5: Stability index vs lateral load transfer distribution at the front



EQUATIONS

EQUATION 13

$$\omega_0 = \sqrt{\frac{K_B}{m_B}}$$

EQUATION 14

$$C_B = 2 \cdot \omega_0 \cdot m_B \cdot \zeta$$

$$\zeta = \frac{C_B}{2 \cdot \omega_0 \cdot m_B}$$

Where:

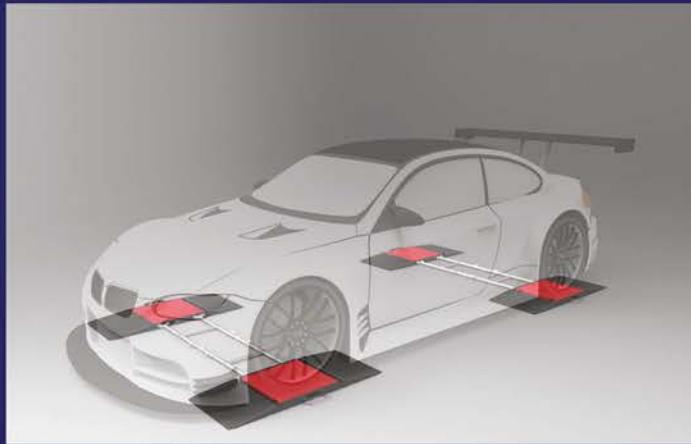
K_B wheel rate of the spring (N/m)

C_B wheel damping rate of the spring (N/m/s)

m_B mass of the quarter car.

ω_0 natural frequency (rad/s)

ζ damping ratio



30

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in ChassisSim's case it allows you to build on the good work done in the shaker rig simulation. I have written at length on how to use lap time simulation (V26N7) but let me summaries two key points. Firstly, when using lap time simulation you have to be as deliberate as when you are running the car and you have to look at the data through a slightly different lens. You always log the data and make a running record of it as if it is an actual test. Also, you are looking for small consistent changes. I discussed this at length in my article about how to use simulated data (V26N10) but your changes will show primarily as differences in cornering speeds.

But do not get tied up in correlation because correlation is a consequence, not the end goal. If I had \$5 for every time I've seen someone obsessed with correlation in this business I would have retired as a multi-millionaire to a sub-tropical island long ago. What happens with correlation is that as your tyre and aero model evolves the correlation happens as a by-product. The better your driver, the quicker the process is, but never forget this. **Table 1** shows some rules of thumb for cornering speed correlation.

The exception that proves the rule is ovals, since you have to have representative speeds in order to match the tyre loads.

You also don't have to be perfect for something to be useful. For example, **Figure 8** is an example of the correlation I used to get a fair way down the road with a VdeV sports racer driven by an amateur driver. As always the coloured trace is actual, black is simulated.

Summing up

At this point it would be wise to summarise what we have been through here. First, you always need to remember that race engineering comes down to grip and handling, with the latter being quantified by the stability index. We then use data and a rudimentary vehicle model to derive the tyre model. Once this is done, we use this model to determine the lateral load transfer at the front we should be running.

After this we then move on to use testing/open loop simulation to see the combination of springs/pressures/suspension geometry we need to achieve to get the required tyre heating. We then determine our quarter car damper ratios using the damper guide. Finally we then finish the job off by using the shaker rig and lap time simulation tools.

The important thing to remember is that race engineering boils down to grip and balance and what we have presented here is the game plan for achieving this. We have articulated the method of how to use hand calculations, what to look for, and how to use simulation tools like ChassisSim as calculators, as opposed to magic wands. If you can get your head around all this then you are well on your way to figuring out how to get the best out of your car. Past issues referred to in this piece be purchased from: www.chelseamagazines.com/shop

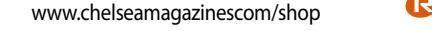


Figure 6: Damper set-up guide

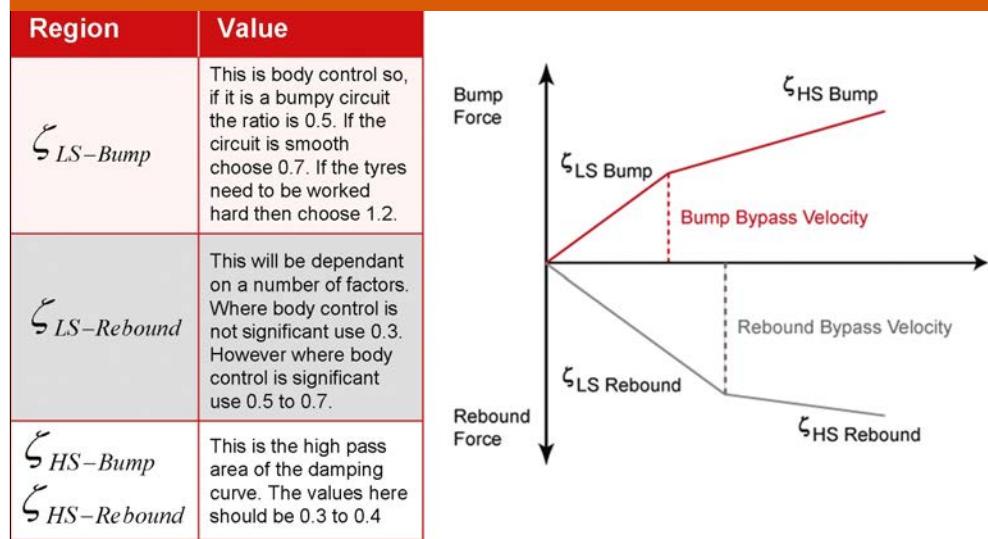


Figure 7: Outputs from the ChassisSim shaker rig simulation toolbox

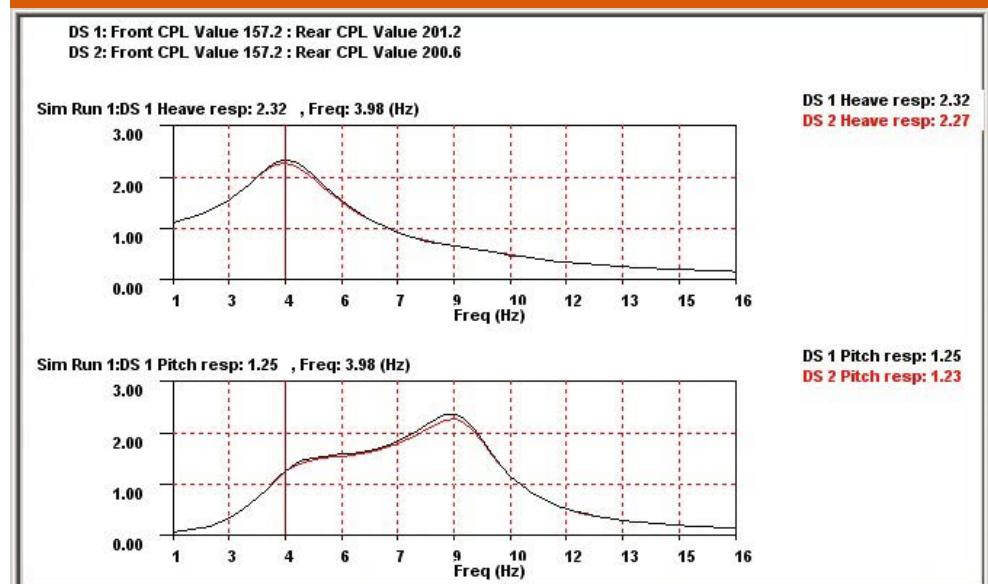
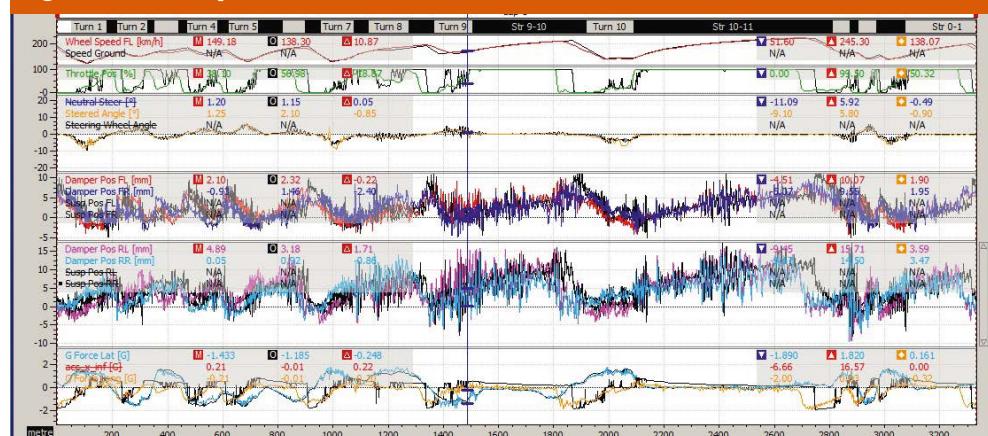


Table 1: Rules of thumb for lap time simulation correlation

Corner speed	Delta
80-120km/h	1-2km/h
120-160km/h	2-3km/h
160km/h +	3-4km/h

Figure 8: VdeV sportscar correlation with an amateur driver



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