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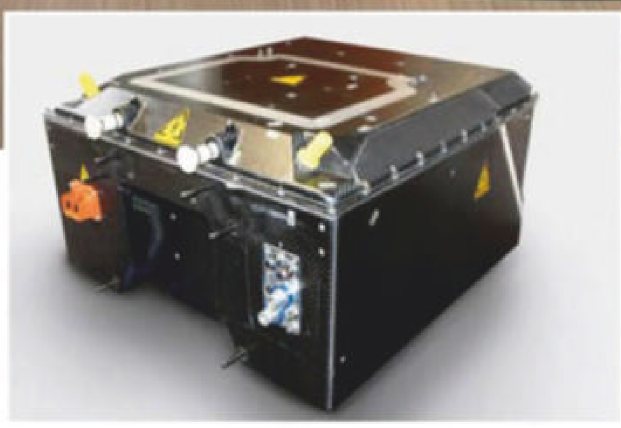
Porsche GT3

Will the new 911 racer live up to the legend?

Hydrogen power

The car that's bringing fuel cell technology to Le Mans



Power packs

How to make a high-end motorsport battery

McLaren Formula 1

What went wrong with the once-great team's MCL33?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CONTENTS – MARCH 2019 – Volume 29 Number 3

COVER STORY

COLUMNS

FEATURES

TECHNICAL

BUSINESS & PEOPLE

The WRC teams unveiled their 2019 liveries at Autosport International. Arrayed left to right are cars from Ford (M-Sport), Toyota, Hyundai and Citroen

Dose of truth

The hidden dangers of 1970s Formula 1 and what they teach us about consequences

The law of consequences tends to permeate existence. Nevertheless, foreseeing it will not transport us into Nirvana. Still, being discriminating in my extra-track behaviour, I have never had any STDs. However, I am an expert in clap clinics, especially Brazilian ones.

In fact, every time I went to a particular one, located close to the usual hotel for the F1 circus racing at Interlagos, the receptionist would welcome me with a smile and ask: 'Ah, Mr Ricardo! And what have you brought in this time?' This was because, being a local and speaking the language, I got used to having team members, and not only from my own team, sidle up discretely and say furtively: 'Ah, I seem to have a problem.' At which point I knew what was coming.

Prude awakening

Britain in the 1970s was considered (by the British, anyway) to be the country that had the most liberated attitude to sex in Europe. The truth was that it was a buttoned up, prudish and rather old fashioned country that had not yet recovered from the Victorian Anglican ethos.

On the Continent, however, liberality in these matters was influenced by the Catholic work-around of having your sins pardoned every Sunday by rather dubious entreats to go and sin no more. This can be proven by the fact that no politician in Europe has been brought down by indulging in the fleshy pursuits.

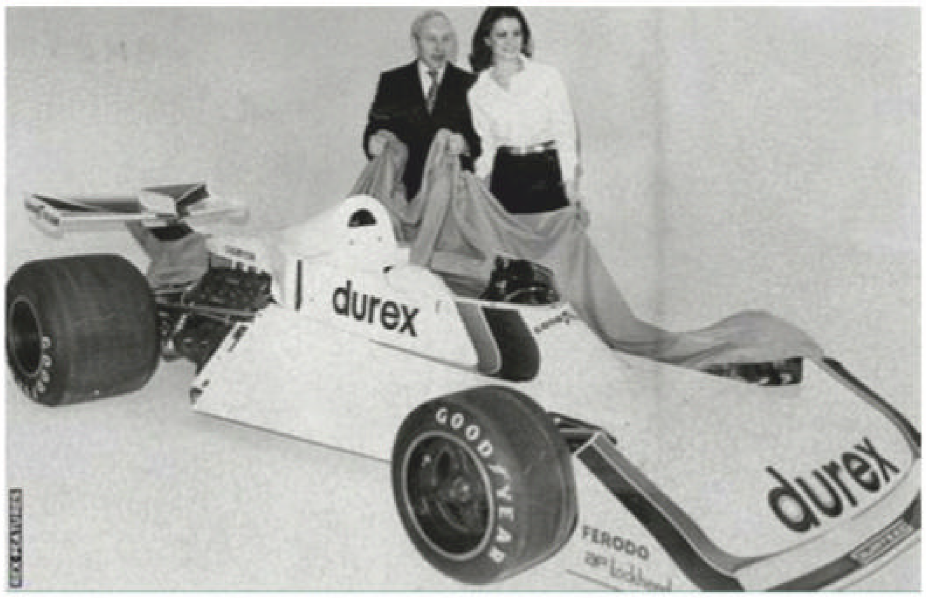
Brazil operated on the principle that 'there is no sin south of the equator', plus the weather encouraged everyone to be skimpily dressed, which led to other temptations.

Anyone who has struggled to simultaneously unclothe himself or herself in the freezing back seat of a car in England and try to indulge in exchanging bodily fluids understands the problem.

But back then race tracks were rife with ripe young things hunting racing drivers, as they were somehow the embodiment of derring-do, and the drivers usually unattached, too. James Hunt would not be very PC in the era of 'me too'.

Before I'm accused of being a misogynist here, remember I am merely describing what went on, not necessarily endorsing it. The teams might have been busy, but they always found time for the surplus left over by the drivers, and particularly the Brits seemed to go hog-wild when abroad, with the expected consequences. Beer was also often involved. Not only did I have to take them along to the clinic, I usually had to extract them from jail after their nightclub forays in dodgy places ended in the usual argument about the bill and the arrival of the local Bobbies.

The Brazilian strain of the bug was particularly fierce, a Godzilla-like creature that would shrug off one hundred thousand units of penicillin without batting an eyelid, as they had been naturally selected by the locals, unfettered by any regulations, self medicating and gulping down a couple of million units routinely, just in case.



Race rubber: condom maker Durex had a famous sponsorship deal with the Surtees team in the 1970s – some might say it suited Formula 1 at that time

Evolution being what it is, any surviving bug could only be destroyed by napalm, flame-throwers and a bevy of bell, book and candle waving exorcists, if you were lucky, as many of the cohort which had not spoken to me found out on returning to the UK, when they had to keep going back to the doctor for something that had turned chronic.

Clapped out

Out of delicacy, no names will be mentioned here, even though it was a long time ago. You know who you are, chaps, and your loving spouse, proximate family, friends and employer will never have to know the sordid details if you use a small, brown envelope stuffed with high denomination, unmarked bills addressed to the RRD Benevolent Fund for Expensive Toys. But I digress.

The point is, we know the consequences of over-using antibiotics, and we should also know by now the consequences of having the car manufacturers lead the rule making process, or having a conglomerate operating a racing series for profit, but being apart from it.

Bang for buck

Much like testosterone fuelled lads, they cannot help but to revert to their core instincts, and don't even have the excuse of too many beers. But times have changed, in racing as in society. After all, there was a time that when herpes and chlamydia were diagnosed it was considered rather extreme, whereas today it would be preferred to HIV, much as the procurement of sponsors and increase of public ownership for racing are but symptoms of the underlying malaise, rather than the sport striking the right balance between technology and entertainment.

All this can be factored in in any long-term forecasting, and be catered for or blocked, depending on your views and position. They are not important, as the only thing one can prepare for is one of the pieces of the puzzle one has to assemble. A probably apocryphal cautionary tale I like concerns Europe in the mid '30s, when a thoughtful gentleman looked around at the prevailing political mood and implications, subsequently moving to a tropical paradise, far away from the chaos he foresaw in Europe. The problem was, the tropical paradise he envisaged was on an island in the Pacific, called Guadalcanal – the scene of much fighting in 1942-43.

All the changes discussed in regulations and lobbying by concerned parties will have huge consequences to what racing will be like in future years, but one is prepared to wager that it will not be what the participants expect. Some decisions will suit the prevailing conditions and be hailed as extremely wise and clairvoyant, after the fact.

Meanwhile, I have stocked up with popcorn and settled down to await the outcome. I don't know if I am going to like the result, but there will be some interesting changes, so deal with it, even if it does entail going to the doctor later to sort out the worst outcomes.

Back then race tracks were rife with ripe young things hunting racing drivers, as they were somehow the embodiment of derring-do

Formula GP3

Has replacing the *real* Formula 3 with an all-new concept been a terrible mistake?

I guess few knowledgeable people were surprised when the new single-make chassis/engine combination which is replacing the traditional Formula 3 concept was revealed (see Racecar Engineering, V29N2). Given that the FIA and Liberty have handed over the whole FIA F3 Championship shooting-match to Bruno Michel and his cohorts, lo and behold it clearly resembles a warmed-over GP3 car. In case anyone is unaware, this same organisation has been the previous promoter of this now-defunct category, as well as GP2-now-F2.

My first observation is why has such a radical change to a highly successful formula of over 40 years standing taken place when there has been no massively expressed desire from Formula 3 teams and drivers for this to happen?

Get one three

The direction in which Formula 3 has been *forced* – there is no other word for it – has got under my skin. The logicality of F4, F3, F2 being the formal three steps to Formula 1, which FIA President Jean Todt has espoused for some time, makes sense on the face of it. Of course, this ladder was in place for many years (for F4, substitute Formula Junior, Formula Ford and other national junior categories). Then the FIA allowed alternatives to be promoted by car companies and individual entrepreneurs, which severely undermined this easy-to-understand route upwards. There was Formula Opel, various guises of Formula Renault, and the ditching of the original Formula 2 in favour of Formula 3000 at the end of 1984 (primarily as a dumping-ground for obsolete F1 engines), which then begat the commercial GP2 and the GP3 championships. All of these had their good points. But they muddied the water as far as the driver (and team) ladder was concerned.

But F3 survived, sometimes booming, sometimes struggling, but with a stunning record of delivering drivers who were then successful in F1 and other top categories. Although becoming more sophisticated, refined and safer, by retaining similar dimensions, tyre sizes and power/weight ratio the cars kept their unique identity. Not the least of this was due to the instantly-recognisable and ever-present side airbox 'torpedo', now gone.

The new FIA F3 International Championship has completely discarded all this, replacing the cars with larger, more powerful but much heavier machines that no longer have any specific identity. Hankook tyres have also disappeared, in favour of Pirellis. In a stroke, the best reasons for F3's longevity and success have been kicked into touch.

As a highly-experienced F3 entrant confirmed to me, young drivers need to learn the fundamentals of race driving and racecraft. This is best done with a very 'pure', light, responsive car that's not too expensive to run (and under the new championship regulations, drivers are likely to get just half the mileage per season than previously). It's also important that the racecar remains consistent in its performance. This allows the rookies to concentrate on learning and honing their driving skills and racecraft.

XPB

Formula 3 at Macau. The category has been a favourite with engineers and drivers for decades but now an upgraded GP3 will bear the F3 name

Rubber check

Yet Pirelli's products are notorious for requiring great attention to their rubber management once an initial couple of fast laps have been recorded. And, if some might say that the company is the supplier to the two senior categories so drivers might as well get used to their tyre peculiarities from the beginning, you must also bear in mind that only a fraction of these hopefuls will ever graduate to Formula 1. The rest will more likely be racing in other categories with different manufacturers' products. F2, not F3, is the right place to learn such specific tyre management, in preparation for the final step upwards.

Although now being a mandatory support race for F1, a downside for the new F3 (apart from doubtless being in the arse-end of the paddock) is that the demanding circuit of Pau no longer forms part of the championship. Worse still, the standalone epic event, the season-end Macau GP, is unlikely to be able to safely accommodate these much bigger and faster single-make racing cars. This is despite it also being long-regarded as a true indicator of driving talent to which almost all top F3 teams and drivers are drawn each year.

All this also means that, rather worryingly, Bruno Michel (once described as Flavio Briatore's right arm), Dallara, Mecachrome, (previously also a Briatore involvement) and Pirelli exclusively controls and supplies both F2 and F3. It seems to me that far too much power has been put in the hands of a commercial organisation here.

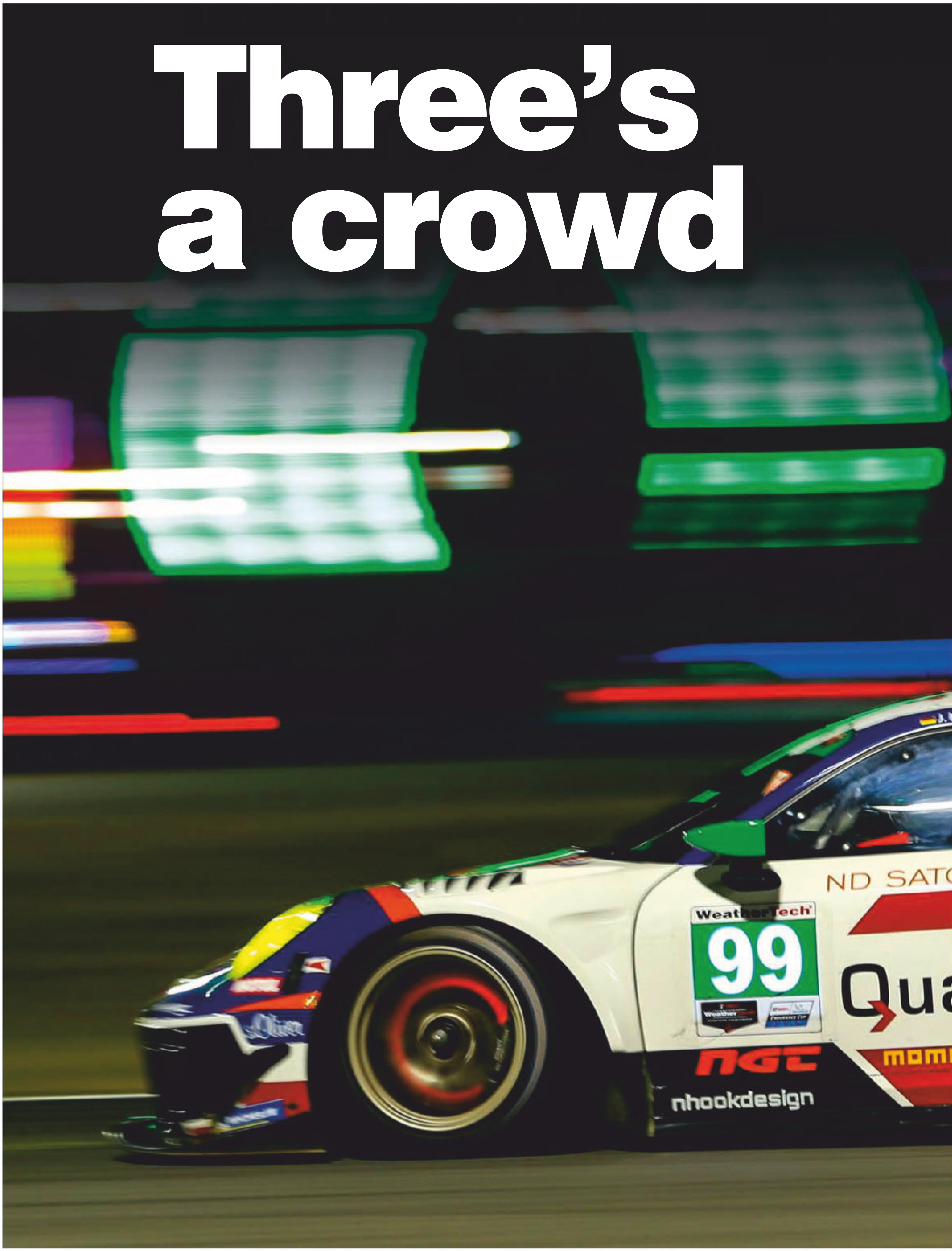
Meanwhile, entries from Van Amersfoort Racing and Motopark have not been accepted, despite their lengthy and impressive Formula 3 team credentials. Apart from being – jaw-droppingly – without explanation, this is very concerning. Providing that teams can reasonably prove – through past history and signed driver contracts/guarantees – that they have the wherewithal to contest the championship properly, surely it is the FIA which should make the final call on who can compete? After all, Statute 2.3 of the FIA includes a commitment to 'the fair and equitable running of motor sport competitions'.

Wheels of industry

For ease of transition, appointing Michel's organisation to run F3 alongside its F2 set-up at grands prix no doubt made this an easy decision for the FIA. It's also natural, I guess, that partners who have worked together well may wish to continue their association. But promotion of young racing drivers should not be more important than the protection of the racing industry, without which the sport could not take place. Members of this vital infrastructure are in many cases being prevented from carrying out their business by simply being excluded from participation. These F3 decisions may well drive a final nail into the coffins of some of these, as one-make regulations have done to many other motorsport companies.

The promotion of young racing drivers should not be more important than the protection of the motorsport industry

Three's a crowd



Porsche is the latest manufacturer to have introduced a new GT3 model for the 2019 season and has targeted a more driveable car for its customers

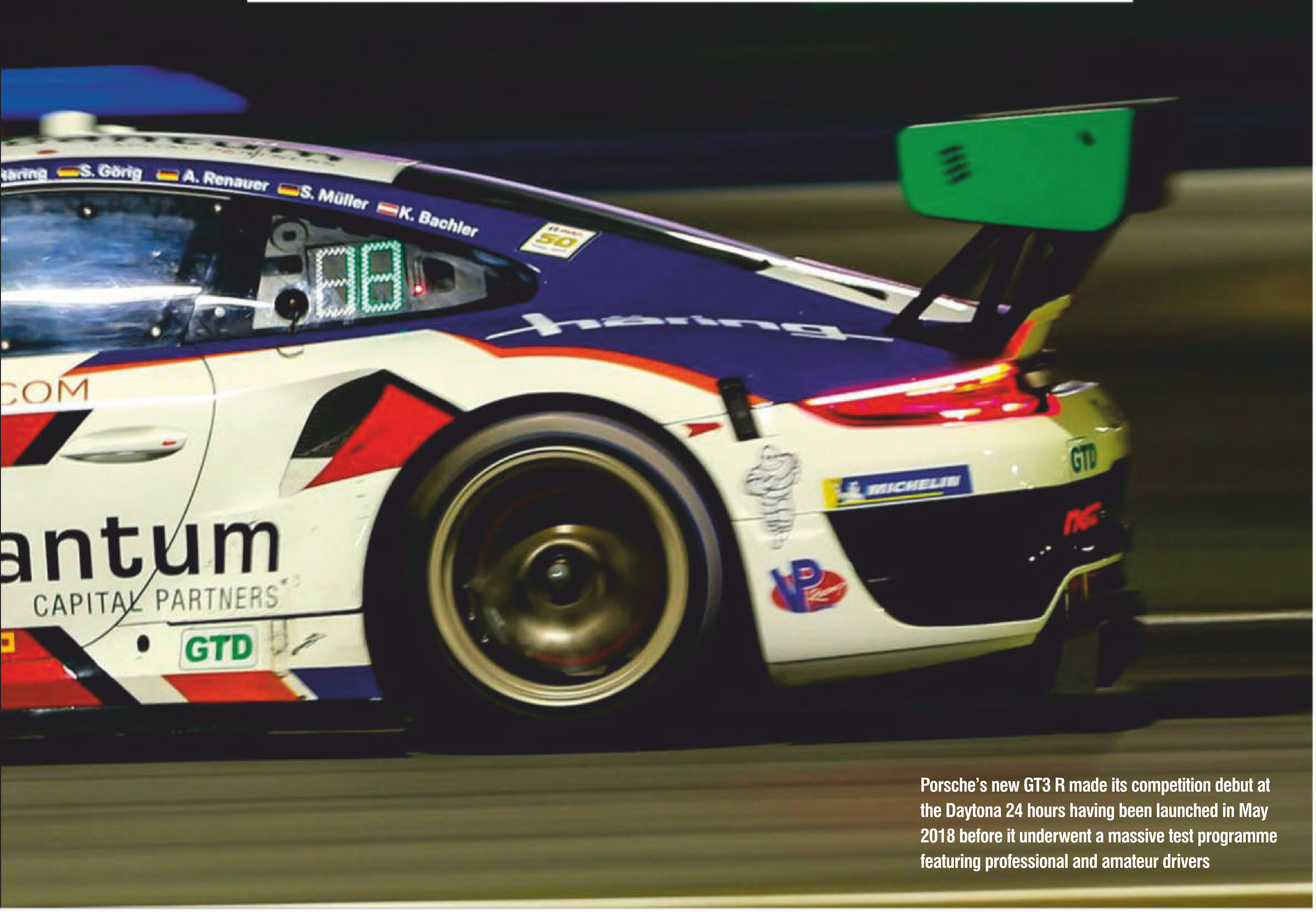
By ANDREW COTTON

Porsche is the latest manufacturer to present its new customer racing model for GT3 racing, the 911 GT3 R. It is based on the GT3 RS road car, and compared to the outgoing model sports new aero, more front grip, a new front suspension, better safety and vastly updated driver aids.

The car was officially launched at the Nurburgring 24 hours in May, 2018, and has completed an extensive test programme in the hands of many different drivers, but made its competition debut at the Daytona 24 hours in January 2019. The development programme focused on improving driveability to cater to Porsche's amateur drivers and extract more performance for its professionals; cost; servicing, and on reducing time in the pits needed to make set up changes during practice sessions. The result is an impressive piece of kit, although whether or not it will be enough to beat the best of Audi, Lamborghini and McLaren, each of which has produced updated cars, has to be determined.

The challenge facing manufacturers competing in this category is immense. GT3 racing takes place all over the world, and in all different formats, presenting the designers and engineers with a unique challenge. From the cold temperatures of Daytona during the night in January, to the heat and humidity of Suzuka in July, and from the needs of the professional drivers in the Intercontinental GT series to the amateur driver at whom the design is primarily aimed; from the sprint format of Blancpain and the US series to 24-hour endurance races, so the cars must be versatile. They also have to meet a target price point, nominally €500,000 or below, and be competitive in all conditions. Oh, and they also have to run on different tyre brands, mostly Pirelli, but also on Michelins in the IMSA series in the US, and customer teams have a choice at races such as the Nurburging 24 hours, including Dunlop and Hankook.

Perfecting this in one package is not easy and plans can also, as in Porsche's case in 2018, come unstuck



Porsche's new GT3 R made its competition debut at the Daytona 24 hours having been launched in May 2018 before it underwent a massive test programme featuring professional and amateur drivers

Porsche has worked hard on the six-speed gearbox, and particularly on improving the gear shift mechanism

rapidly. The manufacturer introduced updates to its GT3 for the 2018 season, at which point Pirelli also produced a new tyre developed to work better for the rear mid-engine cars such as Audi and Lamborghini, but the D2 tyre did not suite the re-worked Porsche at all.

During the development planning stage of this generation GT3 R, Porsche also tried to introduce the rear-mid engine concept that the GTE/GTLM car boasts. It argued that, as there were no waivers for the GTE layout, by regulation it could run the same concept in GT3. That plan was blocked by other manufacturers, and by organisers, leaving them with no other option than to run with the rear engine layout, and that played its part in the decision to stick with a normally aspirated engine.

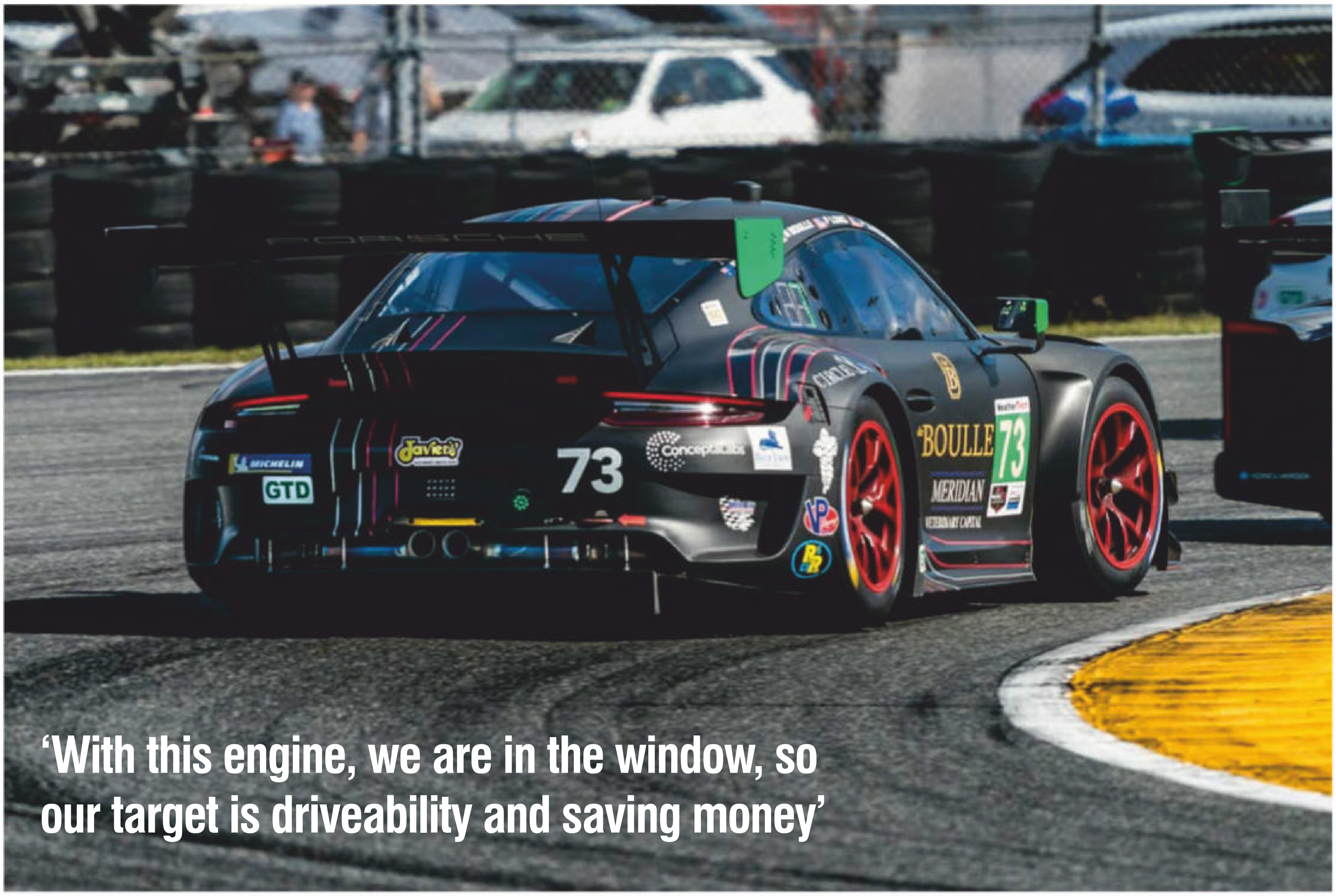
Officially, the decision to stick with the normally aspirated engine came from within Porsche on the grounds of cost, weight, and serviceability. Also, the option to run the turbo engine taken from the GT2 would have caused further headaches for the PR team trying to sell the car as a pure GT3. 'You have to have the balance between performance and the business case of the customer at the end,' says Porsche's GT3 R programme manager, Sebastian Golz. 'So, you have the BoP to set the performance window, and if the car wasn't in the window we would have to take weight out. With this engine, we are in the window, so our target is driveability and saving money. If you put in a turbo engine, you increase the weight, and as this is a rear-engine car, the driveability would move in the wrong direction. You also have cost savings, so you don't have turbos and coolers, so in a crash you would have more to change.'

Powerhouse

One of the big problems with the old car was the power delivery, which came at the top end of the rev range. Porsche has kept much of the production direct injection engine, but changed the camshaft timings and brought the power band lower in the rev range compared to the old car, in a bid to make it more driveable not only in normal circumstance for the amateur driver, but also in the wet. The engine still revs to 9,500rpm, but by then the power has dropped off slightly.

Porsche has also worked hard on the six-speed gearbox, and particularly the gear shift mechanism. An electronic shift actuator has been introduced that makes gear changes smoother, making a particular difference on the downshifts into a corner. '[With the pneumatic electric shifter] if you hit the tooth, it would stop…and then go in,' says Golz. 'The new system increases the life of the gearbox and, again, improves the driveability. If you go out of a corner on full throttle, and you hit a tooth, it may not go in [immediately]. So now it is a smoother change and the car is therefore more stable. It's the same on the brakes; if the gear goes in smoother then it is better balanced and you will not lose your grip on the rear tyres.'

Another driver aid introduced is an electronic-hydraulic actuator on the clutch. It's a long way of describing an effective launch control, but has the added bonus of engaging neutral if the car is spinning, with the potential to save the engine if a driver spins and rolls backwards, which has in the past damaged the engine as the clutch was not engaged. The driver can now launch out of the pits without needing to modulate a clutch pedal, which could in the sprint races make up positions. It also helps in the event of a standing start. 'It helps us with the gentlemen drivers, because



'With this engine, we are in the window, so our target is driveability and saving money'

Little changed at the rear; the engine delivers power lower down the rev range, making the car easier to drive and the rear wing is mounted underneath to reflect the road design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Safety has also improved in the new generation model, as with all new cars as manufacturers realised the net worth of their average clientel

it is a Porsche, with a low capacity engine that needs high revs and it is not easy to start it,' admits Golz. 'For reliability, if you spin and are rolling backwards then your engine is destroyed if you do not push the clutch at the right moment. The clutch opens by itself, the engine is idle, so when you stop you just select the right gear and go.' The downside is that engaging reverse is now a two-handed job, with one hand on the clutch paddle, another selecting reverse on the driver console in the middle of the car, which is entertaining to watch but not practical.

Quick change

The final change to the gearbox is the ability to change the pre-load on the differential using a single allen key, albeit a long one. The ability to make this change in the pit lane is aimed at improving serviceability and increase track time.

This last point is particularly relevant to the set-up of the car, which again Porsche has worked to improve. 'We are using a concept that you do a set up on the car in the morning, and if you go into a session you can do fast changes on the car,' says Golz. 'In the session, if you want to change the camber, you can take a shim out and a shim for the toe, or if you want to adjust the ride-height you can put a double shim in the toe and camber area, and you don't have to measure it. You know what you have. It is a five-minute change, but before it was a half hour job.' Porsche has also carried over from the RSR the ability to refill the fuel tank on either side of the car, depending on the direction of the circuit.

Wealth protection

Safety has also improved, as it has with new cars from all manufacturers who realised the net worth of their average cliental. Porsche has introduced a new chassis with the roll cage bowed slightly around the left side of the driver, as with its big brother, the RSR. This puts more load through the chassis in the event of an accident with the obvious intent of reducing an impact on the driver. Side-impact protection is also increased by the construction of the driver's door, which consists of a carbon-fibre, Kevlar and aluminium construction with energy-absorbing plastic foam. As is now standard, the seat is fixed to the floor, and the different driver sizes are accommodated by sliding pedals and steering wheel. The fixed seat means that the drivers are all best protected by the B-pillar in the event of a side-impact. Around the driver, work has been undertaken to improve the experience, with a new display on the steering wheel and with the whole dashboard ergonomics improved. 'We moved the car to the next level so the customers are able to make a lot of changes to the car,' says Golz. 'Tyre temperature, brake temperature, ride height sensors and so on are ready to race, and the system has more capacity to make changes, while the old one was limited.' Air conditioning has also been introduced for the first time, which will certainly help the driver to maintain concentration during the hotter races.

Flow chart

However, there is no point in having a lovely car that is slow. The previous generation model was less competitive in high ambient temperatures and addressing this meant an all-new aero package, with the engine intakes moved to the side and ahead of the rear wheel arches. The previous design saw the airflow over the top of the car directed into a single scoop in the engine cover, but the air had been warmed by the front-centre mounted radiators. Porsche has estimated that the temperature of air going into the engine is between 5-7degC lower, which they hope will reduce negative impact on performance at a hot race. The side intakes have not produced a drag penalty, says Porsche, and the company believes that the car is more aero efficient. So efficient, in fact, that it did not feel the need to produce a swan neck design on the rear wing supports; the wing is still attached underneath which resembles the road car architecture, and Porsche says that it was within the FIA and SRO's target for aero efficiency.

The front splitter is raised to reduce pitch sensitivity under braking, and maintain airflow to the rear diffuser

TECH SPEC: Porsche 911 GT3 R (991 Gen 2)

Bodyshell
Lightweight body featuring intelligent aluminium-steel composite design; removable escape hatch in roof in accordance with the latest FIA regulations.

Engine
Water-cooled 6-cylinder boxer engine (rear mounted); 4-litre; stroke 81.5mm, bore 102mm. Power, over 404kW (550bhp) without restrictors, actual output dependent on FIA BoP (restrictor); 4-valve technology; direct fuel injection; dry sump lubrication. Electronic engine management Bosch MS 6.4 with integrated data acquisition.

Transmission
Porsche sequential 6-speed constant-mesh gearbox; mechanical slip differential with external pre-load adjustment; racing clutch; paddleshift with electronic shift drum actuator.

Suspension
Front: Double wishbone; motorsport vibration damper, 4-way adjustable; anti-roll bar, adjustable by blade position; power-assisted steering with electro-hydraulic pressure feed. Set-up changes without new alignment via shim system. Rear: Multi-link rear axle; machined aluminium control arms, stiffness optimised with high performance spherical bearings; motorsport vibration damper, 4-way adjustable; anti-roll bar, adjustable by blade position.

Brakes
Two separate brake circuits for front and rear axles, adjustable by driver via balance bar system.

Front: 6-piston aluminium monobloc racing brake caliper; steel brake discs, multi-piece and ventilated (390mm); racing brake pads; twin-flow brake cooling ducts. Rear: 4-piston aluminium monobloc racing brake caliper; steel brake discs, multi-piece and ventilated, (370mm); racing brake pads; twin-flow brake cooling ducts

Interior
Ergonomic centre console aligned to driver with digital multi-touch panel; multi-function racing steering wheel with quick release coupling and shift paddles; racing bucket seat in accordance with FIA standard 8862/2009; integrated air conditioning; 6-point safety harness.

Fuel tank
FT3 120-litre safety fuel cell with fuel cut off safety valve; changeable for left and right refuelling.

Wheels
Front: One-piece BBS alloy wheels, 12.5 J x 18. Rear: One-piece BBS alloy wheels, 13J x 18.

Tyres
Front: Michelin transport tyres; 300/680-18. Rear: Michelin transport tyres; 310/710-18.

Electrics
Cosworth colour display CDU; Cosworth Logger CLU (6GB memory); Cosworth power management system IPS48 MK2; Bosch LIN 175A alternator regulator; Bosch racing-ABS, generation five.

Dimensions
Overall length: 4629mm; overall width front axle: 197mm; overall width rear axle: 2002mm; wheelbase: 2459mm.

Total weight
To be determined (BoP dependent)


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Porsche has estimated that the temperature flowing into the engine is between 5-7degC lower, which they hope will reduce negative impact on performance at a hot race

Centre mounted radiator layout is carried over from the old car; brake cooling is either side, and designed for more adjustability, again with ambient temperatures in mind

The interior of the car has been designed for better driver comfort, while the LCD is new and more driver focused

Attention was also turned towards the front splitter, which is raised slightly at the leading edge to help with airflow to the floor, particularly under braking. While Ferrari raised only the centre section of the nose to help feed the rear diffuser, Porsche's solution is a little more subtle. 'The lip is like a little fishnose; before it was just flat with a sharp edge,' says Golz. 'That reduces the sensitivity of the device. If I brake and have pitch, I have to avoid a major shift of aero balance. If I cut the airflow from the ride height [at the front], my aero balance goes completely as the air can't get to the rear diffuser and the balance is gone.' The car is less sensitive to ride-height changes, too, which is all designed to help the customer team.

Rubbered up

It is at the front that most of the work has been undertaken, with improved airflow through the wheel arches, a larger front tyre, and a double wishbone suspension. The suspension layout is a change from the MacPherson strut used in the old car and is again more serviceable for racing teams used to handling such a design. The larger front tyre helps to improve grip, particularly under braking, and Porsche says that the design is also safer. 'The increased tyre size, from the 660 to a 680, gives you more potential and more safety because you have more air in the tyre, and the tyre is able to handle more load,' says Golz. The new front tyre size helps the drivers go deeper into the corners under braking, and that feature has been further endorsed with a change of brake suppliers and new ABS software. The company went from PFC to AP for the calipers, and also introduced the latest generation Bosch ABS system, which Porsche says is a big improvement on reliability.

Dial back

There is little change at the rear of the car; the wing is the same as that of the first generation car, rear suspension kinematics have changed slightly, but there were no major changes needed as the weight distribution characteristics were similar to the previous car.

This is certainly a step up compared to the old car, both in terms of overall potential, but also safety and comfort. Porsche actually dialled in too much aero for the SRO's team, which forced the marque to remove turning vanes in the floor before homologating the design. With a wider operating window, better ability to perform in the hotter conditions, and with testing having focused also on the car working with other tyre manufacturers, Porsche believes that this car will be more competitive in more conditions than the previous car. It will be sold for competition all over the world, so there is a lot riding on this latest generation 991.

Plus four

Porsche launched its new Cayman GT4 early in January, and therefore completed its customer racing portfolio

By *RACECAR* STAFF

Porsche's new GT4 is based on the 718 Cayman and is Porsche's entry-level customer car. It can be raced around the world and draws heavily on production car design

Porsche used the Daytona 24 hour test session to launch the latest in its customer racing range, the new 718 Cayman GT4 Clubsport which will compete around the world in national series.

There are a number of changes to the car compared to the outgoing model and the development team has, as with the GT3 R, concentrated on improving the driveability of the car. Porsche tells us that this is their first production car to feature bodyparts made from natural carbon fibre composite material (CFRP), sourced from agricultural by-products such as flax or hemp fibres, and with similar features to carbon fibre in terms of weight and stiffness.

Four pot

Powering the 718 GT4 Clubsport is a four-cylinder 3.8-litre flat-six engine producing 425bhp (313 kW), a massive increase of 40bhp compared to the outgoing model. Power is delivered via the Porsche PDK dual-clutch gearbox with six gears and mechanical rear axle differential lock. The lightweight MacPherson strut front suspension is taken from the 911 GT3 Cup car, while the racing brake system features steel brake discs all-around.

Tipping the scales at 1,320kg, the new 718 Cayman GT4 Clubsport is delivered with a welded-in safety cage, a racing bucket seat as well as a six-point safety harness. The base 'Trackday' version is aimed at amateur drivers who want to take part in private track and clubsport events without major effort and outlay. This version of the car features a fixed shock absorber arrangement. The ABS, ESC and traction control assistance systems ensure forgiving handling at the limit and can be deactivated. Also delivered from the factory is the air-conditioning system, a rescue hatch in the roof, a handheld fire-extinguisher and an 80-litre FT3 safety fuel cell. Additionally, the non-road-homologated race car can be serviced at all Porsche Dealerships.

This is their first production car to feature bodyparts made from CFRP

Shock tactics

The 718 Cayman GT4 Clubsport 'Competition' model has shock absorbers that can be adjusted in three stages. The 115 litre safety fuel tank is suitable for long-distance events. Thanks to a brake balance system, the bias can be adjusted between the front and rear axle as the driver prefers. An integrated air jack system helps the teams to guarantee fast pit stops.

A lightweight kit adds lightness to the Competition variant and includes lightweight BBS wheels, carbon fibre bumper, rear deck lid, front wheel arches, bonnet, and rear diffuser.

Porsche Motorsport North America has already sold and delivered 11 of the new cars with ten more on order for customers and the first of them competed at Daytona at the end of January. Both versions of the car can be ordered immediately and will be delivered to teams around the world from February.

Nowhere to hide

A switch to Renault's power unit was supposed to return McLaren to the sharp end of the grid in 2018, yet the once-mighty team endured yet another dismal season. But is it really fair to conclude that its MCL33 was simply a poorly conceived Formula 1 car?

By SAM COLLINS

It's an understatement to say 2018 was a disappointment for McLaren. The Woking-based team had started the season full of hope, for after struggling with Honda power units for four seasons it had switched to Renault, a proven race winner with Red Bull. But it all came to nothing. So where did it all go wrong?

With much of the blame for previous failures having been pinned on the Honda power unit and not the chassis it was no surprise to see that the overall design of the 2018 MCL33 seemed to be very much a gentle evolution of the previous year's MCL32, except for the addition of the now mandatory Halo around the cockpit. Of course, this 12kg titanium structure did necessitate an all new monocoque, but beyond that, when comparing the two cars, this was something of a rather tough 'spot the difference' contest. And while McLaren's technical leadership had not tasked its engineers with creating an evolutionary car concept, the MCL33 did indeed, ultimately, owe a lot to the 2017 model.

'We did not constrain our engineers to evolve the 2017 car, it was just something that we came to,' Simon Roberts, McLaren Racing's chief operation officer says. 'There were a few things on the car we wanted to fix from the 2017 car, mostly in terms of mechanical installation. The 2017 car developed well through the season, it did not seem to be a bad platform, so we thought that if we fix some of the mechanical issues, improve the weight distribution, things like that, and continue in the same vein we would have a good car, but that did not work out. We should have taken a bolder step.'

'We thought we would have a good car, but that did not work out. We should have taken a bolder step'

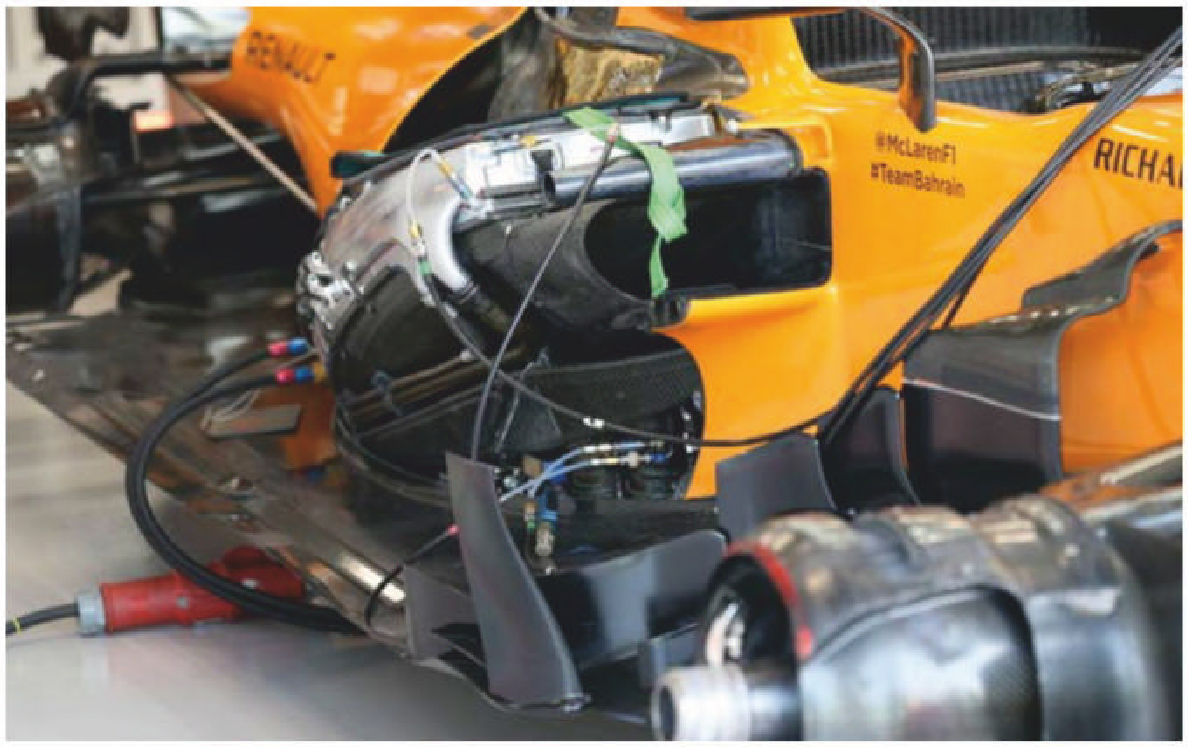
One of the biggest changes the team had to deal with, of course, was that very late switch from Honda power to Renault. 'We always had in the back of our mind, with the difficulties we had had with Honda, the potential that we would have to change,' Roberts says. 'That did not stop us starting the design process and the car was originally designed around the Honda. Then in the second half of 2017 the decision was made that we were going to change power unit. Obviously you set out to design a car to win the championship, and with this one the task had then become to also change the engine, that was something that came quite late.'

Change of heart

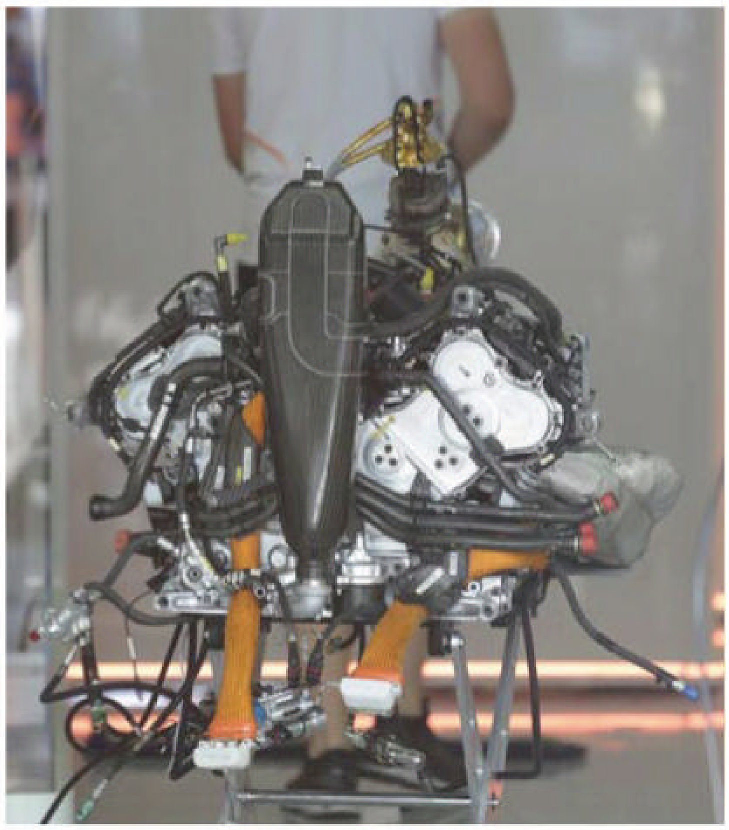
Switching from Honda to Renault was a significant task due to the two power units being notably different in shape and concept. The Honda has a split turbocharger with the compressor at the front of the engine block and the turbine at the rear, with the MGU-H mounted between the cylinder heads. The Renault has a more conventional layout with compressor and turbine both mounted at the rear of the block. To change between the two required significantly different pipework, a new bellhousing and large changes to the rear of the monocoque. McLaren, like most teams on the grid, uses a composite transmission casing, which has a relatively long lead time.

'We had to re-tool the bellhousing, rather than use spacers to adapt what we had, but it was a real challenge,' Roberts says. 'In a crude way you end up with space at the front and the back of the block, but we were desperate to avoid that from a weight and reliability point of view. Ultimately I don't think that the installation was compromised, we just did a lot of hard work around it. It was a really great effort, but unfortunately I think we paid for that late change as we rushed a few things. Had we not changed the engine I don't think that the racecar would have looked a lot different, but we might have had a better start to the year and brought updates in more quickly.'

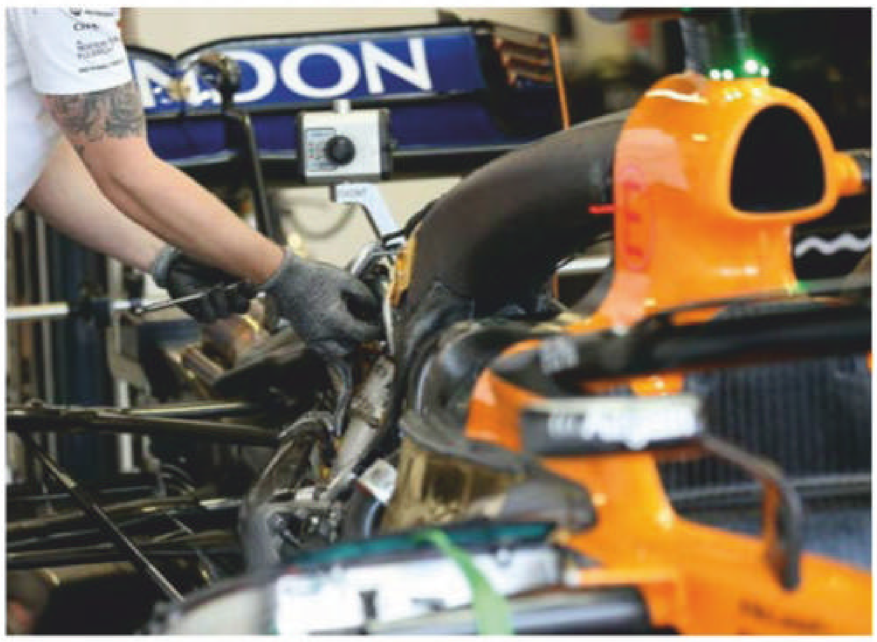
From the moment the first pictures of the MCL33 were shared it was apparent that it featured neither the short Ferrari style sidepods or the centreline cooling concept used by other teams such as Mercedes and Toro Rosso; indeed the McLaren was the only car on the grid not



McLaren was quite proud of the MCL33's cooling system, which featured some remarkably small air inlets



The team opted to use the Renault power unit for the 2018 season



The MCL33 did not use centreline cooling, largely due to centre of gravity concerns

TECH SPEC: McLaren MCL33
Chassis In-house, carbon fibre monocoque
Power unit Renault RE18, turbocharged 1.6-litre V6 with MGU-H and MGU-K in compounded layout. Lithium-ion energy store. Direct injection
Transmission In-house with carbon composite casing, eight forward gears and one reverse, electro-hydraulic actuation
Suspension Double wishbone with pushrod (front) and pullrod (rear), torsion bars and dampers
Electronics McLaren Applied Technologies; including chassis control, power unit control, data acquisition, sensors, data analysis and telemetry
Clutch Multi plate carbon
Brake system Akebono brake calipers and master cylinders, brake by wire system, carbon discs and pads
Cooling system Calsonic Kansei
Steering Power assisted rack and pinion
Wheels Enkei
Weight 773kg min (including driver, excluding fuel)

to feature at least one of these concepts. With the chassis changing, plus the power unit and the transmission, it could be expected that the bodywork and aerodynamic concept might be different, yet, as mentioned, the MCL33 looked very similar to the MCL32. The car featured just a small engine air intake on the roll hoop, as well as relatively small ducts in each sidepod. In fact, it not only looked simple, but also under-cooled. The press and public were not the only people to be surprised by the MCL33's cooling layout.

'Renault were shocked when they saw our car, with the size of the air intakes,' Roberts says. 'They really questioned us strongly, asking if we were sure we had got it right, and if we were getting enough air. I don't want to say that the cooling system is class leading because that sounds a bit arrogant, but the guys did a really good job, especially in terms of efficiency, it was great. Had the car been quick everyone would have loved it, but it wasn't, and if a car is not quick then people kind of miss those details.'

As for the centreline cooling layout and the short sidepods McLaren decided against using them for reasons beyond the thermal demands of the rear end of the car. 'We didn't use centreline cooling due to concerns over centre of gravity, which is higher with that layout,' Roberts says. 'If you look at some of the

Switching from Honda to Renault was a big task due to the two power units being different in shape and concept

cars using centreline cooling they also have quite large sidepod inlets. I think more teams have converged on our type of solution in terms of coolers. Certainly the teams with the lower Ferrari style central crash tubes have had to.'

Keeping cool

Interestingly, switching between power units had a smaller impact on the cooling system than might have been expected, Roberts tells us. 'The heat rejection is slightly different and the cooling requirements are different, but the cooling concept in terms of where the radiators were positioned did not change. That was more driven by the aerodynamic package than the power unit. We did have to change some of the coolers, obviously, but had we kept the Honda we would not have done much different, it was just the sizing of the coolers really.'

With the change of power unit and transmission it could be expected that the rear suspension, mounted on the gearbox casing, would also change but here too the differences were minimal. 'We didn't change the rear suspension concept. The gear casing was designed and tooled before we decided to change,' Roberts says. 'We might have moved some of the legs around slightly but it was not major, the gearbox and suspension layout was essentially as originally intended. Internally it is a mechanical layout, we have not gone the hydraulic route, we just have nice packaging.'

Overall, the rear suspension is fairly conventional with the driveshaft passing through the lower rear wishbone. However, the upper wishbone is notable for being very short, picking up on a very long extension of the upright. This is covered in a composite shroud giving the appearance of a single piece component. Torsion bars are pullrod actuated.

At the front the suspension is a conventional double wishbone layout with pushrod actuated torsion bars and dampers. But Roberts is reluctant to go into detail, preferring instead to discuss the general principles of suspension systems in Formula 1 at present.

'Most of the suspension travel is in the tyre, so what the suspension really does is get the right mechanical balance in the car, and to a certain extent hold the car where you want it for the aero, but that is where you can get in a mess,' he says. 'I think the differentiator on the grid is that you have cars that have got highly developed wide aero maps, which can allow a lot more suspension travel and still retain a high degree of performance; then there are cars which have very sophisticated devices linked to suspension which allow them to hold the car at certain attitudes. In the last two years there has been quite a bit of that. We played around the edges of that, but generally speaking we have not raced it because it's a trade off of performance *vs* weight *vs* complexity and reliability. I think if you go the hydraulic route you have a lot more freedom to play in some of those spaces, if you go mechanical you have other benefits. It's a trade off between those additional pipes, weight, issues with the car and things like that. It's a compromise and you have to decide where you want to sit on that.'

Winter of discontent

The MCL33 ran for the first time during pre-season testing, and after just a few laps a minor failure saw one of its wheels fall off. As the test continued it was clear that there were other issues with the car, too. 'We were disappointed with winter testing,' Roberts says. 'We obviously had a late engine change, but we thought we had done enough. We found a few reliability issues that needed fixing. That impacted us in terms of how much resource we had to work on the upgrades for the year. So we got off on the back foot. It was nothing to do with Renault, it was all our own work. In the early part of the season we ended up kicking ourselves for not getting the upgrades out faster.'

The upper wishbones at the rear of the car were covered in a composite shroud which gave them the appearance of a single piece component

'In the early part of the season we ended up kicking ourselves for not getting the upgrades out faster'

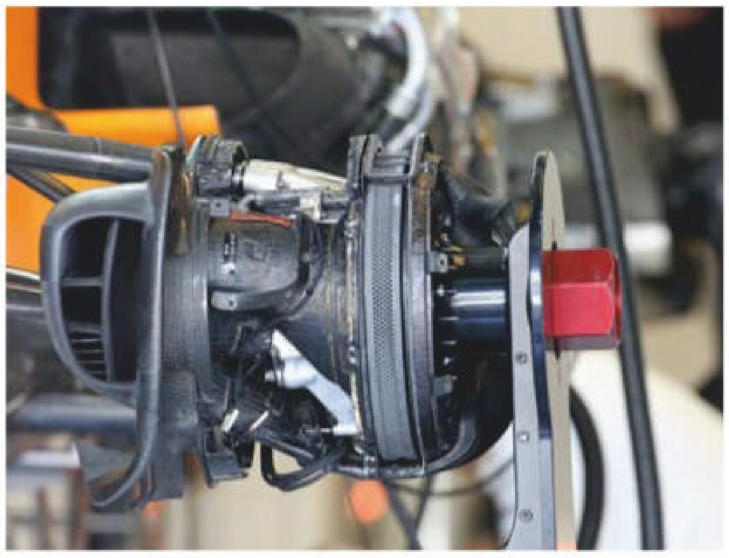
Falling short

Through 2018 the MCL33 failed to score a podium finish and McLaren ended the season sixth in the championship. It was not the return to form that the team had hoped for and the car was widely seen as a poor design outperformed by both Red Bull and Renault, which both used identical power units. But Roberts contests that this was not the whole story.

'It is easy in hindsight to look back and say that it was not a great F1 car, but the work that went into it and the dedication of the team was tremendous,' he says. 'A couple of times during the season I found myself stood at the front of the garage looking at the thing thinking what a beautifully engineered racing car it was, and wondering why it just wasn't faster. In the detail it's a really nice car but as a complete package it just missed the mark in terms of performance.

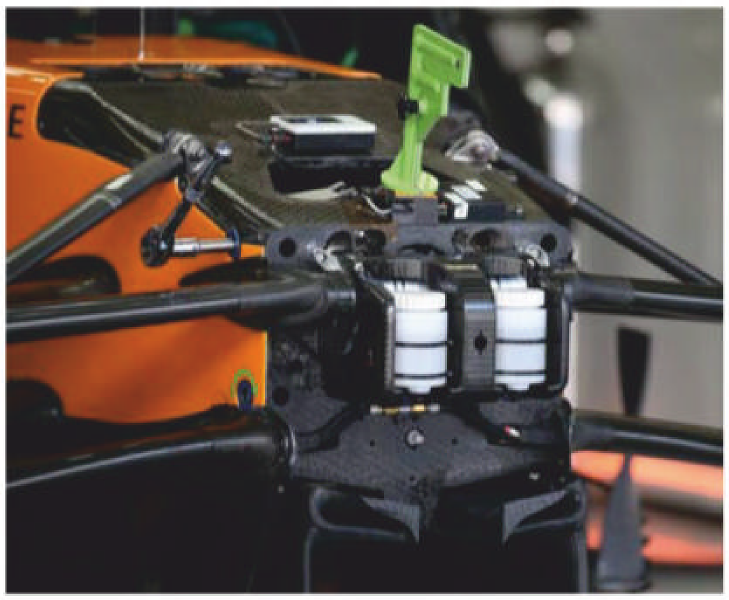
'There are parts of the car that worked really well, there are some things that we are really proud of on it,' Roberts adds. 'Some of the good things I can't discuss because I don't want to give away any competitive advantage, but in general our race pace was consistently better than our qualifying pace. We didn't design the car to be bad in qualifying but some of the stuff that worked well definitely helped over a race distance. Overall we raced the car as well as we could, both of the guys got everything they could out of the car on many occasions, especially [Fernando] Alonso. The race engineers and strategists did a great job with what they had to work with. To come sixth with that car was no mean feat to be honest.'

After the initial roll out the car was fitted with a new ducted nose, clearly different to anything else on the grid, and this is one of the parts the



The brake set-up featured Akebono calipers and master cylinders

Composite gearbox and rear suspension. Note the short upper wishbone that picks up the extended upright



Pushrod actuated torsion bars and dampers were used at the front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The suspension was designed to give the car a wide operating window and it did have better pace in races than in qualifying

team is most proud of. 'Other teams have copied bits of our nose,' Roberts says. 'Nose concepts are interesting as you commit to it and optimise the racecar around it, I think that went very well for us on this car. When you are racing people don't see what is going on behind the scenes, but our nose crash programme went really well, it showed the depth and breadth of experience we have here at McLaren.'

Blown chances

Another of the parts of the MCL33 which did work really well, according to the team, also highlights one of the biggest weaknesses of this design. 'Ironically, the front wheel blowing was probably class leading, [but] unfortunately that was not something this car needed, it needed a lot of other stuff,' Roberts says. 'In hindsight we focussed on something, took it to the ultimate degree, but it did not yield the results we had hoped for. Other teams who do not use it at all spent time and effort on other things which turned out to be more productive, it was really good engineering, and really good execution, but not right for this car.

'Unfortunately there were other parts that did not work at all, things we would have done differently had we known then what we know now,' Roberts adds. 'We followed a philosophy that other teams did not follow. We were not trying to be different or clever, we just went down an avenue, and fundamentally could not generate enough outwash on the car to deal with the wheel wakes. That, in a nutshell, is where we struggled. In a straight line it was okay, but as soon as you got to a corner and started turning in you started having issues.'

As McLaren's engineers started to understand the issues with the MCL33 it also turned its attention to the future. With the 2019 regulations reducing the outwash effect it could provide the team with the perfect opportunity to fight back. 'I hope 2019 is good for us, it is a massive change, and a race to recover the lost downforce,' Roberts says. 'After the season we had we have to be a bit humble, we are coming from a long way back. On the other hand I'm sure all the teams are struggling with one thing or another. I'm hoping the changes are a bit of a reset and that will allow us to get back to where we are more accustomed to being. We think we have the right people here, the right tools, we spent a long time trying to understand what was wrong on the 2018 car, maybe too much, this time next year we will know.

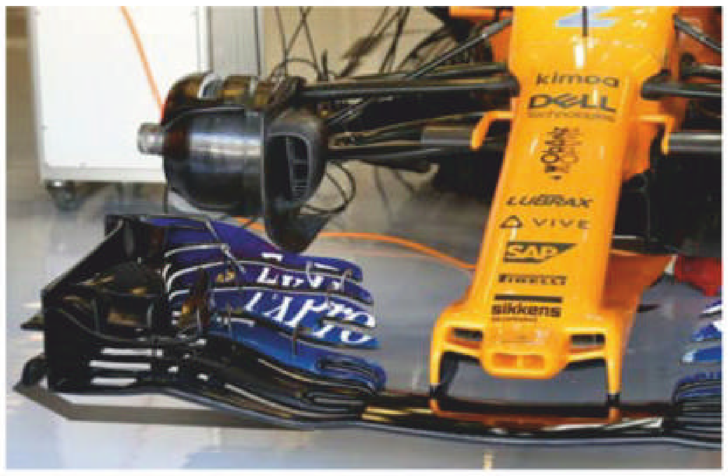
The front axle blowing was very effective, McLaren insists, but this was not what the MCL33 needed

'I think there is a big gap between the top teams and everyone else,' Roberts adds. 'If we were just comparing ourselves to the rest of the midfield then it was very close. The characteristics of all the cars are different, some have got more downforce, some have better ride, some have better drivers. But the Ferrari, Mercedes, Red Bull group is a step different, we are trying to find out how to bridge that now.'

Key signing

During 2018 McLaren lost a number of senior staff including Tim Goss (technical director), Matt Morris (chief engineer) and Eric Boullier (racing director), but in something of a coup it also signed James Key from Toro Rosso. Integrating these changes in the team is an ongoing process, and one Roberts and other senior staff at McLaren are managing carefully.

'We are very conscious that we don't want to upset the team, but you cannot just keep doing what you have always done and expect a different result,' Roberts says. 'So what we have tried to do is realign ourselves and change into a much more pragmatic, down to earth, operation, to be driven by the fundamentals of what makes a good racing car. We have to try to stop ourselves from believing we can do everything and anything, not that it is a bad trait. It is hard to take that out of people but when you are so far off the pace finding half a tenth somewhere when you need 1.5s is just not good value. So the changes we have made are to try and reset that. We need to make it easier, to have open and honest conversations about what works, and what does not, and we need to be down to earth, measured and pragmatic about that. Internally it feels very refreshing, it feels more open, people are happier to talk about things. We all make mistakes and we have to be okay with that. We can't cover things up.



McLaren says that rival teams copied elements of the car's nose

'We are focussed on doing the right things, focusing on our strengths, having the right people in place and getting performance back on the car,' Roberts adds. 'This is a long term plan, it's not about getting a few good people in and if we work hard we will win the 2019 championship, this is a recovery path we are on, this is about building confidence, expertise, and knowledge and getting ourselves back up front in a really sustainable way.'

The McLaren MCL34 is scheduled to be revealed in mid-February, and it should represent the first step on the path to recovery. With the arrival of Key during the season McLaren could be a force to be reckoned with once again, but the team knows it has a long road to travel down first.

'The race engineers and strategists did a great job with what they had to work with'

The VW Polo GTI R5 made an impressive debut on Rally Spain towards the end of last season, a good test for the car as it's a mixed surface event

Sales drive

Volkswagen Motorsport might have replaced WRC dominance with customer rallying, but the early signs are that it is on to another winner with its new Polo GTI R5

By MARTIN SHARP

Volkswagen Motorsport debuted two new Polo GTI R5s on October's 2018 Rally of Spain. These were works outings, but the rally cars in question were aimed squarely at customer use in WRC2, ERC and regional rallies. For this is where VW, for so long dominant at the highest level of the WRC, now sees its rallying future.

Spain was actually a very good test for the new cars, as it was the only mixed surface 2018 WRC rally, and the Polo GTI passed this test with flying colours. Eric Camilli first demonstrated the car's potential by winning three of the first seven stages and leading the WRC2 category after day one by 11.6 seconds. Gearshift problems on day two scuppered his hopes of a win, though. Meanwhile, fellow VW driver, 2003 World Rally champion Petter Solberg, took the GTI R5 to the WRC2 win on the longest stage of the rally, and then finished on the podium for the class.

Not surprisingly, the Polo GTI R5 technical project leader Gerard-Jan de Jongh was wholeheartedly encouraged after the new car's debut event. 'The pace of both the cars was good from the start and the drivers demonstrated that the car is competitive and fast in all conditions,' he said. 'Competition is always different from testing, and a minor defect can have a major impact. But the problem with the shift linkage is easy to eliminate before the car is delivered to customers. So we are extremely pleased with the debut.'

While the Polo R5 uses many of the lessons the team learned with its successful WRC car, very few components could be carried over

The testing de Jongh mentions was thorough, to say the least. It totalled around 10,000km, using no fewer than seven drivers in locations ranging from sea level to 2800 metres and temperatures from -16degC to +40degC, over surfaces which were roughly half gravel, half tarmac, plus a few kilometres on snow and ice.

There was a good reason for the large contingent of test drivers. 'Quite early on in the project we decided we wanted a large number of test drivers to prevent us going down one route,' de Jongh says. 'That helps us, even during a test, to be able to adapt from one driver to another driver with relatively easy set-up changes. I think the car is quite adaptable to different driving styles. That was the goal.'

This is because the car will need to suit customer drivers, and you have to rewind to the week following Rally Australia in November of 2016 to understand why. It was then that Volkswagen Motorsport made the shock announcement that it was to withdraw from world championship rallying as a works team, a move that prompted its technical director Francois-Xavier Demaison to decide on developing and building an R5 car. Demaison carries responsibility for four different Volkswagen Motorsport projects, but has been heavily involved with the development of the Polo GTI R5 from the beginning.

'We decided to do an R5 because we had requests from our importers around the world,' Demaison says. 'They wanted to have an R5 and wanted our support to promote Volkswagen in their national markets. We planned the R5 based on the new generation of Polo; we will sell it to customers and we are sticking to this.'

But Demaison admits it's a new way for VW Motorsport to go about its business. 'This year [we have] to make sure we support our customers as much as we can with the technical support, with the commercial support, and after-sales support…It's a big job for us to develop all this after-sales department because to sell cars, it's nice; it's easy, you build it; you sell it. But behind this you have a customer calling you, and this is completely new for us.'

High five

The Polo R5 is based on the sixth [2017] generation of the production car and on a PQ25 platform, one of VAG's latest generic floorpans. In contrast, the same group's Skoda Fabia R5 uses the earlier PQ24 platform; the regulations allow both cars to have the same track width, but the Polo's wheelbase is some 75mm longer than that

TECH SPEC: VW Polo GTI R5

Chassis/bodywork
Structure FIA-approved, reinforced steel body from production vehicle

Engine
Straight-four engine with turbocharger and intercooling, transversally mounted in front of the front axle; 1.6-litre. Power: 200kW (272bhp) at 5500rpm. Torque 400Nm at 4000rpm. Bore/stroke 82.5mm/75.5mm. Restrictor plate 32mm. Engine management by Bosch

Transmission
Sequential 5-speed racing gearbox, transversally mounted; permanent four-wheel drive with equal torque split between the front and rear axles, multi-plate limited-slip differentials, front and rear; hydraulically actuated double-disk sintered metal clutch

Suspension
Front/rear axle MacPherson struts, dampers from ZF; suspension travel approximately 180mm on asphalt and 275mm on gravel

Steering
Servo-assisted rack and pinion steering

Braking system
Internally-ventilated disc brakes (front 350mm on asphalt; 300mm front and rear on gravel), aluminium brake calipers (four callipers, front and rear)

Wheels
8x18in for asphalt; 7x15in for gravel

Tyres
Asphalt: 20/65-18 (235/40-R18); gravel: 17/65-15 (215/60-R15)

Dimensions
Length: 4076mm; width: 1942mm; height: 1372mm
Track: 1837mm; wheelbase 2540mm

Minimum weight
1230kg (without driver and co-driver)

The Polo GTI R5 has benefited from aero development in the wind tunnel and changes to the front bumper, bonnet, wing mirrors, rear wheel arches and rear bumper are the result

Despite the cost caps on R5 development most of the suspension parts are bespoke. The set-up is MacPherson struts, with dampers from ZF/Sachs – as was used on VW's WRC and Dakar cars

of the Fabia. In principle this might mean more stability in fast rallies, but compromise on the twisty bits (the freedom to go to the absolute minimum wheelbase does not exist under R5 rules). Here, Demaison makes an interesting point: 'If you want my own honest opinion, it's not a key factor for rallying at all. Full stop. We don't care; we have the wheelbase we get. There are many more key points in a rally car.'

While the Polo GTI R5 uses lessons the team learned from the successful Polo R WRC car, very few components could be carried over to the R5. This is because, differently to WRC regulations, R5 rules are aimed at keeping prices reasonable for private drivers through component cost caps and more restrictive diktats.

Cage fighter

The 2017 Polo was not available when the R5 rally car development started, hence early work was through computer simulation. Cost caps limit the number and tensile strength of tubes used in the roll cage design, but principles of the Polo R WRC roll cage design are incorporated into the R5 item; using bigger tubes to arrive at the same stiffness of the WRC cage.

The chassis was ready relatively early, though, so wind tunnel work could commence. Revised designs of the front bumper, bonnet, wing mirrors, rear wheel arches and rear bumper resulted. Some of these changes were styling-driven: 'We also want to give a good-looking rally car to our customers,' says de Jongh.

'I had to make sure that all of our suppliers understood that we had to find a good compromise between performance and cost'

For an R5 rally car, though, there must be suspension geometry compromises, particularly at the front, because the headlamp pods in the wheel arch cannot be modified. 'With all street cars at the moment the headlights are getting bigger, especially because of LED technology and daytime driving lights,' de Jongh says. 'So this is going to be a problem for every rally car, whether it's R5 or WRC, because you have to fit a reasonably standard headlight. With WRC you can modify the housing a little bit, but you still have to have the outer shape of the headlights. So it's a compromise which in my opinion exists for every rally car whether it's R5 or WRC, and you have to find a way around it with your geometry to get to the desired architecture. It makes it a little bit harder because for R5 you must have a completely standard headlight, with housing. The problem is bigger with R5, but it's inherent in every rally car.'

Cost control

The suspension design philosophy is similar to the WRC car. But a stipulated minimal weight and the R5 price limits means the component weights have to be a bit of a compromise.

'Weight is a big issue with any rally car,' de Jongh says. 'As a rule, however, the lighter a part is the more expensive it is. As such, I had to make sure the suppliers understood we had to find a compromise between performance and cost. For example, we designed 90 per cent of a suspension part, took this design to the potential suppliers and asked them what price they would be able to supply it for. The important thing here was the quantity. We sometimes only needed a handful for the Polo R WRC. In the case of the Polo GTI R5, designed for customer sport, we are talking about 50 or even more parts. That has a big influence on the price.'

On the damper side of things, VW's long Dakar and WRC experience with ZF/Sachs dampers meant that it was always going to be first choice for the R5. 'We always had a very good relationship with Sachs and this project benefits from that,' de Jongh says, going on to explain that: 'There are very few road car parts in the suspension. Uprights and dampers are bespoke, and we do the kinematics calculations in-house, using knowledge from the WRC.'

But not with the budget of WRC, of course. 'Sticking to the budget with an R5 represents

a major challenge,' says de Jongh: 'We have gained similar customer sport experience in touring car racing with the Golf GTI TCR, and we were able to build on that experience for the R5.

As for the anti-roll bars, unlike in the WRC R5 anti-roll bars must be solid which, in most cases, requires the outer diameters of solid bars to be machined to precise tolerances: 'But I wouldn't say that it makes it more expensive than a [hollow] WRC bar,' says de Jongh.

'The R5 regulations [are] a puzzle to figure out,' de Jongh adds. 'With the same components for the front and the rear and for gravel and tarmac, it's a big challenge, [but it] makes sense for the customers because you reduce the cost price of the component by using the upright from the left-front on the right-rear, for example; you don't need to buy so many different spares. [But] some things in the R5 regulations almost make it a bigger challenge than a WRC car; because you are so limited in your options. For the designers it's a different challenge; quite a nice challenge also, to do good suspension kinematics with a limited amount of power.'

Surface tension

As far as suspension changes while actually competing on an event are concerned, Spain was actually the ideal rally on which to test this, for as mentioned earlier, it's a mixed surface event with both tarmac and gravel. Teams are allowed 75 minutes to switch from gravel suspension to asphalt, and Demaison actually considers this a more involved task for an R5 than a WRC car. 'It's a bit more complicated than the WRC because in the WRC a lot of parts were designed for weight and serviceability.'

'It's very difficult to reach the minimum weight with an R5 rally car, so we have no ballast'

There are other differences, too. 'It's very difficult to reach the minimum weight, so we have no ballast; the only ballast we could have is with lighter or heavier protection,' Demaison says. 'But that's it, because with the cost cap, and it being a new generation of platform and also a five-door car, it's all weight, and it's difficult to get [to] the minimum. It's a big challenge to be at the minimum weight.'

Polo ponies

Moving that weight is a Volkswagen power unit. Freedoms exist in engine choice for R5, but it must derive from one of the group's production models. The team chose the 2-litre unit which is used in the road-going Polo GTI, suitably de-stroked to 1600cc for R5 use.

This is also the unit used in the Skoda Fabia R5. 'From the word go we had quite good communication with Skoda; they've been very helpful,' de Jongh says. 'We shared knowledge on the engine and saw some potential to change some things. We've shared our experience with Skoda; so we both benefit.

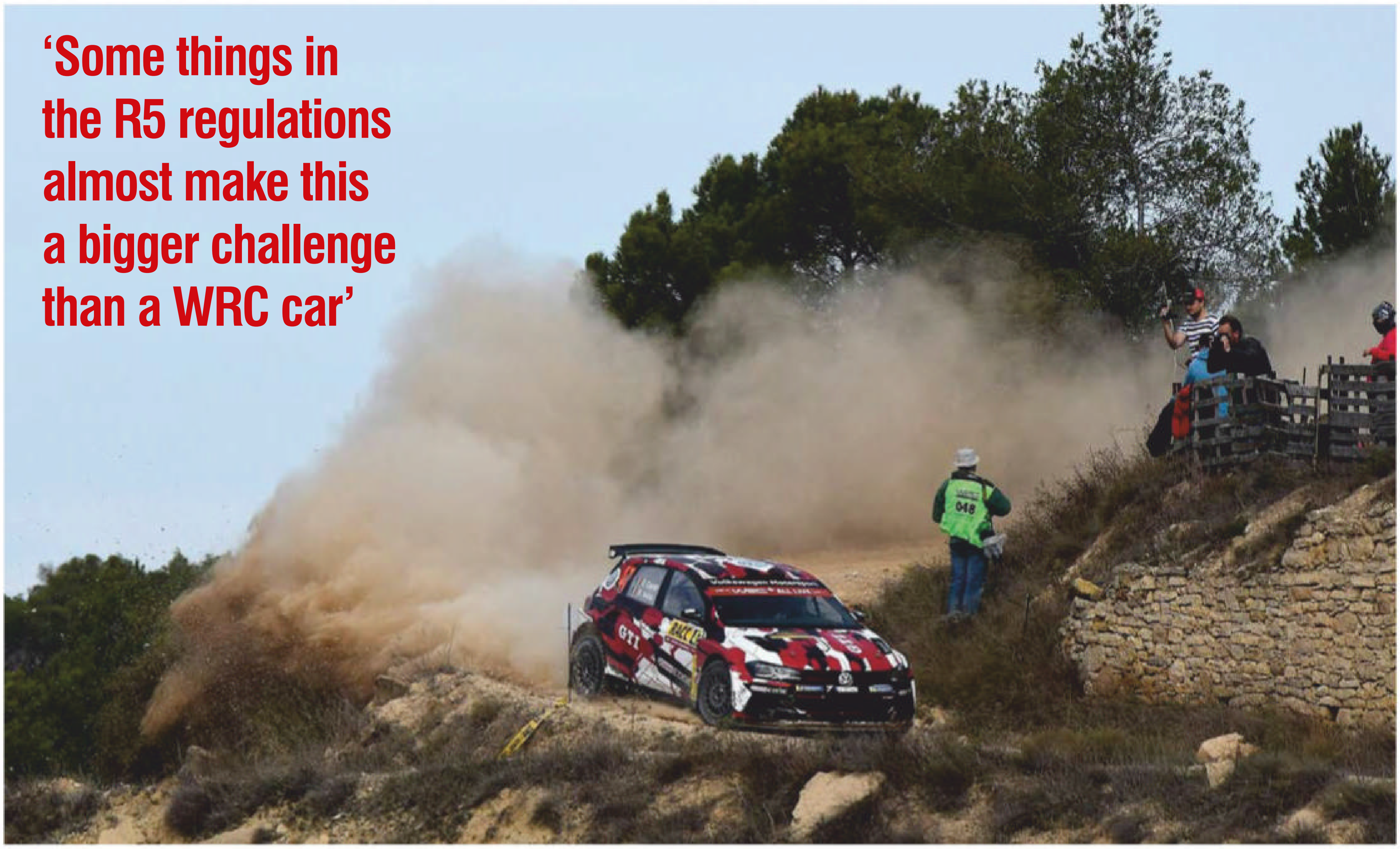
'Our benefit was we weren't starting with a blank sheet of paper for the engine,' de Jongh adds. 'Our engine is slightly optimised compared to their engine at the moment. But Skoda knows the improvements we have made so they can include them in their next homologation.'

The FIA has set R5 engine rebuild distances at 2000km for interim work and 4000km for major rebuilds and Volkswagen Motorsport has said it is currently planning to carry out engine rebuilds for its rallying customers.

The power unit delivers the drive via a conventional Xtrac gearbox, while the rear differential housing is bespoke; because the team wanted to have similar transmission architecture to that of the Polo R WRC, in which the electro-hydraulic rear-drive disengage clutch was placed between the gearbox and rear diff. 'This clutch is not in the rear diff,' Demaison says. 'By the rules you can't have it on the gearbox, so it's in the middle, like the WRC.'

It's worth noting here that, although it is a works operation, Volkswagen Motorsport must make profits in order to fund internal combustion engine-powered competition cars. 'We will only get a budget from our board to do electric cars; petrol cars we have to finance,' says Demaison. 'So if you look, our customer projects are IC engine because we have to sell cars to pay for them. It's simple; you want to do competition with IC engine? You have to finance it. From the board we get money for electric projects; for the rest we have to find a way to do it, so it's a customer project.'

'Some things in the R5 regulations almost make this a bigger challenge than a WRC car'



The Polo packs a 1.6-litre turbocharged straight-four powerplant that produces 272bhp. That power is transmitted through all four wheels via an Xtrac sequential 5-speed gearbox

Circuit brakers

The brave new world of Season 5 has presented Formula E teams with a number of challenges, not least of which is developing and refining the recently introduced brake-by-wire systems. *Racecar* investigates

By SAM SMITH

Rear lock-ups are less of a problem on the new Gen2 FE cars thanks to their brake-by-wire systems – though care is still needed with the front end, as this picture proves

Proper recuperation demands a brake-by-wire system, to keep the Formula E racecar both stable and predictable

It's been all change for Formula E for its fifth season: an all-new futuristic-looking racecar; no more mid-race car swaps, plus a new battery with better capacity and more power. But beyond these headline-grabbing changes there have been other, less obvious, improvements, starting with the stopping.

Because the new Gen2 Formula E racecar is a good deal quicker than its predecessor, the braking challenge on the seriously sinuous street circuits Formula E races on has been brought into even sharper focus. Brembo, which won the contract to supply some of the hardware, has concentrated on shifting every possible gram of weight from its calipers, with the front and rear items weighing in at 1.2kg and 1kg respectively, meaning these are significantly lighter than any F1 caliper.

Live wire

But while that's impressive, the real technical challenge in Formula E has been with the rear brakes. Previously the FE cars used driver managed regenerative braking, but no active function to control the brake bias. This is why drivers often locked-up or lost control entirely, because the state-of-charge in the battery and

All but two of the 11 Formula E teams are using the LSP-conceived IBSe brake-by-wire system

LSP's IBSe system. An electric motor resides inside and this drives a ball-screw that converts rotation into forward and backward movement

the drop-off in regeneration unbalanced the racecar. For Season 5, brake-by-wire (BBW) systems are now allowed, which in theory should make life easier for the driver, who will now fully control the front brakes only.

Stop and go

The regulations limit the power accessible to the Formula E cars to 52kWh (which is equivalent to only six litres of petrol) per race. In order to be able to race with that little energy at a good pace, energy management, and hence recuperation, is key. Proper recuperation demands a BBW system to keep the car stable and predictable. A lot of systems and control units have to interact, while quite a bit of arbitration work also has to be done.

But what systems are the FE teams using to achieve this? We can reveal that all but two of the 11 teams are using the LSP-conceived IBSe system – DS Techeetah and Mahindra Racing are the exceptions, having developed their own in-house systems. Both have been reticent to discuss details, but they are known to have been working on their packages since early 2017.

LSP GmbH has been more forthcoming, though. 'For electric, or hybrid cars, recuperation acts as an additional brake torque on the axle/wheels,' LSP's Simon Zollitsch says. 'The amount of the brake torque coming from the electric motor is strongly variable and influenced by things like charging status of the battery – full is full, and if it is almost empty the power for recuperations needs to be reduced too – battery temperature or the status of the inverter.'

The old approach was to set recuperation to fixed levels and then coach the driver to handle the switching of these levels

Torque split

The old approach was to set the recuperation to fixed levels and then coach the driver to handle the switching of the levels. 'With a BBW the driver is completely decoupled from the actual brake, so if the control software is working properly, the brake torque requested can be split into electric and hydraulic braking torque without the driver even noticing,' says Zollitsch.

Other assistances that are possible via a BBW system are online diagnosis of the brakes,

Formula E's tech future

It looks likely that the current car will be in use up to and including the 2021-22 season (Season 7), but those involved in the technical roadmap for the series are never the less looking ahead to the future. 'It [the next iteration] has to be decided because we have to discuss if it is advanced enough,' Professor Burkhard Goeschel, president of the FIA's Electric and New Energy Championship Commission (ENECC) says. 'The chassis is not really a big issue. It is more how modern the battery will be in the near future and if we can make some improvements on the battery because it is the core element.'

A key question regarding the future performance of Formula E centres on the technical management of batteries, particularly their make-up regarding cell chemistry and how electrodes are developed. 'We have to see how much freedom we have to change the battery because bigger changes are coming from the electrodes,' says Goeschel. 'Then if you change the electrodes the battery is more or less new. We are thinking about how far do we go, should we extend to a year for the present cycle or not? It is an open game at the moment.'

The new Gen2 car has been a success but Formula E is already thinking about what might replace it

A predictable braking performance is especially crucial in Formula E due to the proximity of the walls at the street circuits on which it races

'The brake-by-wire can be decoupled from the hydraulic brake circuit in case of an unexpected situation or failure'

online arbitration of brake balance (according to vehicle speed, aerodynamics, race situation) and launch control functions, among many others.

An electric PMSM motor resides inside the IBSe system, and this was developed in-house at LSP especially for this use. This electric motor drives a ball-screw that transfers the rotation of the motor into forward and backward movement of a hydraulic plunger. The in-house developed electronics enables the device to control the pressure in a range that is between 0bar to 110bar precisely and quickly.

Also, several safety-functions are performed online and diagnose the status of the brake-by-wire and also the brakes at all times.

'The third, and a very important part of the IBSe, is the valve block, with which the BBW can be coupled into the brake circuit, but also, which is a key benefit of our system, decoupled from the hydraulic brake circuit in case of an unexpected situation or failure,' says Zollitsch. 'Like this, the vehicle's brakes work like a normal brake with the driver's pedal being connected directly to the brake calipers.

'Since racecars are always prototypes, this is a crucial part of the IBSe. It ensures that the car can be stopped safely, even if our customers' vehicle control unit breaks down, power is lost, or other things happen which lead to a malfunction of the BBW,' Zollitsch adds.

There is little doubt that Formula E is currently on an ascendant arc in many areas, including technical relevance. Manufacturer projections on how many electric vehicles they will be selling in the next two decades vary, but there is no disputing the fact that more EVs will be on our streets and motorways in the near future, which makes this tech hugely relevant.

Race to road

This is not lost on DS Automotive, and its very own BBW system will be a significant race to road technical case study in years to come. 'We deliberately set out to harness and accelerate our BBW system and race it successfully before we implement a lot of this tech into our road cars,' DS Performance technical chief Xavier Mestelan Pinon says. 'We think this is a vital way to show customers that we are a laboratory for the road and that we put our systems through hell to ensure they can be relied upon.'

For LSP, Formula E makes perfect sense because it is already established and also provides a neat synergy between the company's development process and its significant and successful work in the automotive sector.

'Formula E is only one of very few purely electric race series,' says Zollitsch. 'More importantly, it is big enough to handle a concept like recuperation management and active braking, since this is no plug and play solution. Formula E is a very progressive race series, which is picking up all the questions that come along with electric mobility.'

Brake time

With an additional year likely to be added to the present new rules cycle taking the Gen2 car up to and including the 2021-22 season, the immediate concern about the next iteration of Formula E car is slightly on the back burner (see box out). But for LSP the opportunities in Formula E should extend beyond the current racecar. 'Of course, there is always the aim for lighter, smaller, more powerful solutions in all forms of motorsport,' says Zollitsch. '[But we're working on] a more precise control that helps Formula E teams to balance recuperation torque and brake torque even better.'

Zollitsch adds: 'However, one has to bear in mind, that this is a braking system, and Formula E is running on small inner city circuits. So the highest standards for safety always have to be the number one priority.'

Black magic

Small sports prototypes aimed at the customer racing market are extremely common. Barely a single Autosport Show, PMW expo or PRI show goes past without the wraps being taken off a couple of new designs. From time to time, however, one comes along which features something truly different, and that is the case with a new car to come out of the UK.

Called the Revolution, this is the first product to come from a new company set up by Phil Abbott, one of the founders of the Radical Sportscar company. This new car has an impressive spec sheet, but what really makes it stand out from the crowd is its chassis; not only is a composite monocoque but that monocoque uses an unconventional manufacturing technique which reduces costs and labour.

The story of this chassis, however, starts in Germany, when a teenager named Dominik Dierkes found a new interest. 'When I was about 13 or 14 years old, I became interested in special materials,' he says. 'When you are that age you sort of believe that they are magic, and can do so many different jobs, [such as] titanium, special alloys and composites like Kevlar. That interest did not go away and I ended up studying mechanical engineering at University.'

Dierkes enrolled at Hochschule Osnabrück (University of Applied Sciences) and in 2009 found himself working on the institution's Formula Student entry. Looking back at the results now, and images of the car, it seemed unremarkable but it had one detail that was somewhat unusual.

Student union

The composite chassis was constructed using vacuum resin infusion. This process differs to the standard construction technique in that it uses vacuum pressure to essentially suck resin into the permeable laminate. In theory it can offer a very strong and light component, but the use of this process in a competition car chassis was rare at best at that point.

'We did our own carbon tub using a resin infusion process, but we had some issues with it, and we didn't have the knowledge we do today,' Dierkes recalls. 'In the end it was quite heavy and over-engineered. One factor was that we didn't get all the resins that you really need to, but overall the project was a success and for a Formula Student car it was really good. Working on it, though, gave me the idea for the membrane tube infusion hose (MTI).'

This concept allowed air to pass through the suction hose used in the infusion process, but not resin. It proved to be a good concept and Dierkes patented it and went on to found a successful business selling the hoses, DD-Compound. 'We found customers in many different markets; aerospace, automotive and marine. But in about 2009 we decided that we had all this knowledge and decided to do something with it, so we tried to talk to our customers about what could be done with infusion. But we found that for most it was a second choice manufacturing process, [and] it was not something many would consider. I didn't understand why as the possibilities it offers are fantastic, you get the best quality

'I sort of believed special materials were magic'

With roots in a Formula Student programme, a new method of creating a carbon chassis has now been perfected and is available for purchase as the Revolution, although the cross-over applications don't stop there

By SAMUEL COLLINS

'To prove what we could do, we started to make parts ourselves'

parts with the same weight and performance as conventionally made parts' Dierkes explains.

While vacuum resin infusion has been used for a number of applications, notably in the marine industry and in wind turbines, few were willing to consider using it for complex structural parts such as a monocoque. Despite this, Dierkes decided to set up a new company capable of doing just that, DD-Composites.

'To prove what we could do we started to make parts ourselves, and the first automotive project we did was to make the bodywork for a Radical SR3, which was then entered into a number of races,' says Dierkes. 'Working on that, we got the attention of Phil Abbott, and after a little while he told us about his new project, and that he wanted to do something really innovative with it. So we explained to him what we thought we could do, and he put it to Pete Watts who was working on the project with Phil. He has a lot of experience in composites, but has worked with the conventional pre-preg process his whole life at places such as BAR-Honda and McLaren. When we told him about our process he was quite sceptical about it, but after we showed him some data he thought it was worth a try, and we did it. When he saw the numbers on the final chassis he was really impressed.'

Bonding exercise

The process to construct the monocoque using Dierkes' version of resin infusion then began in earnest. 'We decided to do the tub with infusion, but in one shot,' Dierkes explains. 'We still do it in two halves. While we could do it in a single piece but we decided not to as there are some advantages which come from bonding them. But other than that we could do everything in one process; all the layers, the core and the inserts in one single curing process. If you do it in pre-preg you have to do the outer skin, bond the core and a lot of other processes.'

The prototype tub for the Revolution car – the first production composite chassis to use resin infusion

Cool runnings

With the conventional lay-up technique, carbon fabric sheets are pre-impregnated with a resin, usually an epoxy, then this is laid up in the mould, the core is then bonded to it and then the other skin. The core with this approach is often made from aluminium, Kevlar or nomex honeycomb, but with the infusion process both skins are in place and a special foam core is used.

'The foam creates a resin honeycomb structure once infused,' he says. 'This gives the benefit of a very light core material and the stiffness of the honeycomb structure. We have also found that the foam core also acts as a

Dominik Dierkes of DD-Compound working on first Revolution car

Resin infusion uses a curing process at only 80degC, which represents a significant energy saving over conventional pre-preg techniques. Note the vacuum lines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‘We found it has better surface quality than pre-preg but the same weight’

kind of damping element, [because] usually with a carbon tub there is a lot of vibration. However, with this chassis it is reduced a lot.’

Perhaps unsurprisingly, this being the first application of its kind, the resin used in the Revolution monocoque is a specially developed product from Hexion, which Dierkes claims offers a good surface finish without pinholes.

Once the resin has been infused into the bagged component it is then put into an oven to cure but this is a major area of cost saving according to Dierkes; ‘Our curing process saves a lot of energy as it is at a much lower temperature than the conventional process, 80degC rather than 140degC, and on top of that we don’t need a pressurised oven. We only do a single curing process and with the conventional process it is more than one, so overall it is about an 80 per cent reduction in energy.’

Extremely large structures can be made using resin infusion, such as boat hulls and turbine blades but until now the process is almost unheard of in motorsport although the company is working to change that through its Revolution racecar

Testing conditions

Another cost saving compared to a conventional monocoque construction comes from the materials handling, and the amount of time required to work on the structure.

‘Infusion is much less expensive because if you use pre-preg material, the fabric has to be shipped to a pre-preg maker, the resin has to be put in it, then it has to be transported in a refrigerated condition, and this increases the raw material cost a lot,’ claims Dierkes. ‘Everything we use is stored at room temperature. Using pre-preg is just far more time consuming than using infusion, as with our process you only bag everything once, only cure it once. It’s just faster. I think overall it is maybe 30 per cent more cost effective than a pre-preg tub process and you get the same performance.’

A quick bit of research will show, however, that vacuum resin infusion is not without its shortcomings. Dierkes may make the process sound easy, but it isn’t, although it can offer more consistency than a conventional lay-up.

‘I think the only real shortcoming compared to pre-preg is that, pre-preg is a little better at dealing with very tight corners,’ says Dierkes. ‘The thing about the infusion process is that it works well if you know what to do. If you make a mistake you have completely destroyed the part and you have to throw it away. On a pre-preg part that is not such a big issue. It is one of the reasons that people don’t like infusion as much, because you have to work properly. However if you know what you are doing and do it right with infusion you get a perfect result every time.’

The first completed Revolution Racecars monocoque was wheeled out of the DD-Composites facility in Germany and shipped to England for assembly into the prototype Revolution car, but not before being subjected to a significant amount of testing.

‘Of course we tested it to FIA specifications, and we have used inserts of the highest grades of aluminium,’ says Dierkes. ‘Beyond that, though, we wanted to see how the chassis performed. We tested it and found that it has a better surface quality than a pre-preg monocoque, but it also has the same weight and without losing any stiffness.’

All the mounting points on the tub are made from high-grade aluminium to offer the strength needed

Cross application

While the performance of the Revolution monocoque sounds good, the gains made with some of DD-Composites’ other projects outside racing are even more impressive. ‘We have done a 45ft race boat catamaran in the USA using the infusion process,’ explains Dierkes proudly. ‘We took out about 40 percent of weight for a 30 percent increase in stiffness. It is smart engineering, if you have smart people, wanting to look at new solutions then you will be ahead.’

He puts that philosophy into practice too, not forgetting that the roots of his company and its technology lie in Formula Student, DD-Composites works with a number of FSAE teams on their chassis, sharing expertise on how to make structures using resin infusion.

The Revolution will be the first commercially available car with a tub using infused composites, while the mounting points are all high grade aluminium. ‘It really is a first, except for a few Formula Student teams, and the teams which are doing them are supported by us,’ concludes Dierkes. ‘We don’t mind sharing our knowledge with them, because if you keep everything to yourself you are going to lose your advantage anyway, because you are not developing. At some point, someone will overtake you and you won’t even realise it. In the end, we are innovators and we want to be one step ahead and the technological leaders.’

While DD-Composites is currently working with Revolution on its new car, scheduled for a new one make series during 2019, it is also open to approaches from other non competing projects, and a single seater design something Dierkes is keen to do in the future. It could be that this process offers a true revolution in the world of racecar construction.

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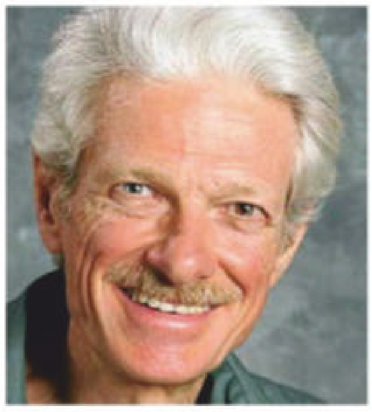

Rock the roll: a centre of rotation myth debunked

Why using a classic roll centre height definition may lead to confusion

Q I have seen roll centre height defined as the height at which a horizontal force applied to the sprung mass in the *y-z* axle plane will cause no roll. How does this compare with your method of roll centre assignment, as you have been discussing recently? [See last month's issue, V29N2]

THE CONSULTANT

A This is perhaps the oldest definition I know of, and is used by both SAE and ISO. However, both have appended notes to the effect that the roll centre is not a true instantaneous centre of rotation. They have done this in response to criticism.

At the simplest level, this definition agrees very well with resolution line roll centre height. I define roll centre height as the virtual vertical moment arm length for the geometric roll moment, or the ratio or coefficient (having units of length) describing the relationship between lateral force and geometric roll moment. In theory, when the lateral force acts at that height, the roll moment thus created will be equal and opposite to the geometric roll moment, and no roll will occur.

On an independent suspension there's nothing holding the contact patches a fixed distance apart when the car is in motion

Beam counters

With beam axle suspension, roll centre height can easily be tested with the vehicle stationary on the workshop floor. With independent suspension, it's not necessarily so simple. With independent suspension, the system has different dynamics when the car is in motion than when it's stationary. When the car is stationary in the shop, the floor holds the contact patches a fixed distance apart, although of course the tyres are laterally compliant. Disregarding compliances, a typical independent suspension approximates a four-bar linkage, specifically a Chebyshev linkage. That's a four-bar linkage with two of the links crossed over each other. The sprung structure is one link. The force lines, the lines from contact patches to front view instant centres, are the two links crossing over each other. The road surface or floor, holding the contact patches in fixed locations, is the fourth.

In this situation, the force line intersection really is a true instantaneous centre of rotation for the sprung mass with respect to the ground – but the suspension can't move the way it does when the car is being driven. If the force line intersection is in the middle of the track and not at ground level, and the sprung mass cg is directly above it, the suspension can't move in ride or two-wheel heave at all; that would require the track to change. With pure trailing arm suspension, theoretically the car can't roll, because that requires the track width to increase. If the force line intersection is off-centre, the car can move in both ride and roll, but not independently. It has to move in roll to move in ride, and vice versa, and both vertical and horizontal forces create moments about the force line intersection.

This is why we usually have to roll a car with independent suspension backward and forward before scaling it, after having it up off the wheels. If we don't, we won't get accurate ride heights and wheel loads. With beam axles at both ends, it is sufficient to merely bounce the car to reduce effects from stiction (ditto with pure trailing arms).

Motion carried

When the car is in motion, with a beam axle the axle holds the contact patches a fixed distance apart, so the system acts the same as it does when the car is stationary in the shop. But with independent suspension there is nothing holding the contact patches a fixed distance apart. The contact patches exert *y* forces depending on their loading and slip angles. The car can move in ride and roll in any combination. Track width is continually changing. When the right and left suspensions have unequal jacking coefficients, the car's behaviour in response to a lateral force varies depending on what proportion of the force is reacted at each wheel. Of course, it is impossible to push laterally on a car when it's being driven, but it is possible to confirm this on a kinematics and compliance rig.

With beam axle suspension the roll centre height can easily be tested with the vehicle sitting stationary on the workshop floor

Side-bite on a dirt track racer

Q It is a commonly held belief in dirt track oval racing (without a top wing and sideboards that change everything) that weight transfer from the inside tyres to the outside tyres is necessary for side-bite.

Is this thinking in fact correct, or is it only necessary that the centre of gravity is above the roll axis to avoid undesirable outward slide, that is a loss of side-bite, and body/chassis roll is a side effect and not the cause of side-bite?

THE CONSULTANT

A For this to be so, tyre load sensitivity would have to work oppositely on dirt and pavement. That is, the lateral coefficient of friction (μ_y) would have to increase with normal force on dirt rather than decrease. Friction would have to not only increase with load, but increase at an increasing rate. It would have to be desirable to concentrate tyre loading rather than equalise and disperse it.

But if that were so, all sorts of other things would change: narrow, high-pressure tyres would beat wide, low-pressure ones; statically right-heavy cars would beat statically left-heavy ones; adding wedge (increasing static LR/RF diagonal percentage) would free up the car (add oversteer in a left turn); and we'd get greatest lateral force by tilting the tops of the tyre out of the turn, to make the tyre shoulders dig in. We know that these things don't happen. Or at least, mostly don't. But there are some complexities that muddy the waters a bit.

On dirt that's fairly loose – not packed, yet not so soft that we need maximum flotation – it actually does work to concentrate loading and make the tyre penetrate. However, we mostly race on packed dirt. If the dirt is just moist, a tyre's tread may indent the track surface a little. But for the most part, the track surface is harder than the tread rubber, and mechanical interlock mainly comes from the grit in the road surface indenting the tyre rather than the tyre tread indenting the road surface. When the tyre slides, we are shearing the rubber at least as much as the track surface.

Tread carefully

A dirt track is often in a condition where the fastest tyre is a slick. We don't often see full size cars running slicks on dirt, but generally their tyre choices are defined by the rules, and the required tyres already have some tread in them. Also, often the tread compound has enough hysteresis so that tread blocks that are too big will overheat and chunk, so we have to groove the tyres simply to make them survive.

Wedge can actually free a dirt car up, on entry. It is common to set dirt cars up with lots of rear brake and use the brakes to get the rear end sliding on entry. Then more load on the left rear and less on the right rear gives us greater retardation force on the left rear and less on the right rear, creating a leftward yaw moment. The effect of this can persist well beyond the point where the driver gets off the brakes.

Finally, it is common on both dirt and asphalt for people to think they're increasing load transfer when they're actually decreasing it. In particular, dirt car rear suspension set-ups often exaggerate roll – hike the left rear corner of the car and make the right rear corner ride low. This makes the car look like it's sitting down really hard on the right rear. But in reality, the left rear is getting more load and the right rear is getting less: the car is gaining wedge. This hooks up the rear – unless the rear wheels steer out of the turn at the same time.

Just making the car run at a bigger aerodynamic yaw angle can help it corner. The side of the car, and the wing side plates if present, can generate side force aerodynamically. If the car has roll oversteer, making it roll will increase aerodynamic side force by increasing aerodynamic yaw.

Lateral load transfer may not increase lateral tyre force, but rearward load transfer will increase forward tyre force in a rear-drive car. And when it is power sliding, we are using a significant percentage of our rear tyre thrust as cornering force. Putting ballast up on the roll cage may not be the best thing for *y*-axis tyre force, but it may help mid-turn speed in some cases by increasing *x*-axis force.

Elastic banned

Regarding the case of the 'winged over' sprint car, does that really change everything? Not really, but it does change the direction of the elastic load transfer, and some of the effects of spring rate changes. The wing side plate force does reduce rightward load transfer, while adding some *y* force, but most of the car's load transfer is geometric rather than elastic, due to the high roll axis, and this is still rightward.

Does the cg need to be above the roll axis to maximise side-bite? Again, not really, but unless the roll axis is really high the cg will inescapably be above it anyway.

It's common to set dirt cars up with lots of rear brake and then use that to get the rear end sliding on entry

Is weight transfer from the inside tyres to the outside tyres necessary to maximise side-bite when running on oval dirt tracks?

CONTACT

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Slip Angle is a summary of Claude Rouelle's OptimumG seminars

Skid row: analysing car balance with driver data

In part two of his analysis of a driver's key performance indicators OptimumG president Claude Rouelle looks at how the steering integral can help identify understeer and oversteer in a racecar

Vehicle balance is commonly associated with the words *understeer*, *oversteer* and *balance* itself. Very simply, understeer happens when the front tyres of the car lose grip making the car go forward instead of turning. Oversteer causes the rear axle to snap out, making the driver reduce the amount of steering or counter steer. When a car follows the corner path and it does not oversteer nor understeer it is said that it is neutral steer. To define these in engineering terms, understeer is a lack of yaw moment and oversteer is an unnecessary over-yaw moment.

GOODWOOD

A key difference between oversteer and understeer is that the former is much more fun – especially in a Ferrari 250 GT SWB

Slide rules

Contrary to an oversteer situation, an understeering car is usually less evident and more progressive, and it can be difficult for an amateur driver to know that they are understeering, and even difficult for the engineer to identify it – even more tricky to quantify it. Some specific analysis of multiple channels such as steering wheel angle, throttle, brake, yaw rate (with the gyro) or lateral acceleration could help. Let's start with a simple one.

To analyse the vehicle balance we will be looking at a key performance indicator (KPI) called 'steering wheel angle integral'. We are going to show here how you can relate it to the vehicle's balance variation throughout a track session.

To assess the vehicle balance, that is if it's oversteering or understeering, the easiest way is to set a nominal steering reference lap. A reference lap is one in which the driver makes a lap slightly slower than the fastest lap he could set, say, around 95 per cent of their normal pace. When driving 'slowly' we can assume that tyre slip angles won't go past their peak. We need a reference, even if it is not a perfect one, and this reference will be the driver's opinion – remember that with a racecar there are too many inputs to be spot on in our performance prediction, and so we work in deltas, in trends, in sensitivity and in slope.

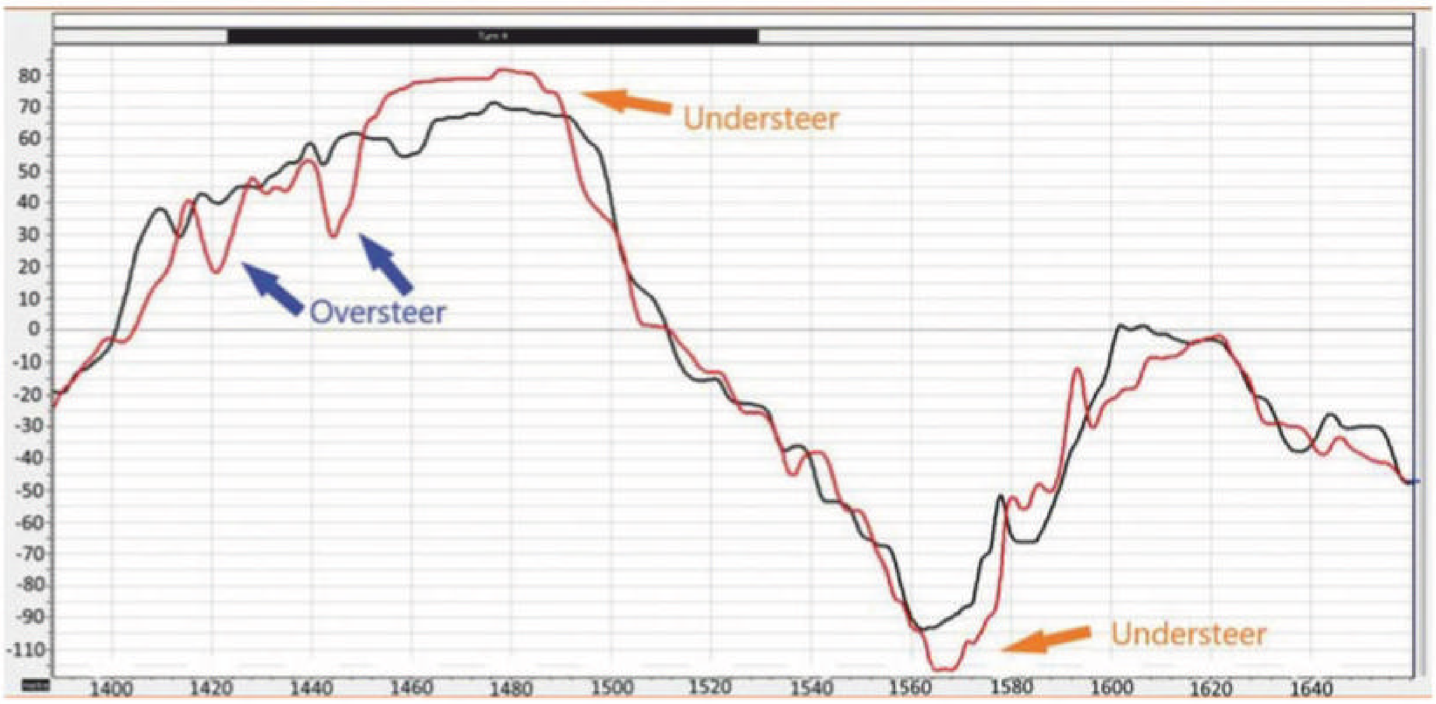


Figure 1: Steering wheel angle with reference lap (in black) and fastest lap (in red) with handling states indicated

In a relatively slow lap, with a 'happy' driver, we can consider we have no serious oversteer or understeer (at least from the driver's point of view), hence this lap is called the reference lap. By overlaying it with a normal lap, the engineer can spot oversteer and understeer. An example is shown in **Figure 1**, where the steering wheel angle of the fastest lap (in red) and the reference lap (in black) for a corner are plotted. The steering wheel angle is plotted in the *y*-axis. By looking at the red and black steering values it becomes clear the areas where the driver is fighting understeer or oversteer.

The car has difficulty in corner entry; noticeable here by the fact that the driver needs to reduce its steering at the 1420m and 1444m mark. At the apex (1450-1480m)

Overlaying the steering wheel angle channel on top of the reference steering wheel readout can be very insightful

the driver needs to steer more, indicating that they are most probably fighting understeer.

We could have plotted other channels such as yaw rate or the lateral acceleration and we would have obtained a similar conclusion. Why then would it be useful to go through the effort of setting up a reference lap and comparing the steering wheel angles? Because if objective data analysis is confirmed by the driver's subjective comments (the word subjective not taken in a pejorative way here) then we have gained a significant confidence in the data analysis that can only help the driver's communication with the race engineer.

Steering integral

Overlaying the steering wheel angle channel on top of the reference steering wheel can be very insightful. Points of interest can be quickly identified, especially if combined with the previous key performance indicator – steering smoothness, as discussed in the previous article (January issue, V29N1).

However, the real gain in using the steering wheel angle lies mainly through the use of the key performance indicator, the steering integral. This is a maths channel resultant from the integration of the steering wheel angle over a lap. Simply put, we are looking at the total amount of steering done by the driver in the lap. A high value means that the car has a tendency to understeer. The lower the value, the more the balance will shift towards oversteer (again, at least from the driver's perspective). By plotting this metric, we can have an idea of how the vehicle balance changes with time, as tyres wear out, the fuel is consumed, and so on.

Figure 2 illustrates this case. The *y*-axis represents the steering wheel angle integral metric, and the *x*-axis the lap numbers. As the session progresses, if the car is perfectly balanced, no tyre degradation, and a perfect driver, then they would always be steering the same amount, resulting in a constant steering wheel angle integral (represented by the orange colour). What actually happens is that either the driver will need to steer more (green colour) indicating a more understeered car or to steer less (red colour), which is typical of oversteer behaviour.

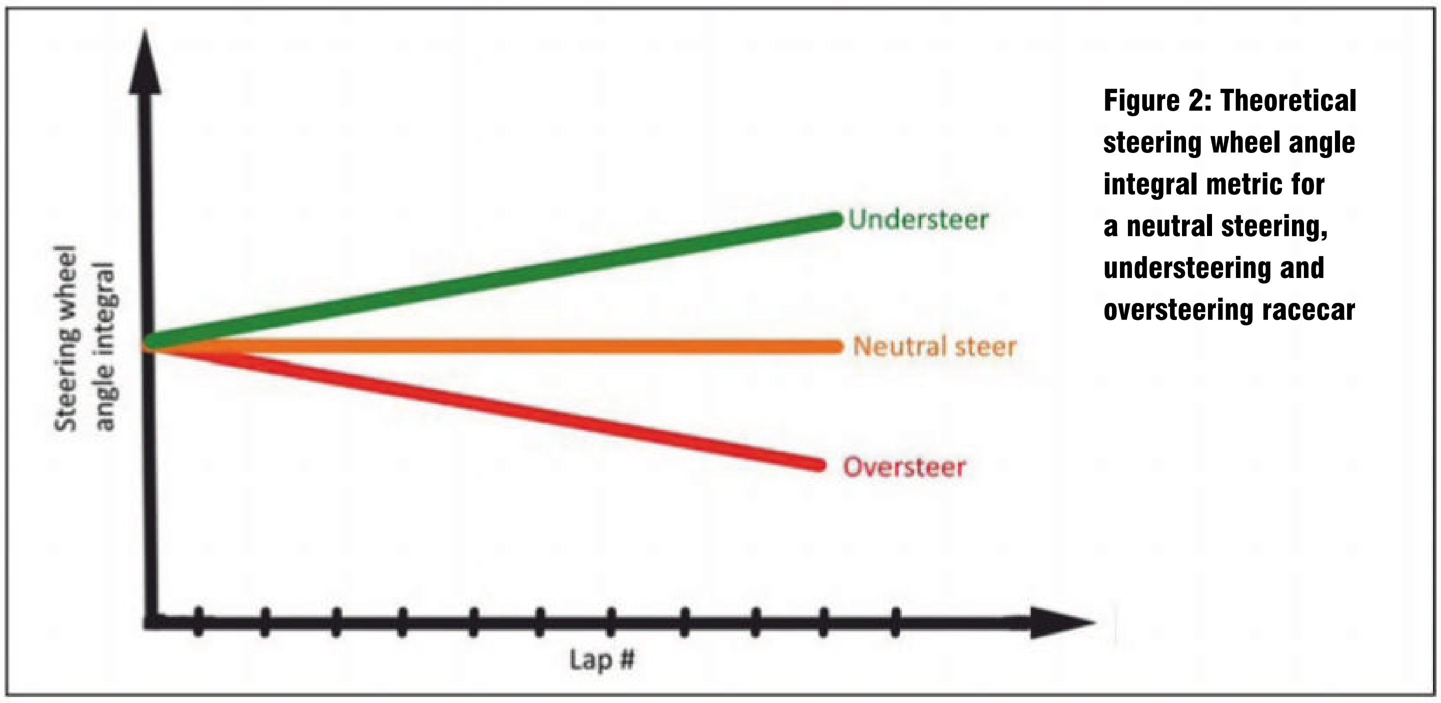


Figure 2: Theoretical steering wheel angle integral metric for a neutral steering, understeering and oversteering racecar

Table 1: Maths channel equations to create the steering wheel angle integral

Math channel name	Math channel equation
Steering Wheel Angle Integral	integrate(abs('Steering Wheel Angle' [deg]), 1, range_change("Outings:Laps"))
Steering Wheel Angle Integral KPI	stat_max('Steering Wheel Angle Integral' [deg],1,range_change("Outings:Laps"))

If a driver is too slow they exaggerate the amount of steering angle required to negotiate a corner

The steering wheel angle integral is calculated by using the Integrate function available in the analysis software MoTeC i2, and the result is displayed in **Table 1** and **Figure 3**. This function takes three arguments. The first entry is the data that we want to integrate, in this case the *abs*('*Steering Wheel Angle*' [*deg*]). Notice that we use the *abs* function for the case where the steering signal is negative, since this would even out with the positive values when calculating the integral. The next argument is to set a condition to integrate only when this condition is true, in this case we want to always integrate, so we put the number 1, which MoTeC interprets as a true condition and will integrate always. The final argument is to decide when to reset the integral, we use the *range_change* ('*Outings:Laps*') to specify that we want to start the integration again at the beginning of each lap. Finally we can use the function *stat_max*() to calculate the maximum value of the steering integral.

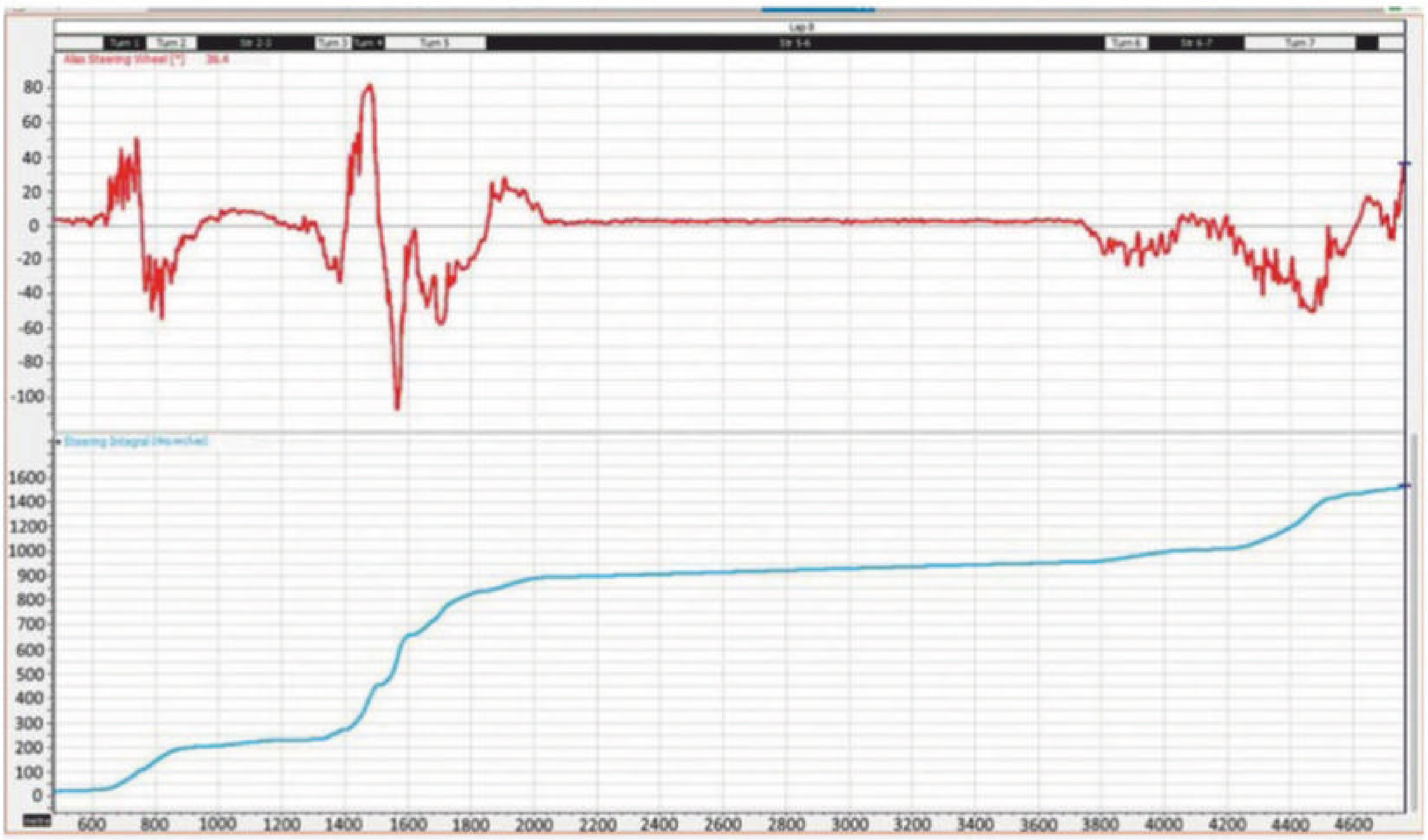


Figure 3: Red is steering wheel angle for a lap while blue is the steering wheel angle integral obtained from Table 1

Nominal steering

The trick is to do a low speed lap to get the 'nominal steering', and then compare the steering integral of this lap with the one of a normal lap: steers more (understeer tendency), steers less (oversteer tendency).

Besides comparing the nominal lap with other laps, if we use the second equation from **Table 1**, we can plot for each lap the steering integral and from there have a reference of how the steering wheel angle integral changes during a session. The results of this operation are presented in **Figure 4**, where we analyse the steering integral of four different drivers with the same car (same set-up, same tyres) during an endurance race simulation.

Head to head

From **Figure 4** we can make some conclusions and correlations with the steering integral and the number of laps. First, as the session progresses the steering integral value keeps increasing for drivers A and B, while it remains constant for drivers C and D, and between them they have pretty much the same slope as the session progresses.

Drivers C and D seem to be managing the tyres much better, because their steering integral slope varies little, unlike drivers A and B. You can see that driver A is fighting understeer. In a future article we will study why this understeer occurs for driver A and not so much for the other drivers. There are other KPIs that will explain this.

Instead of plotting the steering integral versus the lap number, another way to look at data is to plot it against the lap time, which is illustrated in **Figure 5**. In this chart, another dimension is added by applying a colour gradient to the data. The lightest, or faintest, colour represents the first lap while the darkest, or boldest, colour is the last lap for each driver. Note that the data shown in **Figure 5** is not from the same data set as **Figure 4**, they are from different tests.

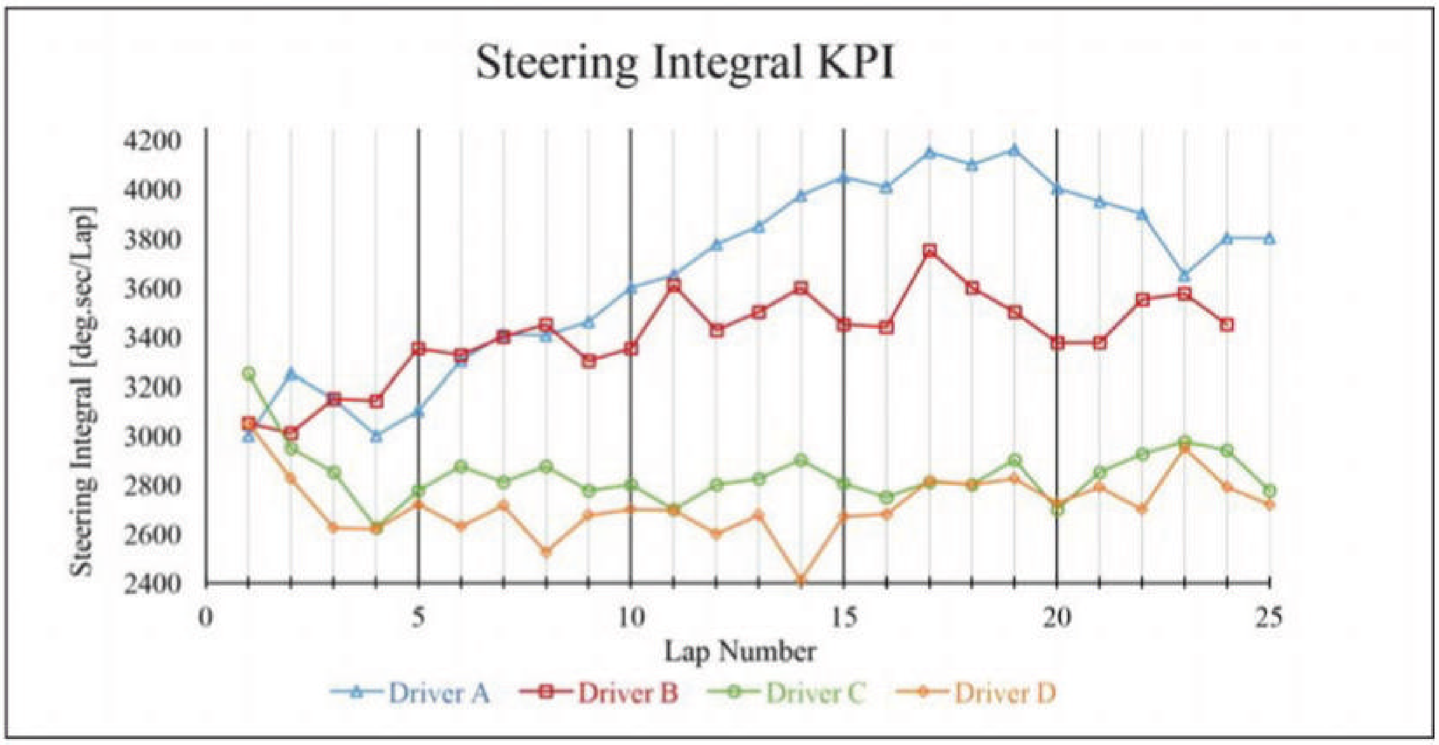


Figure 4: Steering integral KPI versus lap number for four drivers. Drivers C and D seem to manage their tyres well

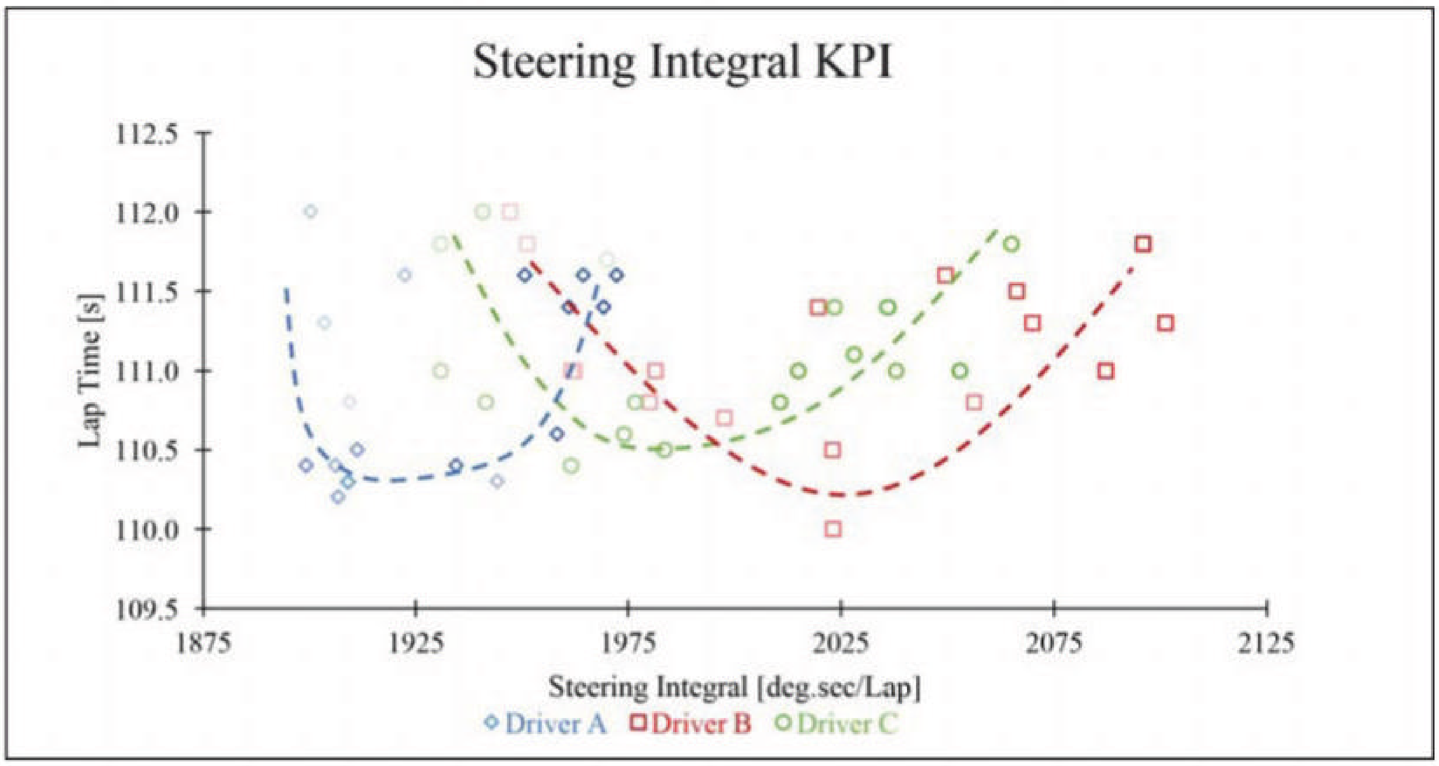


Figure 5: Steering wheel angle integral KPI versus lap time – faintest colour is first lap while boldest is the final lap

Data analysis

In this test, we can conclude that driver A was the quickest driver, and the fastest lap times were achieved when the steering integral was lowest. The data of all drivers show a trend where around a certain steering integral value they have their fastest laps. Comparing all drivers, it seems that driver A (blue) needs less steering integral (less understeered vehicle) compared with driver B (red), a more understeered vehicle. The colour gradient allows the engineer to see that as the session progresses all drivers steering integral, as well as their lap times, increased, possibly due to tyre wear. The colour gradient highlights that driver B (red) and driver C (green) have a much smoother understeer gain when compared to driver A (blue), who did some fast laps consistently but then was slower with more understeer during the last laps.

Their steering integral as well as their lap times increased, and this was possibly due to tyre wear

In conclusion, when looking at the steering integral special attention should be paid so that we are only examining the large deviations. Small changes that are within a certain margin of error should be neglected.

When setting the reference lap, if the driver is too slow, they will exaggerate the necessary amount of steering angle required to negotiate a corner due to the larger steering angles required at slower speed. The car should be driven just slow enough to prevent any unbalance from tyre slip angles.

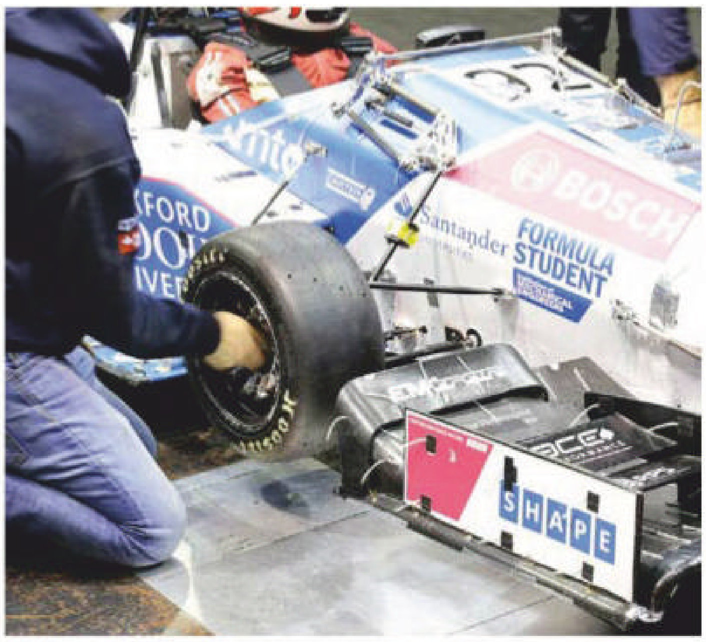
The steering integral can give the engineer a very good idea about the balance variation of the car over time. It is useful to investigate set-up changes, compare different tyres, evaluate trends in vehicle balance as tyres wear more, as fuel load gets lower, and assess differences in driving style and differences in track conditions.

Note that different vehicle set-up is often required for different driving styles, as shown in **Figure 5**, where the lap time as a function of the steering integral is illustrated.

Reducing wheel diameter on a Formula Student car

Our Formula Student study concludes with some tyre size and yaw angle experiments on the Oxford Brookes OBR18

The Oxford Brookes OBR18 Formula Student car sports a complex aero package which was developed in CFD



The aero effects of smaller diameter tyres were evaluated

This month we bring our Formula Student study to a close with a look at some aerodynamic aspects not previously examined in this column. Our guest in the MIRA full-scale wind tunnel was, once again, Oxford Brookes University with its OBR18 car. The team was the highest placed UK finisher in the Silverstone-based competition last July, and the car featured a complex aero package that had been developed extensively in CFD.

In our previous two issues we saw how the OBR18 set a new high in downforce and efficiency (-L/D) among the Formula Student cars we have tested in the past few years (January, V29N1) – to recap the data is reproduced in **Table 1**. Then, in our last issue (February, V29N2), we examined the responses of OBR18 to changes of rake and ride height, and encountered downforce reductions at increased ride heights, plus front wing stall and aerodynamic flutter at decreased ride heights.

Table 1: Oxford Brookes OBR18 data compared to other Formula Student cars previously tested by *Racecar Engineering*

	CD.A	-CL.A	-CLfront.A	-CLrear.A	%front	-L/D
UH15	1.249	1.959	1.150	0.809	58.7%	1.568
TBR14	1.597	2.708	1.116	1.592	41.2%	1.696
OBR18	1.240	2.787	1.313	1.474	47.1%	2.248

Table 2: The effects of fitting smaller diameter tyres

	ΔCD.A	Δ-CL.A	Δ-CLfront.A	Δ-CLrear.A	Δ%front*	Δ-L/D
Smaller tyres	-18	+132	+89	+44	+0.9%	+127

** Changes in %front are absolute, not relative*

Smaller tyres

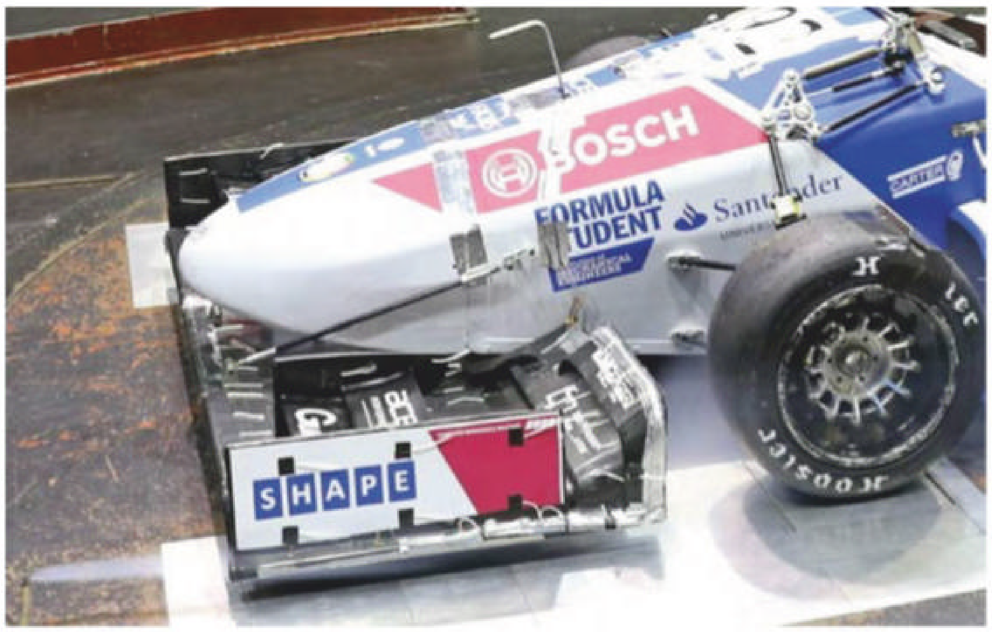
The Oxford Brookes team had also brought a set of smaller diameter tyres for us to try, 16in instead of 18in. Ride heights were reset to the same as baseline with pushrod adjustments. The results (at zero yaw and zero steering angle, these parameters being mentioned because of what came next) are shown in **Table 2**, as 'delta (Δ) values', that is, as changes from the baseline coefficient figures. The drag reduction, which amounted to 1.3 per cent, was no surprise, and could probably be attributed largely to the change in frontal area.

The increase in total downforce, which amounted to 4.8 per cent, and the downforce at both ends of the car were more interesting, though. The front downforce increase, at 6.9 per cent, was more than double the rear downforce percentage increase. This obviously suggests there was a gain from the front wing, and we could reasonably speculate that the smaller front tyre presented less blockage and thus allowed improved, probably more energetic, flow from the front wing, which in turn enabled it to develop more downforce.

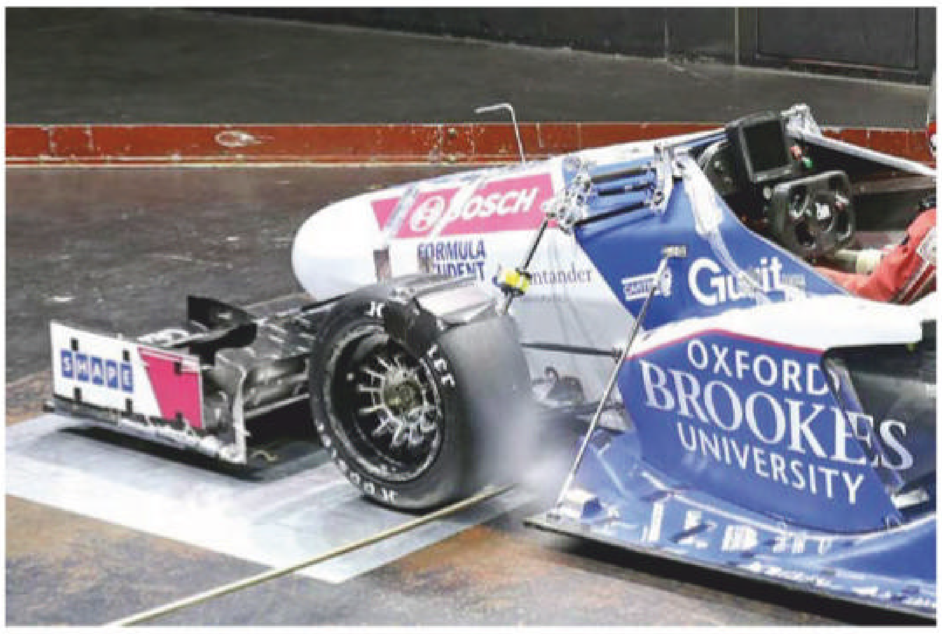
The more modest increase in rear downforce seems unlikely (by virtue of the large vertical separation and the rear wing span being within the insides of the rear tyres) to have arisen because of improved rear wing performance, although there may have been a small contribution. The alternative then is that the underbody was able to contribute some more rear-biased downforce. The smaller front and rear tyres may have assisted here; increased mass flow and/or improved quality flow may have been able to enter the underbody because of the smaller diameter front tyres. And the smaller rear tyres could have improved the egress of air from under the profiled sidepods, and also reduced the ingress of disturbed air into the rear diffuser.

Some interesting combinations of steer angle and overall yaw angle were also evaluated. From logged data and simulations back at base the team had determined the

The smaller tyre presented less blockage and thus allowed improved, probably more energetic, flow from the front wing



Changing the tyre diameter clearly had an influence on the performance of the front wing



The smaller tyres also had an effect on the airflow to the underbody of the OBR18

steering angle and effective aerodynamic yaw angle in both the skid pad condition and in the average turns of the autocross and endurance sections of the Formula Student competition. With not a great deal of time remaining in our test session there was no opportunity to map a range of angles as would have been preferred, and the results are given in **Table 3** of just one set of steer and yaw angles. Steer angle was to the left, obviously representing a left turn, while the yaw angle was applied to the right (clockwise viewed from above) to represent the actual direction of the wind on to the car in left turns in the skid pad (2.3-deg yaw) and an average other turn (5.0-deg yaw) scenarios.

It is apparent that simply applying steering lock did not tell the same story as applying yaw angle to simulate the angle of the approaching air in a relatively small radius turn. Applying steering lock only saw a very small drag increase and what amounted to a 1.9 per cent total downforce decrease, which was all at the front of the car, probably because of the additional blockage to the flow departing from the front wing, with a small gain felt at the rear, probably just through the mechanical cantilever effect of the loss at the front.

However, once yaw angle was applied, drag appeared to reduce slightly. In fact this was because the wind tunnel's drag force measurement vector was no longer aligned with the wind direction, but when the measured side forces were taken into account the total force along the vehicle's longitudinal axis barely altered. The reduction of downforce, however, was real and greater than with steer angle only, and now came from the rear as well.

Simply applying steering lock did not tell the same story as applying the yaw angle

Flow quality in the outer diffuser is significantly affected by the rear tyres, so changing tyre diameter will have influenced this too

Table 3: Steer angle and yaw angle

	ΔCD.A	Δ-CL.A	Δ-CLfront.A	Δ-CLrear.A	Δ%front*	Δ-L/D
13deg left steer	+3	-52	-75	+23	-1.9%	-44
Steer + 2.3-deg right yaw	-10	-103	-84	-19	-1.4%	-61
Steer + 5.0-deg right yaw	-25	-159	-93	-65	-0.7%	-80

** Changes in %front are absolute, not relative*

Indeed, the rear showed a greater response to yaw than the front, and at the larger yaw angle the rear losses were not far different from the front losses. The obvious primary source of these rear losses was the large rear wing end plates masking the wing, although it is likely that the underbody saw losses too.

In the balance

The changes in balance, as shown by the %front value, were relatively modest. In the smaller yaw case, representative of a larger turn radius, the balance shift was rather more than it was in the larger yaw, tighter turn case.

However, the difference in the actual forces at the tyres in the different steer and yaw conditions was very small (less than a kilo at the rear tyres, almost no change at the front tyres), and it seems unlikely that they would be detectable by the driver. And it could be argued that the driver won't feel what the cornering grip level and balance are until its in the 'steer plus yaw' condition anyway.

Any differences between the straight ahead data and the steer plus yaw data are, in one sense, academic anyway, although when examining the transition from braking in a straight line to the corner exit phase then changes in the front to rear grip balance might perhaps be more tangible.

Next month we will be starting a new project in the MIRA full-scale wind tunnel.

Racecar Engineering's *thanks to the Formula Student team at Oxford Brookes University.*

CONTACT

Simon McBeath offers aerodynamic advisory services under his own brand of SM Aerotechniques – www.sm-aerotechniques.co.uk.
In these pages he uses data from MIRA to discuss common aerodynamic issues faced by racecar engineers

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The hard cell

In part two of our investigation into the use of hydrogen fuel cells in motorsport *Racecar* explores the challenges facing the development of the technology with an in-depth case study of the ground-breaking LMPH2G sports prototype

By RICARDO DIVILA

GreenGT's LMPH2G has been built to demonstrate the possibilities of hydrogen fuel cells in racecars. It can reach 100km/h in 3.4 seconds and has a max speed of over 300km/h

In last month's issue we examined the potential for hydrogen fuel cell racecars (V29N2). But now it's time to turn our attention to what has to be the most high-profile of existing projects. Here we will look at the design challenges inherent in a change of motive power from the classic internal combustion engine to hydrogen, and how GreenGT, the maker of the revolutionary LMPH2G, has overcome many of them.

But first we need to back-pedal a little to put the LMPH2G into some sort of context. The first fuel cell project attempted by GreenGT was the H2, a proof of concept car. This was presented as a potential Garage 56 contender, the ACO's slot for allowing new technology to be demonstrated at Le Mans, not constrained by the regulations so as to enable revolutionary concepts to run at the race.

The powertrain for the GreenGT H2 was two electric motors powered by electricity generated in a PME hydrogen fuel cell, the pressurised hydrogen being stored in carbon fibre cylinders that hung on the sides of the car. These reservoirs could be hot-swapped via a quick-connect dry-break coupling.

The development work carried out on the original GreenGT H2 racecar enabled various new technology components to be validated, while also discovering the operational problems attached to the concept.

Gassed up

The powertrain layout for the second, closed cockpit, version of the car – the LMPH2G we are examining here – maintained the rear-wheel drive layout of the H2, with the centrally positioned fuel cell carried in a carbon container and effectively replacing the conventional engine as a stressed member. There was also a third reservoir added to the layout, so there were two placed on the sides and one behind the cockpit.

Compared to more conventional racecars, the whole packaging ends up more complex, because of the new technology parts, plus accessibility and running requirements. Yet the design of the prototype still had to determine

The centrally positioned fuel cell, carried in a carbon container, effectively replaces the conventional engine as a stressed member

TECH SPEC: LMPH2G

Chassis
Carbon LMP chassis with steel sub-frame; double wishbone pushrod suspension; carbon brakes

Power unit
GreenGT electric-hydrogen powertrain (4-stack fuel-cell with polymer electrolyte membrane) producing a constant 250kW; four electric motors (two for each rear wheel); maximum output of 480kW at 13,000rpm (653bhp); 2.4kWh KERS delivering 250kW for 20 seconds

Performance
Maximum speed: +300km/h; 0–100km/h in 3.4 seconds; 400 metres from standing start in 11 seconds. Range is equivalent to other racecars with comparable performance, the current refuelling time is three minutes. The emissions into the atmosphere is water vapour only

Transmission
Direct drive to rear wheels (ratio:1:6.3); no gearbox, no clutch, no mechanical differential; electronic torque management system

Hydrogen Storage
Fuel tank capacity is 8.6kg of hydrogen at a storage pressure of 700bar

Wheels and tyres
Front: 30/68-18 Michelin Pilot Sport GT(hub12X18); Rear31/71-18 Michelin Pilot Sport GT(hub13X18)

Dimensions
Length: 4710mm; height: 1070mm; width: 1970mm; wheelbase: 2970mm; front overhang: 1000mm; rear overhang: 740mm

Weight
1420kg in working order (front: 39.8 per cent, rear: 60.2 per cent). Weight variation at refuel: 8.6kg

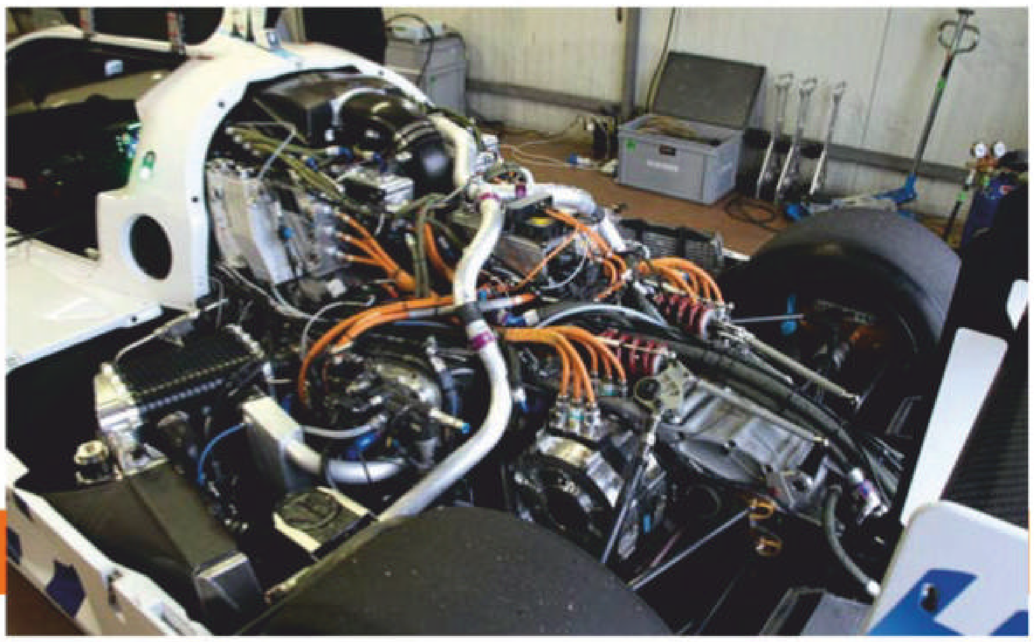
the systems layout considered as a racecar, complying with the safety and dimensional regulations, to optimise the use in a racing environment. For an efficient cost process the use of as many existing elements as possible was included in the design brief. As the systems are developed, more bespoke items will be fitted as the technology matures.

KERS and effect

For this second iteration of the concept, and to improve the energy efficiency, a Kinetic Energy Recovery System (KERS) was added to the car, harvesting part of the energy required to retard the car through the rear wheels using the electric motor functioning as an alternator and storing it in a buffer battery, to be deployed in acceleration as required. Considering that all the power applied to the wheels is electric through the two motors per wheel, this also enables traction control and torque vectoring to be electronically controlled. This had been explored on the first car and has now been further developed on the LMPH2G.

Through GreenGTs proprietary software, the aspects mentioned above also open up a

The original GreenGT hydrogen racecar was the H2, which broke cover in 2012. This was an experimental prototype that packed two electric motors and a PME fuel cell



Under the skin of the LMPH2G. Two electric motors can be seen here (there are two more on the other side). The orange power lines go from the inverter to the motors

GreenGT LMPH2G

Key to diagram

1. Electric motors
Four electric motors on the rear wheels (two on each) provide propulsion.

2. Hydrogen reservoirs
The dihydrogen (H_2) is stored in three pressurised (700bar) carbon filament tanks used to fuel the cell. The first two are placed either side of the cockpit and the third just behind the driver.

3. Hydrogen fuel cell
Comprises four stacks, at the core of which molecules of dihydrogen (H_2, stored in the tanks) and oxygen atoms combine to form water molecules (H_2O). This reaction produces heat, and electricity, which powers the car's electric motors.

4. The stack
A layered pile of 230 cells, bipolar plates and hydrogen porous membranes.

5. Air Intake
The ambient air used to produce the reaction within the stacks enters through this vent. It is filtered, propelled towards the compressor, then the humidifier, before entering the stacks.

6. Buffer batteries
Excess electricity produced by the hydrogen fuel cell and by the KERS system (when braking) feeds into high-performance cells. The driver can therefore double the car's acceleration potential (250 to 480kW, the equivalent of 653bhp).

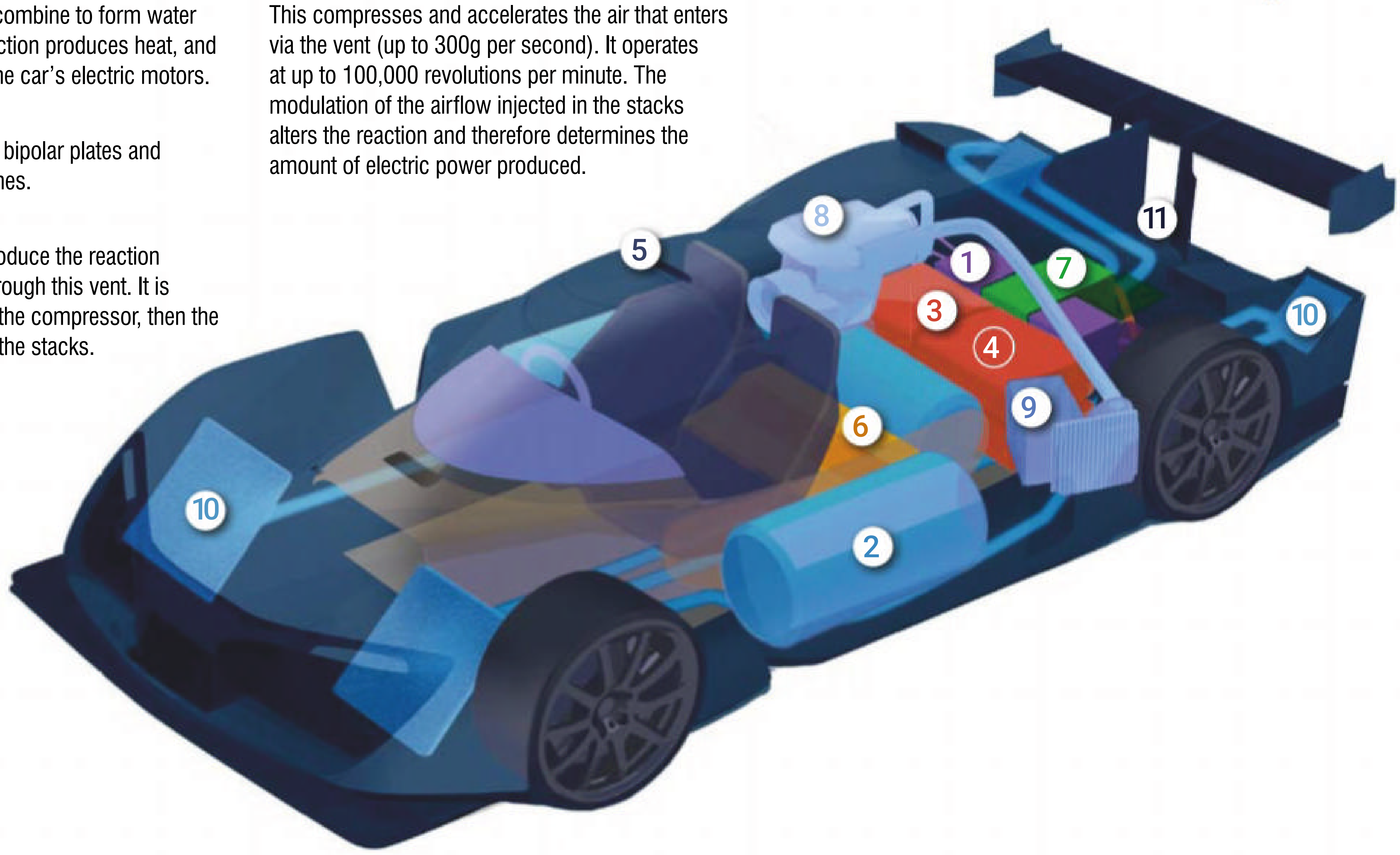
7. Transmission
A special, clutch-less single-speed gearbox manages the rear wheels independently and is designed to reduce grinding.

8. Compressor
This compresses and accelerates the air that enters via the vent (up to 300g per second). It operates at up to 100,000 revolutions per minute. The modulation of the airflow injected in the stacks alters the reaction and therefore determines the amount of electric power produced.

9. Humidifier
Humidified air improves the interaction between oxygen atoms and dihydrogen molecules. The humidifier ensures the level of humidity of the air injected in the stacks remains constant.

10. Radiators and cooling system

11. Exhaust
The only emission produced by the Green GT LMPH2G is water (H_2O). Steam escapes through four vents (one per stack) to the rear of the car, in the middle of the aerodynamic diffuser.



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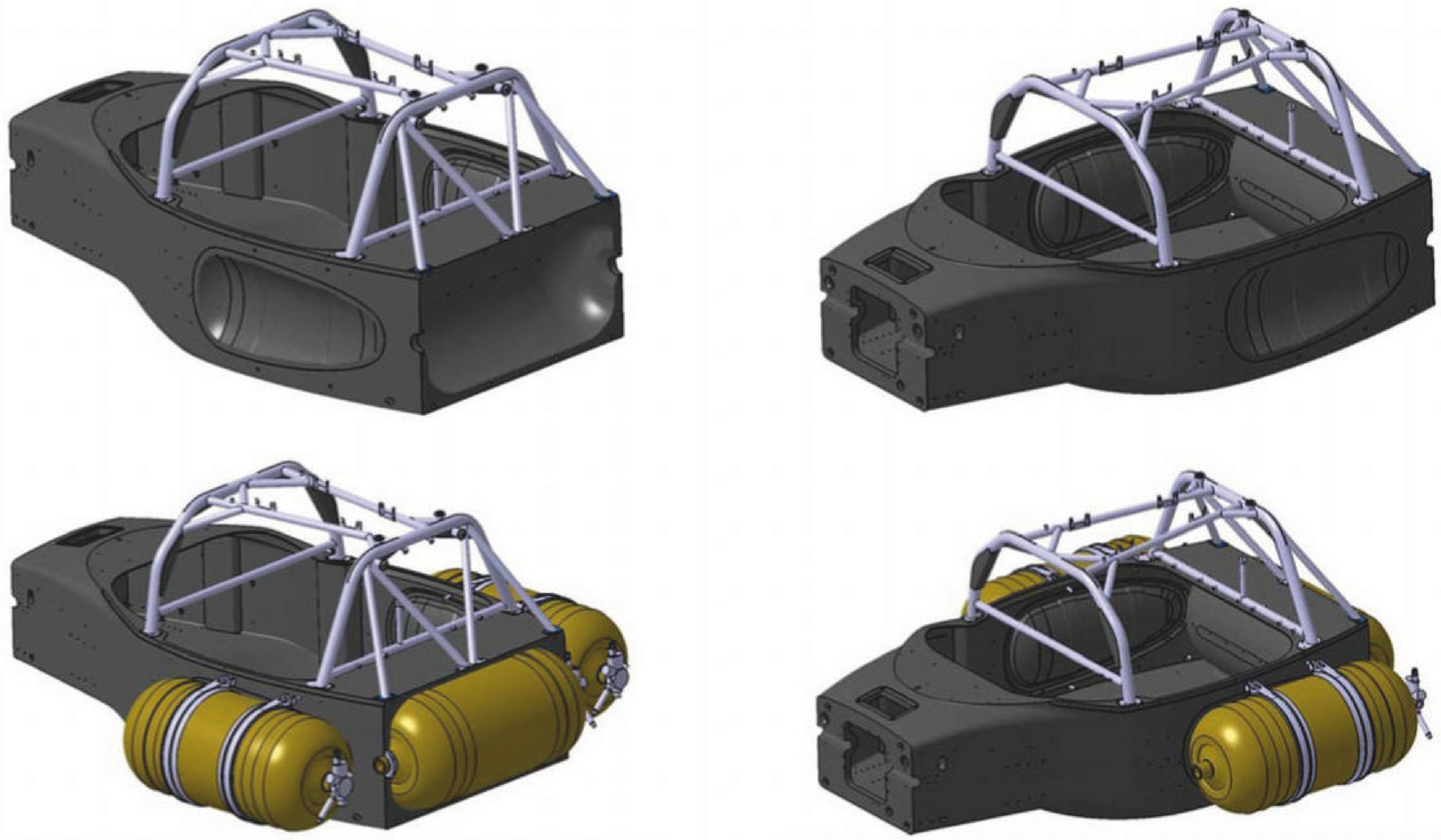


The monocoque was designed to LMP3 internal dimensions but it also had to carry the three hydrogen cylinders – these were originally developed for use in a fuel cell truck

Despite having efficiencies that are higher than internal combustion engines, heat rejection from fuel cells remains a challenge

new way of contributing to the car dynamics, maybe by dialling in understeer or oversteer simply by applying more torque to one of the motor pairs on a single wheel. This is easily done as it's not dependent on any mechanical or hydraulic mechanism, but just by controlling energy deployed to each of the wheels.

Stabilising braking into corners can also be envisaged, by harvesting more on one side. This is similar to fiddle brakes on trial cars, or the system used in Formula 1 where the steering lock and brake pressure on the individual inner wheel or outer wheel calipers were tied together. This was banned in F1.

While we're in this area, the suspension design is the classic double wishbone, pushrod actuated through rockers with coil spring over coaxial damper units, roll couple being controlled by transverse anti-roll bars.

Gas tanks

The monocoque was designed to the current LMP3 internal dimensions, and this tub had to house the three hydrogen containers, which are an off the shelf carbon cylinder (as used on the prototype Renault truck that's powered by GreenGT's fuel cell and motor).

The 700bar containers have a cylindrical shape for better pressure resistance, but they present packaging challenges compared to the any-shape fuel bags that are conventionally used. Because of the current safety regulations for pressure vessels these end up weighing around 100kg, when they are made from carbon. But they do have an advantage of being completely self contained and easily removed for maintenance or repair work on the racecar, as does the buffer battery, placed behind the driver bulkhead on what would be the conventional fuel bag housing.

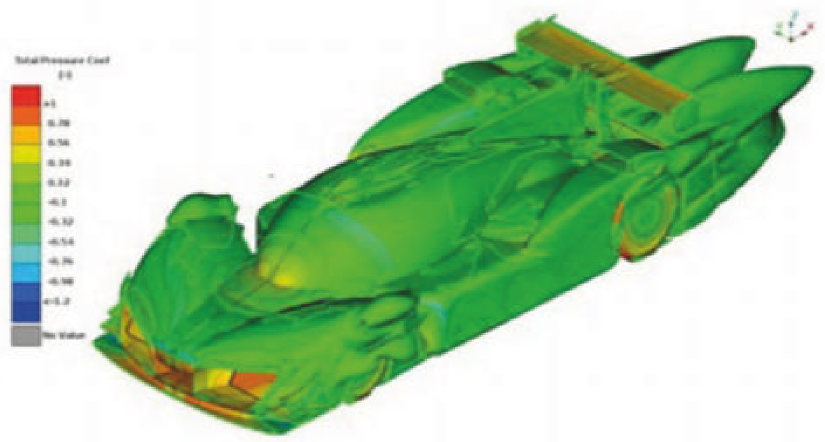
The cooling system on any racecar is one of the fundamental parts of the aero package, as the sheer amount of surface exposed to flowing air needed to dissipate the heat produced by the power system entails a considerable amount of drag, and the pass-through requirements will give problems in housing the radiators and in having space for the ducting, while the exit of the air must produce a minimum disturbance of the car's aero package. If we take a conventional racecar running today we can split the drag/downforce contributions of the major individual components (see **Table 1**).

Table 1: Drag and downforce contributions on a conventional racecar

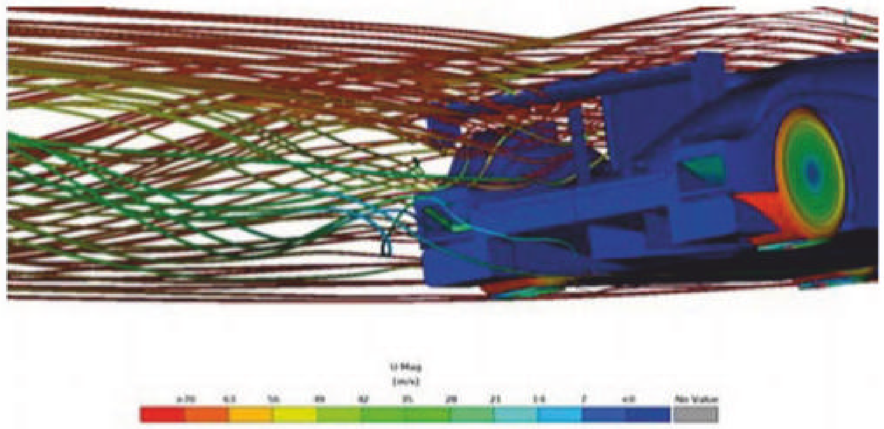
Component (positive values lift)	Cl	Cd	L/D
Front splitter	-43%	19%	-2.26
Front tyres	1%	3%	0.33
Flat bottom	-39%	9%	-4.33
Rear diffuser	-17%	13%	-1.31
Rear wing	-23%	17%	-1.35
Rear wheel	0%	8%	0.00
Bodywork	19%	11%	1.73
Internal drag (radiators, flow through engine compartment)	1%	20%	0.05

Core issues

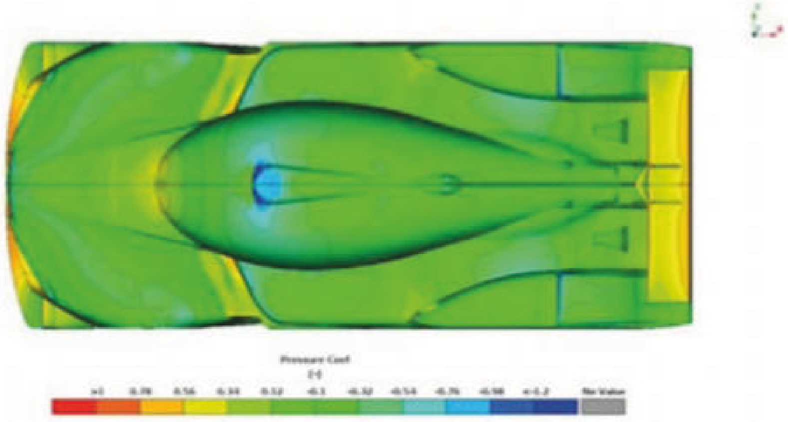
Table 1 shows that the cooling requirement ends up being the major individual drag contributor in any car and this is mainly due to the pressure drop through the core. For an ICE it is a quite direct result of the power produced. As a rule of thumb, considering average efficiency we can say that for each 100kW of

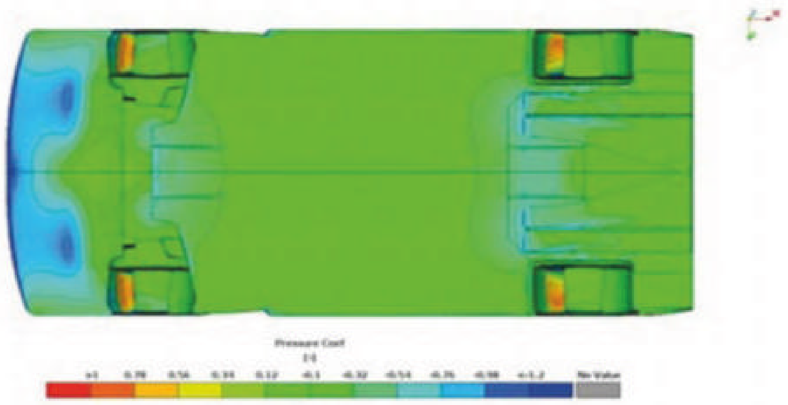


Total pressure plot. The aerodynamic design approach has been conventional so far

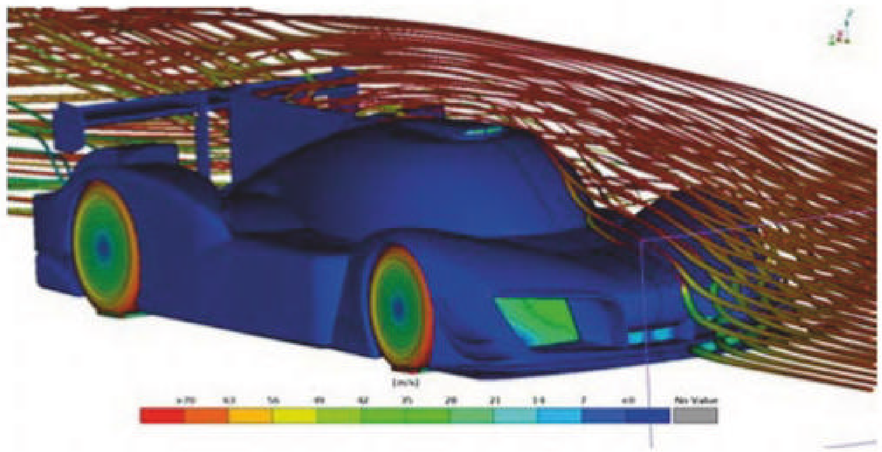


Rear diffuser and oil cooler exit flows. Efficient cooling is still needed on fuel cell cars

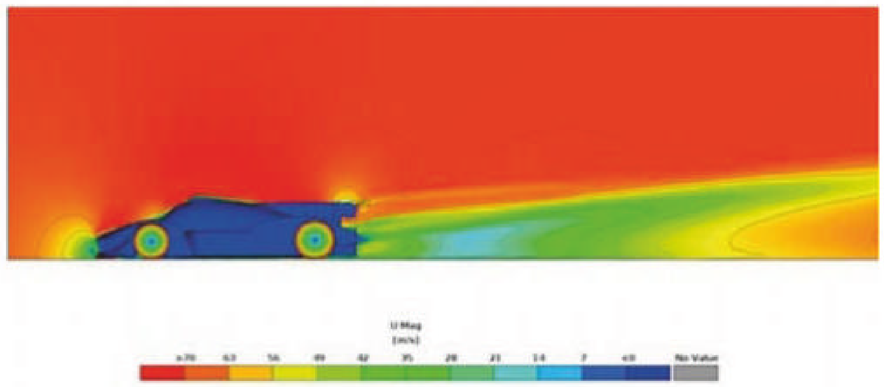




Top and bottom pressure coefficients were plotted on the baseline body shape, which corresponds to the FIA's regulations for the dimensions of a sports prototype racecar



It's expected that the aero approach will change as the car is further developed



Water vapour rather than exhaust gases will affect the aero at the rear of the car

energy from fuel, 30kW will go to drive the car, around 35kW will be lost as heat to exhaust, and about 28kW will be dissipated by the radiators. Major gains in the development of internal combustion engines have been made in improving this ratio. Current F1 engines have attained values of 48 per cent, a direct result of allocating a fixed amount of fuel for the race. In the example above the power going to the wheel will be, then, 48kW. This an aspect of racing which the public hasn't appreciated as it should, half again as much power added for the same fuel energy available.

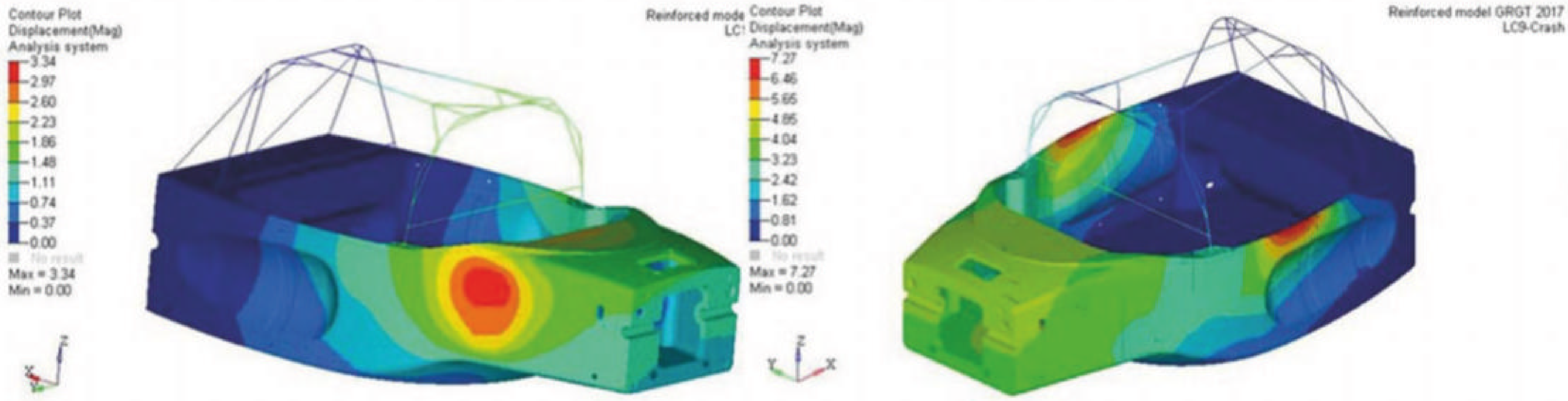
A fuel cell operates on a different principle. But the fuel cell, while producing energy by the chemical process of combining oxygen (from ambient air which contains oxygen, nitrogen, argon and other trace elements) also produces heat as a by-product of all this, so it will also have to be cooled, as will the batteries, which produce heat as a by-product of the chemical reaction when returning electricity when drawn upon. The fuel cell optimum operating temperature is about 80degC. The efficiency of a radiator is directly related to the temperature delta between the fluid being cooled (in most cases water or oil) and the ambient air temperatures – heat exchangers such as water/oil or air/air found on supercharged engines work to the same rules.

Despite having efficiencies higher than those of internal combustion engines, the heat rejection from fuel cells remains a challenge due to the lower operating temperatures and the reduced exhaust heat flow.

Future car layouts could differ when designed as a complete unit to suit the new technology

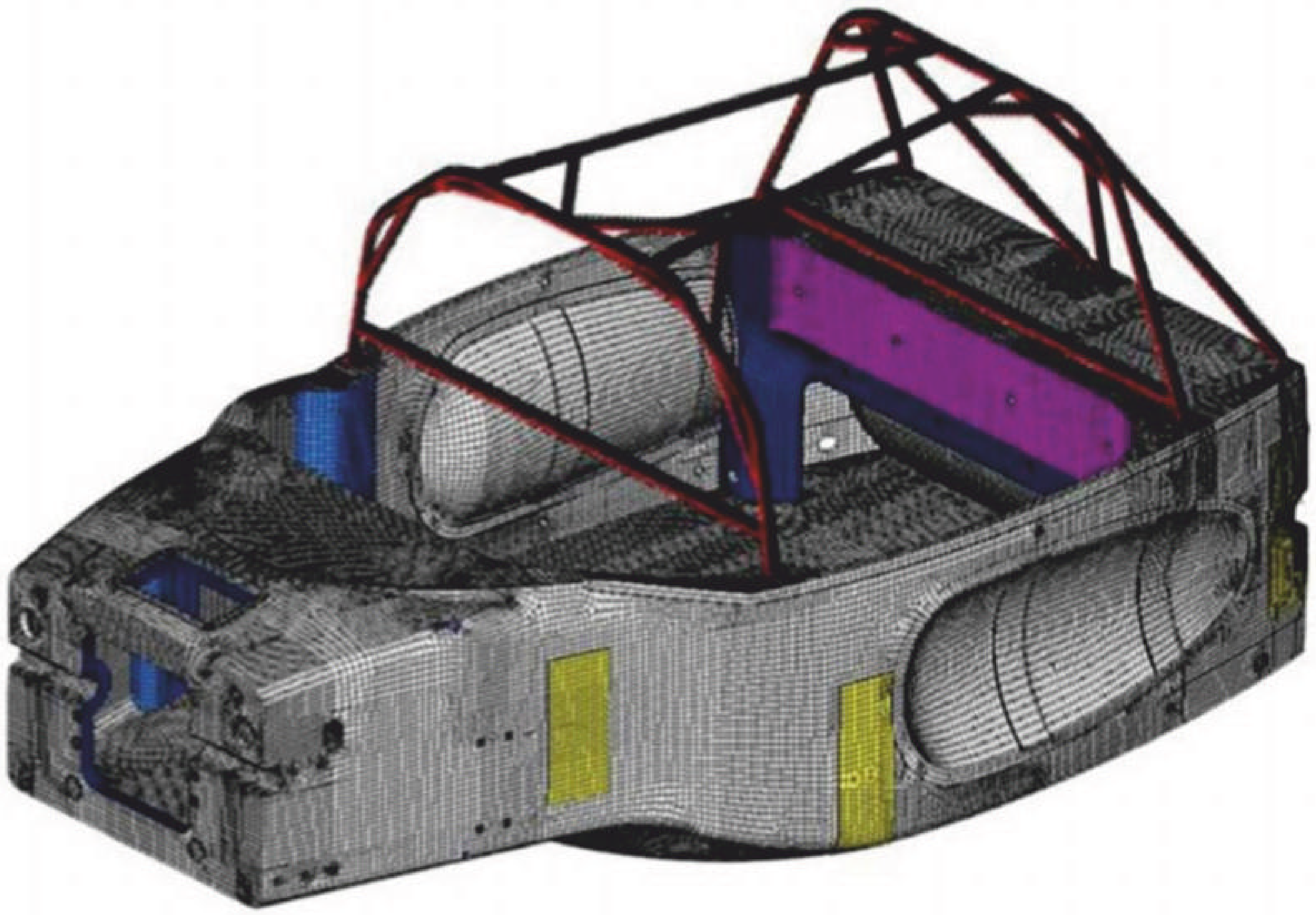
Table 2: Hydrogen compared with other fuels

Property	Hydrogen	Methane	Methanol	Ethanol	Propane	Gasoline
Molecular weight (g/mol)	2.016	16.043	32.04	46.063	44.1	~107.000
Density (kg/m^3 at 20degC)	0.08375	0.6682	791	789	1.865	751
Normal boiling point (degC)	-252.8	-161.5	64.5	78.5	-42.1	27 - 225
Flash point (degC)	< -253	-188	11	13	-104	-43
Flammability lim. in air (Vol %)	4.0 - 75.0	5.0 - 15.0	6.7 - 36.0	3.3 - 19	2.1 - 10.1	1.0 - 7.6
CO_2 production/energy unit	0	1	1.5	N/A	N/A	1.8
Auto-ignition temp in air (degC)	585	540	385	423	490	230 - 480
Higher heating value (MJ/kg)	142	55.5	22.9	29.8	50.2	47.3
Lower heating Value (MJ/kg)	120	50	20.1	27	46.3	44



Impact tests were modelled with special attention being given to the reservoirs, reservoir attachments and fuel cell. Many safety requirements are in the process of being formulated

Hydrogen has the lowest explosive energy per unit of any stored fuel



The monocoque mesh for FEA analysis. A recess for one of the hydrogen cylinders is clear on the flank of the tub in this image

Aerodynamics was examined in CFD and the layout was determined with the need to house two of the three cylinders on the monocoque sides. This in turn meant the main fuel cell coolers had to be fitted in the nose of the car, the usual side radiators being difficult to house. Also, given the placing of other components such as the humidifier, the charger for air supply to the cell and the ancillaries in the engine bay, through-flow there is quite compromised. The exit flow on the side is a corollary of that.

Further iteration of the design will be implemented as the prototype testing refines the systems, with particular attention being given to the aerodynamics, and the complete layout will evolve as the operation of the car validates the concepts. Currently it is close to car layouts developed for ICE powertrains, but future layouts could differ when designed as a complete unit to suit the new technology.

Table 3: Hydrogen volumetric energy density comparison with petrol MJ/m³	
H2 at 350bar	4500
H2 at 700bar	5000
H2 as liquid	9200
Petrol	32000

Table 4: Hydrogen mass energy density comparison with petrol MJ/kg	
H2	120
Petrol	40

Safety issues

The FIA has a series of rules established to ensure the operational safety of ICE engines, lessons having been learnt over the years as to the intrinsic dangers of the systems, such as flammability, toxicity and impact resistance. When hybrids, with electric batteries or kinetic energy storage systems via flywheels, were introduced, a whole new set of safety parameters had to be specified for their use. Fuel cell cars are now going through the same process. GreenGT is working with the FIA and the ACO to determine which will be the future rules for the safe operation in a racing environment of the vehicle. New regulations are being drawn up, with GreenGT investigating all the safety aspects of the systems being developed.

The structural requirements and the parameters for the electric motors and buffer battery are covered by the previously defined regulations, but the reservoirs, fuel cell and refuelling procedures are all new territory and these need to be defined.

The chassis must respect the crash test regulations, much the same as conventional racecars, but with particular attention being given to the reservoirs, reservoir attachments and the fuel cell itself. FEA analysis was done with several configurations, as a way of preparing the parameters of the crash tests to be executed on a fully assembled monocoque for homologation. Similarly, impact tests were modelled and the structure was designed to suit the requirements. ↳

Investigations into the Hindenburg disaster proved that the aluminium paint that coated the airship started the fire, not the hydrogen

Then, of course, there are the safety considerations that arise from using hydrogen as a fuel. The reputation of hydrogen has been unfairly tainted by the Hindenburg disaster in 1937 – when a German passenger airship burst into flames while attempting to dock with its mooring mast in New Jersey. Yet investigations into the Hindenburg incident proved that the aluminium paint that coated the ship started the fire, not the hydrogen.

Actually, hydrogen is a safe gas. Since it is a small molecule, it has a tendency to escape through small openings more easily than other fuels. Hydrogen can leak through holes or joints of low-pressure fuel lines 1.2 to 2.8 times faster than natural gas. But natural gas has an energy density three times greater than hydrogen, so a natural gas leak results in a greater energy release than a hydrogen leak. Since hydrogen is lighter and more diffusive than gasoline, propane, or natural gas, it disperses much more quickly. If an explosion occurred, hydrogen has the lowest explosive energy per unit of stored fuel.

Low risk fuel

Yet there are many mistaken preconceptions about hydrogen, just one of which is that it is a dangerous gas. Discovered by Henry Cavendish in 1776, hydrogen and its properties are now well known and today the risks have been pinpointed and contained by safety measures and standards. Fire prevention professionals now consider hydrogen safer than any other fuel used in the open air. It is understood that the storage tanks meet the strictest requirements in terms of resistance.

As an example, at the LMPH2G presentation at Spa the refuelling pit stop operation was completed by an operator wearing normal clothes – there was no need for overalls or helmet, they simply connected the valve.

Hydrogen (gas) is contained in sealed tanks at 700bar pressure. The tank's seals and contents are systematically checked before the hydrogen is injected. Today there is an array of safety standards, which are applied across the globe. In Paris, several service stations supply a fleet of hydrogen-powered taxis. It is, then, a very well-developed technology from a safety standpoint.

Liquid hydrogen

But that's hydrogen as a gas. Future development could see the introduction of liquid hydrogen as a fuel, which will speed up refuelling and bring several other advantages. To exist as a liquid, H2 must be cooled below hydrogen's critical point of 33K (-240degC). However, for hydrogen to be in a liquid state without boiling at atmospheric pressure it needs to be cooled to 20.28K (–252.87degC).

This will bring several design challenges, such as structural integrity for the reservoirs at cryogenic temperatures and isolation from any heat that would increase the pressure in the tank. But the current vehicle is proof of concept and most car manufacturers have been developing cars for road use on the pressurised 700bar reservoir parameter, and it has been designed to those same values.

As liquid hydrogen expands into a gas the energy to vaporise the liquid would be integrated with the cooling system, reducing the surface area required, as heat from the fuel cell and batteries would be used for this.

Gas station

As to working with the car, discussing the requirements with crew members who were experienced in current ICE cars but have come in to the team, the most striking thing was the steep learning curve of getting to grips with all the procedures required for safe, efficient use at the race track. Safety procedures needed to operate an ICE car with a hybrid battery based KERS system were known, but when the start-up procedures, operational temperature requirements and electronic management of the system is added on, it adds up to a highly technical method of working.

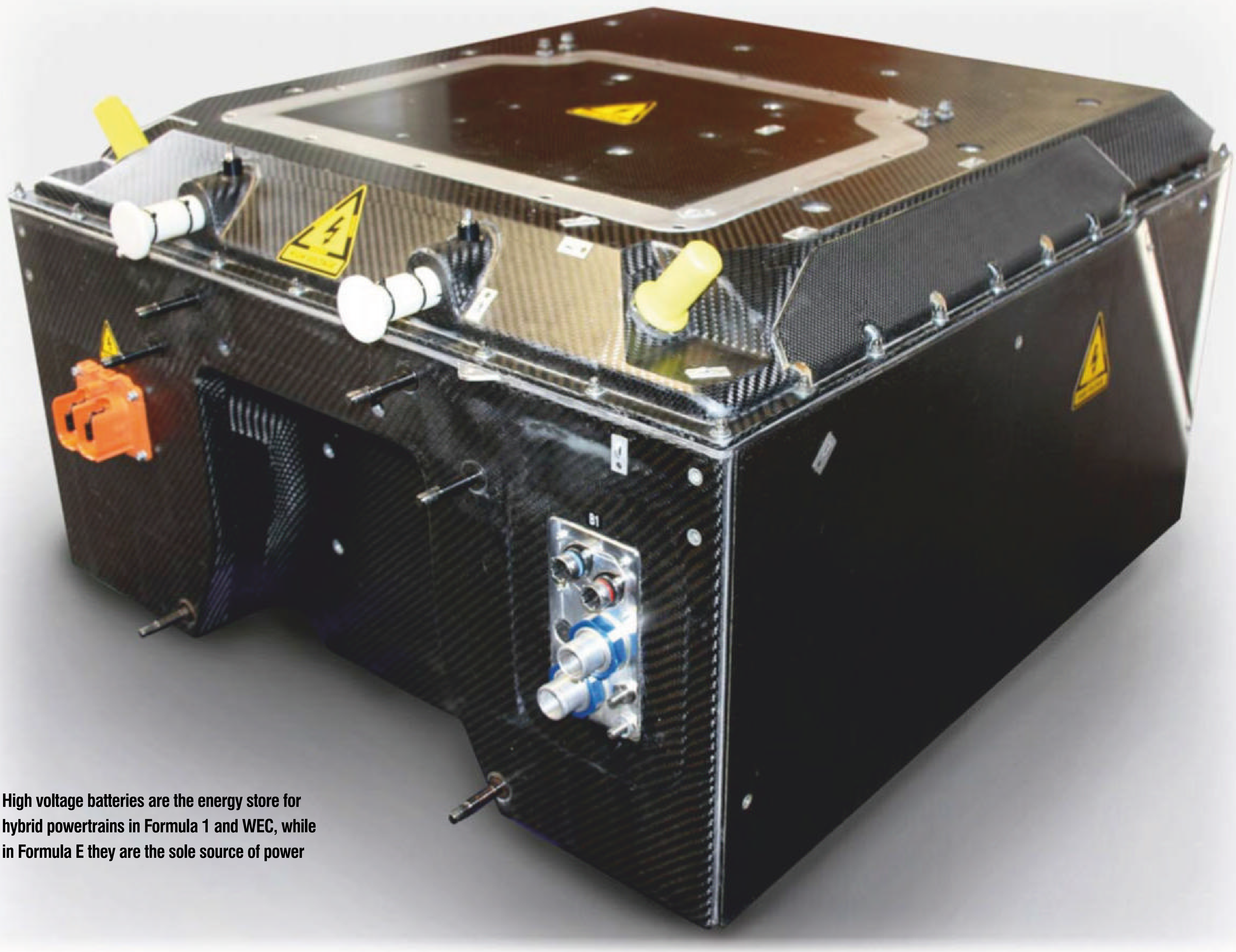
As the car continues to test the operating manual grows daily, as the systems and evolutions of units are explored. It is a complex combination of several distinct technologies, still in its early stages, but will be made easier as the knowledge of use increases. The lessons learned will eventually be incorporated in the every day car, sooner than you think.

The LMPH2G in the pits at Spa. The manual for operating a hydrogen fuel cell racecar is still being written

The GreenGT H2 Speed hydrogen road car is a concept by Pininfarina that was unveiled at the Geneva show

Future development could see the introduction of liquid hydrogen as fuel, which will speed up refuelling and bring several other advantages

Packing power



High voltage batteries are the energy store for hybrid powertrains in Formula 1 and WEC, while in Formula E they are the sole source of power

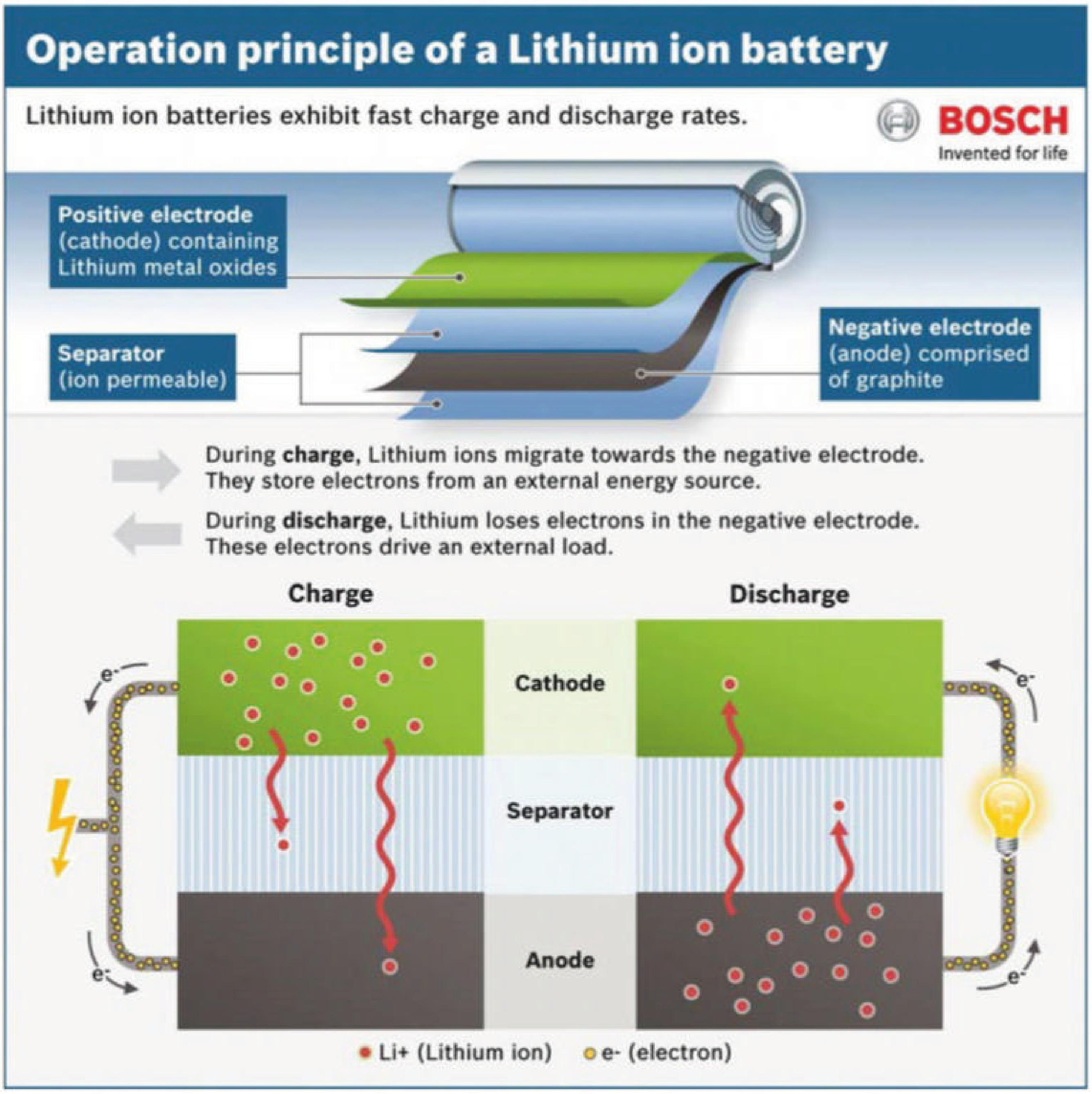
High-end motorsport batteries are at the pinnacle of electrical science and the on-going development rate is as fast as the cars that carry them. We talked to those who work within this buzzing tech sector to find out more

By GEMMA HATTON

We use batteries every day to power everything from electric toothbrushes to torches. But the batteries used in motorsport are a far cry from the AAs we slot in the back of our TV remotes. In top end racing such as Formula 1 the batteries, or energy stores (ES) as they are often called, are made from lithium-ion and these battery packs have a higher power density than a typical internal combustion engine. In fact, these energy cells are capable of lighting up to 10,000 20W light bulbs, and to get the same effect from conventional cells you would need to take up the space of a volleyball court. Yet today's technology means that these specialised cells can be neatly packaged beneath the fuel tank. So how is this possible, and just how do motorsport batteries really work?

One of the fundamental problems with electrical energy is storing it. It has to be stored in the form of chemical energy that can then be converted back into electricity – and this is essentially what a battery does. There are three key components within a battery cell: 1) a positive electrode (cathode); 2) a negative electrode (anode); and 3) an electrolyte. The cathode and anode are connected to positive and negative terminals respectively and are usually made of two different metals. The electrolyte is a chemical that separates the two terminals and this together with a separator, which is a piece of plastic peppered with tiny holes, allows electrical charge to flow freely between the cathode and the anode.

Taking a simple circuit where a cylindrical cell powers a light bulb, when switched on the cell is providing energy to the light bulb and is therefore discharging. This is where a chemical on the anode releases negative electrons and positive ions through an electrochemical process called oxidation. The electrons flow



Bosch

As the name suggests, lithium-ion batteries use lithium ions to move charge between the anode and cathode. This is the most suitable chemistry for motorsport and experts are not aware of any other type being used in the sport at present

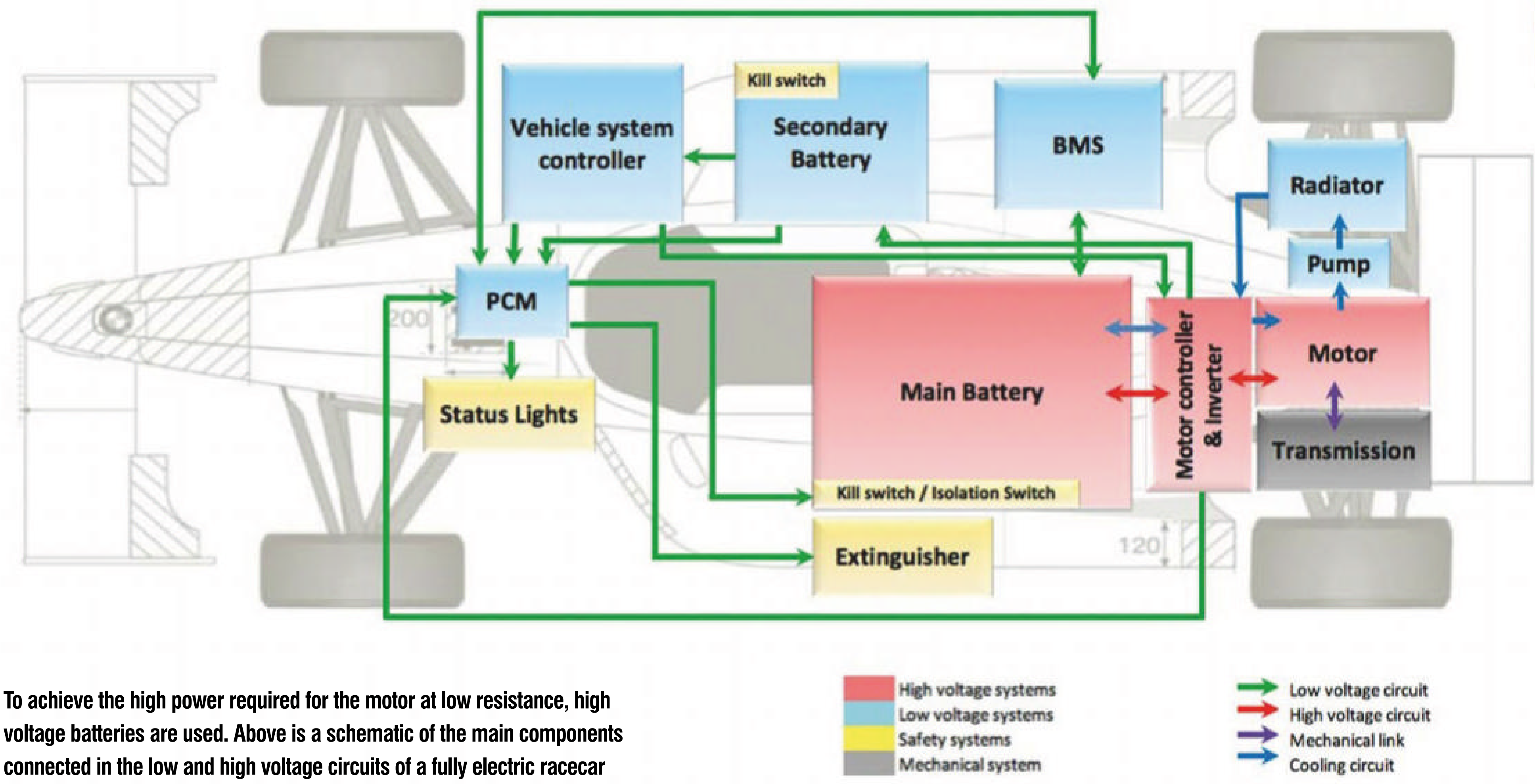
around the external circuit to the cathode, powering the light bulb on the way, while the positive ions flow to the cathode through the electrolyte. Meanwhile, the cathode combines the incoming electrons with the ions through 'reduction' and completes the circuit. The electrolyte allows this transfer of ions between the anode and cathode, ensuring that the chemical potential can transfer from one terminal to the other; converting stored chemical energy into useful electrical energy.

Lithium-ion

In motorsport lithium-ion batteries are the go-to chemistry. This is essentially any cell that uses lithium ions to move charge between the anode and cathode. 'Lithium-ion batteries operate on what we call the rocking chair mechanism,' says Dr Billy Wu, senior lecturer in Energy and Manufacturing at Imperial College London. 'If I want to discharge my battery, I move lithium ions from my anode to my cathode and when I am recharging, I move them back again. The lithium ions go into the material of the anode or cathode through a process called intercalation. Similar to a sponge, the battery electrodes essentially soak up the lithium ions into the structure.'

The most common anode material used in lithium-ion batteries is graphite, similar to the material in your pencil, but there is a lot of really interesting research going on into new cathode materials. 'There are a few common flavours of batteries available,' says Wu. 'BMW use nickel manganese cobalt [NMC], Tesla use a slightly different chemistry, including aluminium with their nickel cobalt aluminium [NCA] batteries, and Nissan use lithium magnesium oxide [LMO]. Each one of these has its pros and cons but when we talk about the different chemistries

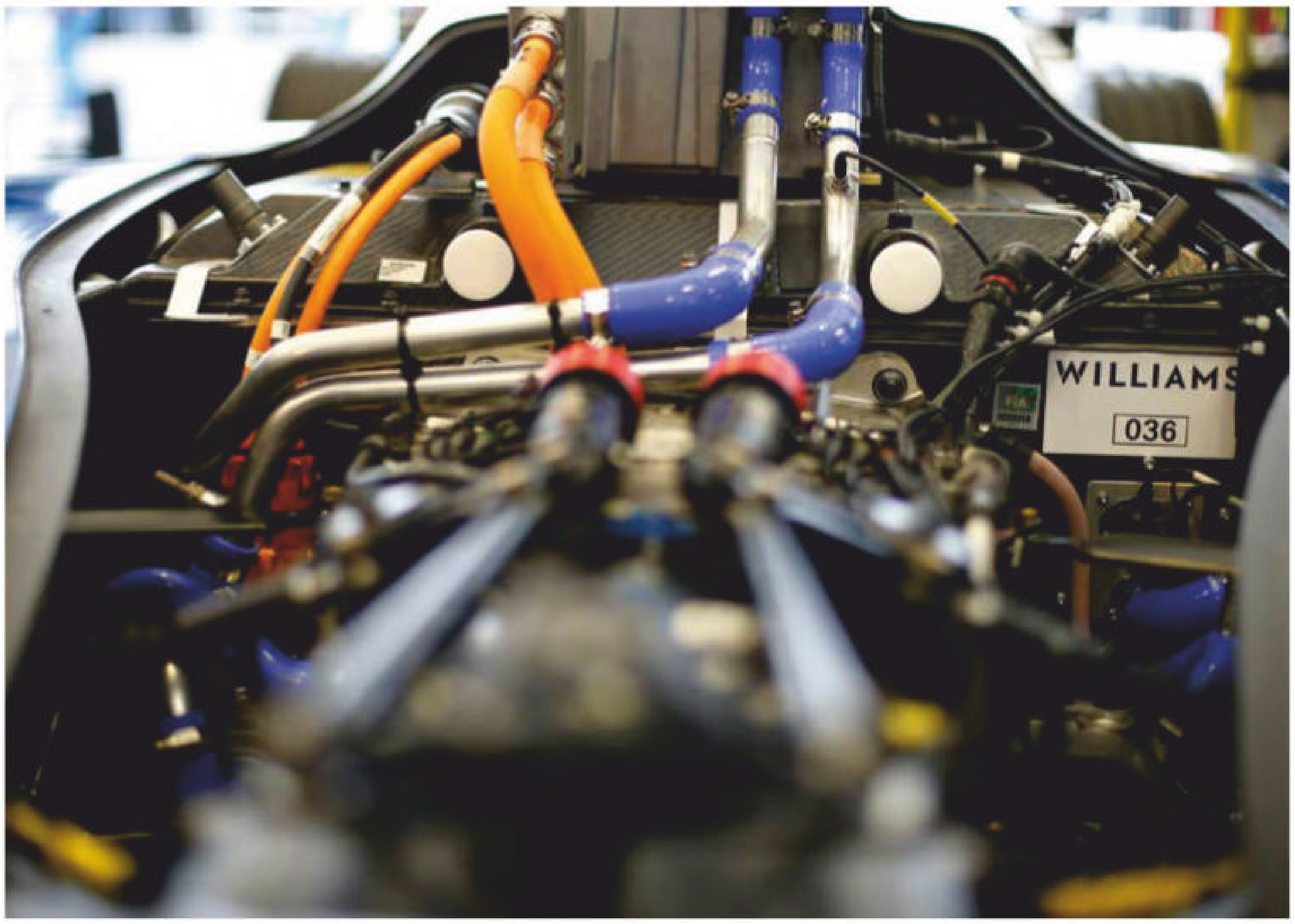
'As a rough rule of thumb if you want more power you have to take a hit in terms of energy density'



To achieve the high power required for the motor at low resistance, high voltage batteries are used. Above is a schematic of the main components connected in the low and high voltage circuits of a fully electric racecar

of batteries we are referring to the different materials that go into the battery.'

As mentioned above, motorsport demands a specific type of cell chemistry; lithium-ion. 'There are a plethora of other cell chemistries out there but these have not yet proved relevant to motorsport, or to a certain extent the wider battery market. In fact, I'm not aware of any other cell chemistry being used in motorsport today,' says Douglas Campling, chief motorsport engineer at Williams Advanced Engineering. 'Lithium-ion is the chemistry that has had the most R&D and is being improved year on year. All the other chemistries are trying to be as good an all-rounder as lithium-ion, and in certain ways can be better. We are working with cell development partners and academic institutions to accelerate the introduction of next-generation battery chemistries. But for now, for motorsport hybrids and electric vehicles, there isn't a better compromise out there yet with the correct technical readiness.'



The Gen1 Formula E battery (above) had two cooling circuits which used dielectric fluid as specified by the regulations. In F1 and WEC the teams are allowed to use water, which is actually both more thermally efficient and less dense

Batteries included

On a racecar there are two types of batteries: 1) low voltage (LV), and 2) high voltage (HV). The low voltage battery is usually a 12V system which is used to power low voltage electronics and safety systems such as the battery management system (BMS) as well as cell monitoring units (which measure the temperature and voltage of each cell), isolation monitoring, current sensors and data logging. The HV battery, on the other hand, powers the electric motors and inverters whilst storing the energy accumulated during regenerative braking. The HV battery also runs the power distribution unit (PDU), the busbar network and the manual service disconnect (MSD).

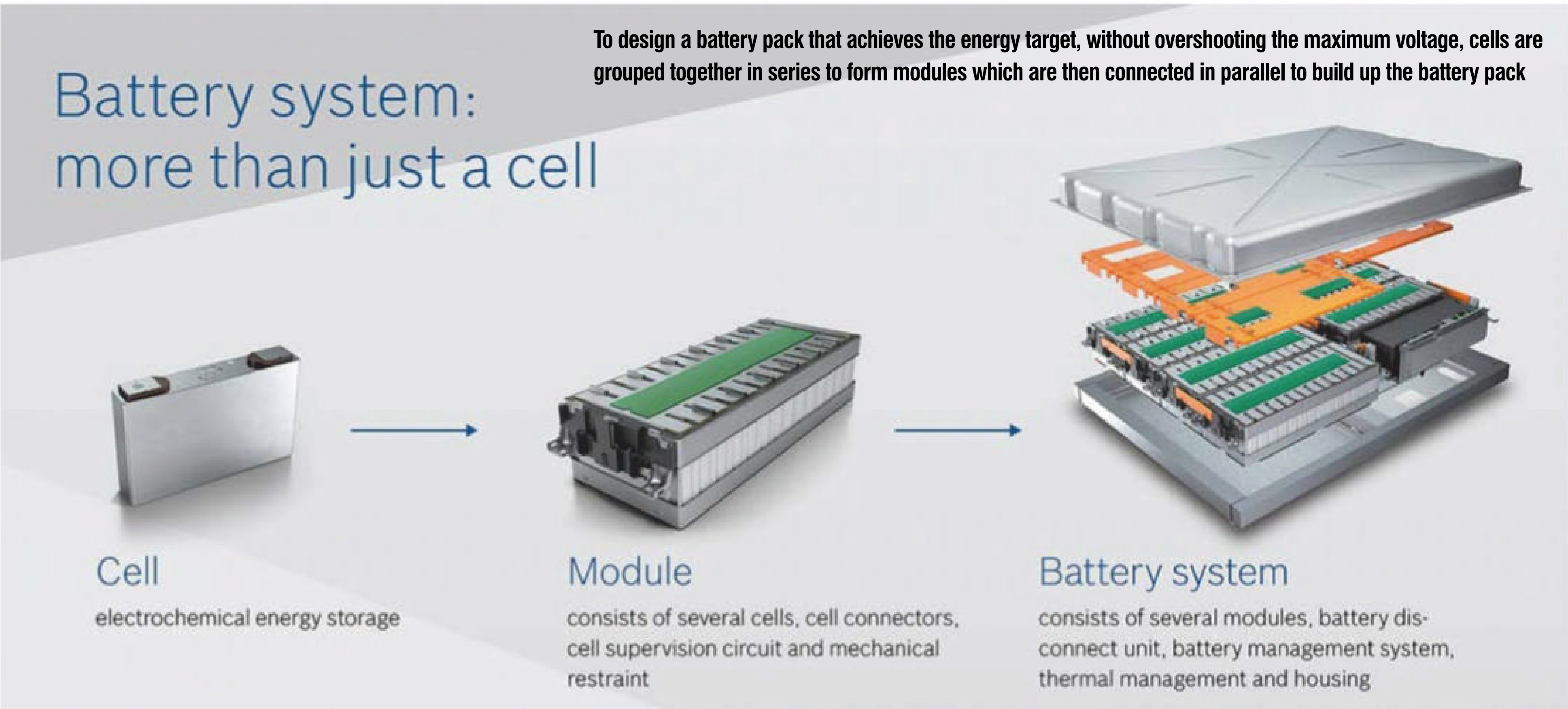
Electric motors require large amounts of power, which is why a high voltage battery is needed. 'Broadly speaking if you want to deliver the same amount of power, there are two ways you can do it,' Wu says. 'Due to Ohms law, where power equals the voltage multiplied by the current [$P=IV$], you can achieve the same power through high voltage, but low current; or high current, but low voltage. The problem is, when you push current through wire there is a finite resistance which causes the wire to heat up to the square of the current.

'So, the heat generated equates to the current squared multiplied by the resistance [$P=I^2R$],' Wu adds. 'Therefore, to minimise the heat generated and improve efficiency you want to reduce the current, which is why the battery needs to be high voltage.'

Although both hybrid and EVs utilise high-power motors and therefore require the use of a high voltage battery, the design, size and layout of the battery differs greatly between a hybrid and an EV road car or a racecar. 'We need to understand what's important for an ES battery in F1, and for a Formula E battery, because they are different beasts,' says Campling.

'The biggest difference is that an ES battery is discharged and recharged multiple times

'Lithium-ion is the chemistry that has had the most R&D and it is being improved year on year'



To design a battery pack that achieves the energy target, without overshooting the maximum voltage, cells are grouped together in series to form modules which are then connected in parallel to build up the battery pack

Bosch

per lap compared to Formula E which has one single discharge over the entire race,' Campling adds. 'Therefore, in F1 you are looking for the best power density; F1 is all about getting the power required for that boost into the smallest package, so volumetric and gravimetric power densities are key. With fully electric, it's an energy equation. You have to get all the cars to the end of the race and you've got a fixed number of joules of energy to do it. Therefore, Formula E is all about getting as much stored energy as possible and using it efficiently, whilst meeting the level of power required.'

Consequently, F1 ES cells have a higher power density (approximately 10-17kW/kg) but lower energy density (approximately 90-120Wh/kg), compared to the Formula E Gen2 battery (approximately 2.2kW/kg and 232Wh/kg respectively). These differences arise from the different chemistries used in F1 and Formula E. 'But even within the same chemistry you can get some cells that are *power* cells and others that are *energy* cells,' says Wu. 'There is always a trade off between power and energy. As a rough rule of thumb if you want more power you have to take a hit in terms of energy density.'

Chemistry set

To meet the extreme power densities required in F1, the most exotic and expensive cell chemistries are used, specifically developed for Formula 1 by specialist battery suppliers such as A123 High Performance Solutions and Saft. This was also the case with the Gen1 FE batteries, where Xalt Energy together with Williams Advanced Engineering developed a bespoke cell. However, this all changed for Season 5 as McLaren Applied Technologies won the tender and partnered with Atieva to develop the new Gen2 batteries, which are rumoured to feature standard 18650 cylindrical cells from Sony Energy Devices.

Once the design requirements of the battery have been defined, concept work can begin. As ever with engineering, there is no perfect solution. The cells not only need to be of the right chemistry, but also the desired size and shape to fit within the packaging constraints of a car. Then there is availability; there is no point designing your battery to use cells that are not available, unless you are willing to invest in the development of a bespoke cell.

When the type and size of cell has been selected, the overall series and parallel configuration of the battery pack needs to be defined to meet the voltage and capacity requirements. The cells are then sub-divided into more manageable modules, which can be built at safe voltage levels. Packaging the correct number of modules will define the final shape and size of the battery. All of these tasks affect the outputs of the battery and require decisions to be made in terms of performance and safety.

'Cells can come in three different formats,' says Campling. 'Firstly, the cylindrical cell

The new Gen2 Formula E battery is rumoured to feature off-the-shelf 18650 cylindrical cells rather than pouch cells

which is absolutely ubiquitous around the world. That's what's in your power tools or your cordless vacuum cleaner. They are named after their dimensions, so the most used cell worldwide is the 18650 which is 18mm diameter and 65mm long – so roughly the size of your thumb. That has a positive terminal at one end and a negative terminal at the other. Then there is the pouch cell which can come in different dimensions but is essentially a flat set of electrodes in a polymer pouch, as opposed to rolled electrodes in cylindrical cells. The positive and negative tabs can be on one end or opposing ends. Finally, there is the prismatic cell which has a hard casing around flat electrodes that can be of custom dimensions.'

When sizing the battery, once the type of cell has been chosen, the next question is how many? This can be calculated initially by dividing the required usable energy of the whole battery pack by the usable energy of an individual cell. Next, the required system voltage, continuous power output and required charge rate must be accounted for. Then the required usable energy of the battery is influenced by the type and number of motors on the vehicle as well as the expected battery degradation. Safety factors also need to be included to account for safety cars or yellow flags, and other racing scenarios, to ensure that the battery is designed with enough capacity to get through a race.

The number of cells in series defines the battery voltage. 'Each cell has a voltage range. Fully charged it's usually around 4.2V and the lower limit is typically 2.5V to 2.7V, but each cell is different,' says Campling. 'You have a range of voltages from the powertrain, and particularly in Formula E, where you're looking for the highest efficiency, you need to be quite specific about the required voltage range of the battery pack. If you connected all the cells in series you sum up the voltage of each cell, so you would reach the upper voltage limit of the battery pack before achieving the required usable energy. Therefore, typically you have to connect a number of cells in parallel to adjust capability without changing output voltage. In this way, you design a battery pack which meets the usable energy target as well as the output voltage target. It is important to maximise the operating voltage, because the higher the voltage, the lower the current, which results in smaller busbars and wiring and therefore significant weight savings.'

'There is a trade-off between using a small cell with a low energy content against a larger cell with a high energy content'

Energy content

Of course, there are many different ways of connecting the cells and modules to meet both the required usable energy and output voltage targets. 'There is a trade-off between using a small cell with a low amount of energy content *vs* a larger cell with high energy content,' explains Anthony Law, head of motorsport batteries at McLaren Applied Technologies. 'For example, the cylindrical 18650 cells give you much more flexibility in terms of the space, number and how many

you can connect in parallel within the battery pack. You can squeeze these types of cells into more unusual spaces, making it a smaller unit to package, whereas the larger pouch types are a bit more limited. So there is a trade off between the additional weight associated with the individual cell type and how they are all connected together, the number of busbars and connections *vs* the flexibility in design.'

Each of these different layouts affects the mechanical construction of the battery and determines its shape. Other considerations that drive battery shape and size include the number of cells in each module; the total number of cells per module should be a factor of the number of cells in parallel. So regardless of the theoretical ideal number of cells, the modules may need to be adapted to meet other requirements. 'In Formula E, the volume required to store the energy to complete a race dominates the overall vehicle architecture,' says Campling. 'The battery is without doubt the heaviest component on the car. It is no longer a 35kg ES battery, but a 380kg battery.'

Running hot

With the battery layout designed, the next consideration is temperature. The hotter the battery, the faster it will degrade. But reduce the temperature too much and the battery doesn't perform as well. 'F1 takes their batteries way above the spec sheet recommendations in terms of temperature, which allows them to get a lot more performance out of the battery, but then it degrades quicker,' says Campling. 'That is absolutely fine in Formula 1 because they can refresh the batteries multiple times a season, but that is not acceptable in Formula E because those teams need a battery to last for a full season. Therefore, the temperature limits are strictly defined based upon outputs from degradation modelling and testing.'

There are two ways in which a battery can degrade. Firstly, there is cycle ageing where the charge of a battery becomes less the more you use it over time. This is due to chemical breakdowns of the anodes and cathodes which degrade while the battery is in operation. Secondly, there is calendar ageing, which is where the lithium-ion cells lose capacity even when they are not in use, which is extremely difficult to model and predict. For Formula 1, calendar aging is not a threat, but for the Gen2 Formula E battery, which needs to last for two seasons, it is a far more serious factor. In addition, there is also the risk of catastrophic failures such as thermal runaway.

'You can get thermal runaway when your battery goes over approximately 80 or 90degC,' says Wu. 'This triggers chemical reactions within the battery which are exothermic and so release a large amount of heat. You end up in this loop where the exothermic reactions generate heat which then fuels the thermal runaway even further. Often, the battery catches fire because the electrolytes used in batteries are flammable. It effectively becomes a mini-flame thrower.'

The delicate balance between battery performance and temperature is what makes battery design one of the hardest tasks facing today's engineers. 'Generally with a battery you are limited in two directions,' says Campling. 'You are temperature limited in one instance and voltage or power limited in another. At low state of charge, or at high battery temperature, the battery management system might start limiting the power availability because you are starting to get too close to the minimum voltage or you are approaching the temperature limit. The trick is to design a battery so that you've got enough in hand so that neither of those issues effect the usage or risk a loss of field equivalency in a formula with a standard battery, whilst taking degradation into account as well.'

Battery degradation can be reduced in two ways. 'You can either use less of its available capacity and/or keep the battery within an optimal temperature window,' says Paul McNamara, technical director at Williams Advanced Engineering. 'If your battery range goes from five per cent capacity all the way up to 95 per cent of total capacity, it will degrade more than if you go from 10 per cent to 90 per cent. Then you have a trade-off between using more cooling, which will increase weight, *vs* packaging more cells to increase the capacity.'

'With Formula E it is all about getting as much stored energy as you possibly can and then using it efficiently'

Cool packs

In terms of battery cooling, there are essentially three options: 1) air cooling; 2) two-phase cooling; and 3) single-phase coolants (liquid cooling). 'Air cooling is where heavy solid heat sinks are attached to the surface of the batteries and between the cells themselves,' says David Sundin, chief scientist at Engineering Fluids. 'This is the most inefficient system as it requires the most weight and is the least flexible. There is also no way of increasing cooling performance as you approach the thermal runaway point as the system is already operating at its maximum design potential.'

Another cooling strategy is to use two-phase coolants, which is where the liquid coolant converts into a gas and is then de-condensed to extract heat from the system. Unfortunately, this system is extremely heavy as the fluorinated fluids required are more than twice the density of water, and to avoid evaporation the system must be fully sealed, resulting in robust battery casings that can withstand the high pressure build up during the cooling process.

Low voltage batteries are also important as every racecar will require some form of starter battery. These are also lithium-ion

'Two-phase coolants have the advantage of being non-flammable, but they have the disadvantage of turning into gas well before the thermal runaway point of the battery,' says Sundin. 'This causes two problems. Firstly, you have to vent all the heated coolant from the system before the closed system explodes due to the pressure build up. This problem is all or nothing because two-phase coolants have a single set phase change temperature, so once this is exceeded the entire coolant begins to undergo the phase change. Secondly, once the coolant has been ventilated out you have no way of controlling or cooling the system.'

However, the most common types of battery cooling utilised in motorsport are single-phase coolants such as liquid cooling. 'The question is whether you flow that liquid through a coldplate or whether you do flooded cooling,' says Law. 'With flooded cooling you use a dielectric fluid, because these are non-conductive so you are taking advantage of the fact that this fluid can be in direct contact with the cells. So you essentially fill the battery up

with dielectric fluid. The benefit of this is that you avoid any additional thermal resistance that you can get when using a coldplate.

'A coldplate is normally a metallic heat sink, with a cooling fluid flowing inside it, which is attached to the bottom of the cells via a thermal adhesive,' Law adds. 'For this, you would ideally use water as it is a much more efficient cooling medium than dielectric fluid and it is less dense and therefore of lighter weight. Further weight savings come from the fact that you are not filling every nook and cranny of the battery, and today's coldplates can now be made with extremely thin walls, yet still be able to withstand the high pressures.'

Once the cooling fluid has flowed into the battery, extracted the heat and then exited the battery, it flows to a conventional radiator where that excess heat is rejected to ambient air, similar to a conventional cooling system for an internal combustion engine.

Water cooler

It is interesting to note that despite the complex array of cooling liquids available, high end categories such as F1 and WEC use just water for their cooling systems, as highlighted above. 'In a racing application you might only use dielectric fluids if instructed to do so by the regulations for safety reasons,' says Campling. 'This was the case in the first four seasons of Formula E – there was no compromise on safety, and this has also been carried over to the new Gen2 batteries.'

The challenge of temperature management is further compounded in Formula E, because there are so many more cells that need to be cooled. Generally, with an F1 ES battery the cells are grouped together in one lump, so the associated cooling solution is more straightforward with one inlet and outlet, whereas in a full EV the cell groups may be in different locations around the battery, which each have to be connected up with the coolant, sometimes resulting in tens of inlets and outlets. Furthermore, calendar ageing also needs to be managed in addition to cycle ageing.

Keeping a watchful eye on the temperature, voltage and performance of each cell in a battery pack that could contain as many as 5000 to 6000 cells requires an intricate network of wiring all controlled by a complex brain: the BMS. 'A bit uniquely to motorsport, in Formula E we had to have a way of handling the control system to equalise the cells so that each battery, as far as the car was concerned, was identical,' says McNamara. 'We had thermocouples and voltage sensing on every single cell so we could monitor the voltage differential and therefore identify which cells were having a harder time than others, depending on where they were located in the battery pack. We could therefore ensure the performance of each pack was identical for fair competition. Throughout the four seasons we also developed new algorithms which allowed us to proactively make changes to any potential problem areas, based on historical data. This meant that we got the number of batteries that required some repairs down from three or four at the start of Season 1 to virtually zero.'

Each cell typically has a positive and negative high current connection that goes from one cell to the next, to allow current to flow between the cells. 'You would also often have cell interconnect busbars that carry the current from all the cells in parallel into the next group of cells or module,' says Law, 'The cells connect to the busbars via either a welded connection, wire bonds or bolted terminals.'

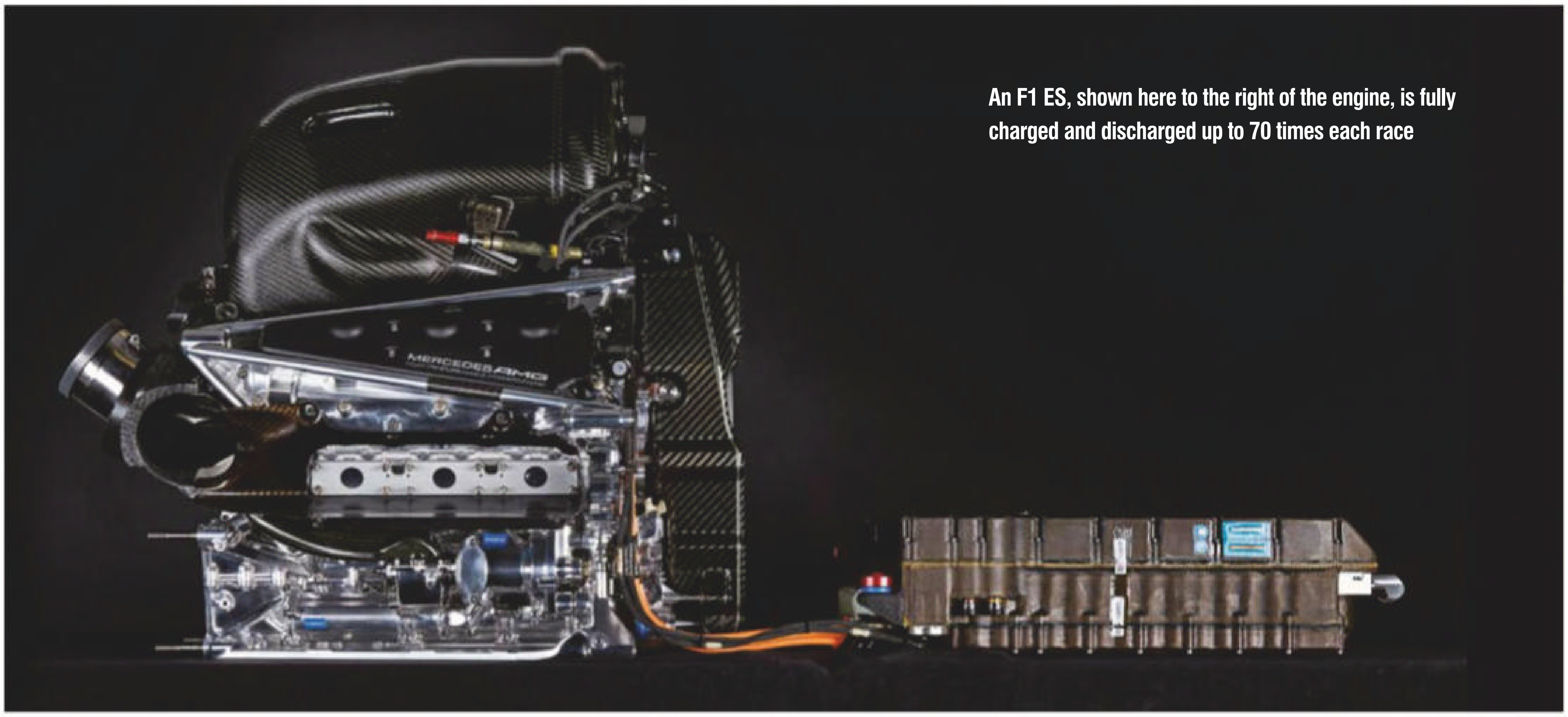
Health check

The temperature and voltage of the cells also need to be carefully monitored, hence the use of thermocouples as well as a low current sensing connection, which is essentially a small wire that connects the positive and negative terminals of the cell to measure voltage. Then there is the cooling system, which can require the cell to be connected to a coldplate through a thermal adhesive, at either the top or bottom of the cell, if this is the chosen cooling design.

'In a great deal of motorsport applications you are trying to measure the voltage and temperature of all, or almost all, of the cells in the battery,' says Law. 'This is because you are trying to operate the cells quite close to their limits of performance, so you need to have a good idea of exactly what the voltage and temperature is of each cell.'

The number, type and packaging of these diagnostic connections are some of the key development areas in motorsport today, along with new chemistries, all in an effort to extract the maximum energy out of the battery for the lightest possible weight. Since 2007, the F1 ERS system has seen an 81 per cent weight reduction, a 56 per cent efficiency increase, while achieving 12 times the power density and twice the energy density. It is this development drive that will continue to change the face of battery technology as we know it.

'In a lot of motorsport applications you're trying to measure the voltage and temperature of all, or almost all, of the cells in the battery'



An F1 ES, shown here to the right of the engine, is fully charged and discharged up to 70 times each race

Examining the why axis

Racecar's numbers man explains why expensive solutions should not be sought until some fundamental questions have been addressed first

By DANNY NOWLAN

One of the most frustrating, and amusing, things with this business is the obsession with the go faster bits. Having been around the scene for 20-plus years you see it comes in waves. In the mid to late 1990s, in the wake of the banning of active suspension, it was dampers and data acquisition. It was thought then that you had to spend $15k to $20k on dampers and data acquisition or you weren't in the ballpark. In the mid to late 2000s it was inerters and driver in the loop simulation. Yet what most motorsport competitors forget is that speed really starts with 'why', and we'll be discussing this here.

The basics

What I mean by 'speed starting with why' is that knowing what makes your car tick, and understanding all the fundamental interactions with the car, is key to making it fast on a consistent basis. It is this knowledge that underpins all the fads that have, and always will, come in and out of motorsport. Once you understand this you will never look back.

The key members of the ChassisSim community understand this, because ChassisSim gives you the ability to answer these questions. It's also one of the reasons I think you are mad if you're not using simulation on a regular basis. But let's look at a few case studies to see why.

The first case study is reading an aeromap, and a typical ride height sensitivity example is shown in **Figure 1**. This is absolute gold dust, as it tells you where to run the car, particularly in the high-speed corners. For example, if we review this map the peak downforce occurs at a front ride height envelope of 2mm to 4mm and a rear ride height of 13mm to 20mm. This has just told you where you want the car to ride from the turn-in to mid-corner section of the turn.

However, this gets even better. If we compare this to the drag map shown in **Figure 2** we can now start to get really clever on the spring package we are going to run on the car.

When you combine **Figures 1** and **2** this tells you not only where to run the car to produce high downforce, but it will also tell you what you will want the front of the car to do when the driver gets on the accelerator. For example, in **Figure 2** it can be seen that the drag is primarily controlled as a function of front ride height. So once we exit the peak area of downforce the drag drops off very quickly.

Consequently, this aeromap is going to dictate that we have a racecar with very non-linear front springs. This screams for us to have a front spring set-up that looks like the arrangement that is illustrated in **Figure 3**.

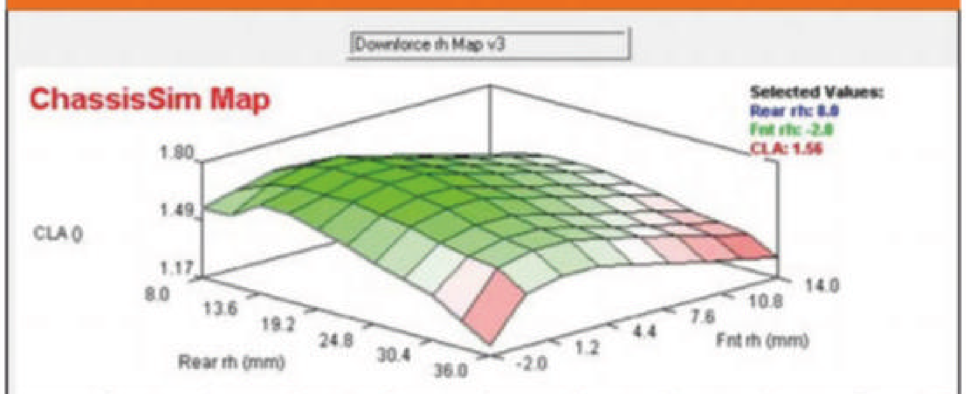
Figure 3 isn't the exact shape, but it tells you the direction you want to go in. As can be seen, you have a very mild rate between zero to 6mm of deflection. Then between 7mm to 10mm the rate increases quite significantly. This 7mm to 10mm deflection point is where you want to keep the car in that ride height envelope. However, as we come off throttle the soft linear rate between zero to 6mm of deflection will ensure the nose pops up, minimising the drag

The great thing about simulation is it gives you the tools to nail this down. An example of this is illustrated in **Figure 4**, which is a simulated plot of an F3 car. The first trace is speed, the second and third traces are front and rear ride height, the fourth trace steering. The fifth and sixth traces are pitches (average of damper movement) and the final traces are spring forces. Now here's the nail. You can combine what we have seen in **Figures 1** to **3** and you can use **Figure 4** to determine what you need from the spring package. For a car with any serious amount of downforce this is a cornerstone to being consistently quick, and the only way you are going to get there is by doing your homework so you know the car. This is also why generating an aeromap is such a critical part of unlocking how fast your racecar can go.

The second case study that illustrates why speed starts with 'why?' is damper rate selection. This comes from the quarter car model and links

What most motorsport competitors forget is that speed really starts with 'why?'

Figure 1: CLA *vs* front and rear ride height



	-2.0	-0.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0
8.0	[illegible]	1.60	1.65	1.65	1.60	1.56	1.51	1.46	1.41
10.8	1.56	1.67	1.72	1.72	1.67	1.62	1.57	1.52	1.47
13.6	1.65	1.70	1.75	1.75	1.70	1.65	1.60	1.55	1.50
16.4	1.65	1.70	1.75	1.75	1.70	1.65	1.60	1.55	1.50
19.2	1.60	1.70	1.75	1.75	1.70	1.65	1.60	1.55	1.50
22.0	1.56	1.67	1.72	1.72	1.67	1.62	1.57	1.52	1.47
24.8	1.51	1.65	1.70	1.70	1.65	1.60	1.55	1.51	1.46
27.6	1.46	1.60	1.65	1.65	1.60	1.56	1.51	1.46	1.41
30.4	1.41	1.57	1.62	1.62	1.57	1.53	1.48	1.43	1.39
33.2	1.32	1.55	1.60	1.60	1.55	1.51	1.46	1.42	1.37
36.0	1.23	1.46	1.50	1.50	1.46	1.41	1.37	1.33	1.29

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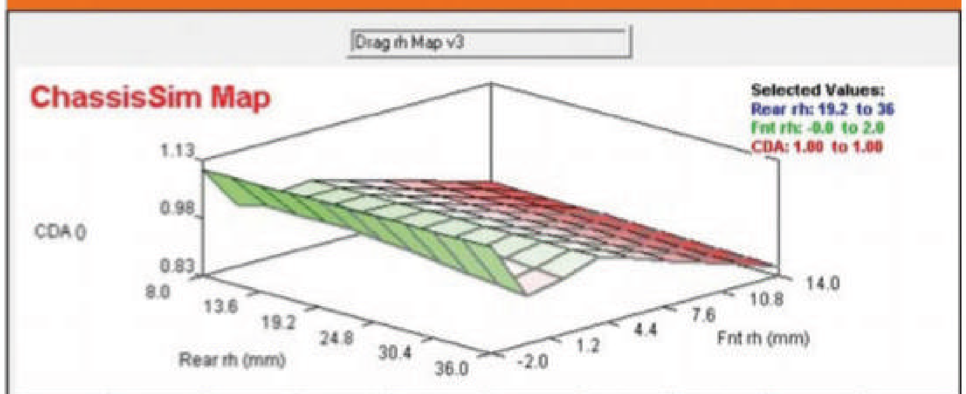
Figure 2: CDA *vs* front and rear ride height



	-2.0	-0.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0
8.0	1.10	0.98	0.99	1.00	0.97	0.95	0.92	0.90	0.87
10.8	1.10	1.00	1.00	1.00	0.97	0.95	0.92	0.89	0.87
13.6	1.10	1.00	1.00	1.00	0.97	0.95	0.92	0.89	0.87
16.4	1.10	1.00	1.00	1.00	0.97	0.95	0.92	0.89	0.86
19.2	1.10	1.000	1.00	1.00	0.97	0.94	0.92	0.89	0.86
22.0	1.10	0.99	1.00	1.00	0.97	0.94	0.92	0.89	0.86
24.8	1.10	0.98	0.99	1.00	0.97	0.94	0.91	0.89	0.86
27.6	1.10	0.97	0.99	1.00	0.97	0.94	0.91	0.88	0.86
30.4	1.10	0.97	0.98	1.00	0.97	0.94	0.91	0.88	0.85
33.2	1.10	0.96	0.98	1.00	0.97	0.94	0.91	0.88	0.85
36.0	1.10	0.95	0.97	1.00	0.97	0.94	0.91	0.88	0.85

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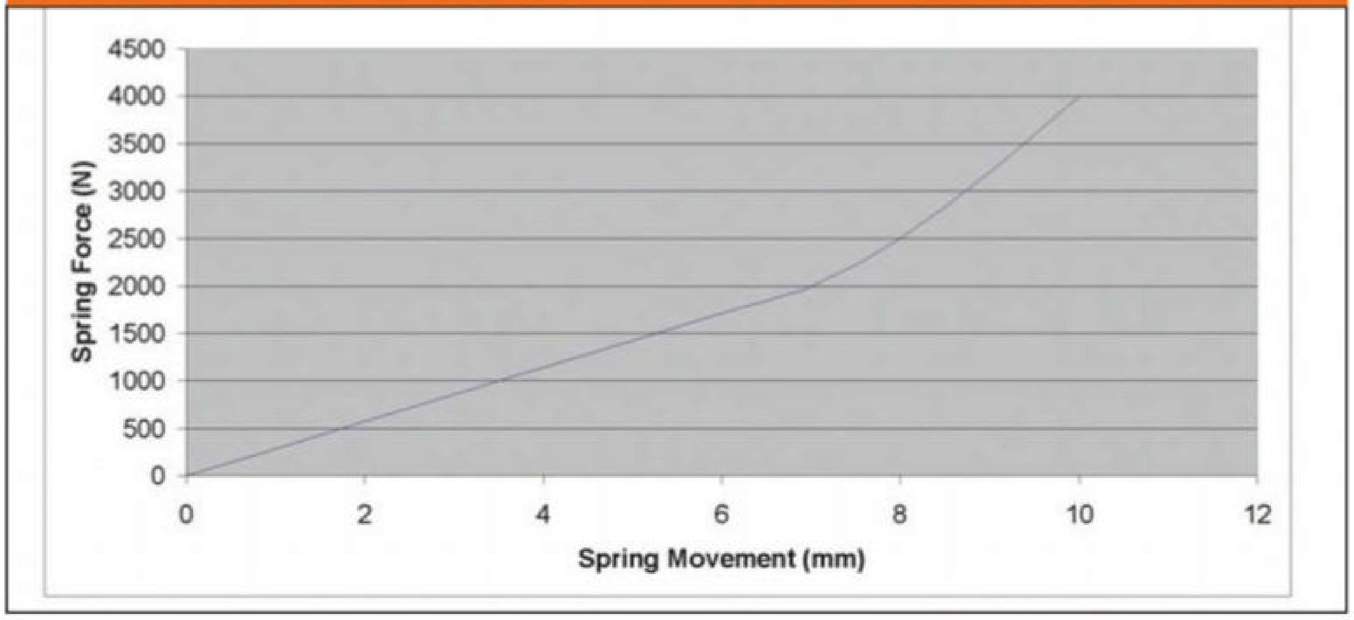
Figure 3: Front spring force *vs* spring movement deflection



quite nicely to our discussion on ride height control. It all starts with the quarter car model, as shown in **Figure 5** – where *xb* is sprung mass movement and *xt* is tyre movement. The great thing about this is that leads us to the two very important equations (**Equations 1** and **2**).

The power of the quarter car model is that given a damping ratio we can readily calculate the damping rate we want. Then, once we know the damping rates we want we can then go to a damper builder and say 'this is the damping curve we want'.

This is why this technique is so powerful. Also, this leads to my damping ratio selection guide, which is actually something that I discussed in my first article ever in *Racecar Engineering*. This is illustrated in **Figure 6**.

Figure 4: Simulated plot of ride heights, pitches and spring forces for a lap by an F3 car

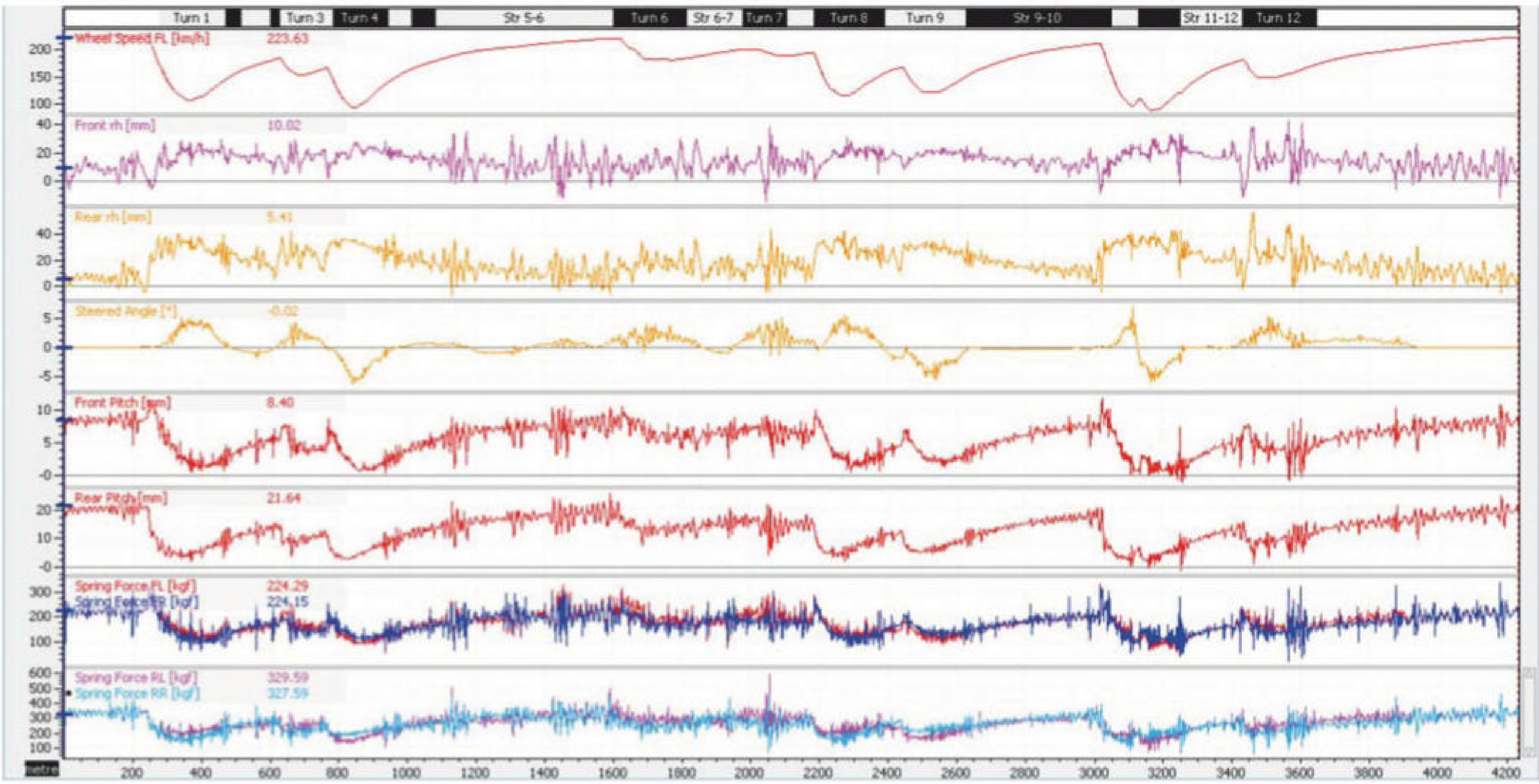
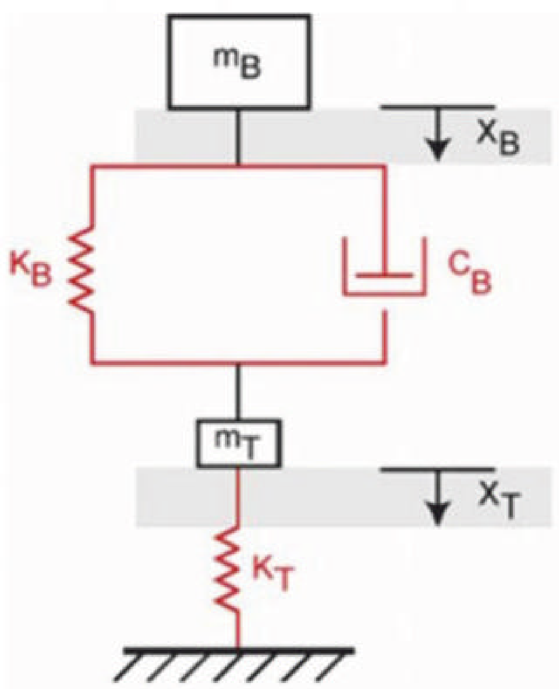


Figure 5: Quarter car model



The parameters are

m_B = Mass of the sprung mass (kg)

m_T = Mass of the unsprung mass (kg)

K_B = Sprung mass spring rate (N/m)

C_B = Sprung mass damping (N/m/s)

K_T = Tyre spring rate (N/m)

EQUATIONS

EQUATION 1

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

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

EQUATION 2

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

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 (kg)

ω_0 = natural frequency (rad/s)

ζ = damping ratio

EQUATIONS

EQUATION 3

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

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

$$C_T = C_f + C_r$$

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

Where:

$dC_f/da(\alpha f)$ = slope of normalised slip angle function for the front tyre

$dC_r/da(\alpha f)$ = slope of normalised slip angle function for the rear tyre

$F_m(L_1)$ = 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)

wb = wheelbase

a = distance of front axle to the centre of gravity

b = distance of the rear axle to the centre of gravity

C_t = slope of total tyre force front and rear *vs* slip angle

C_f = slope of total front tyre force *vs* slip angle

C_r = slope of total rear tyre force *vs* slip angle

EQUATION 4

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

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)

The damping ratio selection guide is a great rule of thumb that has served me, and many members of the ChassisSim community, very well. This also explains the growth in the use of adjustable dampers that emerged in the mid 1990s, because after the banning of active suspension in Formula 1 you now had to get very deliberate about the ways you chose your damper rates – what we have seen in **Equations 1** and **2** form the mathematical bedrock of the importance of all this.

Stability index

The next case study I want to discuss is something that has actually only occurred to me in the last year or so. This idea combines the concept of the stability index with tyre modelling and lateral load transfer.

Firstly, let's very quickly go over the concept of the stability index once again. This measures the moment arm as a percentage of wheelbase of the centre of the lateral forces to the cg, and it's illustrated in **Figure 7**, while the calculation for it is outlined in **Equation 3**.

Here's 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 then 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 of the lateral forces divided by the car'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 really are rough rules of thumb.

Figure 6: Damper selection guide

Region	Value
$\zeta_{LS-Bump}$	This is body control so, if it is a bumpy circuit the ratio is 0.5. If the circuit is smooth choose 0.7. If the tyres need to be worked hard then choose 1.2.
$\zeta_{LS-Rebound}$	This will be dependant on a number of factors. Where body control is not significant use 0.3. However where body control is significant use 0.5 to 0.7.
$\zeta_{HS-Bump}$ $\zeta_{HS-Rebound}$	This is the high pass area of the damping curve. The values here should be 0.3 to 0.4

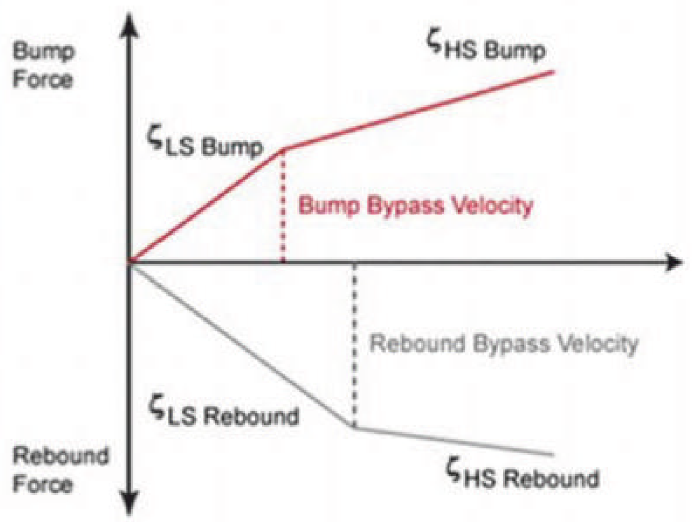
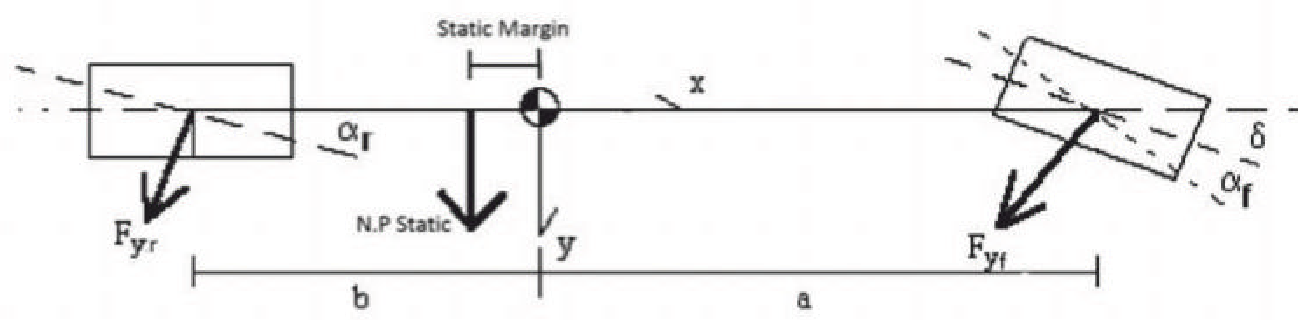
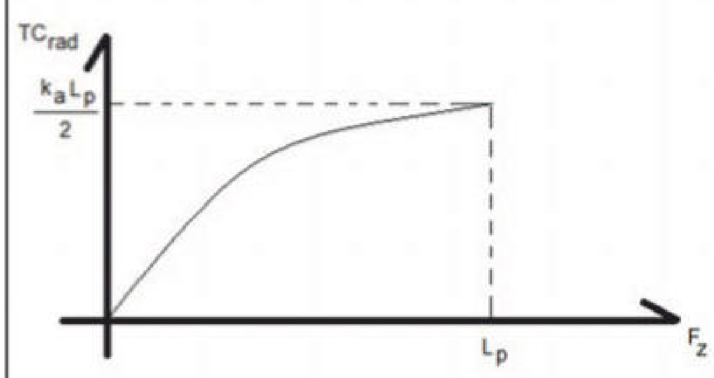


Figure 7: An illustration of the stability index



If you know what your peak tyre loads are and what grip you're expecting you can get a representative tyre model very easily

Figure 8: Visualisation of a second order tyre model



The next step is recognising that a simple traction circle *vs* load characteristic can get us a significant way down the road. To jog everyone's memory, take a look at **Equation 4**.

What all this means in plain English is that any tyre model can be broken down into the visualisation that's shown in **Figure 8**.

Peak practice

What the above shows us 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 your expecting you can get a representative tyre model very easily. Also, while this doesn't give you the full story, it does give you a basic tool to at least get some understanding of what the tyre is doing.

The last step is to combine this with the total lateral load transfer at the front. For completeness let me summarise the mathematics here with **Equations 5** to **10**.

The real significance of the lateral load transfer distribution is that if gives us a first indication of what to expect with tyre loads. This is illustrated in **Equations 11** to **14**.

So, the important thing here is that if we combine this into a static force balance we can then start answering some very fundamental questions about the grip and balance of the racecar. More specifically, we can plot grip and balance as a function of load transfer. This is illustrated in **Figures 9** and **10** .

EQUATIONS

EQUATION 5–10

$$rcm = rcf + wdr*(rcr - rcf); \qquad (5)$$
$$hsm = h - rcm; \qquad (6)$$
$$rsf = (krbf + kfa)*ktf/(kfa + krbf + ktf); \qquad (7)$$
$$rsr = (kfb + krbr)*ktr/(kfb + krbr + ktr); \qquad (8)$$
$$prm = rsf/(rsr + rsf); \qquad (9)$$
$$prr = (wdf*rcf + prm*hsm)/h; \qquad (10)$$

Where:

rcm = mean roll centre (m)
rcf = front roll centre height (m)
rcr = rear roll centre height (m)
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 (m)
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 due to the sprung mass
prr = lateral load transfer distribution at the front
tm = mean track of the vehicle
hsm = moment arm of the cg height to the mean roll centre

EQUATION 11–14

$$L1 = (wdf*mt*g + Faero\_f)/2 + prr*(mt*ay)h/tm + other\ terms \qquad (11)$$
$$L2 = (wdf*mt*g + Faero\_f)/2 - prr*(mt*ay)h/tm + other\ terms \qquad (12)$$
$$L3 = (wdr*mt*g + Faero\_r)/2 + (1 - prr)*(mt*ay)h/tm + other\ terms \qquad (13)$$
$$L4 = (wdr*mt*g + Faero\_r)/2 - (1 - prr)*(mt*ay)h/tm + other\ terms \qquad (14)$$

Where:

mt = car total mass (kg)
ay = lateral acceleration
wdf = weight distribution at the front axle
wdr = weight distribution at the rear axle
$Faero$ = total aerodynamic force (N)
g = acceleration due to gravity (m/s2)

The magic number

The significance of what we have discussed here is that this quantifies and explains where the term the 'magic number' comes from. What the magic number refers to is the lateral load transfer at the front where the car will 'magically' work. Over the years this has gone into and out of fashion. The reason for this is that not a lot of people have really understood its origins, its limitations and what it truly means. Consequently, it goes in and out of fashion depending on how the stars are aligned and who is winning and who is being vocal about it.

The reason why this explains where the magic number is, is that we can see that for a given tyre model we can track what the load transfer will do. So from **Figure 9**, as can be seen, as we plot the lateral load transfer the force moves by 1000N from a 20,000N window. That's a five per cent margin, which is not too shabby.

Practical magic

However, where the magic truly comes from is with the variation in the stability index that is illustrated graphically in **Figure 10**. We are talking global variations in the order of 40 per cent here. Most of your time in race engineering is spent in that maximum grip area tuning the stability index you want, and in a nutshell this is where the magic comes from.

This is not without it's limitations, but it is still an essential building block. But since this is a pseudo-static approximation it will not include the effect of bumps on the track surface. So if you are using this blindly and you have no idea where it comes from you can get lost very fast. That said, this is still a fundamental of race engineering that will give you a mathematical framework to estimate what a set-up will do.

Wizard of Oz

But the important thing is that there is no *Wizard of Oz* moment to everything we have discussed in this piece. *The Wizard of Oz* is one of the most overlooked yet powerful parables in 20th Century Western culture. Dorothy wanted to go back to Kansas, the Lion was looking for courage and the Tin Man wanted a heart. Yet when they reached the Wizard he was a balding old man in a bad fitting green suit. The bottom line was, they had the ability to do it themselves all along. This is the power you get when you start to understand that speed starts with 'why?' With everything we have discussed with the aeromaps, damper rates and the magic number, all we did is use some simple first principles.

So, as I noted at the beginning of this discussion; speed really does start with 'why?' And you must understand this in order to engineer a car that is consistently quick.

Figure 9: Plot of lateral force *vs* load transfer

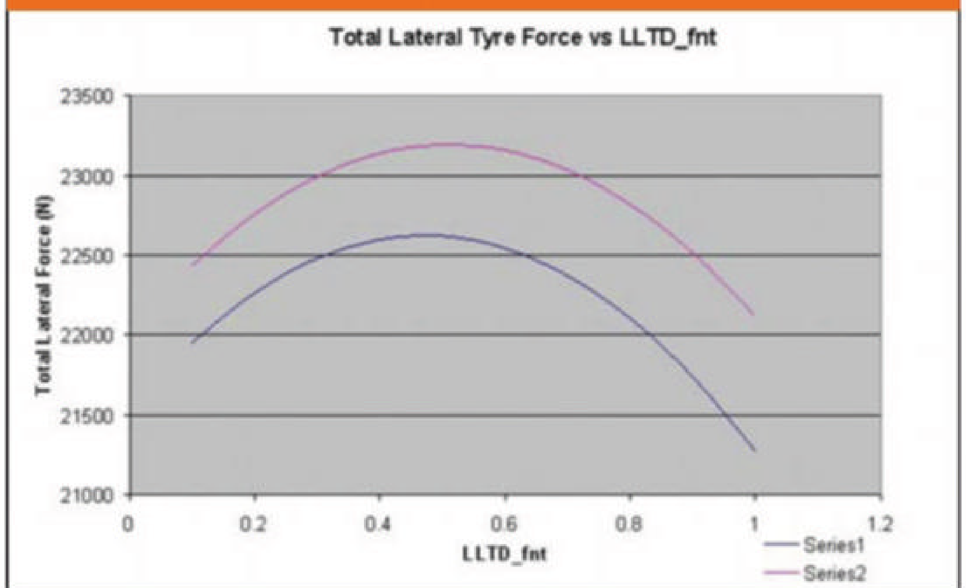
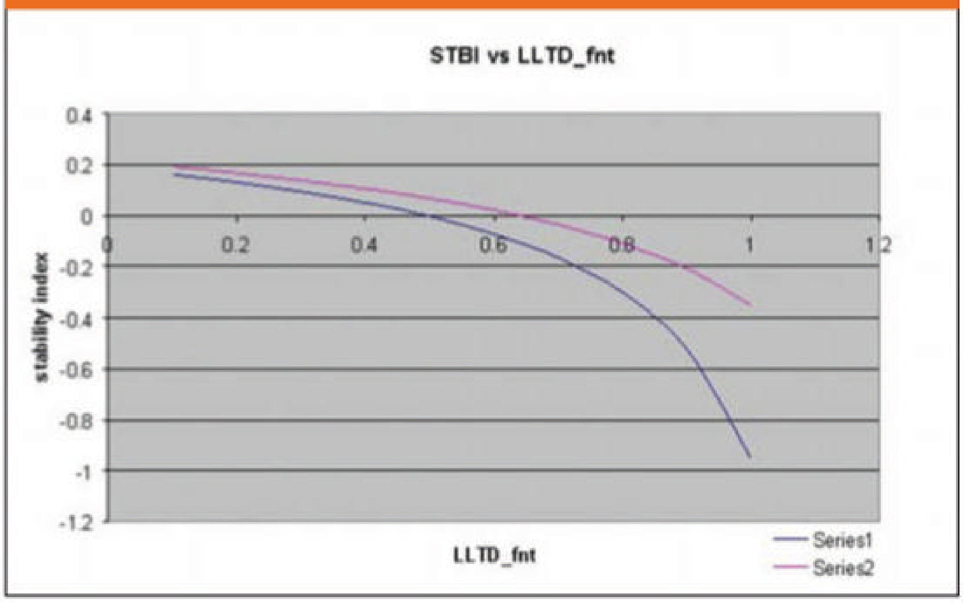


Figure 10: Plot of stability index *vs* load transfer



Electric shock

Could the ongoing drive towards electrification at the expense of other powertrain solutions be seriously misguided? That was the question posed at the MIA Entertainment and Energy-Efficient Motorsport Conference on the eve of the Autosport International Show

By PROFESSOR STEVE SAPSFORD

With much that is said in politics, we can never be sure we're getting the complete picture. The same is true of the UK government's stampede towards full electric vehicles and the developing competition between cities across Europe to ban internal combustion engines as quickly as possible.

Are we sure this is the right approach? Are we sure we are getting all the facts? No doubt you will have been told that battery electric vehicles are zero emissions; indeed, it is even written on the back of some of them – surely that must be good. But is it true?

While the challenges we face are complex and interconnected, they fall into two main categories when we consider road transportation; greenhouse gas emissions (related to global warming, climate change etc.) and air quality (related to health). In this feature we will primarily focus on greenhouse

Might biofuel-ICE offer a better solution than EVs? IndyCar has been using a biofuel blend, E85 ethanol, for over a decade

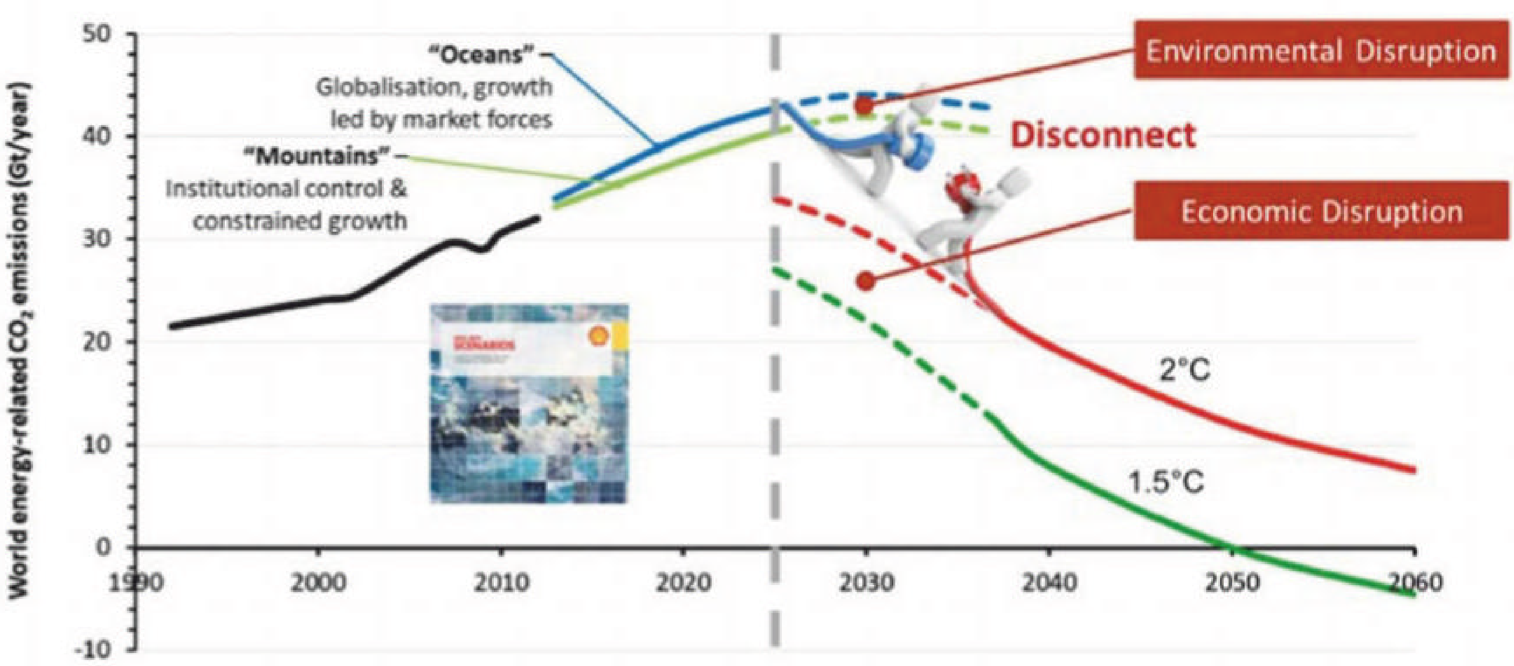


Figure 1: Shell projections based on two alternative scenarios. Both predict us exceeding 40 gigatonnes of CO2 emissions per year between 2020 and 2025

One of the lowest overall carbon footprints is generated by a conventional internal combustion engine that burns a biofuel

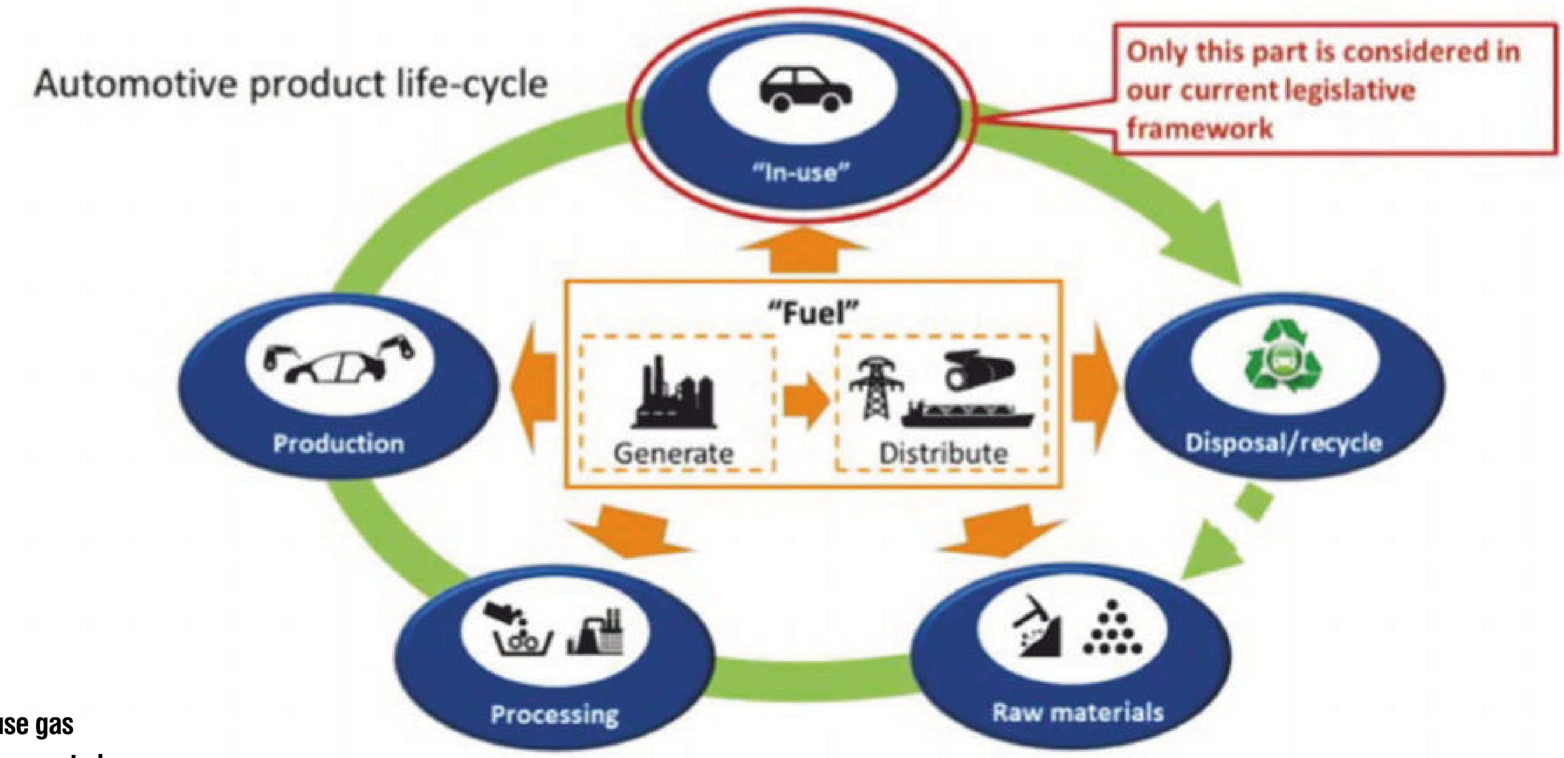


Figure 2: Green house gas emissions that are generated throughout a vehicle's life cycle

The embedded carbon in the production of the electric vehicle is significantly higher than it is in the conventional vehicle

gas (GHG) emissions and we will leave air quality for another time. However, we will touch on it briefly where it is relevant.

The energy/climate challenge and projected future energy scenarios suggest that we will face disruption of some form in the future. The global emissions of energy-related CO_2 has been increasing steadily and this is only set to continue as the world gets more populated and the demand for energy increases further.

Shell has developed some projections of CO_2 emissions based on two alternative scenarios; *Oceans* and *Mountains* (**Figure 1** and box out). Both predict us exceeding 40Gt (gigatonnes) per year between 2020 and 2025. If we then overlay the CO_2 emissions which would enable the target maximum 2degC and 1.5degC temperature increases to be achieved, we see we have a significant disconnect. This will lead to some stark consequences; either environmental disruption if we continue along our present course; or economic disruption as we seek to force a change in trajectory.

The transport sector is committed to reducing its GHG emissions, but there is a genuine concern that the current legislative environment is forcing one particular solution to the exclusion of any of the alternatives, and this approach is the result of only looking at one small part of the picture.

When making our choices regarding the propulsion systems of our future vehicles we really need to consider the GHG emissions generated throughout the entire life-cycle of the vehicle (**Figure 2**). We need to account for the emissions associated with the extraction of the raw materials, processing them to be used in the production of the vehicle, using the vehicle (including the 'fuel' we use, be it electricity, liquid hydrocarbons or hydrogen) and, finally, the disposal and re-cycling of that vehicle; that is, a life cycle analysis (LCA).

So, what happens if we do a life cycle analysis for a passenger car with a number of alternative propulsion systems? Life cycle analysis is not easy. It involves a number of assumptions and so can never be definitive, but **Figure 3** shows the estimated lifetime GHG emissions including the production, use and disposal of a typical passenger car expressed in kg CO_2 equivalent (this means that the greenhouse effect of all the emissions – not all are CO_2 – associated in the processes above are converted to the equivalent amount of CO_2).

Most of the CO_2 emissions for a conventional vehicle are released as we drive them, burning a predominantly fossil fuel. As we hybridise that vehicle, the embedded CO_2 content increases as we add electric drive components such as motors, power electronics and (relatively small) batteries. The in-use CO_2 decreases as we recover and use electrical energy to support the propulsion of the vehicle.

However, things change quite dramatically when we consider pure battery electric vehicles. As you can see, the embedded carbon in the production of the vehicle is significantly higher than a conventional vehicle and this

Oceans deep, Mountains high

The *Mountains* scenario is a world in which those occupying commanding advantage (at the top) generally work to create stability in ways that promote the persistence of the status quo. There is a steady, self-reinforcing, lock-in of incumbent power and institutions. This lock-in constrains the economic potential of some sectors of society, but enables established sectors aligned with market forces to unlock resources that require significant capital and new technology.

As for the less fortunate, the thinness of social safety nets is not completely offset by the growth in philanthropy, characterised by an eruption of foundations endowed by increasing numbers of billionaires.

The *Oceans* scenario paints a picture of a world in which competing interests and the diffusion of influence are met with a rising tide of accommodation. This trajectory is driven by a growing global population with increasing economic empowerment, and a growing recognition by the currently advantaged that their continued success requires compromise. Steady reform of economic and financial structures keeps pace with the development of fast-emerging nations and progressively unlocks the productivity of broader sectors in society. But volatility and multiple constituencies impede policy developments in other areas, so tight resources are unlocked primarily by market forces.

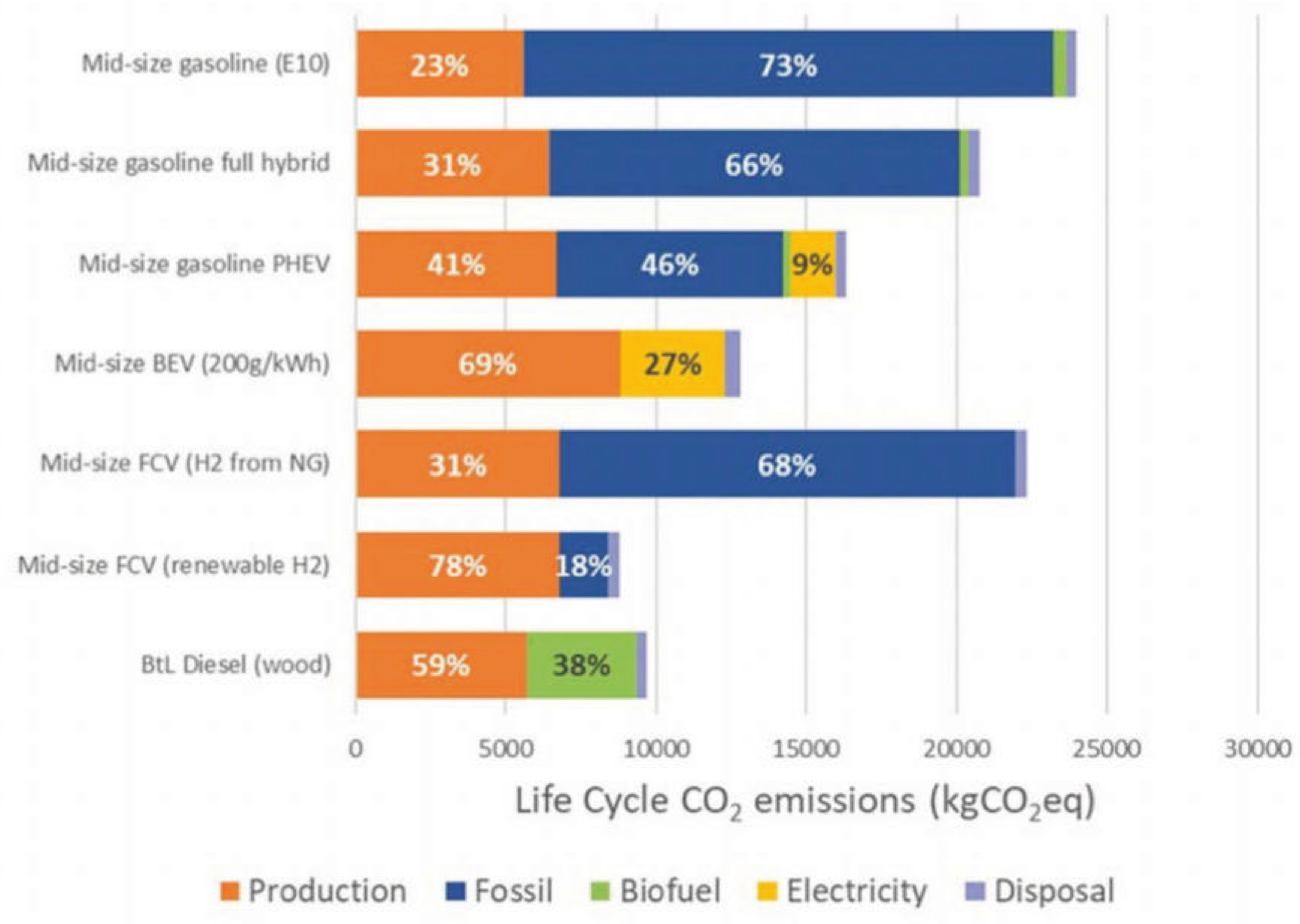


Figure 3: Estimated lifetime green house gas emissions from a selection of powertrain solutions

is dominated by the manufacture of the battery pack. The in-use CO_2 emissions are, by contrast, significantly less, although the size of this contribution does depend massively on the carbon emissions associated with the generation of the electricity used.

In **Figure 3** it has been assumed that the electricity can be generated at 200g CO_2/kWh, which represents a healthy renewable content (UK currently ~300g/kWh). If the electricity was generated by burning coal that figure would be more like 1000g CO_2/kWh, natural gas would be 500g CO_2/kWh and the figure would look a lot worse. Conversely, if it was all from renewables, then that section would reduce to zero.

Hydrogen fuel cells offer an attractive alternative, but only if the hydrogen comes from renewable sources. Simply using methane (natural gas) as the source of hydrogen does not really help us much.

One of the lowest overall carbon footprints is generated by a conventional internal combustion engine that burns a biofuel and this is achieved by virtue of the fact that the production costs in terms of CO_2 are low and the in-use fuel is made from re-cycled carbon.

One particular area of current interest is that surrounding synthetic fuels. These differ from biofuels mainly in their source of carbon. While both can be classed as renewable fuels, biofuels rely on organic sources of carbon such as wood chippings or waste agricultural products such as straw. Synthetic fuels, sometimes called electrofuels or efuels, rely on CO_2 for their carbon. Biofuels and synthetic fuels are of interest because they effectively re-cycle the CO_2 that is released when they are burnt. This technology is being promoted strongly in Germany, particularly by Audi and Bosch, as well as FuelsEurope and CONCAWE.

Our politicians are not interested in talking about anything with an internal combustion engine

However, there is still much work to be done on synthetic fuels. The manufacturing processes are not at scale and they are not currently efficient, requiring a lot of energy to produce, but the rewards are potentially huge: 1) We could refuel at the filling station in exactly the same way as we do now, removing all concerns around range anxiety. 2) We could use all the existing infrastructure both in terms of fuel distribution and IC engine/vehicle manufacture. 3) We could reduce the CO_2 emissions of existing as well as new cars rather than relying on new electric vehicle sales to gradually reduce our CO_2 emissions. 4) The same technology would benefit commercial vehicles as well, where liquid hydrocarbons are the only viable solution for long haul trucks.

The purpose of this article is to raise your awareness of alternative and complementary solutions for future propulsion systems. In making our choices regarding powertrain technology we really should be considering the *overall* impact of those choices, even if that analysis is only an estimate, to avoid unforeseen consequences. Whilst we appear to be on this somewhat blinkered, headlong rush towards full electrification, a more balanced and realistic view would be to acknowledge that there are a number of potential solutions, each with pros and cons according to their application.

Due to the pressures on air quality, it is entirely reasonable that full electric vehicles should be part of the portfolio, especially for city centres, but these are not the only solution. But our politicians are not interested in talking about anything with an internal combustion engine in it and it is almost impossible to get investment for anything related to internal combustion engine development.

I hope this has demonstrated that hydrogen and renewable fuels offer great potential and should be part of the mix, but they do require their share of investment to develop the technology. If we can manage this, the potential impact on greenhouse gases could be significant; if not, we could be missing a huge opportunity and heading for disaster.

AUTOSPORT INTERNATIONAL ENGINEERING SHOW

Halls of fame

The Autosport Engineering show in January once again proved to be the perfect start to the motorsport season

The very best of motorsport technology was on show at Autosport Engineering

The use of new halls was a breath of fresh air at this year's Autosport Engineering Show, as the UK welcomed international motorsport to Birmingham once again in mid-January.

The business started with the MIA's Energy Efficient Motorsport conference on Wednesday, but as interesting as that was, delegates were slightly distracted by the LAMMA Show. This is the largest agricultural and machinery show in the UK, housed in the halls previously occupied by the Autosport International and Engineering shows. But as much as EEMS delegates might secretly hanker after a tractor, there were some business opportunities that could not be ignored.

The Engineering show took place on the Thursday and Friday in its new location. This year the entire event was spread over four halls and more closely resembled the Geneva Motor Show, with stairs between the halls, and large stands in the main hall.

With the show spread out over more floor space, there was a crowd, but no overcrowding. On the other hand the increased floor space simply meant that people moved between the halls less and Engineering appeared to have fewer visitors.

Official figures had yet to be released at time of writing, but organisers were confident that they were consistent with 2018's numbers, an estimated 30,000 for the trade days and 95,000 in total over the four days of the Autosport International show.

Winners of the product showcase awards at the show include Bcomp, which won the Innovation award; Aero Tec for Cross Industry Application, while Texense won the Data and Measurement award. Cartek won the Electronics award for its Speed Marshall system, while Bosch won the Safety and Energy Efficiency categories. Evo Corse won Light-weighting, and Motordrive the Manufacturing and Fabrication award.

Bcomp won the Innovation award for its ingenious natural fibre-based composites solution

Big money deals were negotiated in the MIA's business lounge

Take a bow: The award winners pose with MIA CEO Chris Aylett, front row centre with yellow tie

And the winner is . . .

The Motorsport Industry Association (MIA), now marking its 25th anniversary, hosted its much anticipated Business Excellence Awards dinner at the NEC; where 400 guests saluted the very best companies operating in the racing sector

Nigel Geach of Nielsen Sports receives the MIA Service to the Industry award from Charles Bolton

Kieron Salter of KW Special Projects holding the New Markets Award, presented by Jon Simpson

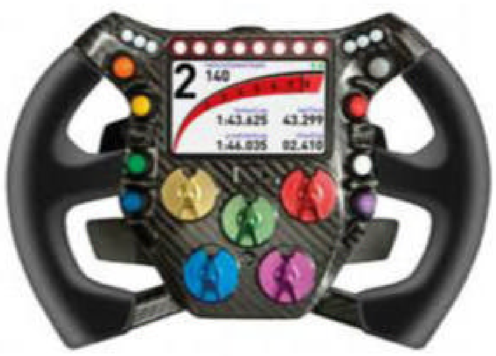
AP Racing's David Hamblin receives the Export Achievement Award from Archie MacPherson

Bob Halliwell of Racing Point Force India receives the MIA Teamwork Award from James Grainger

Jason King (Integral Powertrain) with Technology and Innovation Award, presented by James Sundler

James Nicklin of Precision Technologies; Business of the Year with annual sales under £5m Award

Business of the Year with annual sales over £5m Award was presented to Alcon's Alistair Fergusson



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Low speed pre-ignition can cause serious piston damage

Ignition switch

The director of R&D at Driven Racing Oils explains how using the right lubricant can help neutralise engine-damaging low speed pre-ignition in direct injection turbo powerplants

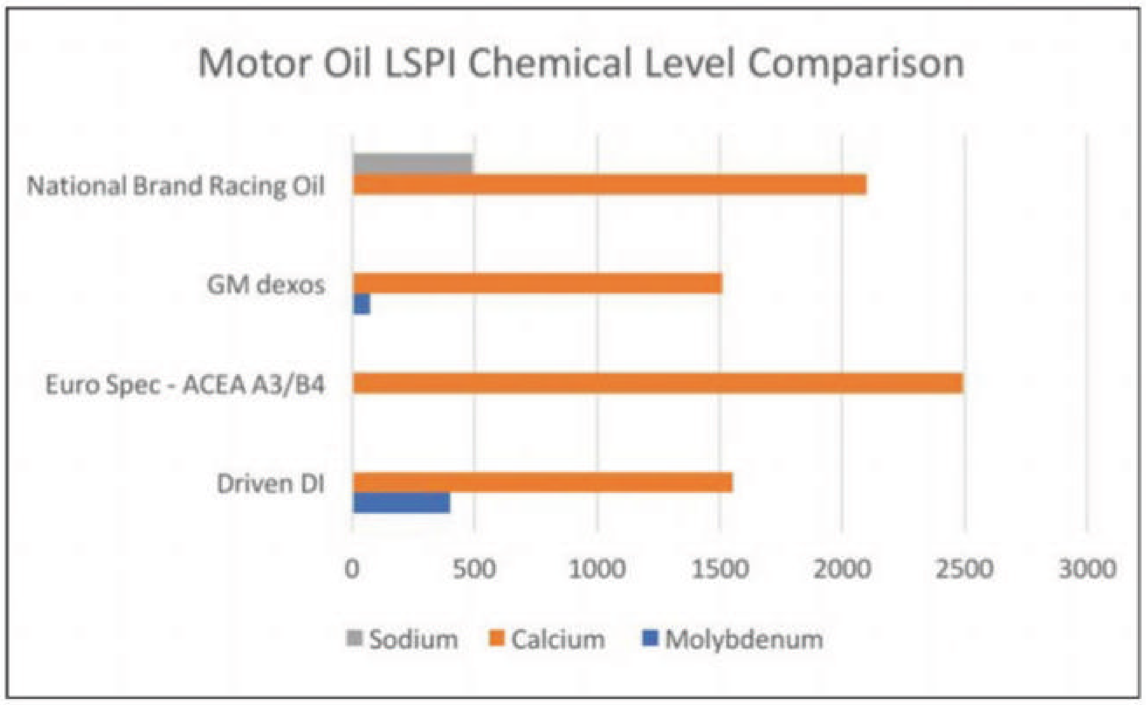
By LAKE SPEED

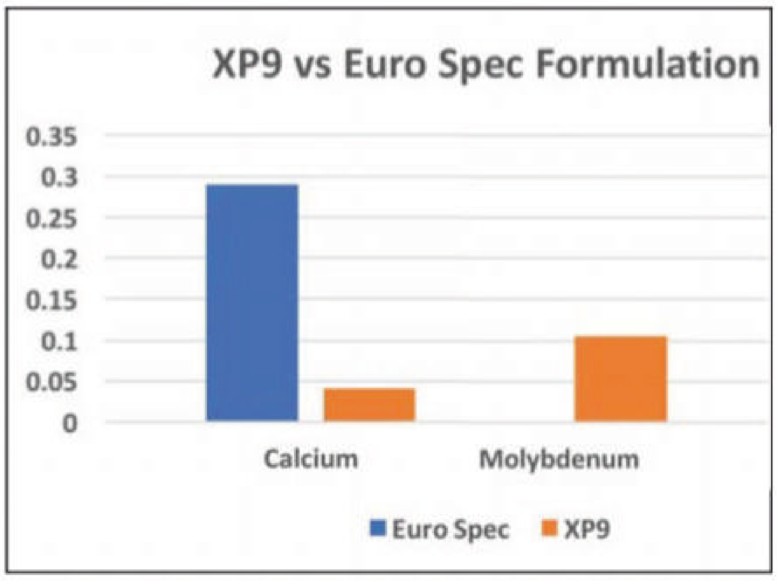
Common in turbocharged direct injection engines, low speed pre-ignition (LSPI) is an abnormal combustion event that can lead to catastrophic engine damage. Normally, combustion follows the spark event as controlled by the engine management system. In an LSPI event, the combustion event begins prior to the spark event, which causes abnormally high pressures within the cylinder. These high pressures can damage the piston.

Low speed pre-ignition occurs in directly injected engines because of the higher compression ratio of these units – 11.5:1 for a GM LT1 and even higher for many others, while a GM 3.8 V6 port injection is 8.5:1 – and also because of the shorter amount of time the fuel has to vaporise. A typical direct injection engine has less than 160 degrees of crankshaft rotation to atomise the fuel compared to over 320 degrees of crankshaft rotation to atomise the fuel in a traditional port injection or carburettor-fed engine. The combination of higher compression and shorter atomisation time make direct injection engines more prone to abnormal combustion events such as LSPI.

As crazy as it may sound, engines don't burn liquid fuel. Okay, the gasoline that goes in the tank is a liquid, but the engine must convert the liquid fuel into a vapour in order to burn it. Just like boiling water changes the water from a liquid state into a gas, an engine vaporises the liquid gasoline by spraying the fuel as a fine mist into the hot and turbulent air moving through the engine. This process is typically called atomisation, and it is simply the conversion of the fuel from a liquid state into a vapour.

If the fuel doesn't turn into a vapour, then the engine can't burn it. Some of that unburnt fuel finds its way into the crevice between the top of the piston and the upper ring land where it mixes with the motor oil that lubricates the





Driven's XP9 Racing Oil is low in calcium and high in molybdenum

Left: Comparison of sodium, calcium and molybdenum levels in oils

cylinder walls. This mixing of the liquid fuel and oil is where things begin to go bad chemically.

It is also important to mention that DI engines create soot, just like a diesel. This can lead to increased abrasive wear in the engine.

Because DI engines offer both fuel economy and emissions advantages, the US Department of Energy provided a research grant to Oak Ridge National Laboratory to investigate ways to overcome the current limitations of DI engines when using mainstream motor oil chemistry. These challenges pushed Oak Ridge National Laboratory to seek out a lubricant development partner that could supply small volumes of custom motor oils and had a keen understanding of engine hardware. So it contacted Driven Racing Oil to provide these custom oils. Driven partnered with EFI University and even invested in its own direct injection engine, a GM LT1, to quantify the results of formulation, tuning and hardware changes in a high performance direct injection engine.

The group found that reducing the amount of calcium detergent and eliminating the sodium detergent in the formula reduced the frequency and severity of LSPI and other abnormal combustion events. Testing also revealed that increasing the level of molybdenum reduced the tendency of abnormal combustion events. Once the main culprits, calcium and sodium based detergent additives, had been identified, research began to understand why they contributed to LSPI.

It is hypothesised that calcium and sodium detergents chemically react with the fuel to create a third chemical that is neither fuel nor motor oil. This third chemical has a lower octane value than either the fuel or the motor oil, so the detonation resistance is lower. Because of the lower detonation resistance of this 'blended' molecule, abnormal combustion results, which we call low speed pre-ignition.

The UK's Mini Challenge experienced problems with low speed pre-ignition in its DI turbocharged engines

This was proven by blending oil formulas that eliminated the sodium detergents and greatly reduced the calcium detergents. These research oil formulas also eliminated LSPI events. This was a key finding, but it also presents a problem for the vast majority of off-the-shelf motor oils. This is because calcium based detergents are the most cost effective detergents, and are widely used in many motor oils, typically in high concentrations.

Science friction

Around the same time, Driven had the opportunity to work with the Mini Challenge series in the UK to help it solve a problem with LSPI in its turbo DI engines. The series had been using a European road spec oil that happened to contain over 2500 parts per million (ppm) of calcium detergent. While using this oil, the Mini Challenge series cars suffered from several engine failures due to LSPI. Once the series organiser and engine builder became aware that these failures were due to LSPI, its fuel supplier, Sunoco, recommended contacting Driven Racing Oil. That resulted in a switch to Driven's XP9 Racing Oil, which contained only 250ppm of calcium detergent, compared to the previous oil with more than 2500ppm of calcium detergent and no molybdenum. Lowering the calcium level to 250ppm and adding 1000ppm of molybdenum eliminated the LSPI related engine failures.

Simply put, motor oils formulated with high concentrations of calcium detergents are the primary contributor to LSPI events in direct injection engines. To avoid potentially catastrophic damage, motor oils must be formulated specifically for direct injection engines to ensure engine durability.

But you may be wondering why the focus is on low engine speed? That's a fair question. At low engine speeds the turbulence of the intake charge is less than at higher engine speed. The lower turbulence leads to less atomisation

The combination of higher compression and shorter atomisation time makes direct injection units more prone to abnormal combustion events

'assistance' by the intake charge. Imagine an engine running at idle at a stop light. The engine speed is low and there is no load on the engine. In this scenario, the fuel charge has less turbulence to assist atomisation/vaporisation as well as lower piston temperatures due to lower engine loads. Both reduced turbulence and lower piston temperatures work against atomisation/vaporisation of the fuel. Now add in back pressure from a turbo, and you have a recipe for reduced cylinder scavenging of a poorly atomised fuel charge. It is no wonder that direct injection engines will show higher levels of fuel dilution in used motor oil samples than port injection engines.

A long, low speed idle followed by hard acceleration is the perfect condition for an LSPI event; increased fuel dilution of the oil followed by high cylinder pressures.

School of hard knocks

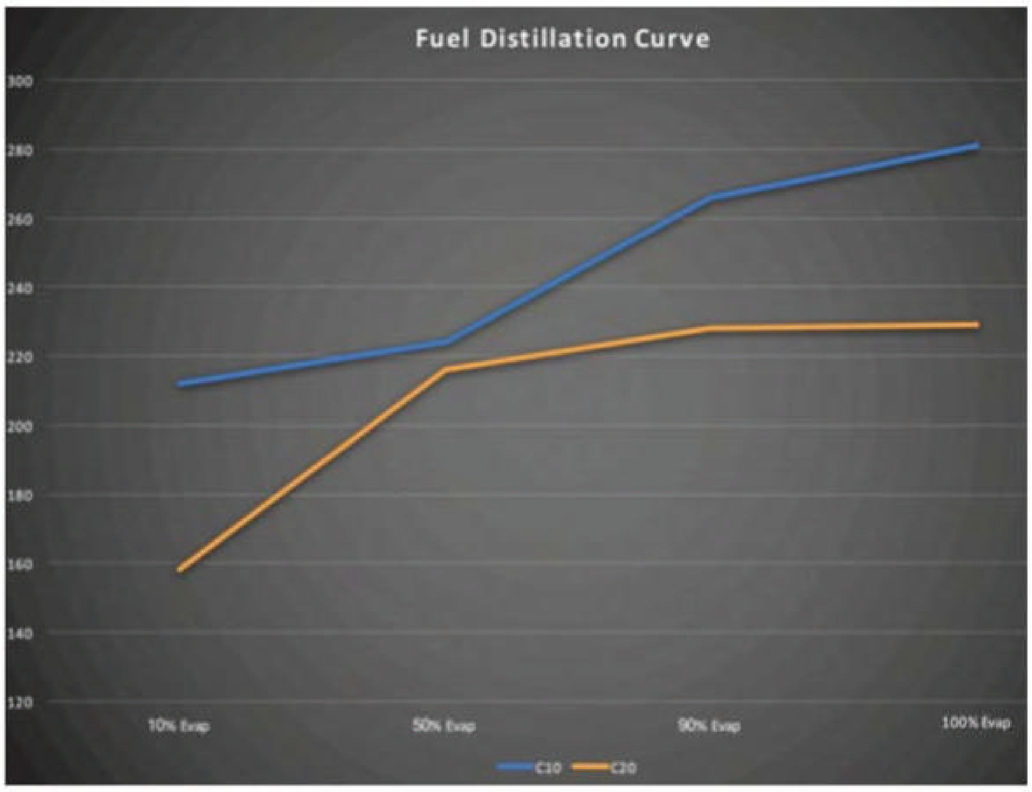
Further proof of the atomisation theory came from a test at EFI University. Utilising the GM LT1 direct injection engine at its testing facility, it was able to data log the factory knock sensors to watch for early signs of possible LSPI events (**Figures 1** and **2**). Ben Strader and his team tested two similar octane fuels; VP C10 and VP C20. While these are very similar in octane, 100 octane for C10 and 98 for C20, the distillation curves of both fuels are drastically different.

Essentially, distillation is a measure of the ease of a liquid fuel to turn into a vapour. The higher the distillation temperatures, the more resistant the fuel is to vaporisation. Conversely, the lower the distillation temperatures, the easier the fuel will vaporise.

Interestingly, the higher distillation temperatures of the C10 fuel caused the engine to knock more than the lower octane and lower distillation temperature C20 fuel. This increased knock due to lessened atomisation/vaporisation of the C10 fuel proved the theory of non-vaporised/liquid fuel contributing to abnormal combustion events like LSPI.

Fortunately, extensive research and engine testing has identified which additives contribute to LSPI and which additives can reduce it. By carefully balancing the formula an oil can be designed to protect against it without compromising on engine wear protection. In fact, a new oil spec is under development to bring new generation oil formulas to the market. In the meantime, avoid oils containing high levels of calcium and sodium detergents in DI engines. GM's Dexos spec oils have been reformulated to provide LSPI protection, and Driven now offer a full line of DI specific oils.

Oils that were built from the ground up to be compatible with turbo DI engines and provide better protection and performance. It is important to pay close attention to the fuel and oil choices for DI engines in order to maximise the performance and durability of these powerful and efficient powerplants.



EFI University tested VP C10 and VP C20 fuels. While these have very similar octanes their distillation curves are drastically different

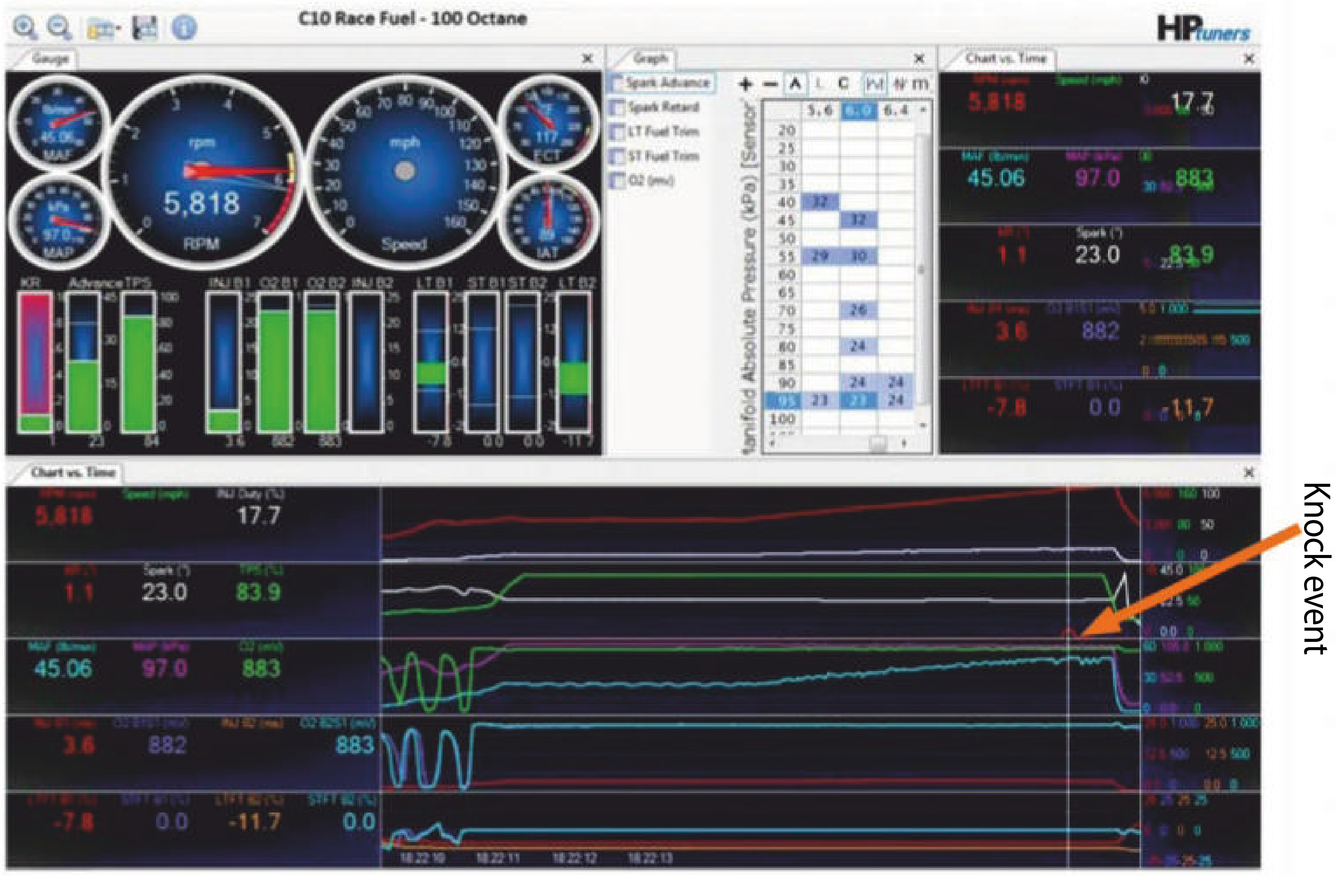


Figure 1: The GM LT1 engine's knock sensors were data-logged by EFI University. A knock event is highlighted above

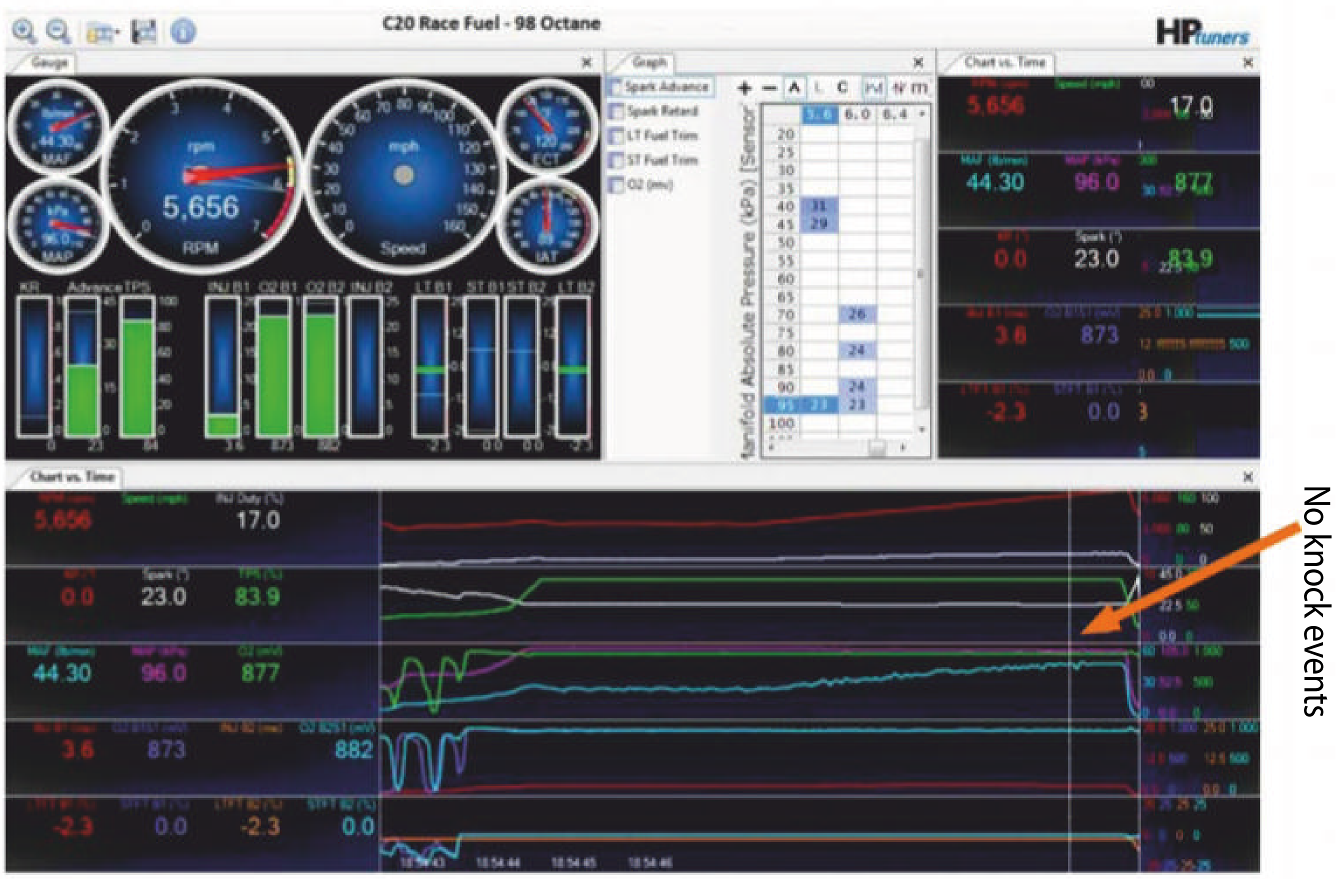


Figure 2: Thanks to the lower distillation temperature of the C20 fuel there were no knock events when this was tested

Driven does more, with less

Independent testing reveals Driven Racing Oils provides more horsepower with less wear

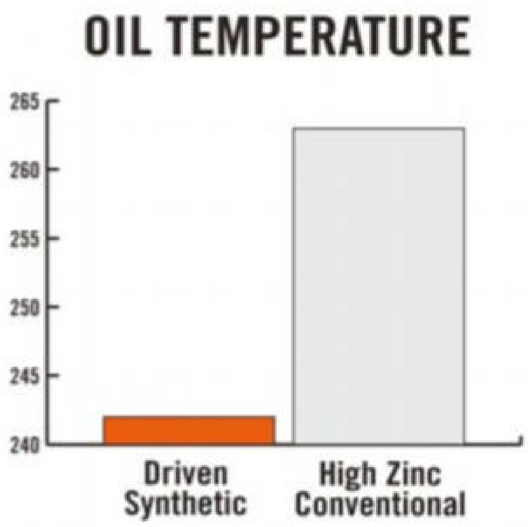
Detailed surface measurements and used oil analysis results all confirm the Driven system of lubricants reduces wear by 76%, provides 2% more horsepower and lowers temperatures by 11ºC compared to conventional, high zinc racing oils.

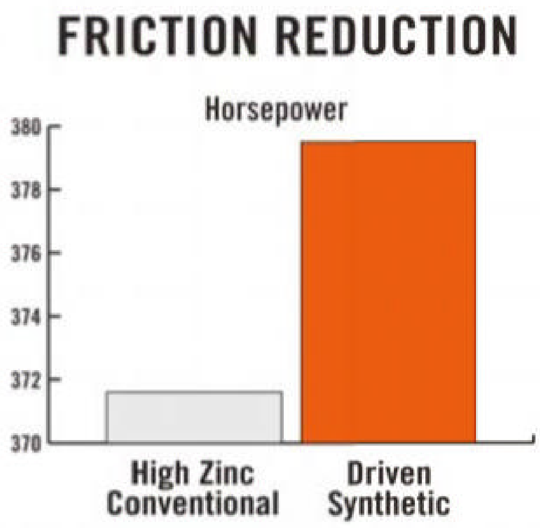
Developed for and used by NASCAR champions Joe Gibbs Racing, Driven Racing Oil provides bespoke products proven to outperform standard synthetic oils and even "high zinc" racing oils. Trusted by professional racing teams around the world for more than a decade, Driven delivers protection and performance you can count on.

The Driven XP range is available in:
0W, 0W-10, 0W-20, 5W-20, 10W-30,
10W-40 & 15W-50 viscosities

'Ed Pink Racing Engines uses Driven Racing Oil in every engine we build. It is the best insurance for long engine life that you can get'

Ed Pink, Hall of Fame Engine Builder





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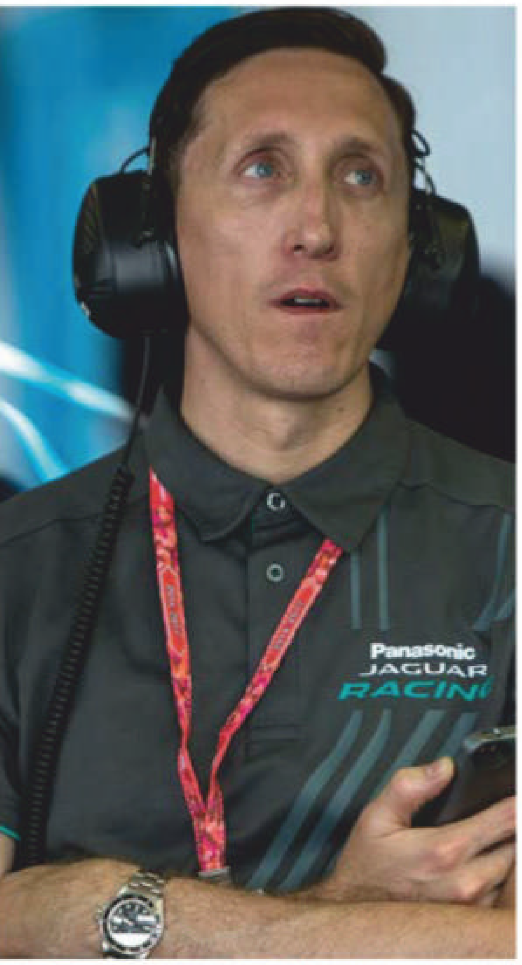
Interview – James Barclay

Jaguar's E type

The Jaguar Racing Formula E boss explains why the championship is still right for the firm and how it's breaking new ground with its I-Pace electric FE support series

By MIKE BRESLIN



'We were the first premium manufacturer to commit to the championship, but we always felt confident that others would follow'

When a major car manufacturer announces it's to shed thousands of jobs those involved in the motorsport industry immediately look at its sporting programme. For however much it's argued that racing improves the breed and gives a good bang for buck in terms of marketing, for the rest of the world it can appear frivolous, even wasteful.

So when Jaguar Land Rover (JLR) ushered in the New Year with news of 4500 job cuts, all eyes turned to Jaguar Racing and its Formula E programme. Yet along with the redundancies was a commitment by JLR to build a new EV battery factory in Warwickshire in the UK. This is because JLR, which up until fairly recently had a product line that was 90 per cent diesel, is going electric big time. Which actually also fits rather well with its motorsport programme.

But this is not news to those in the Jaguar Racing FE operation, including team principal James Barclay, whose background is mostly in marketing and PR – although he has raced himself and he was also involved with the Bentley Le Mans programme. He has recently stated that Jaguar will remain in FE despite the redundancies, but he recognised far earlier that Formula E was right for the company. 'We have a great history in the sport, and for a long time it had been on our radar to return,' he says. 'But it had to be for the right reason, not just for the sake of it, but in terms of something that was very much future-proofed in terms of our direction in the company from a business perspective and a technology perspective, and very quickly that put the focus on Formula E.'

First among equals

Other car manufacturers obviously agree and by Season 6 (2019/20) Formula E is set to boast the most manufacturers ever represented in a single top level championship. Many of these are what might be termed prestige marques – Porsche, Audi, BMW and Mercedes – but the very first high-end car maker to join the party was Jaguar in Season 3 (2016/17).

'We were the first premium manufacturer to commit to the championship, but we felt confident that others would follow,' Barclay says. 'We paved the way for other premium manufacturers to enter, in a way. If you're completely on your own, then sometimes that's good, but in the case of motorsport it's not, because you want to have the competition. For us, it adds pressure, but it also means that success will mean more.'

Yet motorsport history tends to show that car makers come and go. But Barclay, who has recently become the chairman of FETAMA (the Formula E Teams and Manufacturers association), thinks FE might be able to avoid this. 'History does show that, and it has shown it enough for us to see that potentially it could happen in Formula E,' he says. 'But I think what is really important is we need to continue to have the technology roadmap [which outlines the tech that's allowed and will be allowed in the future] and that controls the budget. That means we have things like common chassis, common battery, common aero, and we don't create open technology where it isn't going to advance the core objective, which is electric vehicle powertrains.'

That's not to say FE is not seeing big spending, and while Barclay was unwilling to divulge details on Jaguar's budget, it's known that the spend is increasing in FE – it's estimated that budgets were €10m in Season 3 and €20m in Season 4. 'Of course, it [spending] is growing, but the roadmap controls that as well,' Barclay says. 'Keeping the one day format also keeps it very focussed in terms of what you can do with that money.'

Importantly this roadmap is not drawn up by the teams and manufacturers, but they do have a say on what it contains. 'Fundamentally the decision on the technology and the roadmap is decided by the FIA and Formula E,' Barclay says. 'They are the ones who decide that, through the FIA energy commission, which is a formal part of the FIA. We, however, as a key stakeholder – the teams and manufacturers – have a say in that process, so we're working with the FIA and Formula E on that future roadmap. Fundamentally it's important for Formula E and it's important for the FIA to hear the voice of the teams and the manufacturers, because ultimately we're the ones that are spending the money to go racing. But sometimes you do need someone who ultimately takes that feedback and puts it into a decision and moves that forward.'

On the Pace

Jaguar has hit the ground running this year, with a fourth place in Ad Diriyah (Riyadh). But while its Formula E car – called the I-Type 3 – has been performing well, the company has also attracted attention with its all-new Formula E-supporting spec series for electric Jaguar I-Pace SUVs, which is a world first in one

obvious way, and also perhaps in one less obvious way. 'It's the first ever electric production racing championship,' Barclay says. 'But also it's the first global single-make championship. You have one or two championships, like the Porsche Carrera Cup, that mainly race in Europe with a flyaway, but all of our races are taking place in different continents.'

But why did Jaguar feel the need to widen its electric racing presence in this way, isn't FE enough? 'We very quickly realised in our first season there's a lot of potential for another racing series and we thought that this was going to be an opportunity,' Barclay says. 'We were going to be the first premium brand with an electric road car on the market, which is the I-Pace, so we came to the decision that we should push ahead and do it. It was a big investment for us, a huge investment to make it happen. No one had ever done it before, there's no regulations for an electric production car, so we worked very closely with the FIA, they supported us fantastically well, as did Formula E, to make it possible. There's been a huge amount of development in the car…and I think what we have proven is the relevance of the I-Pace as a performance car; that we can go racing, 25 minutes plus a lap flat out racing with no energy saving.'

Wired up

While just 11 cars started the first race at Ad Diriyah Barclay is confident more teams will become involved soon. 'We had a lot of interest,' he says. 'A lot of people were waiting to see it become reality, and we've had a real spike in interest now, and hopefully that can lead to a full grid come the end of the season. But I think if you compare us with other championships at their start point, we're very comparable.'

With Jaguar Racing now very much committed to electric it seems to be in step with its parent company's strategy, which can only be for the good, but it's also in step with where racing seems to be heading, Barclay believes. 'The one thing that motorsport has always done, is it's evolved, and that is no different now,' he says. 'It's important that we evolve for everyone in the sport, and for the sport itself. If you don't evolve you stand still and you get left behind, and that's the reality. The future of electric racing is really exciting, it safeguards the future of our sport as we move forward and we should be very positive about that.'

Jaguar Racing is now into its third season of Formula E and it says it is committed to the electric race series for the long term

RACE MOVES

XPB

Michel Nandan (pictured) is no longer the team principal at the Hyundai WRC team, having been replaced by **Andrea Adamo**, the firm's customer racing manager. Nandan had overseen Hyundai's World Rally operation since 2013 and was responsible for getting its Alzenau motorsport HQ up and running, and also for the development of the i20 WRC car. Adamo will continue to look after the i20 R5 rally and the i30 N TCR race programmes alongside his WRC duties.

Former Porsche WEC team boss **Andreas Seidl** has been signed up by the McLaren Formula 1 outfit, where he takes on the post of managing director. Seidl will now oversee the team's technical programme and its race weekend operations.

The Joest-run Mazda IMSA squad has shaken up its management structure after a difficult first season for the partnership in 2018. Joest Racing technical director **Ralf Juttner** is now no longer the team's manager director, with **Jan Lange** replacing him in the position – Juttner has moved on to an as yet unannounced project within Joest. Meanwhile, Former Panther Racing and KVSH Racing IndyCar manager **Chris Bower** has joined the team, taking on the role of team coordinator.

Also at the Joest Mazda operation, Multimatic – which produces the RT24-P racecar – has brought in Aston Martin and Ford veteran **Dave Wilcock** to be race engineer on the No.55 Mazda, while in another high-profile personnel change **Leena Gade**, who was a Le Mans winner with Audi Sport Team Joest, has been tasked with engineering the No.77 car.

The Joe Gibbs Racing (JGR) ARCA Series stock car operation has hired **Mark McFarland** as a crew chief. He joins JGR from MDM Motorsports, where he served as team manager and crew chief in its NASCAR K&N Series and ARCA teams.

Jay Frye is now the president of IndyCar, as part of a reshuffle of the management at the top-line US single seater series that was announced by **Mark Miles**, the president and CEO of IndyCar and Indianapolis Motor Speedway (IMS) parent organisation Hulman & Company. Miles will continue as IndyCar CEO.

As part of the IndyCar and IMS management re-organisation (see above) **Mark Sibla**, previously IndyCar chief of staff, competition and operations, has become chief of staff of all IndyCar departments. Meanwhile, **Jarrod Krisiloff** has had his responsibilities expanded at IMS, becoming vice president, facilities and events, while **Dan Skiver** is now director, operations. **Pat Garlock** has been promoted to assistant manager, facilities and events, at IMS.

Legendary F1 racecar designer and engineer **Gordon Murray** has been awarded a CBE (Commander of the British Empire) in the Queen's New Year Honours for 2019. The accolade is in recognition of his services to motoring, after a lifetime spent devising and delivering creative and ground-breaking projects in the motorsport and automotive sectors.

Formula E boss **Alejandro Agag** has stepped up from the role of CEO to become chairman of Formula E Holdings. A new CEO is to be appointed in the coming months to help with the day to day running of the championship while Agag will now concentrate on FE's relationships with commercial partners, host cities and the FIA. Agag replaces **Simon Freer** as chairman of the board.

Former Porsche LMP1 technical director **Alexander Hitzinger** is now a member of the brand board of management for technical development at Volkswagen Commercial Vehicles. Hitzinger comes to VW from Apple, but he had a long career in motorsport including stints at Toyota Motorsport, plus Cosworth and Red Bull in Formula 1, before joining the Porsche LMP1 programme in 2011.

British entrepreneur **Ian Warhurst**, the owner of an automotive engineering company, has purchased the assets of the Bloodhound SSC programme, which folded late in 2018. It's understood that Warhurst intends to continue with the project, which had the target of breaking the Land Speed Record and also the 1000mph barrier.

Binotto replaces Arrivabene as Ferrari Formula 1 boss

Maurizio Arrivabene is no longer the team principal at Ferrari, having been replaced by Mattia Binotto, formerly the Scuderia's technical director.

Arrivabene took on the Ferrari team principal role in November 2014, replacing Marco Mattiacci. He came to the team from long-time sponsor Philip Morris International (Marlboro). It's rumoured that Arrivabene is now set to take on a senior role at Italian football team Juventus.

XPB

Mattia Binotto is now the team principal at Ferrari

Binotto had been technical director since 2016, following the departure of James Allison, but he has been with Ferrari since 1995, starting out as a test engine engineer and then joining the race team in a similar position in 1997. Since then he has worked in a variety of roles, including becoming head of engine and KERS in 2009.

XPB

Maurizio Arrivabene might be going to a job in football

At the time of writing it was not clear who would replace Binotto as Ferrari's technical head but in a statement confirming the departure of Arrivabene Ferrari said: 'All technical areas will continue to report directly to [Binotto]'.

Ferrari also thanked Arrivabene for his time at the team, during which it won 14 of 81 races, had 71 podiums and took 12 pole positions. 'After four years of untiring commitment and dedication, Maurizio Arrivabene is leaving the team,' read its statement. 'The decision was taken together with the company's top management after lengthy discussions related to Maurizio's long-term personal interests as well as those of the team itself. Ferrari would like to thank Maurizio for his valuable contribution to the team's increasing competitiveness over the past few years, and wish him the best for his future endeavours.'

OBITUARY – Glen Wood

One of the co-founders of the Wood Brothers Racing NASCAR operation, Glen Wood, has died at the age of 93.

Wood set the team up with his siblings Leonard and Delano in 1950, and it is now NASCAR's longest continually running outfit, having chalked up 99 Cup level victories from over 1500 starts, while fielding big name drivers such as Junior Johnson, David Pearson, and Cale Yarborough over the years.

Glen Wood initially had success as a driver himself, and in an 11-year career behind the wheel he made 62 starts in top level stock car racing, converting five of these into wins. But in 1964 he hung up his helmet to concentrate on the team.

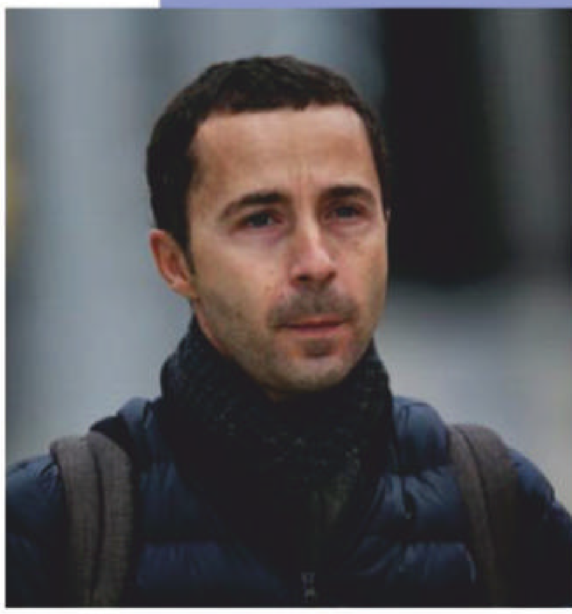
Wood Brothers is particularly well-known for the way it revolutionised pit stops in NASCAR in the 1960s, slashing the time it took to change tyres and take on fuel by half. So impressive were its stops that Lotus and Ford asked the team to act as pit crew when Jim Clark took part in, and won, the Indianapolis 500 in 1965.

NASCAR Chairman and CEO Jim France said of Wood's passing: 'In every way, Glen Wood was an original. In building the famed Wood Brothers Racing at the very beginnings of our sport, Glen laid a foundation for NASCAR excellence that remains to this day. As both a driver and a team owner, he was, and always will be, the gold standard. But personally, even more significant than his exemplary on-track record, he was a true gentleman and a close confidant to my father, mother and brother.'

Glen Wood was inducted into the NASCAR Hall of Fame in 2012.

Glen Wood 1925-2019

RACE MOVES – continued



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Nicolas Todt, the son of FIA president **Jean**, has sold his stake in the ART Grand Prix team which he founded with current Sauber F1 boss **Frederic Vasseur** in 2004. His shares in the very successful F1 feeder series single seater outfit have now been passed on to others involved in the team. Todt will continue to work as a driver manager, looking after the interests of new Ferrari signing **Charles Leclerc**, amongst others.

Jean-Pierre Van Rossem, the money-man behind the Onyx Formula 1 entry 30 years ago, has died at the age of 73. In an eventful life Van Rossem was at various times a politician, philosopher and author. He had not been well for some time and had been campaigning for the right to voluntarily end his life.

JD Gibbs, who was responsible for his father – team owner Joe Gibbs – entering NASCAR, has died at the age of 49 after battling with a degenerative neurological disease for the past few years. Joe Gibbs Racing (JGR) was formed in 1992 and JD was named the president of the company in October 1997.

The world of motor racing was shocked at the sudden death of **Charly Lamm**, who passed away in hospital at the end of January after a short illness. Lamm was Team Principal of Schnitzer Motorsport, and as such was integral to BMW's motor racing history with multiple titles in touring cars and sports car racing.

Veteran Supercars race engineer **Campbell Little** has been appointed motorsport technical manager for the Australian race series. He will report to **Adrian Burgess**, who was recently taken on as head of motorsport. Last season Burgess and Little worked together at the Tekno Autosports Supercars operation.

Ex-Formula 1 driver **Martin Donnelly** has partnered with well-known single seater team owner **Jonathan Lewis** to form a Ginetta Junior race team, which is to be called Apollo Motorsport. The pair have worked together in the past, running a Formula Vauxhall Junior squad. Donnelly raced for Arrows and Lotus in F1 before his career was cut short after a serious accident at Jerez in 1990.

Jay Fabian has been named as the NASCAR Cup Series managing director. He has been promoted from his previous position of managing director of technical integration at the organisation. In the past he worked as a crew chief and pit crew member for Michael Waltrip Racing, before joining NASCAR in 2016.

Jerome Stoll will continue as president of Renault's sporting division. It was announced at the end of last year that he was to be replaced as the head of Renault Sport Racing by **Thierry Koskas**, the executive vice-president of sales and marketing, but it has now emerged that Koskas has left the company and that Stoll will remain in his post.

Sydney Davis Yagel is now general manager of SCCA Pro Racing, having been promoted from the post of senior manager of race operations, which she took up in the spring of last year. Yagel is not only the first female to lead SCCA Pro Racing, she is also the youngest general manager in the organisation's history.

◆ Moving to a great new job in motorsport and want the world to know about it? Or has your motorsport company recently taken on an exciting new prospect? Then email with your information to **Mike Breslin** at **mike@bresmedia.co.uk**

Shifting perceptions

I don't think that there is any shame in admitting that Facebook appears to have my profile well mapped; every time I log onto it there are old races that pop up, and on-board videos that make the hair curl. This time, it was Ayrton Senna at the 1989 Japanese Grand Prix. My wife was out, so I had no one to tell me not to turn up the volume.

Often, I have wondered about what has become of racing since then. The power units I have written about before, but there is also the issue of the paddle shift gearboxes compared to manuals. Senna needed to lift his hand off the (sparsely decorated) steering wheel to change gear, to use the engine to help slow the car, short shifting in damp conditions, it all makes for a fantastic video. The primitive cameras help visually, and the sound of a Honda V12? Thank you.

Semi-automatic weapon

Often the argument has been that motor manufacturers prefer the paddle shifts in their road and racecars, but why? A semi-automatic shift is easier on the gearbox, but we need some element of unpredictability in modern racing outside tyres and DRS, and this could be the perfect time to return to the old ways. A semi-auto shift is also easier on the driver, which should be an argument against it. The prospect of a driver missing a shift and blowing the engine asunder was always something that injected some element of uncertainty into a race.

The prospect of a driver missing a shift and blowing an engine brings an element of uncertainty

Is it fair on the team, if a driver makes such a mistake? After all, they will pay for it for many other races under the engine life rule from the FIA. In one word; yes. They should be able to manually shift properly.

Drivers used to bust out of their talent bubble in a bid to secure the best drive, or shift up to a higher racing category. Over a cup of tea with a former Le Mans winner, we agreed that today's decisions seem to be more of a business transaction. In the days when he was racing, drivers still bought drives, but teams that wanted to win would hire the best talent, not the biggest wallet.

Porsche's head of motorsport, Frank-Steffen Walliser, admitted that many drivers of performance cars sold by Porsche preferred a manual shift, and pondered whether or not to make that a cost option on new cars. And it is not only performance cars that are sold with manual gearboxes; smaller entry level cars are also sold with a manual shift, so there is still that hallowed connect between road and race.

Williams started work on the semi-auto box in F1 around 1986, having spotted the significant speed advantages; among them was the shift change speed, down from 200-250ms to 30-50ms. But Ferrari was the first to introduce it, in 1989. Immediately it was ridiculed, as it wasn't that reliable, and there were some issues; downshifting had to go through every gear. A broken gear, which could potentially be avoided in a manual shifter, could now spell the end of the race. John Barnard wanted it, got it, then others were quick to follow suit.

Williams introduced it in 1991, and Patrick Head believed that it cost the team the championship that year because of its shocking unreliability. However, the scene was set, and it is now a common technology throughout racing. Head, in an interview with *Racecar*, pointed out that returning to a stick shift was considered in 1993, but the plan dropped as it was clearly adding to reliability, and therefore cost saving. The fact that it was a performance advantage that had absorbed enormous investment obviously had nothing to do with it.

'Box of tricks

As is typical in F1, the semi-auto 'box was then developed into the CVT 'box, which was considered a step too far, and that was banned before it was ever raced. So, the technology was allowed, but only to a certain level and not its natural conclusion. Semi-auto 'boxes crossed over into sportscar racing in the late 1990s, with the obvious impact on reliability at longer races such as Le Mans.

However, despite Head's assertion that returning to a manual shift would be like going back to wearing clogs, I raise the question. Motor racing is only exciting if there is an element of uncertainty, either through high tyre degradation or rain. Reliability is less of an issue, but the constant drive towards longer engine and gearbox life is not cost saving.

The investment to make these units reliable for longer periods is soaking up more resource than just what you see in the end product. And I don't see the logic of introducing paddle shifts into production cars anyway. It has got to the stage that diesel cars have paddle shifts, and that makes no sense. Okay, it's faster if you are in a hurry, and you can be in the right gear at the right time, but how often are you in a position to make full use of it in anything other than a supercar, and even then probably on track? It is part of the skill of a driver to be able to shift manually, it can introduce an element of doubt into a result, and it is road relevant.

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