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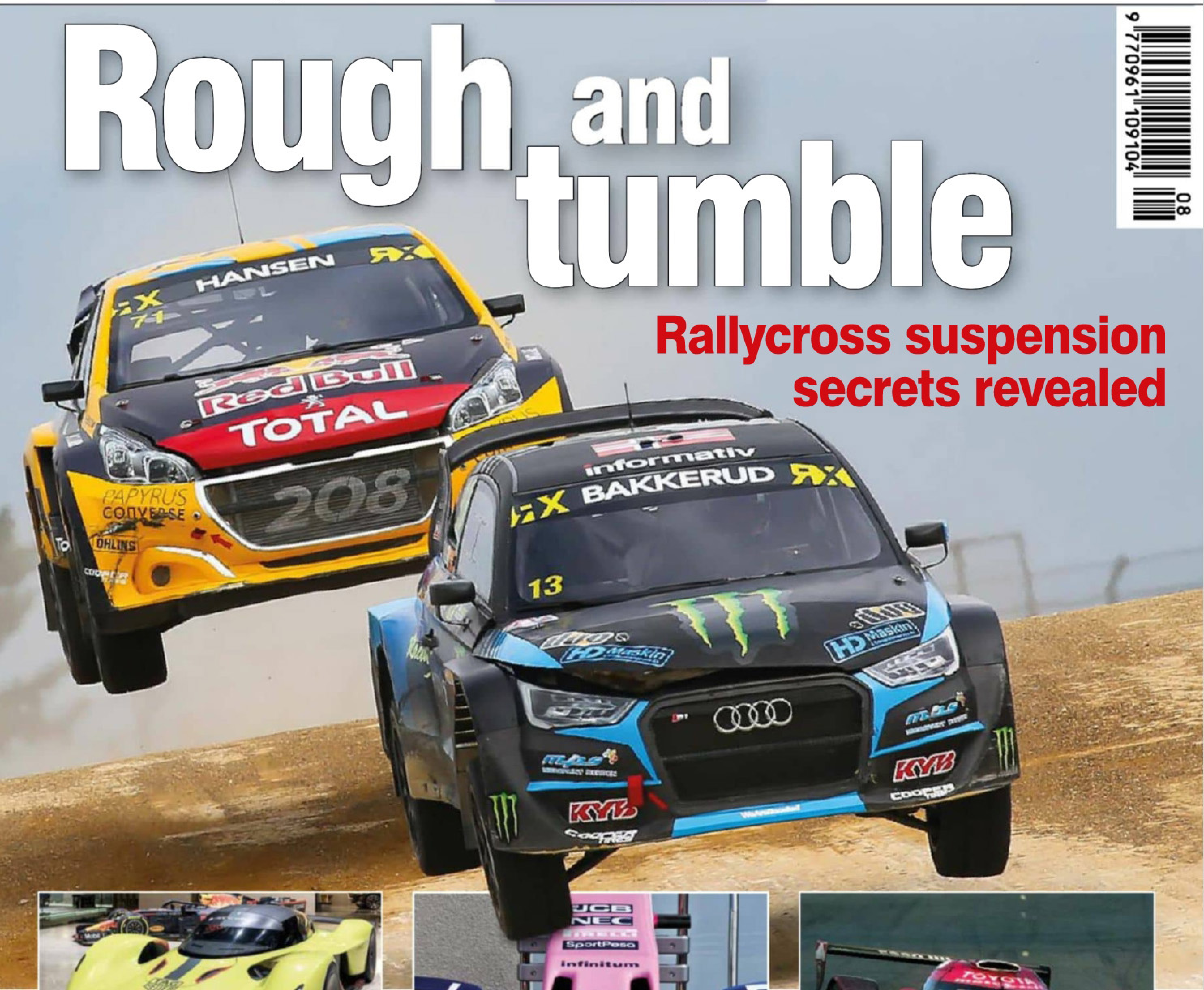
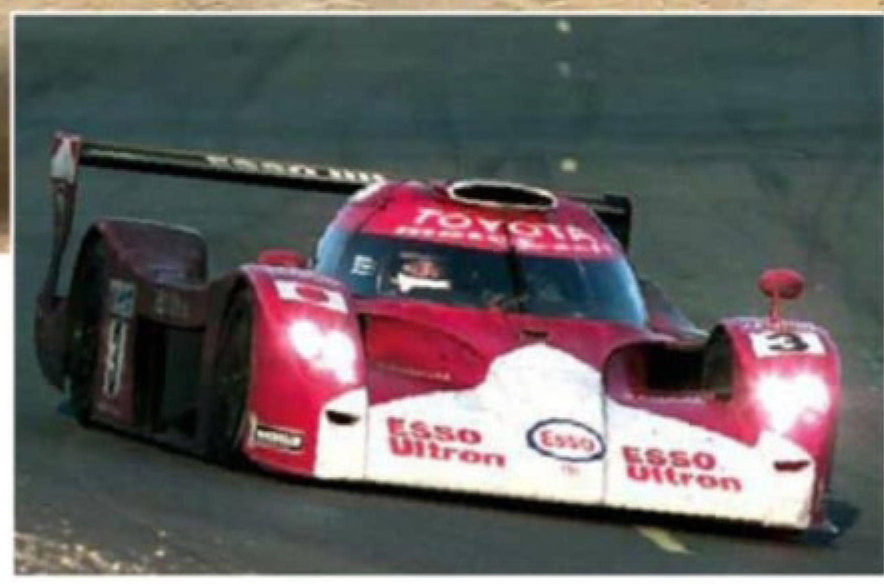


Rough and tumble

Rallycross suspension secrets revealed



New world order
Why hypercars are the answer for the FIA WEC

Racing's future
Peter Wright's vision for a sustainable Formula 1

The TS racecars
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Modern F1 might not offer much in the way of good racing (see page 8) but there's certainly no shortage of run off. This is the Williams FW42 at Paul Ricard

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Back to the drawing board

Our columnist offers some hard-won advice on how to go about designing a racecar

One of the things that I do which is distinct from working with racing cars is giving lectures about the design, build and operation of them. At the start of the presentation the first phrase usually goes along the lines of a caveat: 'I can't tell you how to do it, but I can certainly tell you how not to do it.'

This derives from compiling all the mistakes that I have committed along the years in the business and is into volume XVII by now. This is called experience, but it is really 'oops, I was wrong, let's not make this mistake again.' And believe me, ignorance may be bliss, but it does not make you go faster and it can be very expensive.

Grand designs

The main concepts of design should cater to the following essential rules:

1 There will be a driver in it, and it is your responsibility to mitigate the consequences of any error, maintenance mistake or omission and component failure, either from operating outside the design envelope or being driven in an non-predicted fashion, to keep them as safe as possible. For example, kerbs are a way of keeping drivers inside the white lines, but you know they will drive over them when in search of a faster lap time, so design accordingly.

2 Know your physics and mechanics. Good engineering practice is not innate; it is a compilation of your and others' accumulated experience through trial and error over the centuries, still the basic operating method in most domains. My simple rule for life is 'A good day is when you have learned something new.' The corollary is also being able to disprove something you thought you knew. It is hard to change your mind, but it needs a general spring clean every so often, much like a hard-disk.

Also, be open-minded. Technology ages faster than an avocado, something that was ripe yesterday can usually be discarded as better or cheaper processes come along.

And why does creativity generally tend to decline with age? Well, growing older, we know more. It can be an advantage but it also can lead to ignoring evidence that contradicts what we think we know. It has to do with a tension between two kinds of thinking: exploration and exploitation. When facing a new problem, we exploit the knowledge about the world acquired so far, to quickly find an adequate solution that is close to the solutions already there. But exploring something new can lead to an unusual idea, or less obvious solution, new knowledge. The caveat is the waste of time in considering possibilities that will never work, some discernment is required.

To have discernment implies having knowledge enough about what you are doing, or experience. If you have not got the experience it behoves having teachers. Having good teachers is the transmission of their knowledge and experience, thus validating Isaac Newton in 1675: 'If I have seen further it is by standing on the shoulders of giants.'

3 Innovation is quite often brought about by melding new processes or technology, sometimes from other domains, to produce solutions to a problem. You will never have enough experience of all the technologies you will apply to a design because it is a compilation of several threads of knowledge you do not master, but do understand partially and should have the courage to use.

Quite often, also, there is the application of a solution to a problem you simply don't have, the classic case of a solution looking for a problem. Engineers are the embodiment of 'if it ain't broke, it doesn't have enough features.' Just because you can do it is not a reason for adding a feature.

Drivers have a habit of using kerbs and you will need to factor the likelihood of this sort of chassis abuse in to your racecar design

Keep it simple

4 Beware of over-engineering. The whole concept of engineering is to do more, faster, simpler and cheaper. Know when to stop. Design constraints are driven by knowledge, time and cost.

Being realistic, every design is flawed and incomplete in light of further knowledge but can be adequate for the time. Good enough may be a deprecating view, but if it does the work, it is valid.

5 Pyramids, ships, and spacecraft are examples of what a group of people can do when working together. Big, complex projects that no one can do on their own. Modern racing cars are definitely complex, and any endeavour to extract maximum performance will be intricate when it comes to maximising potential, those last hundredths have a cost. Remember the 80/20 rule (also known as the Pareto principle), which states that, for many events, roughly 80 per cent of the effects come from 20 per cent of the causes. I can attest to its effect; that last one per cent is very, very expensive.

Most industrial processes are the synergistic efforts of many specialists in big groups able to join efforts. Again, you will never master all you need, so ask the composite shop, lathe operator or CNC specialist.

Anyone that has been operating a machine or process all their professional life will know more than you do, that's why they are specialists; ask them what they recommend and why. The product will be better and you will have added to your knowledge base.

Even putting dimensions on your drawing should cater to the preferred method of the specialist, as they will have to do the inputs. But be careful, changing the frame of reference to what the process requires can introduce mistakes or, at best, lose valuable time.

Sunk without race

6 Sunk cost fallacy. A killer, this one. Once you have invested a great deal of time, money and credibility on any project or design, it will take a lot of courage to admit it is not going to work as well as it should and then put it out of its misery, with you taking a new tack or approach.

7 Group think can distort judgement. The biggest cock ups I have seen on track are the result of the design office having a mistaken view of a solution, but as everyone agreed the obvious (in hindsight) flaws were discounted. Be critical.

So, armed with some painfully acquired precepts, go out there and make your own mistakes. It will be fun. Some of the time.

Once you have invested a great deal of time, money and credibility into any project it will take a lot of courage to admit it is not going to work

Spoil sports

Why top-level stewards need to learn to use a little bit of common sense

I hope that the Canadian GP five-second penalty debacle will *not* have faded from its controversial post-race headlines by the time this column is printed. Regardless of the rights and wrongs of the incident (if indeed there are any), Sebastian Vettel's more measured later comments about his disillusionment concerning current F1 have contained much which should be listened to. Most important of all, they should be acted upon. The FIA's obsession with safety and correctness at all costs has become an *Ancient Mariner's* albatross circling over the sport. I am not signed-up to the 'rules are rules' view, rather I respect the time-served opinion that rules are for the (strict) obedience of fools and the guidance of wise men.

If further ammunition for my argument is required Le Mans provided it. Previous outright race winner Nick Tandy had to take a stop-and-go when his Porsche GTE crossed the pit-exiting white line by less than half a tyre width. Class-leading Pro-Am pilot Ben Keating suffered a similar penalty for slightly wheel-spinning his Ford GT out of his pit. Had Tandy joined the track dangerously, or Keating disappeared up pit-road in a tyre-smoking, fishtailing departure, then fair enough. One assumes that there are safety reasons behind these regulations, but neither incident could possibly have been described as creating a risk, nor gaining an advantage.

Against the rules

These are only the examples I saw; doubtless there were more. To me, such pettifogging bureaucracy indicates that stewards cannot be trusted with making intelligent assessments of cases such as these. This cannot be so. After all, in the real world we entrust the fate of people charged with grave offences by such a process. Is governance of motor racing more difficult than this? The stewards' room is no place for lawyers or administrators, unable to grasp that milliseconds often decide a driver's actions. It should be only for stewards with proven motor racing competence and experience. Racing is a tough competition, rather than a test of drivers' and teams' adherence to every detail of the rule book. The concept of a warning for a minor discretion 'but second strike and you're out' doesn't appear to resonate within the sound-proofed chambers of the FIA and the ACO. Political correctness has insidiously inserted itself into racing and it's time this was halted and, in many instances, reversed. Let common sense prevail.

Spec parts

Other current head-shakers move me to comment. The editor expressed in last month's magazine his criticism of the move to single-sourcing of certain Formula 1 components. I detest such restriction at this level of racing and agree wholeheartedly. Why go down this innovation-destroying, thin-end-of-the-wedge route, purportedly aimed at cost-saving, when an overall budget cap is to be introduced which would include these same parts anyway?

XPB

At the Canadian Grand Prix the F1 stewards robbed race fans of what should have been an epic dice for the lead between Vettel and Hamilton

But such contradictions abound. On one hand the FIA clings to a fiendishly-expensive power unit which has, at best, limited production-car value, on the other it concentrates attention on trying to minimally reduce the cost of wheels and brakes. Limits on super-expensive materials already exist, together with a homologation process limiting development during the season, something I've long advocated, this is a far better solution.

Moves to remove F1's Friday free practice promote another rolling of eyes, and illustrates the incredibly narrow views held by too many. F1 needs to be an event, not just a race. Build-up of interest and anticipation among fans and media at all levels can only be beneficial in Liberty's aims of generating more revenues. The sport badly needs to encourage interest from the younger generation – precisely those who might not be able to afford Saturday and Sunday ticket prices. Observation of grandstand bums on seats during P1 and P2 shows substantial spectator presence on many occasions. This means additional revenue for the track owners and race promoters, plus financial viability to the myriad of merchandising, food and drink concessions providing essential services.

The argument mainly put forward is, again, cost-saving. In the scale of F1 expenditure, one day less away from base – if indeed this would be the result – and reduction in engine/transmission running is really not such a big deal. Looking at the extravagance of the hospitality paddock I have to stifle a laugh. Most of the teams currently complain of having too few sponsors, so why have such massive edifices and the phenomenal cost of transporting and manning them around the world? Too many celebrity hangers-on occupy them, who bring very little to the show really. Some of the travel expenses could, I'm sure, be trimmed as well. And frankly, in some cases there are too many personnel employed who are over-rated and thus overpaid, as the recent drastic lack of performance from certain teams has starkly shown.

Good Friday

Another argument being made is that with 21, or even more, races on the calendar, removal of Friday practice relieves the load on team personnel, especially mechanics. This is a very fair point, but rotation of mechanics between track and base responsibilities is not beyond managing, as is successfully carried out in other activities similarly reliant on skilled team members. Making any major repairs incurred in P3 in the unnecessarily short time before Q1 might be adrenaline-filled, but it's exhausting for the personnel concerned. Friday track-time allows for proving developments – simulation doesn't always get it right – while simultaneously giving new drivers invaluable track time. I have before suggested that P1, at least, should be limited to rookies – who would bring money to the smaller teams for the privilege. So why shut off this cost-effective opportunity? If it's the random effect of less data-gathering that floats some peoples' boats, better to substantially reduce the amount of on-board acquisition. Or is this too simple?

Such pettifogging bureaucracy indicates that stewards cannot be trusted with making intelligent assessments in cases such as these

Future tense

With environmental pressure building and the danger of a dwindling pool of race fans just how will Formula 1 survive in the future? Prompted by two very different Swedes our technical consultant has formulated his own ideas

By PETER WRIGHT

It looked like some sort of dark, Scandi April Fool joke. First there was Greta Thunberg, the 16-year-old Swedish schoolgirl who refuses to attend school while politicians refuse to do something about a future that holds few prospects for her, and in April toured Europe by train to berate politicians and the Pontiff for their inertia in doing anything about climate change. Then, shortly afterwards, Swedish racing driver Stefan Johansson wrote a three-part article about the future of F1, advocating, among quite a few other things, 1400bhp Formula 1 engines.

In fact, Johansson's article was a fine, courageous and timely piece, reviewing very broadly the whole of F1's potential future in respect of economics, technologies, relevance, regulated competition, sporting issues, entertainment and, of course, its effect on the rest of motorsport. Inevitably it was from the viewpoint of a driver, but Johansson is also a commentator and has had a broad experience in motorsport, so should be listened to. That said, it doesn't mean I agree with him. I'm not qualified to write about the economics, so will try and stick to the technical and sporting matters, and, with over 55 years as a fan, the question of whether motorsport, and Formula 1 in particular, is entertaining.

Of course, one cannot ignore the economics totally. When I started off in F1 in the late 1960s motorsport, including F1, was funded by someone putting on an event, encouraging competitors to turn up to compete by offering starting money plus the promise of prize-money, and the promoter hoped enough fans would show up to pay for the show. If all involved: promoter, entrants, teams, car constructors, drivers and fans went home satisfied, the event was repeated the following year. No one became very rich and a few rich individuals became poorer. Few constructors were industry- or state-supported, and even if so, it did not guarantee dominance. It was a good business for those who loved motorsport.

Two interrelated things changed this reasonably sustainable status quo: television and sponsorship. TV vastly widened the

Former driver Stefan Johansson has presented a raft of suggestions as to how he would improve F1

Rookie Nikita Mazepin was able to turn in some decent laps at Barcelona. Does this prove the Mercedes is too easy to drive fast?

Even junior categories such as Formula 3 suffer from the effects of too much aero dependence, leading to too little passing

audience and, as we now know so well, if you can get people's attention you can influence them and persuade them to buy stuff. Sponsorship put brands on to prime time TV without the need for commercials. But, as any snake oil salesman knows, to gain and hold attention you have to entertain people.

That's entertainment

With more than half the world living in cities and another quarter in suburbs, people turn to entertainment to 'take them out of themselves'; to relieve the stress and often boredom of modern work and living. Music, films, video gaming, and sports provide the bulk of entertainment, and in total make up around a $1trillion a year business. Of this, Formula 1 is around 0.3 per cent, while video gaming is now 15 per cent and rising fast. The competition for bums on seats and eyes on screens is intense. Motorsport is finding it ever tougher to compete for the attention of young people, who are showing a declining interest in cars.

Cars have had a number of bad reputation hits recently, being held up as a major contributor to both global warming and the toxic air in cities. Whether vehicles will be able to be fossil-fuel powered, or even permitted in cities in the future, remains to be resolved politically, economically, and technically, but the passion for them and their ability to go fast is waning; while the numbers watching motorsport are declining.

Entertainment must still be emotional – passion, fear, laughter, anger, excitement – and, while motorsport has exploited passion for the motor car, it is losing influence. It is the passion stirred by the exploits of other people that entertains. Fans of football (soccer and American), rugby, baseball etc. are moved from joy to tears by what happens to their heroes on and off the field. The only motorsport personality that approaches generating that sort of passion today is Valentino Rossi. The personalities of racing drivers have been isolated from the fans. There is now so much perfection in how they and their vehicles perform, there is little to be in awe of.

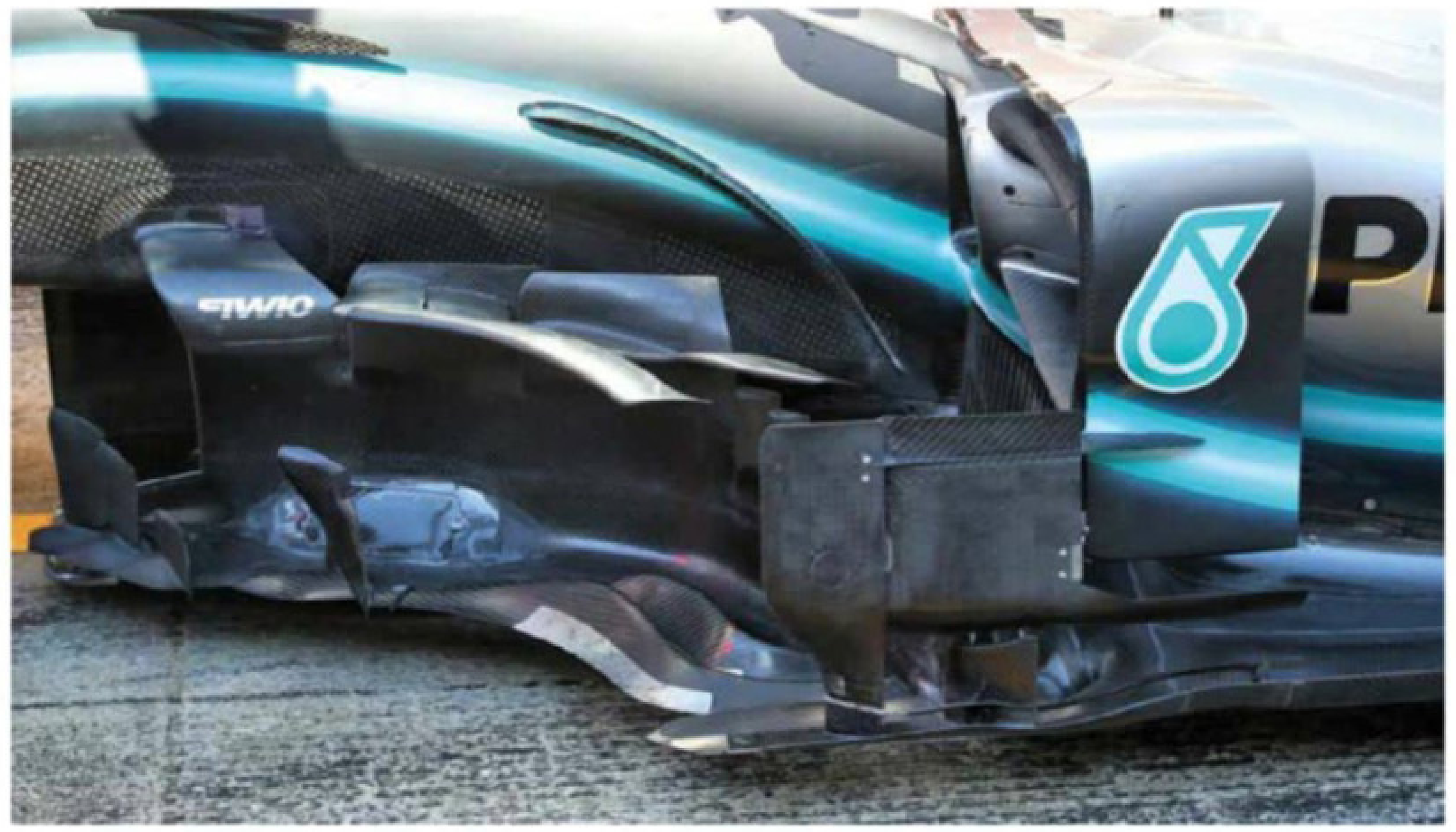
This is a magazine for engineers, and so I won't go off into a discussion about racing driver personalities, but it is still worth noting that since Michael Schumacher stopped racing in F1 attendance and interest in Germany has fallen away to the extent that a German GP is no longer economically viable. This is in spite of a German multi-world champion in Sebastian Vettel, and a supremely successful German car in the Mercedes. Neither of the latter is now able to provoke the required passion.

From an engineering perspective, what contribution does or could the car and the way it is operated make towards the entertainment provided? Sports become popular entertainment when they test and demonstrate an individual's skills, strength, endurance and ability, either alone or as part of a group or team, to vanquish others in a regulated competitive endeavour. Since the Romans raced chariots popular sport has provoked the passions of people. So why is F1 and much of the rest of motorsport failing to do so now, except perhaps for the participants themselves? Which is maybe why those same participants are not successfully sorting out the problem.

I believe there are two basic problems with motorsport as a sport: firstly, the way the cars are operated has become too optimised and too physically easy. It is too perfect to either tax the drivers in controlling them at the limit, or to do so for two hours. Neither from the track-side or the sofa is it possible to see that the drivers do anything extraordinary, or even that a car is operating in a realm much beyond normal experience: 1000bhp, 200+mph, *5g* – where? Lewis Hamilton hardly has to apply opposite lock and doesn't break a sweat when he gets out of the car after leading from lights to flag.

Motorsport is finding it ever tougher to compete for the attention of younger people, who are showing a declining interest in cars

Neither from the edge of the track or the sofa at home is it really possible to see that the Formula 1 drivers do anything extraordinary



The aero approach in the sidepod area can be fiendishly complex. This is the Mercedes at the Barcelona test

Helmut Marko recently summed it up after Russian driver Nikita Mazepin led the test days' times in Barcelona after the Spanish Grand Prix. 'That a second-class F2 driver is fast right off the bat in the Mercedes shows how superior it is.' Mazepin, on his first day in a Formula 1 car, drove a lap that was right up there with the top regular F1 drivers the week before, and completed almost two GP distances in the day.

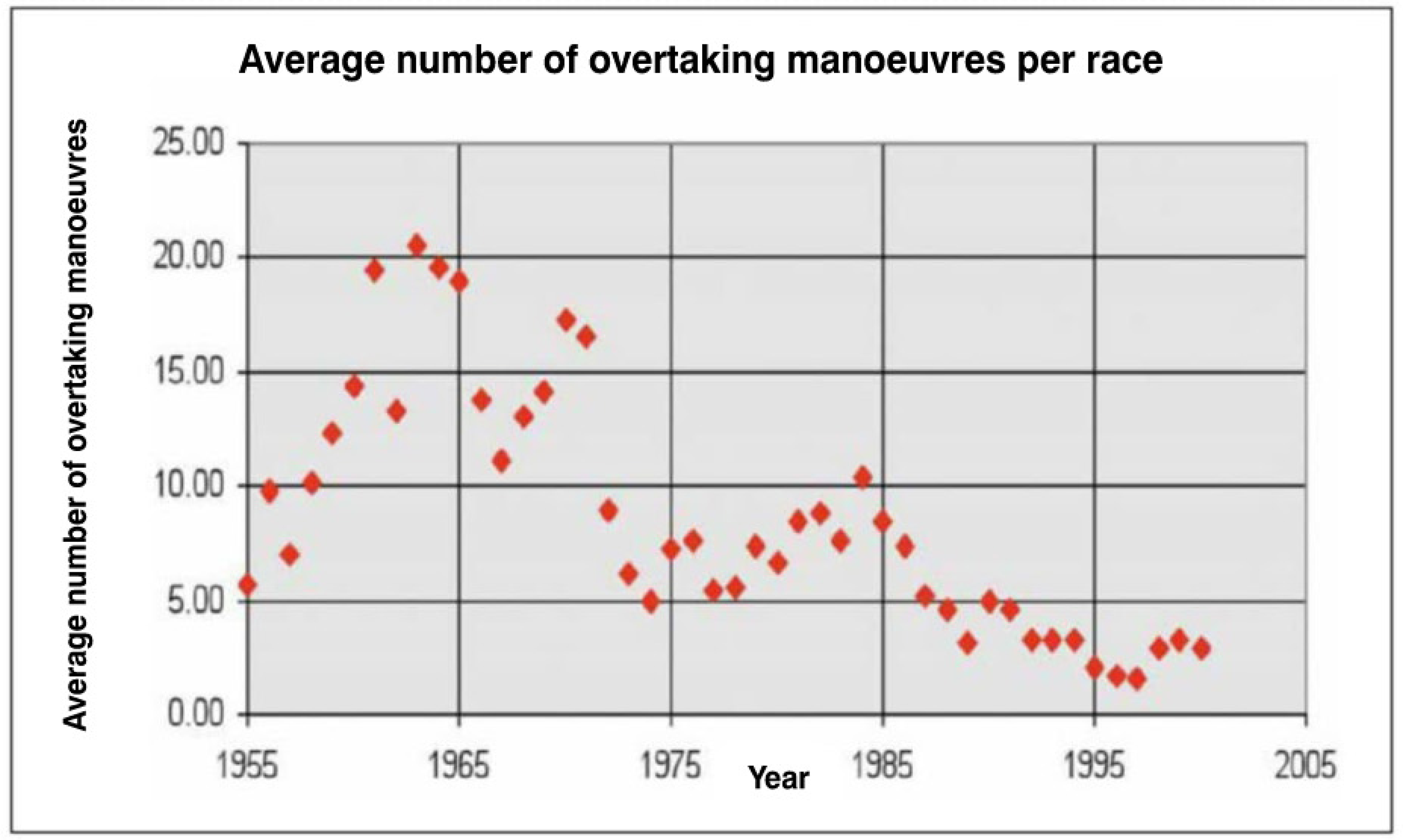
Technical overkill

What has happened to racecar driving at the highest level? Fifty years ago, F1 teams were generally less than 50 people, with maybe five to ten in the design department driving drawing boards and slide rules. In the late 1980s, design and development departments started growing, with engineering graduates recruited to run wind tunnels, test rigs, and computers. Today, 30 years later, teams are 500 to 1200 strong, and equipped with the latest CAD, CFD, FEA, wind tunnels, hardware-in-the-loop test rigs, 6-axis motion simulators, and unlimited computing power and speed.

Every part of the car – ICE , turbines and compressors, the electrical energy systems, gearboxes, multi-channel data systems, aerodynamic details (which are checked three times: CFD, wind tunnel and on track) – and tyres are now optimised using computer codes developed by aerospace.

Universities are churning out smart engineers who have been brought up with these tools. How the driver should manage tyres, fuel, electrical energy and the race overall is simulated and optimised in real-time and controlled tightly. It is not surprising that the only excitement occurs when things go wrong, and that doesn't happen very often in the well-funded, well-organised teams. The teams and drivers strive for the optimum and the result is never going to be exciting to watch.

The reality is that this cat is well and truly out of the bag and has disappeared over the horizon. Make radical changes to the cars, 300 or 1500bhp, zero aerodynamic downforce and skinny tyres, and it would be the same.



Data derived from Jabby Crombac's lap charts shows average number of position changes per race from 1955 until 2005

The engineers and drivers would optimise everything because that yields the fastest lap time and is the way to win races.

The second problem is that the drivers, even the most skilled racers, are unable to engage closely with their opponents, with the victor eventually emerging ahead. A friend who follows F3 closely commented to me recently that there are plenty of really good drivers emerging from the cut and thrust of karting who are very quick in a single seater. Unfortunately, they cannot demonstrate their skills as *the cars prevent them from racing*.

The root causes of this stem from the same era as the first issue: the 1980s. It was then that FISA, as the governing body was then called, eventually banned ground effect by eliminating skirts and mandating flat bottoms. Downforce was drastically reduced, to be replaced by 1000bhp turbocharged engines and wide, sticky tyres. Cars were not nice to drive as engineers stiffened suspensions to try and control the long, wide, flat underside of the car. Driver skill was paramount in these years of Nelson Piquet, Keke Rosberg, Niki Lauda, Alain Prost, Ayrton Senna and Nigel Mansell.

They battled within half a second of each other and whether they overtook did not matter, as the driving was exciting. Then gradually, over the decade from 1985 to 1995, the engineers tamed the flat bottoms with ever more sophisticated aerodynamics, developed in CFD and 60 per cent wind tunnels, and complex suspension systems to control the geometry between floor and road. Sidepods were cut back, front wings gained elements, end plates were developed that controlled vortices to guide the air around the tyres, the radiator intakes and the edges of the floor. These devices became more effective as ever-expanding aero departments got on top of the technology, and

The wake of a preceding racecar reduces the energy of the free-flow and introduces vortices and eddies that upset aero devices

the flow was optimised in pitch, roll, yaw, and with steering angle. From 1985 to 1995, average position changes per race reduced by a factor of four. This is the problem we have today.

What they could not do so well was to combine optimised performance with tolerance to disturbances. The wake of a preceding car reduces the energy of the free-flow and introduces vortices and eddies that upset these devices. The loss of downforce behind another car means that it cannot overtake unless the following car has a 1.5 to 2 seconds per lap speed advantage. Drivers soon learned that to try and do so was liable to damage their tyres, leading to an overall loss of race performance. Better to wait, falling back 1 to 1.5 seconds for something to happen to the car ahead, or for a strategic advantage arising from pit stops. Result: boring racing.

DRS was introduced to help the car behind make up for the debilitating loss of performance, and Pirelli was asked to introduce degrading tyre choices, to open up strategic opportunities. The banning of skirts generated the need for all these vanes and vortex generators, in-wash and out-wash devices that make the flow so sensitive to turbulence. The addition of flat bottoms increases the sensitivity of the car to its attitude. The clever aerodynamicists, with their teraflop-hungry tools, have recovered all and more of the downforce, and so we are back to the same sensitivity to the energy loss behind another racecar. This particular cat could be put back in the bag; FOM has caught the cat and is wrestling with it, but it isn't going to be easy to get it back in the sack without getting severely scratched, 2021-concepts, India-Juliet-Kilo-or-whatever notwithstanding.

A new approach

The key question is whether there is a set of technical regulations to give us a car such that the best drivers in the world can entertain us. Stefan Johansson suggests this. Powertrain:1400bhp; open cycle; open fuel; open energy recovery. Tyres: open to competition; 18-plus inch rims. Weight: reduced by 150-200kg. Aero: limit to 30 per cent of current level; standard front wing and no DRS. Electronics: standard; reduced or no driver adjustments. Communications: pit to home base; no. Overtaking: push to pass. Such a car would make most racing drivers very happy!

But they are too late for 2021 to 2025. It looks as if it will be business just about as usual for these five years. What state F1 and motorsport will be in at the end of that period is anyone's guess, but let us suppose we still need a new set of technical regulations for the period of 2026 to 2030 and beyond this.

In 2025 Greta Thunburg and her striking school friends will be in their 20s. Global 'natural' disasters may have convinced the population of the world that she is right and it will have turned on the politicians who do not do something about the state of the planet while there is still time. How will Formula 1 and motorsport fit into this scenario? This is the issue that, by itself, will have the most influence on the motor industry and the future of our sport.

While discussing what sort of racing car might fulfil society's and the fans' requirements for the second half of the next decade, I should make a few points about Johansson's proposals.

The powertrain should be discussed last, once the rest of the racecar/tyre package is defined. The key element is the aerodynamics and I totally agree with what Johansson says about this … as far as he goes.

Downforce plays no useful role in the automotive world and it has had a major negative effect on motor racing. Get rid of it! Jimmy Clark, in the wingless Lotus 49 (450bhp) is far more entertaining and apparently skilful than Lewis Hamilton in a Mercedes W10, and there was nothing inhibiting overtaking and close racing. Regulatory control of bodywork

Overtaking action is rare in Formula 1 these days, even with the help of DRS. Since the banning of ground effects in the early 1980s the aero has worked against the following car

Downforce plays no useful role in the automotive world and it has had a major negative effect on motor racing. Get rid of it!

The 1968 season saw both sponsorship and wings introduced into Formula 1, sowing the seeds of many of its current problems. This is a recent picture of a Lotus 49 from that year

can easily establish a small window that determines the permitted lift/downforce figure.

The consequences of zero downforce? Overtaking, with no need for DRS or push to pass; less drag, less power and less fuel consumption for a given velocity; less damage to bodywork with the associated performance loss; less cost – CFD, wind tunnel, bodywork, people – less effective performance from spend/budget, and therefore more equality.

Weight and see

Then there's weight. Currently in Formula 1 it's 743kg minimum empty, but including driver, of which 75kg is the driver and his safety equipment, and about 40kg the safety features of the car. To reduce the 630kg that is left by 150 to 200kg (24 to 32 per cent) is a tall order and expensive. Leaving out the hybrid system would save 40 to 50kg, which would be a start – this would be up to the supporting motor industry.

As for the rubber, in the past tyre competition has been very expensive due to the demand for extensive testing by the tyre manufacturers. It also splits the grid into two or more races. I don't believe anyone, except possibly Michelin, really wants this.

Our writer sees no advantage in switching to 18in wheels, saying this will just mean added expense for the Formula 1 teams

As for 18plus-inch wheels, I have no particular feelings about this other than that I hate them on the road. As the late John Miles used to say: 'They are rubbish, terrible for both ride and handling as anyone who drives on them on British, potholed and tram-lined roads will attest.' The 13in wheels and tyres currently used on a Formula 1 car have been developed over decades as part of a sophisticated suspension system, and so a fashion-driven change to 18inch wheels will present expensive new problems. There is no need for the better braking that larger wheels would enable. Yet this change will probably happen.

There should be no need for three tyre specifications for each event, or for mandatory tyre changes during a grand prix, but that is more of a sporting matter.

Then there is the electronics and communications. We are in the age of electronics and computers, and road cars are ever more dependent upon them. They are a part of engineering, and it would be difficult to strip F1 cars of data and controls systems.

Whether the team needs to communicate with both its driver on track and its home base during an event is really a sporting matter, but there are safety and cost issues relating to failures, which makes communication desirable.

Which brings us to the powertrain. Once the weight, aerodynamics and the tyres are determined, and a top speed that impresses fans selected, but one that does not obsolete circuits – Johansson's 250mph/400km/h top speed would present some problems – maximum power can then be selected. Without downforce and with sensible width tyres, around 700 to 800bhp would probably be adequate.

Road relevance

If the motor industry can financially and socially still be interested in F1 in 2025 for the purpose of selling its products, then relevance is likely to be important. A non-fossil fuel, i.e. synthetic, plus ICE and energy recovery is likely to be the formula – some variation on what we have now.

If entertainment is all that matters, then a fire-spitting, ear-popping, high revving ICE will be needed. Something like a 2.4-litre, 18,000rpm, V8 should do, and that could easily be reinvented at low cost to make up for the lack of industry funding. Whether they would last seven or more events, I don't know.

Incidentally, is it possible that the sound of a high revving, normally-aspirated V8, V10 or V12 was the *only* thing that made F1 exciting over the last few decades? Having watched some of a video of the amazing, electric VW ID.R taking the EV record for the Nurburgring, slower only than a Porsche 919, I suspect so.

Choosing a path

It is between these two scenarios that I believe the discussion will rage. The real issue is relevance versus entertainment. Johansson suggests that the thermodynamic cycle and energy source should be free, to encourage the motor industry to work with the clever people in motorsport and come up with the best solution for both racing and for road transport. Unfortunately, then the cost would become prohibitive, as every manufacturer would have to explore every potential solution to find the winning specification.

Clever people in the motor industry have, of course, already looked deeply at this. The Formula 1 powertrain regulations today tie down almost every dimension of the ICE, simply to prevent the level of development necessary to determine the optimum bore/stroke ratio, valve included angles, crankshaft journal diameter etc. Opening up the formula would explode the R&D necessary, and I doubt the industry could afford or indeed would be interested in this at a time when they are investing so heavily in their own futures.

Should direct communications with the driver and with mission control back at the factory be banned from Formula 1?

Without downforce and with sensible width tyres, around 700 to 800bhp would be adequate

Will such a car, and the racing that is arranged for it, capture and hold the attention of enough people to fulfil the objectives of the rights holder, the teams, and a few manufacturers? I have grave concerns about whether motor racing will be able to compete with other more human-intimate sports, films and video games. For sure motorsport will hold an attraction for those who can participate, those with the resources and time to drive racing cars, old and new, and to campaign them at some self-funded level and frequency. Some of this activity is already televised and attracts a large number of visitors, but nothing like to the level necessary to sustain the F1 commercial interests. Combining races into a wider event, with concerts etc. providing a broader experience, and making GPs into a real 'grand prix', with seriously large prizes for the winners, can only help attract the large number of people that high-level motorsport needs.

However, to provide real sustained entertainment to a large number of people, they themselves need to participate. Video games provide the opportunity to race in comfort, safety and at low-cost. Racing yourself or your mate is one thing, racing Hamilton, Charles Leclerc and Max Verstappen would be quite another. Once the games developers truly allow a player to participate in real-time, in an actual event, I believe motorsport would engage with the generation that has been brought up with the personal computer. Just watching F1 will not be interesting or entertaining enough. Real-time, real-event racing games have been predicted for years, but the technology to make it work is not trivial. It requires total cooperation between event participants, the gaming industry, and reliable, high-speed networks. It is all becoming possible.

Future formula

When we fully realise that we have been conned into believing that we can sustain a growth rate that doubles the consumption of the Earth's resources every 20 years, and the consequential trashing of the planet and its atmosphere, and we wonder why we were so stupid as to not do something about it while we still could, (science tells us that this is the next decade). We will formulate a way forward for Formula 1 and the rest of motorsport that will be acceptable to society and allow us to continue to enjoy the human and technical challenges it offers, while fuelling our passion for the sport.

Taking the rough with the smooth

There are few motorsport disciplines that ask for more from the suspension than rallycross, where the cars are required to corner quickly on tarmac, slide on gravel and fly through the air all in the space of one hectic lap. But just how do WRX teams meet these conflicting demands?

By GEMMA HATTON

'The suspension in WRX is very interesting because of the freedom the regulations offer'

If you are unfamiliar with the FIA World Rallycross Championship then allow me to enlighten you. Imagine merging the brutal environment of a rally with the chaos of a touring car race, add a jump in, and some drifting, and you are getting close. The 600bhp turbocharged Supercars punch 0-60mph (100km/h) acceleration times faster than F1, so the dash to the first corner becomes a six-way drag race. This is followed by six laps of hardcore racing on tracks where up to 67 per cent of the lap surface is dirt, while the other 33 per cent is asphalt. Then there is the joker lap, which is an alternative section of track that adds at least two seconds of lap time which every driver needs to complete once per race. In short, WRX races are close to controlled carnage.

Yet while rallycross is great entertainment, it also presents a rare and fascinating engineering challenge. Just how do you go about designing and setting up a car to maximise performance when it has to both drift on dirt like a rally car and accelerate on tarmac like a GT racer? 'The difficulty is you have tarmac with very good grip and then you have gravel sections of the track with much less grip. Getting a good car to deal with both is tricky,' explains Kenneth Hansen, team principal at Team Hansen and a 14-time FIA European Rallycross champion.

Surface tension

Graham Rodemark, engineer and crew chief at Team Hansen, adds: 'In many of the circuits, especially the newer ones, you have the F1 aspect of very smooth and fast tarmac corners where you don't need that much travel within the suspension system and you want really hard springs to support the car. Then when you are racing on the dirt surface you want to start using a WRC gravel rally kind of idea. Trying to combine that with a formula car-style suspension for tarmac is tricky, so in rallycross it is all about achieving a happy medium.'

To complicate matters further, due to the loose nature of the dirt surface every time

‘You have a much better chance of winning a race if you go into the first corner first and we definitely set up the suspension for the start line’

a wheel drives over it the material moves or compresses, resulting in an ever-changing racing line throughout a race. ‘For the drivers it is very important that we give them the right tool to feel confident and read the track because the clean line is always changing on the dirt surface,’ says Hansen. ‘You have to stay on the clean line, otherwise you will go off onto the loose dirt and lose grip, just like in Formula 1. And the clean line can be very strange sometimes – not at all [where] you think you’d want to [go].’

Soft option

This need to get an accurate sense of the ever-changing levels of grip on the dirt surface means that drivers actually prefer a car with a very soft set-up. This differs to conventional racing on tarmac, where drivers usually want a car with stiff suspension featuring stiffer springs and higher damping forces so that the chassis reacts instantly to any driver input. This is because a suspension that is too stiff on the dirt surface can lead to a loss of grip.

‘The lap time in WRX is very sensitive to grip levels, more so than in other formulas, which are usually less traction limited. So, the drivers are more and more willing to accept a car that has a relatively “lazy” frequency response, in the search for more grip,’ says Paul Doe, chief designer at Prodrive and the brains behind the innovative suspension design of the GCK WRX car. ‘It’s all very well having a precise car that you can flick around, but typically that loses you grip and that’s what ultimately kills the lap time. I think that is one of the main difficulties for the driver and that’s what is perhaps the difference between the very best and the very good drivers; understanding what the level of grip is and how it is evolving during a race.’

The key to achieving the sweet spot in this delicate balance between racing on tarmac and racing on dirt lies within the suspension design. The primary role of the suspension is to ensure that the tyre remains in contact with the track, with the largest contact patch possible for increased grip. ‘At the end of the day, the suspension is there to try to maximise the grip from the tyre, by presenting the tyre to the road in the best possible orientation,’ Doe says. ‘That includes controlling the movement of the tyre relative to the chassis as well as minimising the load variation on the tyre contact patch, because the more you minimise that load variation the higher your grip.’

In addition to maximising the tyre’s contact patch, the suspension also has to absorb bumps and undulations in the track as well as effectively control the behaviour of the chassis to these inputs. This is particularly important in WRX, because each circuit features a jump, which can be up to two metres high. With cars approaching these jumps at around 120km/h (75mph), designing the suspension and dampers to cope with the brutal impact of landing as well as controlling the resulting chassis behaviour is critical in rallycross.

‘You have some tracks with quite big jumps that are very aggressive on the car, particularly at Silverstone, but then on the other hand you have high grip tarmac,’ says Doe. ‘So, the damper is like a rally damper that has to be both a tarmac and gravel damper at the same time. Therefore, the damper needs an even wider range of capabilities within a single unit.’

Shock tactics

Added to this challenge is the individual nature of each jump. Conventional ‘table-top’ jumps allow the cars to jump up, over and land on the downhill section of the jump. But the one at Silverstone is aggressive in height and also

With an ever-changing track surface on the gravel sections of a rallycross circuit drivers need a good feel for the available grip and so the cars often use a soft suspension set-up

Dampers are really put to the test on the jumps in WRX, where they require a soft rebound yet a stiff compression. Silverstone's jump, at two metres, is the highest of the season

'The damper for World RX is like a damper for a rally car that has to be both a tarmac and gravel shock at the same time'

in profile, so if the drivers take it particularly fast the cars actually land way past the jump, at ground level, resulting in an extremely large drop for a 1.3-tonne car. 'That drop causes massive damper speeds so it is a big challenge for the damper to absorb that,' says Hansen. 'When we have discussed the jump here [at Silverstone] before, some of the engineers couldn't believe it was possible to have that magnitude of damper speed. I think it's one of the most difficult parts for the suspension because you also don't want the damper to be too stiff otherwise you will lose grip.'

'When you land you need the full stroke of the damper, so when it is in rebound, it pulls the tyres in and you only have 40mm to compress which is too short to absorb the full force of a 1.3-tonne car falling two metres to the ground,' says Daniel Pitsch, head of motorsports at Road Racing Engineering. 'So, you also need a really soft rebound when you are in the air but you need a stiff compression when you land to absorb the weight of the car. Also, what we learned is that the damping speed in these low speed areas are actually not that far away from what we see in our GT damper products.'

Another factor to consider within the suspension system is the start. 'You have a much better chance of winning if you go into the first corner first and we definitely set up the suspension and everything around that, solely for the start line,' says Rodemark. 'Quite often the drivers will want to make a change to help with their performance on track, but I don't allow it because although it might be faster around a corner by two tenths, if you are going into the first corner in sixth place there is not much point.'

By the book

As ever with any motorsport engineering design problem the first port of call is the regulations. In some categories, particularly if it involves production-based racecars, the regulations specify that certain aspects of the production car's suspension have to be carried over to the racecar. This can include the overall layout or concept, or having a front subframe which is interchangeable with the production car, as is the case in WRC. In the more extreme cases the rules can also specify that the location of the pickup points on the chassis must either match or be within a certain distance to those of the production car, like in GT4 for example. Furthermore, any clever trickery such as active dampers, interlinking dampers or composite links are typically banned to minimise costs.

WRX has some restrictions such as those relating to the front chassis legs which are necessary to meet the crash safety standards, but otherwise there is no link whatsoever to the production car. This means that not only are the suspension pickup points free, but there is also no requirement to carry over any subframe mounting points. 'WRX is very interesting because of the freedom that the regulations offer which is fundamentally you can do almost whatever you like,' says Doe. 'After that you are then into a packaging problem because if you are in a production-based formula you've potentially got a bodyshell which you have to deal with and you may have a certain allowance to modify it, but not necessarily full freedom, so packaging is a big exercise. Then, you have quite varied conditions, so you need to make a system that is adaptable between the dirt and tarmac.

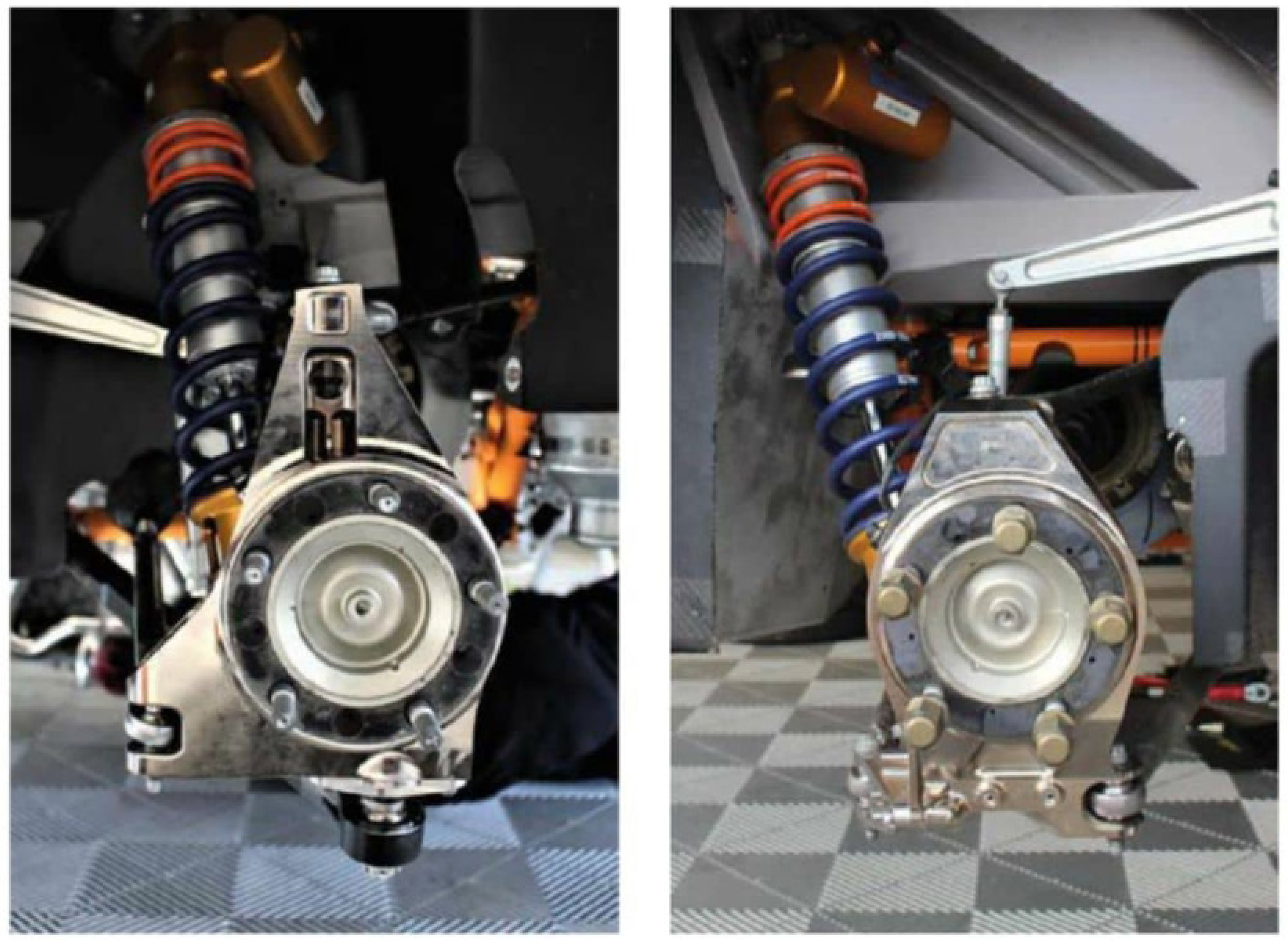
'What I've tended to see over the years is that the projects where you are really given the time to thoroughly design the suspension, the end result often looks very simplistic,' Doe adds. 'But that simplicity comes out of months of fighting and optimising. Suspension design is a multi-layered puzzle which is fun to try and solve, but if you develop something that looks elegant and simple it is probably right.'

With the majority of WRX cars conversions of those used in the WRC, the MacPherson strut is consequently the most popular type of suspension system, despite the freedom in the regulations. 'Our [Peugeot] 208 uses a MacPherson strut combined with roll bars at the front and the rear depending on where we go and what we do,' explains Rodemark. 'I think the set-up of the MacPherson strut gives us quite a wide range of adjustability and much more availability in the roll control. We don't feel it restricts us in any way.'

Bold design

There is one car on the WRX grid that has a completely unique suspension design, however, and that is because the team had the opportunity to start with a clean sheet of paper. Last year GCK entered WRX with two Renault Megane RS RXs that had been designed and built in conjunction with Prodrive. This year, despite GCK stepping back from its involvement with Prodrive, the Meganes still retain the revolutionary suspension system.

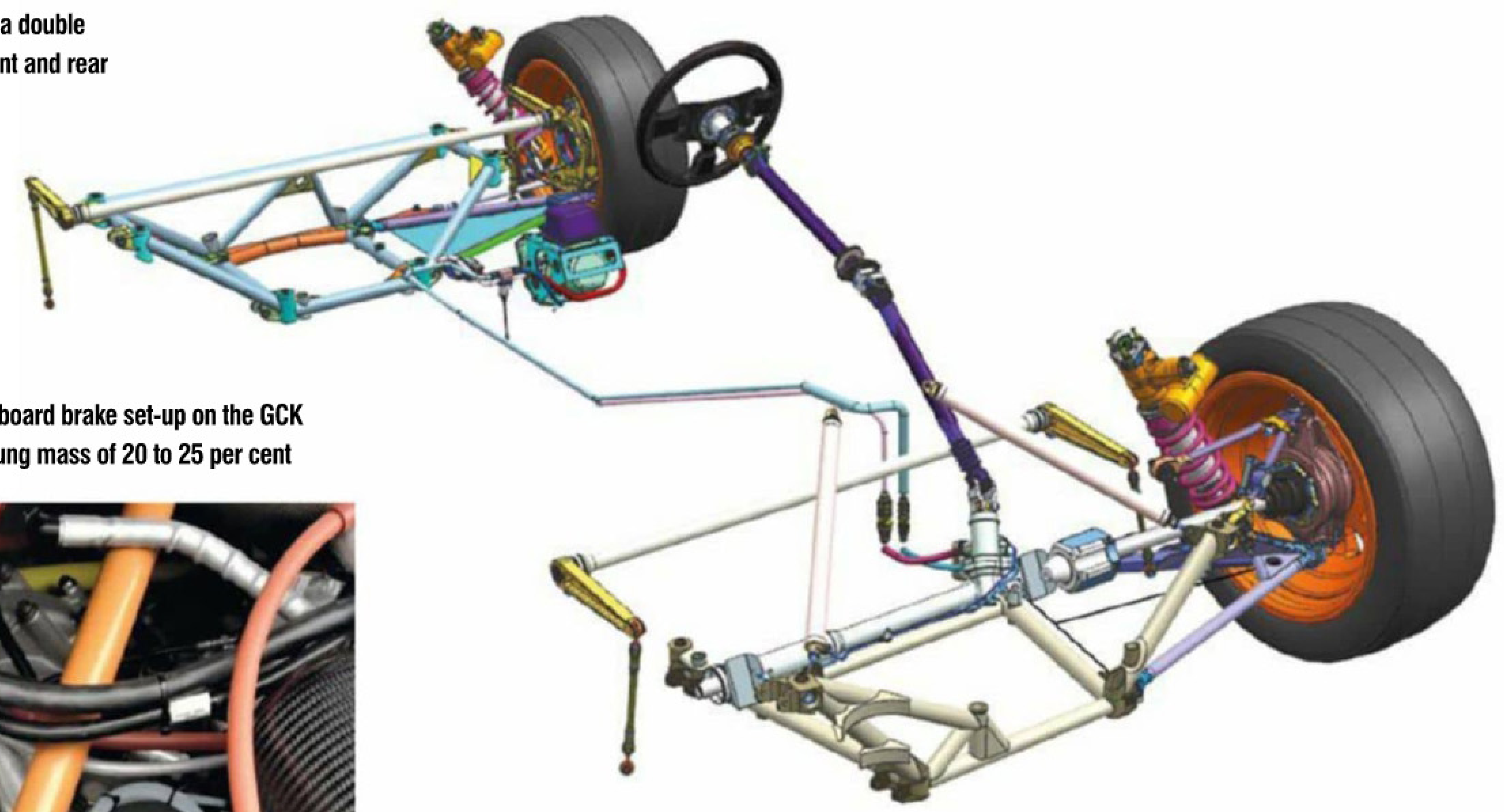
'When we came to do the WRX project with Guerlain Chicerit [GCK team owner and driver] it was quite nice to have a clean sheet of paper,' Doe says. 'I think to do something optimised you wouldn't start with a WRC regulation car because there are just too many other freedoms to exploit. One of the key decisions we took fairly early on was to run the brakes inboard, which really changes a lot of the fundamental suspension design. We were trying to maximise grip and unsprung mass is a key factor affecting tyre load variation and therefore grip. Brakes are quite heavy, even rallycross spec, so they make up a decent percentage of your unsprung mass. In F1 or GT you fight to shave grams off your unsprung mass, whereas here we are talking about taking a big lump of cast iron and a massive brake caliper and putting it inboard, which resulted in a 20 to 25 per cent change in unsprung mass. Also, with such short races the brake temperatures are less of a concern.'



The front (left) and rear (right) wheel hubs and inboard brake design of the GCK Renault Megane RS RX

The immediate consequence of locating the brakes inboard is the need for an unconventional wheel design as the wheels are normally packaged around the brake system. 'If you go to a wheel supplier, the first thing they'll say is "can you send us the brake package?" So, it was quite interesting speaking to the wheel suppliers as fundamentally no one makes a wheel like the one we needed for the Megane,' says Doe. 'Looking at the cross section of the wheel it is more similar to an aircraft wheel rather than a car wheel, which created manufacturing problems as 99 per cent of motorsport wheels are made from either castings or from forgings. In our case, the wheel is such a different shape that there was no tooling to make what we needed. In the end OZ helped us out with the tooling so we were able to do a cast magnesium wheel.'

The GCK Renault Megane uses a double wishbone suspension layout front and rear



Below: A major benefit of the inboard brake set-up on the GCK Megane is a reduction in unsprung mass of 20 to 25 per cent

Early FEA studies of this bizarrely-shaped wheel revealed further advantages. This unique configuration was much stronger and stiffer for the same weight compared to conventional motorsport rims, particularly on the inboard tyre seat. This is where there is usually substantial wheel deformation during cornering which affects camber compliance. Therefore, Prodrive's design allowed the team to run much lower static camber, leading to further benefits in terms of braking and traction.

'We then looked at the geometry,' Doe says. 'We knew we wanted to achieve lower friction than a MacPherson strut, but with better camber gain characteristics, so we looked into some double wishbone layouts. Of course, the main thing there is what to do with the damper. The rear axle is not so bad because

Rallycross engineers have to achieve a delicate balance between setting up the car to drift on dirt like a rally car yet accelerate on tarmac like a GT

'Some of the engineers couldn't believe it was possible to have that magnitude of damper speed'

‘Putting the brake discs inboard on the Renault Megane RS RX unlocked some new possibilities that weren’t originally there’

you can place the damper offset from the centreline of the upright and get it to clear the driveshaft. But at the front, where you have a steering axle and a driveshaft, it is quite a tough job to fit the damper in. There are a couple of ways of doing it. We looked at pushrod type suspensions, but we would have had to position the dampers quite high up which we weren’t happy with in terms of packaging and centre of gravity. Whereas pullrod suspension wouldn’t work because the camber change and wheel travels meant that we couldn’t achieve the desired motion ratios on the damper.

‘What we decided to do was basically place the damper so it just skimmed past the driveshaft which meant it ended up where the brakes would normally be, which was a rare option because we had moved them inboard,’ Doe continues. ‘Fundamentally, we ended up with a double wishbone concept with the dampers positioned low in the car allowing a concise load path from the damper through to the tyre contact patch. This meant we could achieve a very stiff arrangement, with extremely light upper wishbones, an optimised wheel and low unsprung mass – probably much lower than everyone else. All of this came from the ability to put the discs inboard which unlocked some new possibilities that weren’t originally there. I still think a pushrod type suspension would have been possible, but I don’t think it would have brought enough value for the compromises it would have made. The centre of gravity would have increased in the car and certainly complexity and cost would have gone up.’

Geometry set

One of the unknowns with such a design was the effect on steering geometry. This is well known for outboard braking cars. Here, all the brake torque is applied outboard which imparts torque onto the upright. Whereas during acceleration the torque comes down the driveshaft, resulting in two different forms of load application. With the inboard, brake force is applied essentially through the driveshaft only and therefore the kinematics are very different.

‘I would say that with both cases [acceleration and braking] coming down the driveshaft it is easier to control the torque steer and stability under braking because you’re not trying to deal with two different systems that are applying longitudinal forces,’ Doe says. ‘It is the same system which allowed us to make something that was predictable for the driver. During the first tests the driver feedback was very positive, the assumptions we had made had worked and we didn’t need to do any revisions on any of the kinematics on the car.

For 2019 GCK switched from Ohlins to Bilstein. Damper design is a challenge due to the tight confines of the wheel housing

It was the first spec that was designed, was successful, and is still running on the cars.’

The dampers were originally designed by Ohlins and were made specially for the Megane RS RX. These incorporated the same flow technology that it uses in its WRC and motocross dampers, helping to improve pressure control within a robust package. However, for 2019 GCK swapped to Bilstein, which was then tasked with developing its very first rallycross damper, but also one that would suit the unique demands of the double wishbone and inboard brake design of the GCK racecars.

‘The low unsprung mass makes life much easier for the damper, but what is not so good is the wheel housing, because everything is so tightly packaged,’ explains Pitsch. ‘You also need a much higher motion ratio. For a MacPherson strut the motion ratio is about one, so when your damper provides 10,000N of force, nearly all of that is on the wheel. Whereas on the Meganes when we need 10,000N on the wheel, the damper must provide approximately 70,000N. This is because there is such limited space and the travel is also long, so you need long springs and therefore a long damper housing as well as the adjustment housing. It was a lot of work to get the correct damper performance with the packaging constraints.’

Shim stacks are also incorporated within the dampers as these absorb the high frequency of racing over small stones throughout the gravel sections. Of course, the fundamental principle of damping is to adjust the flow rate of oil through a series of orifices which in turn absorbs the forces exerted on the wheel from the track’s surface. However, part of this force is converted into heat due to the resistance of the oil being forced through the orifices within the damper. So a damper can actually get pretty warm.

‘In GT, particularly in endurance races, the combination of the damper increasing in temperature together with the influence of the temperature from the brakes can affect the viscosity of the oil which then gets thinner and decreases the damping force,’ says Pitsch. ‘In WRX the races are only six laps long and there are pauses in between so this isn’t so much of an issue. But at Spa we saw temperatures of 10degC, so the oil is like marmalade that has to be forced through a hole, whereas in Abu Dhabi temperatures were over 40degC, so the oil is like water. Therefore, we have developed a new system to compensate for these temperature differences. When temperatures are high and the oil gets thinner, the damper decreases the size of the hole to achieve the same level of damping force, which is all done automatically within the damper. This ensures stable damping throughout the temperature range so the driver always gets the same consistent feedback.’

Dark arts

The challenge of maximising suspension performance whilst coping with the different demands of both tarmac and gravel running is quickly becoming a dark art. For every event, almost every race, teams and suppliers are continuously updating and tweaking their suspension characteristics in an attempt to gain those all important tenths of a second. With WRX promoter IMG having a vision of expanding the championship into new countries and race tracks, it seems that there will always be an extra element in this multi-layered suspension puzzle to solve.

Racing into a new ERA

While Formula E provides battery-powered motorsport at the very highest level, where can young race engineers and drivers learn the basics to help build a career in this lucrative arena? The all-new Electric Racing Academy (ERA) initiative might be the answer

By SAM COLLINS

Electric car racing is nothing new, indeed EVs were racing at Crystal Palace in London when Queen Victoria was still sitting on the throne, but in recent years it has certainly become ever more relevant. The automotive industry is heading to a future where all passenger cars will likely have some degree of electrification. In fact, some nations are moving to make it law that by 2030 all passenger cars sold must have either a hybrid or fully electric powertrain.

This has, in part, led to hybrid vehicles being used in the two top categories of motor racing, Formula 1 and LMP1, and also the rise of the all-electric Formula E championship. Formula E started out as a purely one-make championship, but has more recently opened up a number of areas for development, such as the motors and inverters (though the battery remains fixed). Manufacturers have piled in and costs in the championship are starting to escalate.

However, with the limited scope for technical development in Formula E and other series – there being only four manufacturers building Formula 1 power units and only one racing a hybrid car at Le Mans – there is very limited scope for engineers to learn about electric motorsport. But one Belgian businessman hopes to change all that, with his new Electric Racing Academy (ERA).

'I had been talking with some of the management of the circuit at Zolder about finding a way to use the track when noise restrictions were in place,' Dieter Vanswijgenhoven, the ERA Championship technical and business director, explains. 'It was not until I got chatting with Beth Georgiou [now the ERA sporting director] that I realised that there was a really big gap in the market. She told me that from her work running the UK Formula Student competition she had become aware that there was a real shortage of graduates who knew much about designing and engineering electric cars. Not just in terms of Formula 1 and other motorsport, but the major manufacturers are really struggling to get people with the right skill set even for production car development. Formula Student has done a lot to raise the skill levels, you can see that with some of the cars that run each year, like the one from ETH Zurich. But Formula Student is really a one-off kind of deal. So we decided to set out to create the solution to these issues, and that is how the Electric Racing Academy started.'

School run

In the mid 1990s there was an all-electric single seater category in the USA called Formula Lightning. It was aimed at universities and each team would utilise an identical chassis, but the teams were allowed to develop their own batteries and motors. It was moderately successful and lasted about a decade before folding, perhaps because it was a bit ahead of its time. Initially Vanswijgenhoven had pretty much the same idea, an all-electric racing series aimed at colleges and universities.

'We thought of it as a "super Formula Student" with grids made up of university teams, but proper wheel to wheel racing on real tracks,' Vanswijgenhoven says. 'The idea was simple, to use a common chassis and let

'There is a real shortage of graduates who know much about designing and engineering electric racecars'

the teams develop their own battery and motor solutions. Soon, though, word got out to some non-university teams and individuals about what we were doing and they wanted to get involved too. So we decided to open it up to anyone who wants to enter, as long as they are not a manufacturer or works backed team.'

Sparking interest

But the ethos of the championship remained the same: a proving ground for teams and organisations wanting to get involved in electric racing, and there has been a lot of interest, in particular from tuning companies. 'One of the key things about this series is that we want it to be affordable, initially because we were looking at universities, but now mainly because so many small and medium sized companies have shown very serious interest,' Vanswijgenhoven says.

One market that the series founders had not considered was young drivers, but almost as soon as this new initiative was announced many were contacting them looking for drives. 'Formula E is clearly a success, and the drivers are well paid to race in it,' Vanswijgenhoven says. 'But for a young driver there is not really any option to learn how to race electric cars. There is just electric karting, and that's really just low performance rental stuff, and then there is Formula E, a full on professional championship, there was nothing in the middle until we came along. That gave us three different key customers for the series: young engineers, tuning businesses and young drivers. Once we understood that it really had an impact on a lot of things, in terms of what the series would be, not least in terms of the car design.'

It was then decided that the series would have two classes racing together on track, both based around the same car, but one class would be aimed at engineers and companies, the other at drivers. 'We will have two classes, the first of them is the Sport Class, where you run our basic package, and that includes battery and motor, every car will be identical,' Vanswijgenhoven explains. 'The second, which will eventually be the faster class, is the Innovation Class. Here we have created a fair amount of technical freedom. The teams will be able to develop batteries, motors and their own bodywork within some limitations which will stop the costs getting out of control and also keep things safe.'

While the full technical regulations have yet to be finalised it is expected that there will be a

'For a young driver there is not really any option to learn how to race electric cars'

The ERA series founder and technical director Dieter Vanswijgenhoven pictured with the Dome F110/EV monocoque

'Teams will be able to develop batteries, motors and their own bodywork, within some limitations'

TECH SPEC: ERA Dome F110/EV
Chassis Carbon fibre F110 F4 monocoque produced by Dome Composites.
Powertrain All electric, 130kW single motor, 24kWh lithium based battery.
Suspension Double wishbone with pushrod actuated dampers front and rear.
Transmission None.
Dimensions Length: 4341mm; width: 1740mm; height: 950mm; track: 1550mm front / 1490mm rear.
Weight Approximately 620kg.

For race engineers and drivers hoping to work in Formula E there are not many opportunities to learn about EV racing. The all-new ERA series intends to fill this gap

'The team at Dome really understood what we were trying to do and bought into it'

maximum power level for the motor (or motors) and various safety requirements. In terms of the racecar much of the core package has to be retained, including the outboard suspension, monocoque and front and rear impact structures and some body parts.

'We created that to be a little bit of an engineer's playground,' Vanswijgenhoven says. 'Every Innovation Class entrant will have to start off with a basic kit of parts from the Sport Class car. They then have the option of developing the following parts: battery, motor, inverter and driver interface. We are looking at freeing up the rear bodywork, sidepods and some other parts, and we are also considering making dampers free in the Innovation Class too.

'But we have to retain all the safety critical parts,' Vanswijgenhoven adds. 'I think it will give young engineers a lot to work on, and will also help drivers learn not only how to drive an electric car but also how to develop one. But we are taking care to ensure it does not become a spending war. To race in the Sport Class you simply have to buy a car and enter it into the series, but there are enough common parts that if a team wanted to step up to the Innovation Class then it would be totally achievable.'

Sourcing a chassis

With the classes and overall objective of the series defined Vanswijgenhoven had to find a racecar to use. But while the open wheel single seater market is crowded in Europe, there were no obvious solutions for an electric powered car. 'I didn't see the point in creating something entirely from scratch, there are plenty of good chassis out there so we looked around to see which one to go for,' he says. 'We considered initially opening it up to allow any F3 tub car homologated in the last 10 years to be used but it quickly became clear that costs could get totally out of control that way. So we decided that we would have to go for a one-make chassis and realistically that would have to be a current Formula 3, F3-R or F4 chassis. We did think about the old Dallara SF14 or Swift Super Formula cars, but that was overkill.

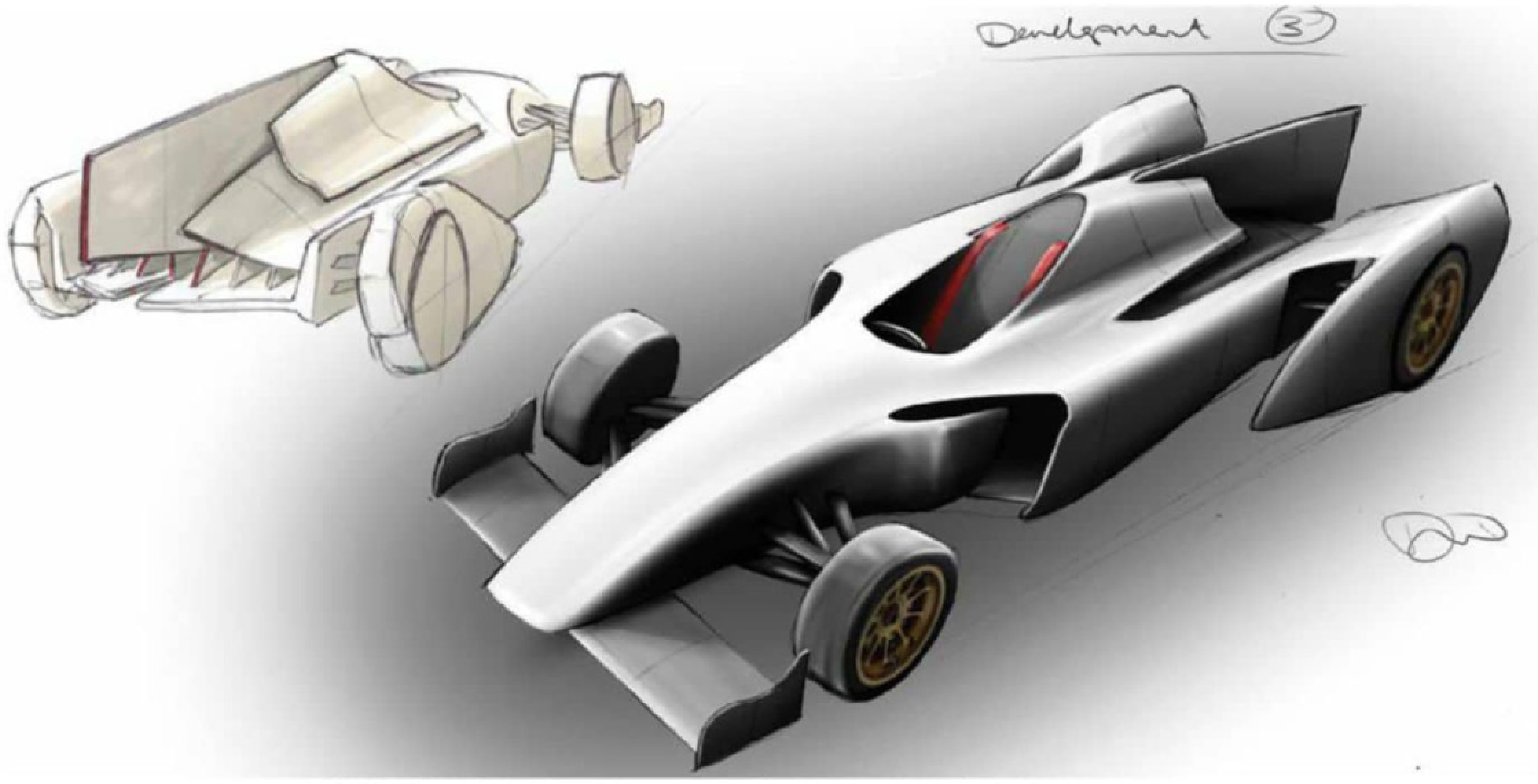
'We met with most of the major European manufacturers of course, but a chance meeting lead us to Dome in Japan,' Vanswijgenhoven adds. 'They already had two different F4 cars racing, one in the JAF series and one in the FIA series and a Formula 3 Regional chassis under development (see RCEV29N6). The team there really understood what we were trying to do and bought into it, and when we visited their facility in Japan we were blown away, they had everything we needed.'

One of the questions that the series had to tackle was whether to utilise a Halo on the car, for while usage of the cockpit protection structure is becoming more widespread it

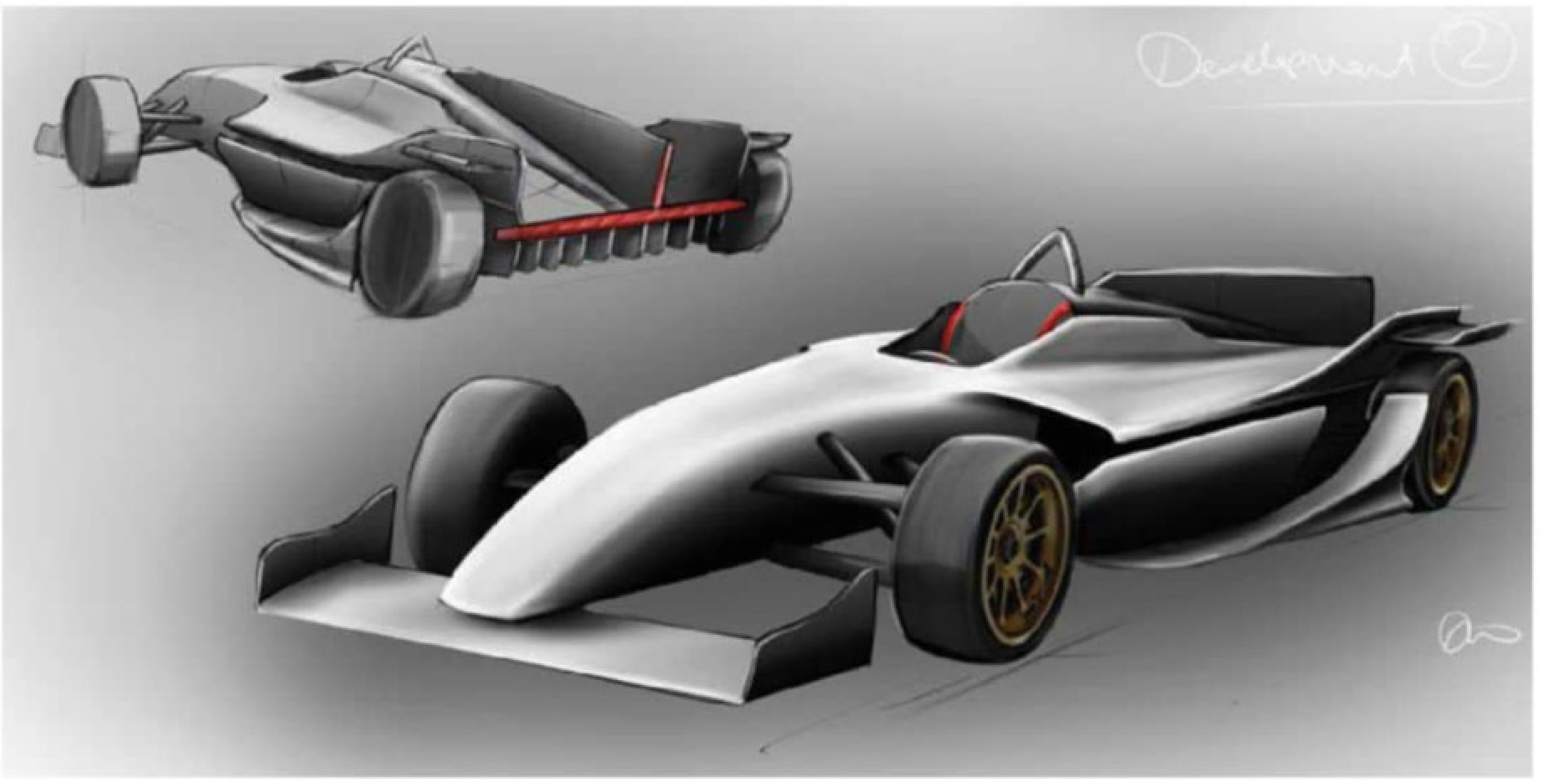
Dome F110 in standard F4 trim. ERA has designed a frame for the rear so the suspension pick-ups will remain the same

Coventry University students were asked to create concepts for the ERA series bodywork; this design is by Daehyeon Kim

Kim's design from the front. ERA has decided to run without a Halo but it did toy with the idea of a fighter jet style canopy



Left and below: Dylan webdale's visions of an Innovation Class car. In this class development of the bodywork and the sidepods is allowed



'We have designed a frame to carry the loads on pretty much the same paths as they would do on the combustion powered Dome F110'

is not mandatory outside of FIA classes. 'We considered the F111/3 regional F3 car with the Halo, or we thought about trying to retrofit Halo or a fighter plane style canopy to the F108 JAF F4 car,' Vanswijgenhoven says. 'Mooncraft did a version of that tub with a canopy and it looked great, but really all it did was add weight, complexity and expense. We knew by then that our car would already exceed the safety requirements expected at national level so we opted for the initial car to go without Halo. So we eventually settled for the F110, the car currently used in FIA F4 in Japan. It's a decent car, well proven, and from a great constructor.'

However, the Dome F110 was designed specifically as a FIA F4 car, with a combustion engine and sold as a complete package. The ERA car, being electric, did not need many elements on the bill of materials so a project started to re-work the F110 into the Dome F110/EV. 'In terms of the wider car we are using the complete monocoque, front impact structure, rear impact structure, suspension and uprights from the standard Dome F4,' Vanswijgenhoven says. 'At the rear we wanted to retain the entire suspension layout. But the F110 rear suspension picks up on the transmission casing, and we have no transmission at all, so no casing. The engines too are semi-stressed, and we have no engine, so basically behind the back of the monocoque we had a big hole and some wishbones dangling there. To fill this big void we have designed a frame to carry the loads on pretty much the same paths as they would do on the ICE powered F110, the suspension pick ups are in the exact same position. There is just not a combustion engine and gearbox there. This also allowed us to retain the rear impact structure and rear wing mounting points.'

Design study

The F110/EV will also look very different to the standard Dome F4 car. With all cars racing in the Sport Class being identical Vanswijgenhoven decided to give the car something of an aesthetic overhaul. To do this he engaged a group of automotive design students from Coventry University, and asked them to come up with concepts of what an electric racecar, based on the draft regulations, could look like. The results were striking, and one of the designs will be used by all the Sport Class cars, while the other designs give an idea of what could potentially be done in the Innovation Class.

'We wanted the series to have its own distinctive look, not be just another open wheel class, so we have come up with a look for the car which is something a bit different,' Vanswijgenhoven says. 'We are finalising that package now but it's pretty cool, and we will be testing it over the summer to make sure it is stable and not too draggy.'

One area of the car is still being kept under wraps, and that is the Sport Class powertrain, the organisers will only give vague details of it. 'I have to keep that a little secret for now, as we don't want any teams to get a head start, but it is a 130kW single motor, a 24kWh battery capacity, and we have some nice custom-designed safety features included,' is all Vanswijgenhoven is willing to put on the record. However, *Racecar* understands that a number of the components used come from current production cars, in an attempt to keep costs under control. This is very much an aim of the ERA initiative, and the organisers expect the series to be low cost, comparable to buying and running a F4 car for a season.

The first Dome F110/EV is currently under construction and by the time you have read this will have conducted its first shakedown runs. It will then undertake an extensive testing programme before the final car is revealed later this year. The series is expected to start in mid 2020 with races in the Netherlands, Belgium as well as potentially in the UK and France.

This car has taken on its own bold identity and no longer resembles a Juno, hence the name change

One New Zealander's desire to find a bit more speed from his Juno SSC racer has now escalated to the point where he's building what amounts to an entirely new car, dubbed the Matos. Our man down-under has been keeping a close eye on the project

By DR CHARLES CLARKE

Transformer

The Matos has been the subject of intense CFD development

A group of motorsport enthusiasts and professionals are currently building what could be described as the ultimate national-level sports racer in Auckland, New Zealand. The project is the brainchild of John Ryall, a successful Auckland businessman and passionate weekend racer. He has always yearned to build the ultimate sports prototype racer and compete in the New Zealand Sports Car Series.

To this end he bought a Juno 2-litre Mugen Honda powered SSC car in 2014. This had about 250bhp, but that wasn't really powerful enough. So Ryall set about 'improving' the racecar.

When he came across the CFD expertise of David Higgins of Kinetic SIM and the composites skills of Gregor Haeberlin of Haeberlin Composites, what started as a DIY renovate and rebuild project very quickly became a very professional racecar re-manufacture. Also key is the mechanical and fabrication expertise of Grady Homewood of Hitech Motorsport Ltd. If these individuals weren't available locally, this project would never have got off the ground.

ReinCarnation

The plan, until half way through the rebuild, was for the car to be a 2-litre, 4-cylinder, with the wheel and tyre configuration as per the original. But after extensive discussions with Juno, the car spec became a V6 with wider wheels and tyres that were NZ compliant, but which could be easily converted to FIA Group CN.

The basic idea was to get a more powerful engine and corresponding drivetrain, lighten the body and improve the aerodynamics. By a process of elimination, this led to a Ford Duratec 3-litre V6 (now bored and stroked to close to 4-litre) capable of producing around 500bhp, a Drexler gearbox and a carbon fibre rebuild of the entire car – except the cockpit, which is staying more or less the same.

'In its original configuration the Juno is fairly fast,' says Ryall. 'But in line with the bodywork improvements we were trying to make it even faster. It was a fairly logical step to do some CFD in order to improve things even more and the project just developed and evolved from there.'

The final car will be renamed as a Matos for commercial reasons to do with Ryall's business, and this name is already trademarked.

'What started as a fairly simple exercise to give us a little bit more speed, turned into a complete re-manufacture and rebuild,' Ryall says. 'When everything is finished, with a bigger engine and the new bodywork, it should weigh about the same as the old car. The projected all-up weight including driver is 600 to 620kg, depending on how things go, which gives us about 1bhp per kilogram [1000bhp/tonne]. It's really a go-kart with very sticky tyres.

'We have bigger wheels and tyres so as to give it a little bit more traction with the increase in horsepower we have, but this necessitated wider front and rear guards [fenders],' Ryall adds. 'The additional volume was created on the inside of the wheel houses and we've developed a system whereby we can accommodate wide and narrow tyres by swapping out the outside of the front guards.'

The moulds for all the new body panels are made from carbon fibre. 'Most people make their moulds from fibreglass for low volume production, but the rigidity of the mould is important,' says Ryall. 'So Gregor [Haeberlin] went the extra mile and made carbon moulds. With carbon moulds the part comes out of the mould with more precision, there is no flex or dimensional changes and it fits exactly. With fibreglass moulds there is usually a considerable amount of hand finishing and fitting required to make the bodywork fit together as seamlessly as possible.

'Precision is important because in a race situation the scrutineers tend to be exact to within about plus or minus 2mm, so you can't afford to have bodywork that isn't exactly to the right dimensions,' Ryall continues. 'We're also using some hi-tech fixtures to fix the bodywork to the frame – these are used in satellites and are starting to be used in some motorsport applications. They are so discreet you can't see them on the surface of the car unless you look very closely.'

Born again

UK racecar maker Juno makes what it calls the CN and the SSC chassis. The CN is slightly bigger, but the SSC seems to have been more successful. But there stills seemed to be some room for improvement. 'As we were making a carbon body for this car we decided to do some fairly extensive CFD investigation to improve the aero as well,' Ryall says. 'The floor is quite different to most sportcars in that it's flat for most of the way from the front splitter to the start of the diffuser at the rear. It's only needed under the pointed part of the

When the Matos project is completed there will be very little left to suggest this car started life as a Juno; only the cockpit will remain the same. It will be campaigned in the New Zealand Sports Car Series

The final look of the Matos will be very close to a smaller version of the pre-closed cockpit LMP cars

bodywork at the front, so the floor is almost triangular, a bit like a floor on a Formula 1 car.'

Most of the expense in a project of this nature is in the design and the preparation of the plugs and the composite moulds. 'Once the moulds are complete and we've seen some good quality parts coming off the moulds, we will get a better idea of the costs involved to build a fully carbon body,' says Ryall. 'By the time it's finished we imagine this will be a unique car, with the only close competitor being the Norma M20 FC from Norma-Auto-Concept in France.'

The carbon manufacturing process of the moulds is a vacuum infusion process with a relatively low temperature cure, rather than the more expensive autoclave process. The finished body uses pre-preg carbon with Nomex honeycomb core construction. The plugs for the moulds were made from CNC machined laminated MDF. The machining was done by Jackson Industries in Auckland, which also did much of the machining for the Americas Cup boat for Emirates Team New Zealand.

Rear view

Once the front is done the next step is the rear bodywork and the engine cover. 'The rear moulds were made using polystyrene plugs,' says Ryall. 'The polystyrene plug was covered in fibreglass and a combination of Duratec Polyester Surfacing Primer and PTFE film. The mould material is resin infused carbon and is made up of three or four layers, which is about 2mm to 3mm thick. Polystyrene doesn't like polyester resin, but epoxy works fine.'

The baseline CFD analysis for the original Juno was done with data taken from the car's body. The racecar was measured and modelled to produce point cloud data, which was then cleaned up and converted into surface data, and then transferred to CAD.

'There are two engine intakes on either side of the engine cover for the new engine configuration,' says Ryall. 'In the early stages there was no real point in producing too much detail for the engine cover until the engine and the final details were available. We feel we have achieved a great result working this part out as we went along. The rear fin is all part of the support for the rear wing. We're trying to use the existing Juno mounting points so that we can swap the body panels on and off easily.'

Most of the expense in a project of this nature is in the design and the preparation of the plugs and the composite moulds

The final look of the car will be very close to a smaller version of the pre-closed cockpit LMP racecars, Ryall tells us.

'The 3D printed mirrors are one of our favourite pieces,' says Ryall. 'These were designed and made from CRP Windform material by Dominik Scheurer, of Scheurer Swiss, in Zurich. Dominik has a background in LMP and F1. We are grateful to him for his advice on many other areas of the build.

'Sportscars don't really need lights [in New Zealand], but we've made our own version. The intention is to put an LED light strip where the headlamps would normally go, just to have some lights to flash if necessary.'

One of the things that prompted the body project was that in the original Juno the front splitter was just a piece of plywood. 'The original body evolution project came from trying to develop the plywood splitter into something a little bit more useful from an aero perspective,' says Ryall. 'A lot of the LMP cars at the time were using concave surfaces in the splitter so that a lot more air was passing underneath the car and the hoops from the nose to support the splitter. This led us to doing more detailed CFD analysis of the whole car and in particular the front end.'

There are also some ground effect tunnel influences and there is more than a hint of coke bottle shape in the rear bodywork.

'We will be redoing the wishbones using aerodynamic sections at the front to allow for a smooth airflow through the tunnels and minimise the interruption and disturbance to the airflow,' says Ryall. 'The tunnels are continued right to the back, so there is a considerable amount of ground effect aero towards the rear of the racecar.'

TECH SPEC: Matos-Juno

Chassis
Based on Juno SSC; hard points in original positions.

Bodywork
Completely new carbon body parts specified using rigorous CFD analysis.

Engine
Ford Duratec 3-litre V6 (bored and stroked to 3952cc); power, 500bhp, engine housed in custom subframe. Engine management: EFI Euro 8 from OBR; e-throttle with Jenvey throttle bodies.

Transmission
Drexler 6-speed sequential gearbox.

Suspension
Front, re-manufactured using aerofoil sections; rear, refurbished original; custom uprights.

Electronics
Aim data-logging system.

Weight
620kg including driver.

The Matos will be fully equipped with sensors to allow proper analysis of any aerodynamic changes during its development.

From the initial CFD analysis there is an increase of something like 40 to 50 per cent in overall downforce from the original Juno configuration. 'This is all simulation data at the moment, but eventually, when the car starts to run on the track, the information from the sensors will tell us the aero forces and the drag,' says Ryall. 'The convergence in the analytical models was good and the correlation to the actual aerodynamic performance on the track should be equally as good.'

The front fenders will be ventilated so that they have an aero effect as well as helping with brake cooling. There are also LMP-like cut-outs to relieve the pressure and reduce the lift.

'We have had to rebuild the radiators and reposition them for the new engine,' Ryall says. 'The radiators have been moved forward and the exhaust mufflers have been completely reconfigured, with the final exhaust exit through the side just in front of the rear wheels.

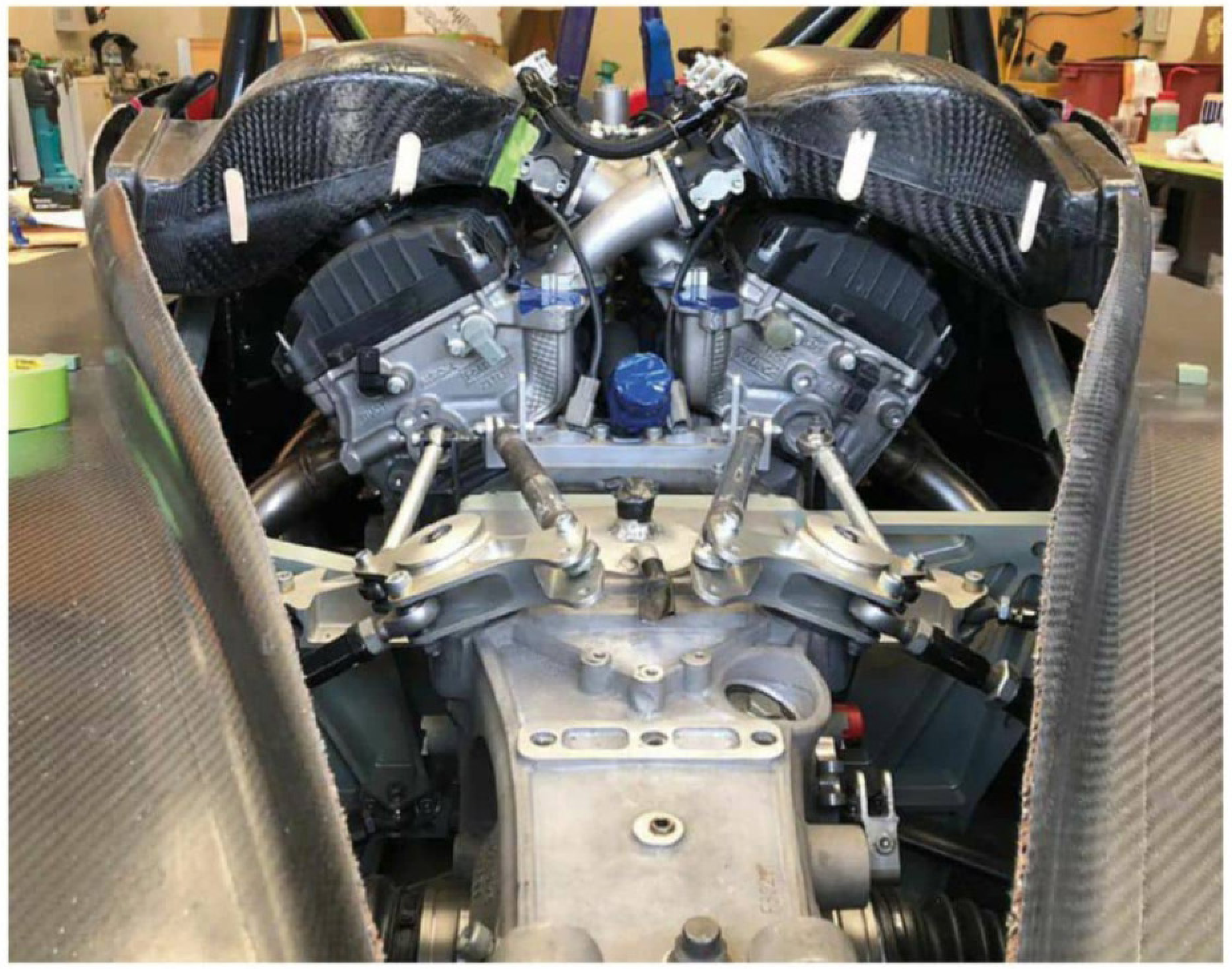
'In the really early days I was experimenting with different diffuser shapes, locations and heights on my old car,' Ryall adds. 'When I realised how even ill-informed manipulation of things like the diffuser could affect the driver experience and the downforce, I decided to do some proper aero analysis for this project.'

Agility test

The car should suit New Zealand tracks as they are quite a bit smaller than European circuits and you need to have a racecar which is relatively nimble. There are no long fast corners.

'Because of the new wheels, tyres and drivetrain we've redesigned the uprights; the original Juno ones are too big,' says Ryall. 'We are planning to remake the rear lower wishbones

There's an increase of 40 to 50 per cent in overall downforce from the original Juno configuration



Power is courtesy of a 3-litre Duratec that's been bored out to close to 4-litre. The gearbox is a 6-speed Drexler sequential

The manufacturing of the carbon moulds is by way of a vacuum infusion process with a relatively low temperature cure. The entire body will be in carbon when the racecar is finished with aero-profile tube to reduce the interference to the airflow through and around the tunnels. The upper wishbones can be standard as they are not exposed to the airflow.

'We allowed 30mm of suspension movement, which is quite a lot for this kind of car,' Ryall adds. 'The front of the car will hit the track before the 30mm of suspension movement is achieved, so it's not really a car for bumpy circuits. But the suspension is adjustable so we can vary height according to the circuit.'

Fender swaps

As mentioned previously, there are two sets of front fender outers for the different tyre sizes. 'We didn't want to make two moulds so we made a spacer for the front guard [fender] mould to produce a shallower front guard for the narrower tyre,' says Ryall.

The light lenses came out very well from the vacuum forming process. 'The vacuum forming mould was fibreglass,' says Ryall. 'The same process for LMP cars uses aluminium moulds, which cost about 10 times as much. The lens is attached to the mould and the carbon guard is moulded around it so it's a perfect fit. Because of the relatively low temperature curing, the lens is not damaged by the heat. Apart from being an elegant solution it also saves on fixtures for the light lens and the carbon resin bond is a lot stronger than if the lens was glued in afterwards.'

The lens material can tolerate 150degC and the temperature in the oven is typically only 90degC. 'Most of the people we've spoken to about this idea told us it couldn't be done, but we've managed to do it,' says Ryall. 'By vacuum forming the lens against a mould taken from the same plug as the guard mould we have achieved a lens that will then fit precisely into the carbon guard mould and be located by its shape relative to the mould, when the mould, with the carbon layup, is subjected to vacuum.'

The fasteners are also moulded with the panels rather than being drilled and glued in afterwards. The fittings for the major components will be the bonded AeroCatch fittings, which will also be bonded in the mould so that they will be flush with the surface of the panel as much as possible. One of the original design criteria was to use all flush mounted fasteners. A lot of the lighter panels are held in place using a ratchet quick release aerospace fastener.

Many of the flush fasteners available require expensive specialist tools to install them. By gluing the fastener in the mould and then moulding the panel around the fastener the installation is much quicker and more accurate.

The passenger side of the cockpit will be covered with a faired-in composite tonneau cover, so the cockpit experience is relatively snug. The rules dictate that the drivers have to sit on one side of the centreline for it to be called a sportscar as opposed to a single seat racer. The fuel tank is located centrally, directly behind the passenger space and driver's seat.

Smoothing over

In the standard configuration the Juno has a single bump behind the driver position and the intake snorkel is usually on the passenger side. There are usually two windscreen bumps in front of the cockpit, but the passenger side is flat on the inside, so the passenger tonneau cover panel will also fair this bump into the rest of the aerodynamic surface.

'We are not using the standard airbox as it doesn't really work well with our bodywork design,' says Ryall. 'So we have built moulds and made our own air boxes.'

All the panels have rebates and offsets so that they fit together exactly, with very small and precise shut-lines which offer a very clean and smooth aerodynamic surface.

This racecar has taken on its own bold identity and no longer resembles a Juno, hence the name change to Matos. But what this project really proves is that a professional racecar really can be produced by enthusiastic grassroots racers without the big budgets of the larger companies. Mind you, we will only really know if they have been successful when the Matos is actually raced. Ⓡ

The outer parts of the fenders can be changed to accommodate different wheel sizes if it needs to run in another spec


The lenses for the LED lights are made using a vacuum forming process with a mould that's taken from the fender's own mould


The team behind the Matos is especially proud of the racecar's mirror housings, designed and produced with CRP Windform

This proves that a professional racecar can be produced by enthusiastic grassroots racers without the big budgets of the larger companies

The TS dynasty

Toyota introduced the first of its 'TS' cars in 1991 but it wasn't until 2018 that one finally triumphed at Le Mans. We trace the technical development of this illustrious line to find out how the manufacturer finally discovered the secret to winning the 24 hours

By ANDREW COTTON

After 27 years of trying a Toyota 'TS' car finally won Le Mans in 2018

The current car is the quickest ever seen at Le Mans, having set an all-time fastest lap in 2017 of 3m14.791s

Toyota is these days the last manufacturer standing in the LMP1 category of the FIA World Endurance Championship. Its programme is paid for by the company's hybrid research and development department in Japan, but its actual development path has plateaued in the last five years as the manufacturer competition has slowly depleted, Audi leaving in 2016 and Porsche following it out of the door the year after.

The three manufacturers tried to find ways to save costs, and elected to only renew chassis every two years, meaning that the TS030 introduced in 2014, and 040 in 2016 followed that pattern. However, with limited competition, the 050 has run since 2016. Yet it is still dominating the championship.

The current car is the quickest ever seen at Le Mans, having set an all-time fastest lap in 2017 of 3m14.791s, with Kamui Kobayashi at the wheel, at an average speed of 251.9km/h. The 050 features more than 1000PS, weighs slightly under 900kg, and packs a twin-turbocharged 2.4-litre engine. It has crossed the line first in every round of the 2018/19 WEC season and in 2018 it became only the second car from a Japanese manufacturer to ever win at Le Mans; Mazda was the first back in 1991.

That was also the year that Toyota started its 'TS' naming process with the all-new TS010, featuring a 3.5-litre normally aspirated engine, a formula that had been decided upon by the FIA to encourage manufacturers to go to Formula 1 (which was then using this engine configuration). Toyota built the engine, but it didn't go to Formula 1 for a further decade. The TS010 was designed by Tony Southgate and built at TRD (Toyota Racing Developments), but it was run at Le Mans by TOM's GB, which operated out of a Toyota-owned facility in Norfolk, UK.

The TS050 is the most recent of the TS family of racecars

The racecar was fast enough to take on the Peugeot 905, but the team already knew this was not going to be a successful season. 'We knew that the car had a problem from during the start of the testing,' remembers Hiroshi Fushida, president of TOM's GB at the time. 'The gearbox was the issue. It was a very heavy gearbox, and almost impossible to shift. After 20 hours, no one wanted to drive the car, it was so heavy. It was internally made at Toyota, but the guy who designed the gearbox didn't have any racing gearbox experience. He was a good guy to design the production gearbox. I proposed that we use the sequential shift, easier for the drivers and less damaging to the gearbox, but he didn't want to listen.'

The gearbox wasn't the only issue; the low minimum weight of 800kg meant that the whole car was built with minimum materials, and the floor was not strong enough to cope with the rigours of 24-hour racing. The 010 raced in three seasons, winning three of its 10 races, but that elusive win at Le Mans never transpired.

Photo John Brooks

The Toyota TS010 was a very quick racecar but it was never really quite strong enough to win the Le Mans 24 hours

The TS020

After the programme finished, TOM's had to find projects so as to keep racing, so it designed cars for the British and Japanese touring car championships, and for British and Spanish F3 through the 1990s. However, for Toyota it designed a 2-litre, 4-cylinder open top car for the LMP675 category, for cars weighing 675kg. 'It was a very small budget, and we tested with Tom Kristensen at Snetterton and it was very quick, but it was only an experimental project, unfortunately,' laments Fushida.

The car was sent to TMG in Cologne, and Fushida believes that some learning was carried over into the TS020 that TMG then created. 'It was a venturi car,' says Fushida, and this was also evident on the TS020, which featured deep tunnels under the car to create downforce. This car, more commonly known as the GT One, was introduced in 1998 and was the first to be designed entirely on CAD, designer Andre de Cortenze almost developing a phobia of pens and pencils. There were drawing offices still in the building at TMG, but they were not used.

The integration engineer at the time was John Litjens, a Dutchman who was also the race engineer on the car driven by Ukyo Katayama, Keiichi Tsuchiya and Toshio Suzuki, and has since risen to become project leader on the Le Mans programme for TMG. 'At that time, CAD was coming up and you had to have a trust in that,' remembers Litjens. 'On the other hand, if you look at what we do now, with the full data management system on desks to make sure you can find your bill of materials structure, that then didn't exist. I was an integration engineer and I had to get the team to build this mock up. I knew which designer was doing which part, so I knew on which CAD station to look for the information, but it was not like now where you have a vertical tree built up and you have the car there, this didn't exist.'

The car was closed cockpit, which meant that the team had to design in doors, hinges and windscreen wipers. The lower and upper part of the chassis were bonded – it was another three years before the former TOM's facility in Norfolk, by then owned by Audi, built the first one-piece tub for the Bentley EXP Speed 8 project.

But the key to the performance of the TS020 was its aero, and intelligent interpretation of the regulations. 'I still think in the end [because] the road car was developed in parallel with the racecar [this] helped with homologation and that helped us to understand the rules, and see if they would follow this logic to allow certain things,' said Litjens. 'For the racecar you could put the fuel cell into the luggage compartment and that was how the regulation was written at that point. We had the most freedom from the aero. If you see where we had the coolers positioned, the inlet was part of the door. You open the door and you open also the inlet duct, but you could position everything nice so the front of the car was clean and free.'

The car went to Le Mans in 1998 but had gearbox issues. The Toyota team did get the repair time down from more than 10 minutes to just over six minutes during the 24-hour race, but there was no way that the car could win. That honour fell to Porsche, but Toyota was back to have another go at the race in 1999.

'It was a very heavy gearbox and almost impossible for the drivers to shift with it. After 20 hours no one wanted to drive the racecar'

For 1999, with more testing than ever behind it and with the speed to match, the TS020 was the favourite to take victory, even against the might of Mercedes, Nissan, BMW and Audi. However, a suspension failure, an accident and a blown tyre accounted for the three-car effort. 'During the night we struggled to keep the lap times up in the cooler temperatures but when the sun came up we were catching and we had a chance to win the race,' remembers Litjens. 'It was full attack.'

The TS030

Toyota withdrew from endurance racing after 1999 and focussed on its Formula 1 project, but by 2012 the decision had been taken for TMG to step back into endurance racing. Peugeot and Audi had worked with Toyota to develop the FIA World Endurance Championship technical formula and this marked the start of the full-on hybrid era. Peugeot had developed a hybrid version of its diesel-powered 908 HDI FAP and even built its own batteries for the programme in-house, while Audi used a mechanical flywheel for its R18. At the start of the year, however, with testing done and the teams preparing for the first race at Sebring, Peugeot abruptly pulled the plug on its Le Mans programme due to financial concerns within the parent company, and significant job losses, which made a racing programme unpalatable.

Toyota had been set for a year of development in 2012, but it was now suddenly asked to step up to a full race programme and to start the championship. It complied, but this meant some compromises had to be made, for not only did it have to step up to a full race team effort before time, but it also missed several stages of the development cycle, which would have focussed on light-weighting.

The team missed the opening races but was ready to go at Le Mans, and even led the race overall. The car was powered by a 3.4-litre V8 normally aspirated engine, and the capacitor was developed by Nisshinbo. The front hybrid that was eventually used by the team was provided by Aisin AW, but that was not used in the first iteration of the car, which ran with only a rear system provided by DENSO. These two companies were OEM partners to Toyota and so both wanted the opportunity to develop their product within its racing programme.

The hybrid system, by regulation, was only able to store 1MJ, already double what Peugeot had developed, but the French manufacturer could see the writing on the wall and knew that these hybrid systems would only become more powerful and more expensive.

'We developed the car to be able to test the front and rear system, but the regulations provided only for a small amount of hybrid energy,' says Litjens. 'Four-wheel-drive would have been better, but it would have been a massive weight, and [when] we started we were far away from the minimum weight because the capacitors were quite a bulky part.

For 1999, with more testing than ever behind it and with the speed to match, the TS020 was favourite to take victory

The TS020, better known as the GT One, was designed entirely on CAD. The car was plagued with gearbox issues at Le Mans in 1998

In 1999 the TS020 was pitted against the might of Mercedes, BMW, Nissan and Audi at Le Mans, yet while it had the pace to win reliability issues and mishaps ruined Toyota's race

'It was a new development and if you look at the technology at the time the super capacitor had a clear advantage over batteries, in what they could take, but the development [progressed] really quickly,' Litjens adds. 'The working range in the temperature was also key.'

Toyota was already racing super capacitors in Japan, and so it was logical to take the system and develop it using TMG's impressive resources. The Japanese were also working with a brake by wire system that took care of the brake pressure feel for the driver whether the hybrid system was regenerating or not. The driver could not tell the difference and could brake as hard at the end of a race as the start as it also compensated for brake wear. 'We had the brake by wire in the 030, but it was partly linked to what the Japanese had already started when they did this hybrid development and that fitted into our car,' says Litjens. 'Cooling had a drag penalty, but the weight was the big thing. I think it was 20 to 30kg, and the capacitor box itself was 65kg or 70kg, so it was a fair amount of weight, so we were always far over the weight.'

For the second generation 030 that raced in 2013, weight was shed at an alarming rate; more than 40kg came from the bodywork alone, a further 5kg from the tub. One of the key differences to the Audi, though, was that the Germans were able to switch off their hybrid system and be able to cope with running at Le Mans without it. For Toyota, that was not an option; the rear brakes were too small to cope without the hybrid aiding the brakes. 'If you would have kept the same size of brakes as standard you would not get the right temperature in them,' remembers Litjens. 'In F1 we had high wear because of the oxidation and you get friction wear, so if it got too cold the car can't cope with that either, so we had to reduce the size and then we had to rely on the hybrid system to work. Everything goes hand in hand, and we could cope a few laps with it not working, but not any further.'

The TS040

The big leap in hybrid development came in 2014, when the amount of stored energy went into the stratosphere. From such a small system of 1MJ, which required a lot of cooling, suddenly the regulations would permit a jump to 8MJ. The organisers did not actually expect anyone to make such a leap, but in year one Toyota was close to being able to achieve it with the 040. The team opted, eventually, for 6MJ to the relief of Porsche as they could then commit to the same having faced cooling issues with their battery. The TS040 was powered by a 3.7-litre engine, based on the previous model but with a lengthened stroke to increase capacity. This engine was developed to run with the fuel flow meter, which changed the concept of the engine from power to efficiency.

Toyota and Porsche both had gasoline powered cars, while Audi ran diesel, and with the Brake Specific Fuel Consumption playing a key part in the new Equivalence of Technology, Audi guessed that its rivals were working together to their advantage. Litjens confirmed that the two 'played the game, for sure'.

For the first time there was now a proper aero war between the three manufacturers. Audi claimed that its tub was getting broken on kerbs, and so introduced a sprung floor to protect it for the 2014 season. Others realised that it was all about ride-height and therefore performance, but it was too late for them to copy it. Toyota produced a flexi rear wing, but that was less of a help to the drivers as they had no idea how much downforce they had through fast corners such as the Porsche Curves at Le Mans. Porsche had flexible rear bodywork that lowered at high speed, reducing drag.

However, the hybrid system remained at the forefront of development. Audi retained its flywheel system for the new regulations, Porsche continued to develop its batteries, while Toyota ploughed on with the super capacitors, which were fast to charge, and fast to drain. However, the capacitors were also expensive to produce, and cost as much to change as an engine – and changing them was a regular occurrence for the Toyota team. The fast-charging nature of the capacitors meant the technology should have had a performance advantage, but it was still a heavy system.

'From the hybrid system the development was done to reduce the weight and from the chassis side we had to do another step to package everything,' says Litjens. 'In the end it was so tough and we were above the minimum weight, but if the performance gained outweighed the weight, then you still have to go for it. And we won the championship.' However, victory at Le Mans still eluded Toyota.

The fuel flow meter changed the concept of the engine from power to efficiency, and this meant a big switch in thinking for its designers

The TS030 represented Toyota's return to top level endurance racing; but it had to debut the car earlier than planned so as to fill a gap left by Peugeot's withdrawal from the WEC

The TS040 boasted a flexi rear wing at Le Mans in 2014, but the wing was quickly withdrawn as it was unpredictable. It won the WEC title but not Le Mans

In 2015 a highly developed TS040 went well in testing but failed to deliver when it mattered and was off the pace at Le Mans

Then 2015 brought a reality check. The team developed the car so that it was '80 per cent new', according to technical director Pascal Vasselon, but the majority of the work had been done on the aerodynamics, with very little undertaken on the powertrain. The team found a big performance improvement and was confident, but it wasn't until it reached the first race that the alarm bells started to ring. 'We were limited in our resources and we raised our concerns,' said Vasselon at the time. 'The first time we put the car on the ground at Le Castellet [for testing], we were 2.5 seconds faster. Then we went to Aragon, 2.5s again. It was a clear gain from the chassis. This was amazing. In F1, with stable regulations, we never saw such a clear gain. Usually you try to convince yourself that you are better but the lap times are not necessarily there. Here, it was a no-brainer. It was a big step and the drivers reported that the car was much better.

But the euphoria was not to last for long. 'At Spa [for the first race], you see everything: high speed, low speed, powertrain, and we saw that we were really behind,' Vasselon adds. 'Where we had made 2.5s, the others ›made five. It was as simple as that.'

The TS050

After Le Mans, in which Toyota just wasn't competitive, the company promised its full support and for 2016 a whole new car was introduced. This was the TS050, which featured a new tub, a new hybrid system with the move to batteries, and a new engine, a 2.4-litre V6 twin turbo. The leap to 8MJ was a welcome one for the drivers, one reporting that he was a little giddy with the extra power. The engine was originally planned for 2017, but development was rapidly accelerated, with senior engineers switching to the twin turbo engine and taking over from the younger engineers who had started the programme and were developing the concept. An 800v battery system was also introduced for this season while Toyota also introduced FRIC suspension, and while this

'Where we had made 2.5s, the others had made five. It was as simple as that'

combination was all a performance advantage, it meant that the team went to every race without a proper baseline from which to work.

'We did a back to back performance test, to see if it brings something, because it costs some weight, but we have seen on a normal circuit some benefits from it,' says Litjens of the FRIC system. 'But if you do a one to one comparison it is very difficult. You have to run quite a lot with the car to extract the maximum from it. It was fun, though.'

The racecar came close to winning Le Mans, that elusive goal, but a link to the turbo broke in the final hour, leading to a sequence of shut downs that meant the car did not take the chequered flag, and was not classified. It was heart-breaking for the team.

Toyota returned in 2017, but this time there was no Audi, the German manufacturer announcing in October of 2016 that it would end its programme. Dieselgate hadn't helped, with large fines on the horizon, and diesel had become a dirty word. In the background, a proposed rule change to go to 10MJ was rescinded, but by the time that decision was taken engineers in Japan had developed an exhaust energy recovery system and dyno tested it before the regulation was scrapped.

Audi's withdrawal left Toyota and Porsche alone in 2017, and again there was drama at Le Mans. The TS050 was quick, but various failures including clutch, electronics following a puncture, and a hybrid system failure cost Toyota the win. Porsche took its third victory on the bounce, and then retired from the discipline to focus on its new Formula E programme.

Audi had left the WEC by 2017 but the TS050s suffered from a litany of reliability issues and Porsche won its third Le Mans in a row

The 2016 Le Mans was heart-breaking for Toyota, its TS050 coming to a halt while leading in the closing stages of the race

Toyota claimed victory with a distance that would have beaten Porsche in the previous two years

The Toyota TS050 won the Le Mans 24 hours for a second time this season

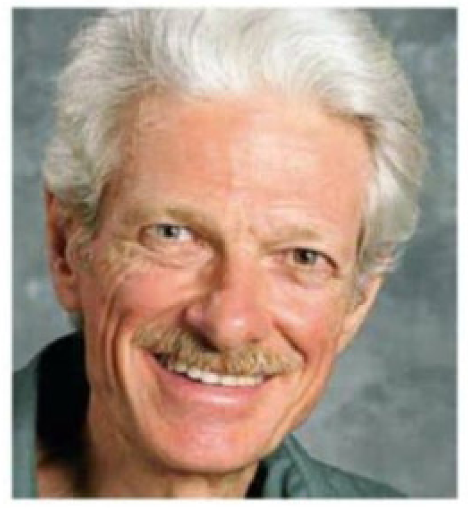
Incidentally, Toyota's battery development meant that the temperature operating window was higher, and the compulsory air conditioning system was no longer required for the battery. The battery therefore reverted to a more traditional water-cooling system.

Alone as a manufacturer for the 'super season' which ran from Spa in 2018 to Le Mans, 2019, Toyota had to find ways to race against the privateers. The team acknowledged that it would have to give up performance to allow the non-hybrids to compete, and reduced its maximum stint length, increased its weight and also reduced the amount of fuel that it carried, but the privateers were still not able to compete (see *Racecar* V29N7). The Le Mans win was of primary importance, and this was Toyota's best chance to clinch it.

Victory at last

'The only thing that really paid off was that instead of having the ultimate push for competition and performance, you can look more at Le Mans and reliability,' says Litjens. 'We changed the private testing completely, to thinking about what can go wrong. The performance we can keep at a good level and work on the other stuff.' And with this approach, finally, Toyota broke the jinx, and claimed victory with a distance that would have beaten Porsche in the previous two years.

The car has now won every race of the 2018/19 season, including Le Mans 2019 on the road, but the results table shows that both cars were disqualified for damage to the floor at Silverstone. The TS050 has won the teams' and drivers' title, and the cars will race on into the 2019/20 season, the fifth year that the team has relied on this tried and trusted chassis.



Anti-roll bars, pinion angles and differing differentials

This month we're looking at how sway bar size affects handling, the myths surrounding pinion angles, and road course versus oval diffs

Q How does the size of the sway bar affect racecars? I know you can run softer or harder springs when you change the bar size, but why is that? And how does it affect the caster and camber?

THE CONSULTANT

A A sway bar, or anti-roll bar, is an interconnective spring, almost always in the form of a torsion bar. It connects a front or rear wheel pair. In its simplest form, it resists only oppositional motion of the two wheels: when they move in the same direction, the bar just turns in its bushings and offers no resistance; when one goes up and the other goes down, that twists the bar and it resists the motion.

The bar and the two springs both resist roll. Together, they create the elastic component of the roll resistance. The geometry of the suspension generally also creates some roll resistance. So, for a given amount of roll resistance, a stiffer bar dictates softer springs.

At a given speed in a given turn, the car will have an amount of lateral load transfer determined almost entirely by its track width and cg height. The front and rear wheel pairs have to absorb this load transfer, and they split it in proportion to their respective total elastic and geometric roll resistances. Assuming equal track width at both ends, if one end of the car has 60 per cent of the roll resistance, it experiences 60 per cent of the load transfer.

So increasing the roll resistance at one end of the car, whether with the anti-roll bar, the springs, or the geometry, increases load transfer at that end and decreases load transfer at the opposite end. Load transfer hurts lateral acceleration capability (side bite), so increasing roll resistance at one end of the car makes the *opposite* end of the car stick better.

BRESMEDIA

Old style anti-roll bar on a Formula Ford 1600 – it's adjusted by sliding the vertical rods on either side along the bar

Roll play

The size of the bar dramatically affects its stiffness. The stiffness varies directly with the fourth power of the diameter. It also varies inversely with the square of lever arm length, inversely with the square of lever arm end to contact patch motion ratio, and inversely with the first power of bar length.

On oval track cars, sometimes the bar and its associated hardware can be markedly asymmetrical. In such cases, the bar can create roll moments in response to vertical forces on the car. In extreme cases the bar can even pick the left front wheel up off the ground when the front end of the car is pulled straight down and the car is not allowed to roll.

Increasing the roll resistance at one end of the racecar makes the opposite end stick better

Changing the bar does not in itself change camber or caster. Using a big bar/soft spring set-up on an oval track car will cause the front end to run lower through the turns, and that will affect camber and caster. In that case, as a general rule, the car will require more static positive camber on the left front, less static negative camber on the right front, and less static caster on both front wheels.

Some say roll bars create more load transfer than other means of resisting roll. That's not true. Roll resistance has the same effect on load transfer distribution, no matter where it comes from. The suspension has to act through the tyres to resist roll, and it inescapably changes their loads in direct proportion to the roll resisting moment generated.

Another myth is that anti-roll bars cannot or should not be used with beam axles. They are less needed with beam axles because these can safely have more geometric roll resistance than independent suspensions, and in some classes in stock car racing they are prohibited on the rear axle. However, they work just fine with beam axles, and are used with them very successfully on all sorts of racecars and road vehicles. They are particularly useful on road racing cars with live rear axles, in conjunction with low roll centres. This combination reduces torque wedge – the change in diagonal percentage that results from driveshaft torque acting through the suspension.

Q What is pinion angle and how does it affect a car? How would you calculate it and around what angle would be ideal?

THE CONSULTANT

A Pinion angle is the side view inclination of the rear axle's pinion shaft. Horizontal is generally taken as zero. Over the years there has been a lot of mythology among oval racers about pinion angle. According to some, the car puts power down better when the pinion shaft has a nose-down attitude.

A NASCAR stock car on a road course (Watkins Glen). Detroit lockers are much better suited to oval racing applications

An abrupt increase in thrust from the outside wheel adds oversteer and creates the 'locker twitch'

Some others say having it nose-up does the same thing. I do not subscribe to any of that myself. I actually think the main effect of oddball pinion angles is to increase U-joint friction, reducing power to the wheels and giving the illusion of more traction.

There may also be a small tendency for the driveshaft to try to straighten itself out when it is running with lots of U-joint angularity, but fundamentally the driveshaft is designed to transmit rotational force only. It is not an axle locating member.

For smoothest operation and good U-joint life, the usual recommendation is to have the pinion shaft statically at the same side view inclination as the crank center-line. For production cars, this will generally be around four degrees nose-up. This is usually measured with an angle finder on the companion flange.

For best U-joint life, we want small U-joint angularity, but not quite zero. We want the parts to move enough so the needles in the cups don't Brinell (indent) the surfaces they run on, but that's usually not a problem.

Adjusting pinion angle

How we adjust pinion angle depends on the type of suspension. In some cases, we get changes in the geometry of things that do locate the axle when we change pinion angle, and these will affect the handling.

With truck arms or leaf springs we can adjust pinion angle by changing the angle of the arms or springs with respect to the frame, or we can change it with shims or mounting pad modifications where the springs or arms attach to the car's axle. Changing the position of the springs or truck arms with respect to the frame changes anti-squat. With leaf springs it changes bump steer. Changing the angle of the axle housing with respect to the springs or arms has no such effects.

Sometimes, particularly with Late Model dirt track stock cars, a Panhard bar attaches to the nose of the centre section. The height of this attachment point will change if we raise or lower the front of the centre section. Lowering it will reduce rear geometric roll resistance. This may add understeer, although not if the car corners with the left rear suspension topped out and the left front wheel off the ground regardless of this adjustment.

One effect of changing pinion angle that is often unrecognised is that it also changes the height of the oil filler plug on the differential. Assuming we fill to the plug, that affects the oil level in the diff. This is one reason that otherwise identical diffs, when used in different vehicles, will sometimes have different filler plug locations. Running too much or too little oil in the unit adversely affects its efficiency and operating temperature.

Q Will you please explain the differences between the rear end differentials of road course and circle (oval) track racecars and why they are each designed the way they are?

THE CONSULTANT

A Stock cars mostly use Detroit lockers. These are not quite true differentials, but they are used for the same purpose: to drive two output shafts from a common input shaft, while allowing speed differences between the output shafts. A true diff maintains a designed torque distribution between two output shafts and lets their relative speed vary freely. A true differential with limited slip adds some sort of friction mechanism that in some manner limits how freely the relative speed can vary.

A locker is different. It drives both output shafts at the same speed ordinarily, but will let one wheel overrun if it receives a bit of reverse torque from its wheel. In most lockers, either wheel can overrun (but not both at once; there is still engine power or engine braking to the slower wheel). This means that there is not a fixed torque split. Instead the torque split can vary freely but the speed split cannot, up to the point where the torque at one wheel goes negative. Beyond that point, the slower wheel gets essentially all the torque, and the faster one has just enough reverse torque to overcome a light spring and unlock it.

When cornering, the outside wheel overruns and the inside wheel drives. This holds true until the driver applies enough power to spin the inside wheel. Then the unit locks and the drive is then shared by the two rear wheels in proportion to the traction they have. There is an abrupt increase in thrust from the outside wheel. This adds oversteer, creating the 'locker twitch'.

Staggering fact

There is also a special version of this device that is used only on oval tracks, where only the left wheel can overrun. One might suppose that this is backwards. Doesn't the right wheel need to overrun in a left-hand corner? It would, except that these units are used with enough tyre stagger to make the right wheel turn slower than the left one in a left turn of the radius that track has. So the outside wheel drives, until the driver applies enough power to make it slip a bit. Any locker twitch then adds understeer rather than oversteer.

Spools, or totally locked rear ends, are used for both oval track and road racing racecars, but they are more popular for the oval race circuits, where tyre stagger can be used. On a road course, a spool makes the racecar understeer, or push, unless the driver is inducing oversteer with the throttle or the brakes. But a driver's ability to do this, and also their inclination to drive this way, varies a great deal.

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Reducing drag and improving balance on a Britcar Bimmer

This month our BMW M3 E46 aero study focusses on wing angle changes, splitter end fences and vortex generators

Having previously raced his 3.2 BMW M3 E46 in the UK's Kumho BMW Championship and the New Millennium series, Piers Reid has now moved into the Britcar Sprint series and, with the help of the MIRA full-scale wind tunnel, he now wants to unleash more of the car's aero potential.

Reid's primary goals were drag reduction and improving aerodynamic balance. With a static weight distribution of around 53 per cent front, our target downforce balance range was in the upper 40s to 50 per cent front. As **Table 1** illustrates, we managed to find both high downforce and low drag balanced set-ups. This month we examine some of the adjustments that helped us to achieve that.

Table 1 also makes reference to wet and dry baseline set-ups. The car arrived at the wind tunnel following an outing at Silverstone, where wet conditions had prompted an increased rear wing angle over that used in previous dry testing. Thus we initially focussed on wing angle reductions from the Silverstone wet setting to dry baseline setting with two adjustments, allowing us to plot the changes in **Figures 1** and **2**. Clearly the responses were essentially linear over this part of the wing's range on this particular car. The wing started at 6.5 degrees (measured over upper surface), and rear downforce reduced by 26 per cent while total downforce reduced by around 16 per cent at the lowest wing angle used at this stage of 2.4 degrees. Front downforce, as measured at the tyre contacts, increased by 15 per cent although not primarily through any aero interaction; most of this response would have been caused by changes to the mechanical leverage from the wing's overhang behind the rear axle affecting vertical loading on the front tyres. While drag reduced by 6.5 per cent, the aerodynamic balance also changed beneficially, as **Figure 2** shows. Once again the response of aerodynamic balance was roughly linear, amounting to a little over two per cent front per degree of wing angle change in this instance.

The Britcar BMW M3 E46 undergoing tests in the MIRA wind tunnel. It came to the session with a wet set-up

Table 1: Baseline aerodynamic coefficients and optimised set-ups

	CD	-CL	-CLfront	-CLrear	%front	-L/D
Wet baseline	0.494	0.698	0.178	0.519	25.5%	1.411
Dry baseline	0.462	0.589	0.205	0.384	34.8%	1.275
'High downforce' balanced set-up	0.477	0.722	0.351	0.372	48.5%	1.514
'Low drag' balanced set-up	0.430	0.603	0.295	0.309	48.9%	1.404

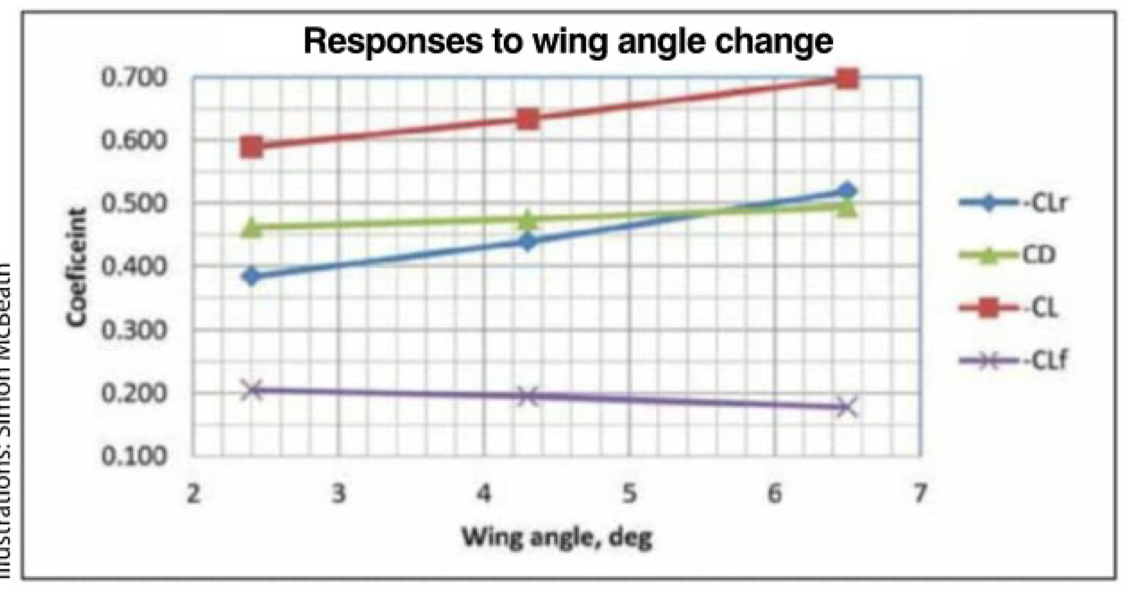
Table 2: The aero effects of the splitter end fences

	CD	-CL	-CLfront	-CLrear	%front	-L/D
Dry baseline	0.462	0.589	0.205	0.384	34.8%	1.275
Small fences	0.477	0.641	0.257	0.384	40.1%	1.345
Large fences	0.480	0.653	0.267	0.386	40.9%	1.360
Large fences (2)	0.484	0.648	0.264	0.384	40.7%	1.339

Front end

After the wing angle reductions aerodynamic balance was still only around 35 per cent front, so focus switched to looking for front end downforce gains. Twin dive planes were already installed, and the splitter featured well-designed front diffusers, so two sizes of fence were attached to the outer ends of the splitter. The bigger fences were initially left unattached at the rear, but were then taped in place. The results in **Table 2** make for interesting reading.

The small fences had created an appreciable, reasonably efficient response, adding 25.4 per



Illustrations: Simon McBeath

Figure 1: This shows the coefficient responses to wing angle changes on the BMW

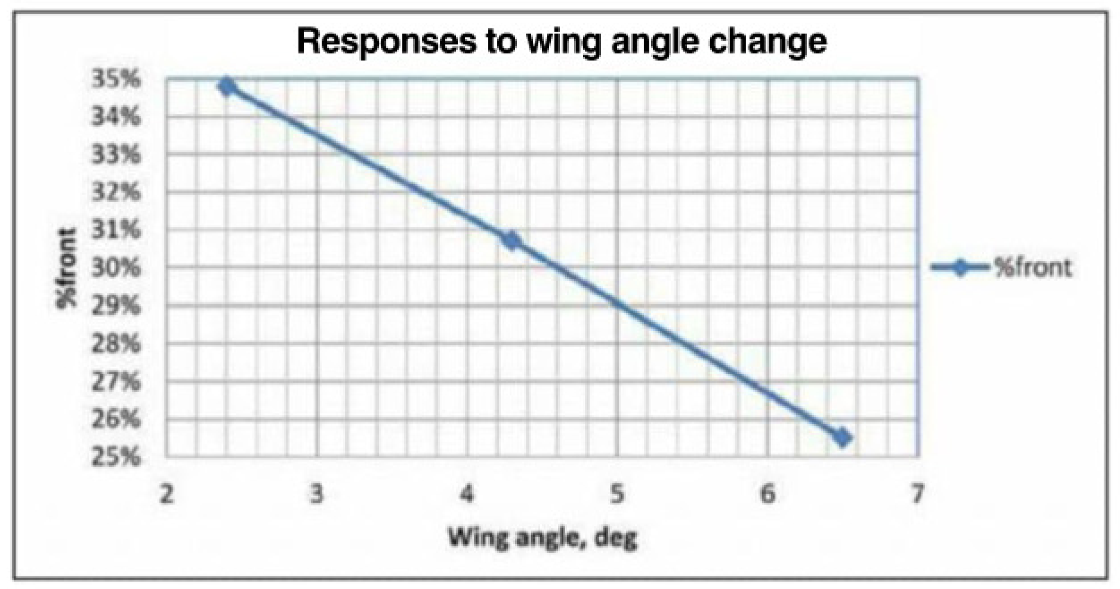


Figure 2: Aero balance response was also linear over the wing angle range tested

cent more front downforce for a 3.2 per cent drag increase, and balance improved to just over 40 per cent front. The larger fence was even more effective initially (+30.2 per cent front downforce for +3.9 per cent drag) but was rather less efficient when it was attached to the wheel arch. In unattached guise with 'wind on' it could be seen bowing outwards, leaving a gap between its top, rear corner and the wheel arch. One might have expected this to reduce drag and downforce compared to when it was attached; in fact drag was slightly reduced but downforce was slightly increased! Perhaps there was improved interaction with the lower dive plane when the fence was unattached.

Conjoined dive planes

A spontaneous question that arose during our session was 'what would happen if we put an end plate between the two dive planes?' **Table 3** gives the answers (as 'counts', where one count = a coefficient change of 0.001, and percentages), and the short answer was 'it didn't help'. But what mechanisms could have been at work here? The end fence would have completely prevented vortex formation under the upper dive plane, and at least restricted vortex formation under the lower dive plane. Vortex lift, or rather vortex downforce, is at least part of the mechanism of downforce production with short, steeply-inclined curved plates like these, where the reduced pressure in the vortex core that spills from the raised pressure area on the top surface to the reduced pressure area under the bottom surface acts on the lower surface of the dive plane. And the vortex itself also helps to maintain attached flow on the underside of the dive planes, which otherwise would likely see flow separation, by increasing upwash in the underside flow. Limiting and preventing this vortex formation would therefore have reduced the downforce contribution of the dive planes in two ways. Note that the effect of such an end plate may be far less marked on shallower dive planes that act more as conventional thin wing sections rather than as vortex-inducing 'canards' like these very steeply angled items.

More vortices and fences

Another device often seen along the rear of the roof of saloon/sedan vehicles is a row of vortex generators. Quite possibly pioneered in this application by Mitsubishi on the Lancer Evo, with its rather steep rear screen angle, the effects in the company's own research using wind tunnel and computational methods were very modest improvements in drag, through reduced flow separation on the rear screen, and very slightly improved rear downforce, through increased flow to the low boot-mounted wing. With the BMW's sleek coupe shape featuring a gentle rear screen angle, and a relatively high mounted rear wing, it seemed improbable that vortex generators on the rear roof line would bring any benefit, but presumption is not always supported by the facts and so we tried them anyway. Within the very small margins of error in our wind tunnel results (better than +/- 0.3 per cent) there was absolutely no discernible effect on drag or downforce.

Another idea seen on a competitor's car was a pair of fences set at about one third and two thirds width on the splitter's top surface. Whether these were to aid structural support or perhaps influence cooling flows is unknown, but once again they made no perceptible difference to this car's data.

Next month, more on dive planes, plus rake changes to find the perfect balance.

Thanks to Piers Reid for supplying the car.

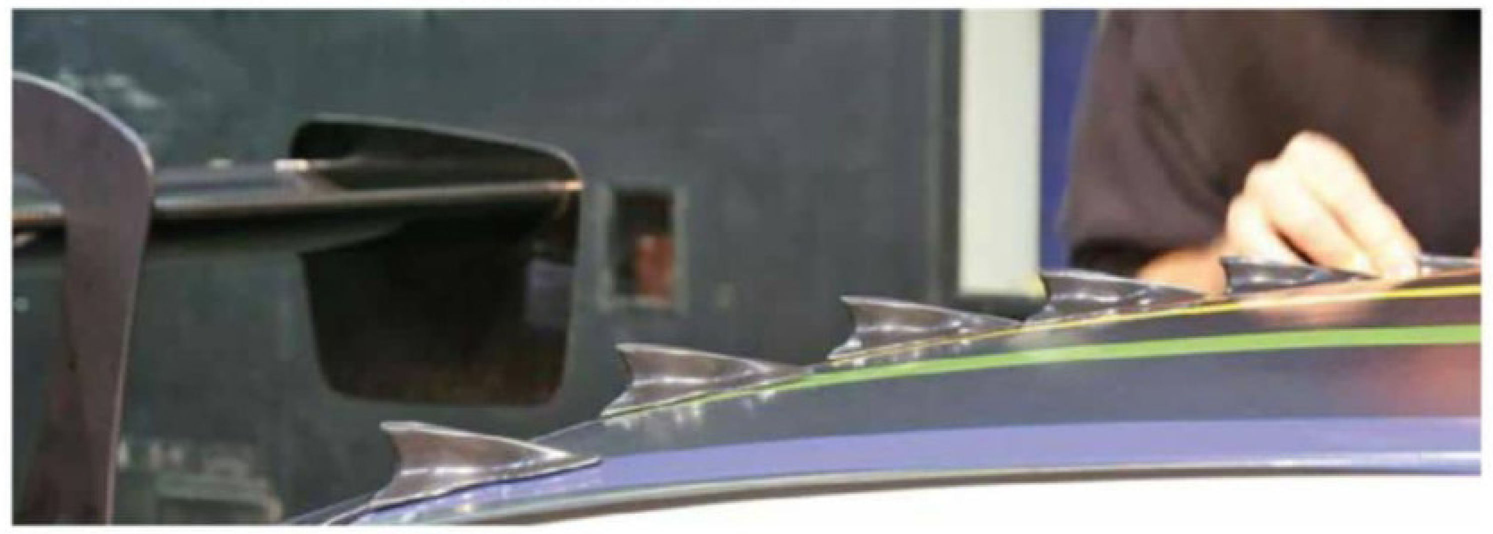
Two splitter end fence sizes were tested; this is the larger one

Might an end plate on the dive planes also prove beneficial?

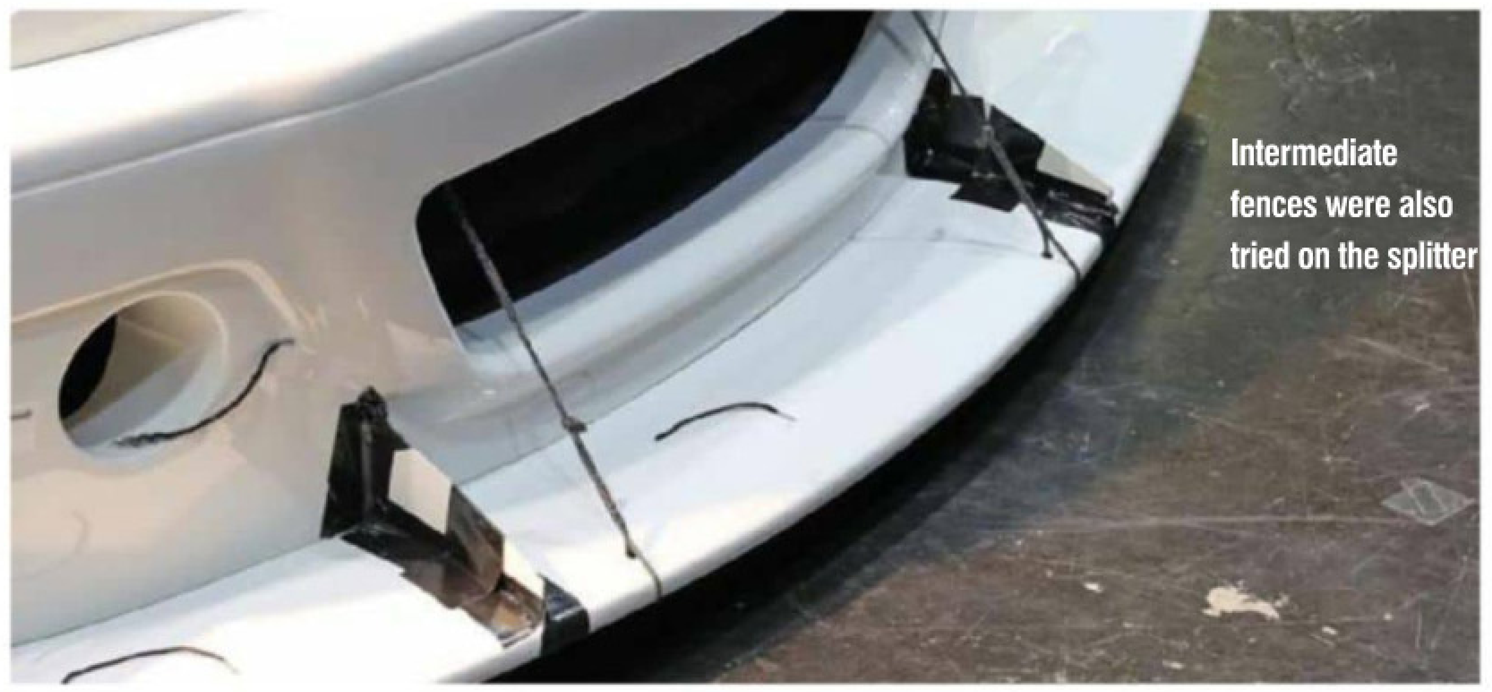
Table 3: The effects of a dive plane end fence

	ΔCD	Δ-CL	Δ-CLfront	Δ-CLrear	Δ%front*	Δ-L/D
Δ, counts	-4	-27	-32	+6	-2.9%	-45
Δ, %	-0.8%	-3.9%	-10.0%	+1.6%	-	-3.1%

* Changes in %front are absolute, not relative.



Would the Mitsubishi Evo style vortex generators on the roof of the BMW really have a noticeable aero effect?



Intermediate fences were also tried on the splitter

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How the Ouest was won

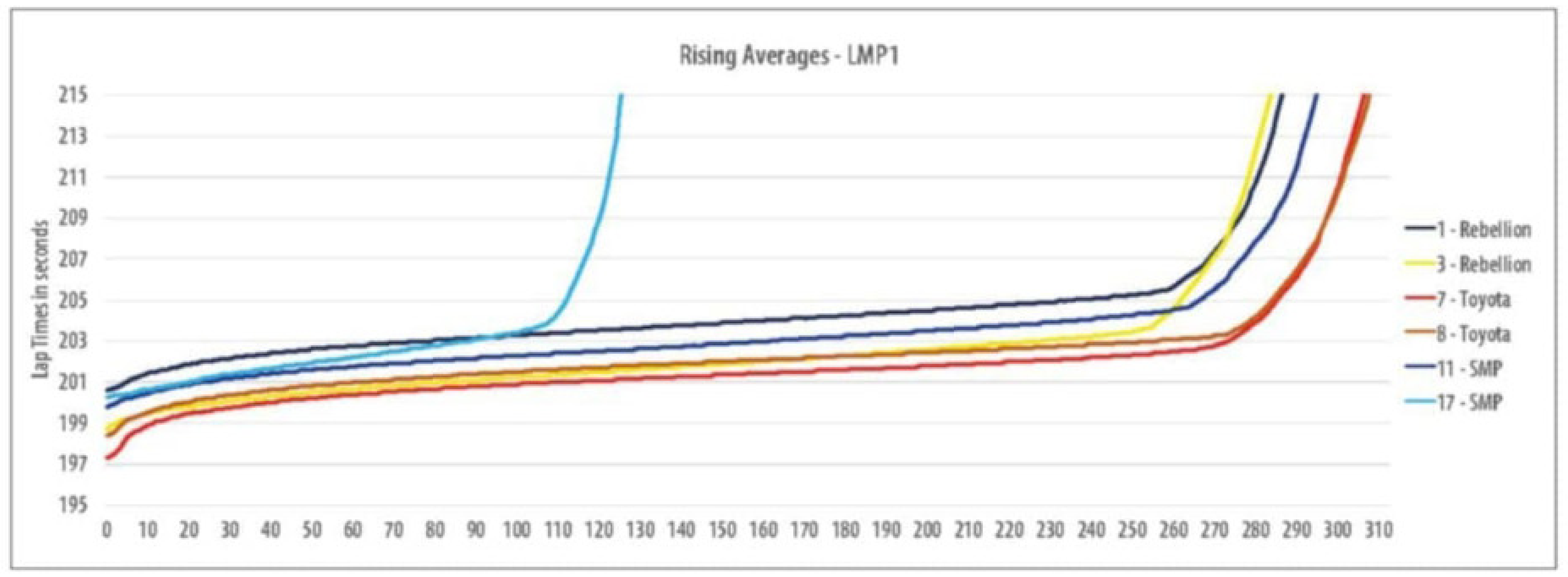
While Toyota dominated at Le Mans this year there was still a surprising result at the flag, with the No.8 car inheriting the win after 23 hours. Here's our detailed review of what turned out to be a fascinating technical spectacle

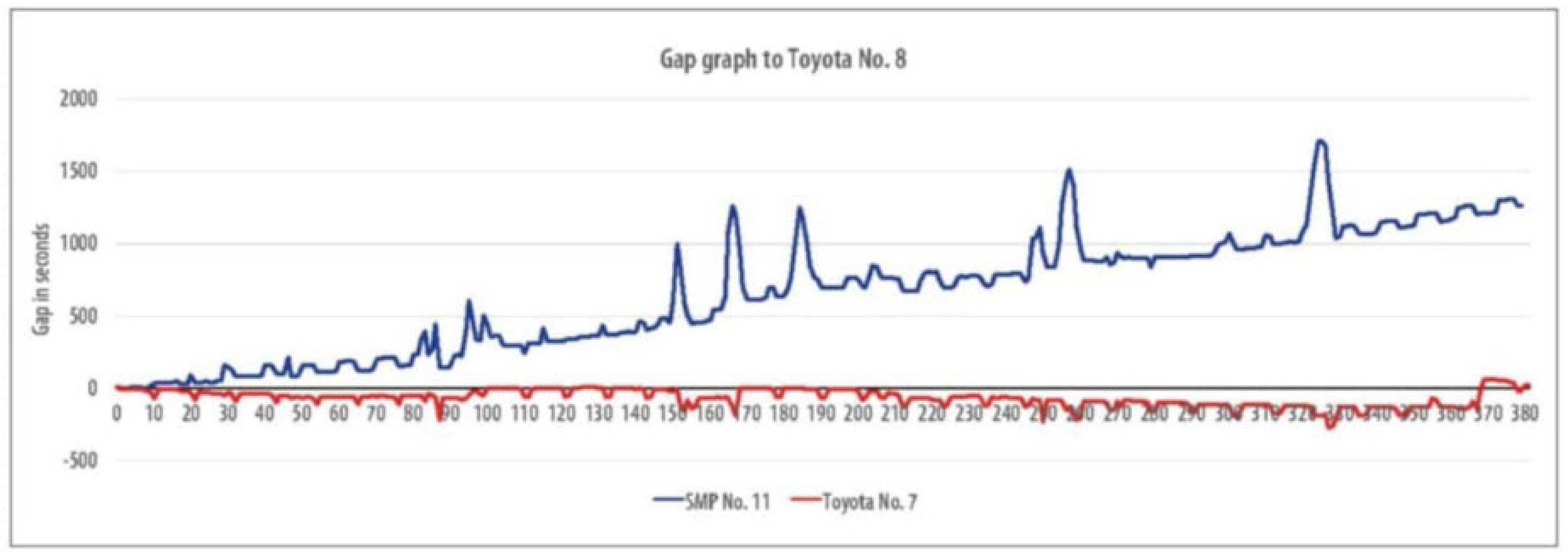
By ANDREW COTTON

The No.7 Toyota was the star of the race and the moral winner, leading 339 of the 385 laps – but it had to settle for second place in the end, finishing 16 seconds behind the No.8

Toyota dominated the final round of the 2018/19 FIA World Endurance Championship as expected, finishing six-laps ahead of the first of the non-hybrids. However, the finishing order was not decided until the final hour, when a wiring fault meant the team changed the wrong tyre on the No.7 Toyota TS050 of Jose Maria Lopez. The Argentinian therefore had to complete a second slow lap with a punctured tyre, and make an extra pit stop that not only cost him his lead of more than two minutes, but also dropped him a minute behind the sister car in the final hour.

The conspiracy theorists immediately claimed that the result was fixed in favour of Fernando Alonso, who would garner more column inches for a victory than Mike Conway, but in truth this was simply the result of Toyota making a mistake, and the crew of No.7, which had dominated the event and led 339 of the 385 laps, had to be content with second place.





Title winners

Victory, or even second place, was enough for Alonso, Kazuki Nakajima and Sebastien Buemi to become the world champions. Conway, sharing the No.7 car with Kamui Kobayashi and Lopez, admitted that it would be easy to say they had finished the season with nothing, but actually they had contributed to the team's first and second at Le Mans two years running, and the same goes for the championship.

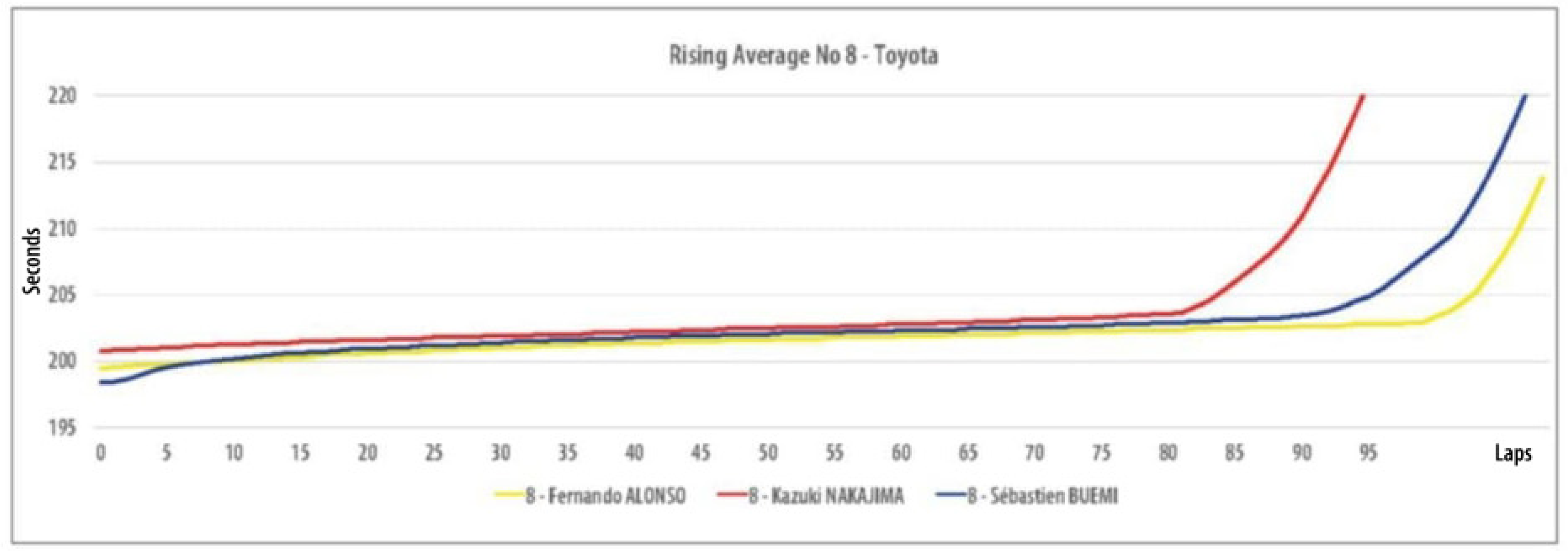
There were changes to the sporting regulations for the 24 hours this year, and the most notable of these was the introduction of the full course yellow (FCY) procedure for the first time. Calling a FCY meant that the pits would close in a bid to prevent anyone taking advantage of their rivals going slowly while they, due to position on track, could create an advantage based on luck. However, these sort of things are never quite foolproof, and so it turned out on the Saturday night as the two Toyotas switched positions for the overall lead of the race for exactly that reason.

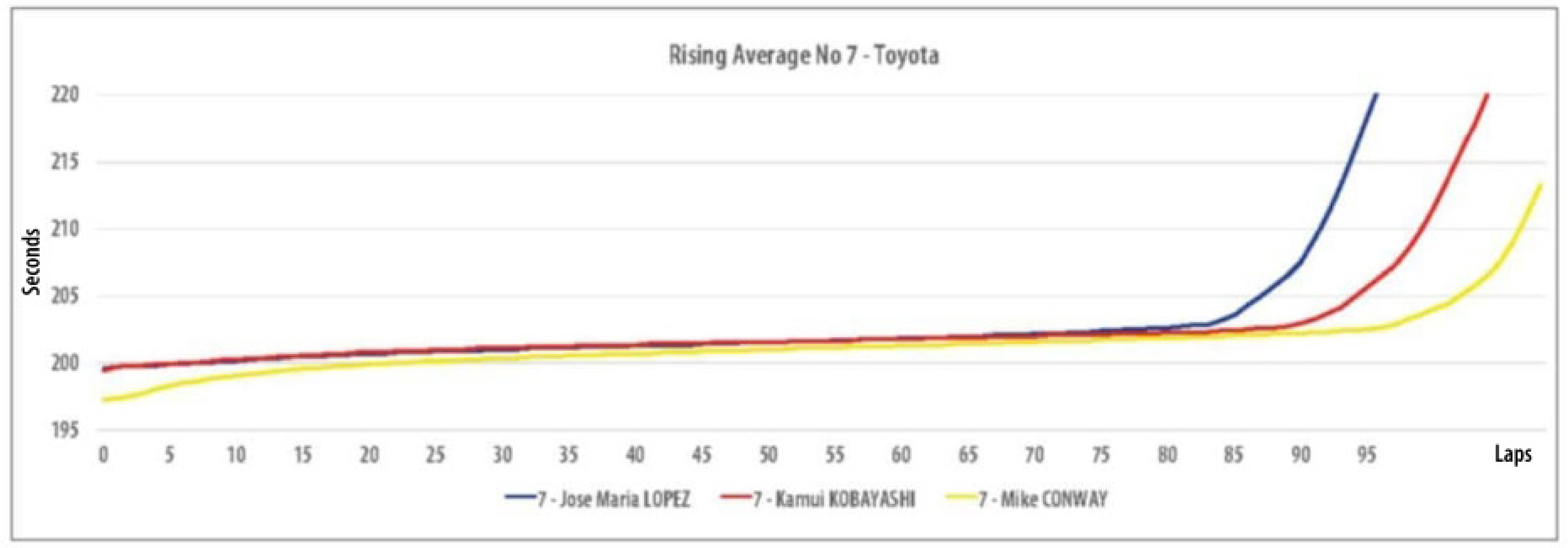
The FCY was used throughout Saturday, but during the night it appeared that the strategy had switched, and that there would be a move towards safety cars rather than full course yellows, as major barrier repair required the use of heavy machinery and it was actually safer to have the racecars behind safety cars to create gaps in which the track was empty.

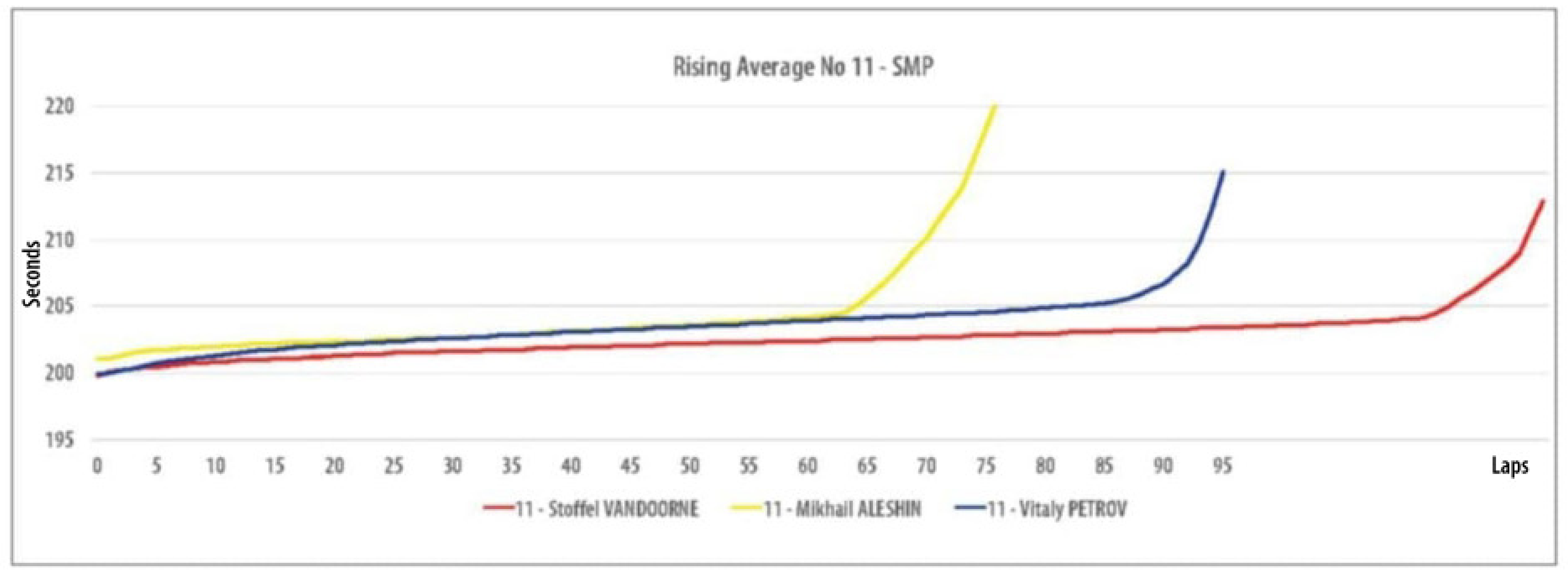
The focus of the race director was on the GTE-Pro category, although according to Toyota the regulations actually stated that the GTE-Am cars would be given priority in the slow zones. Assuming that this was a typing error, this meant a slow zone would remain active until all the race leading GTE challengers would go through before it was lifted, in a bid to reduce the impact on a race result.

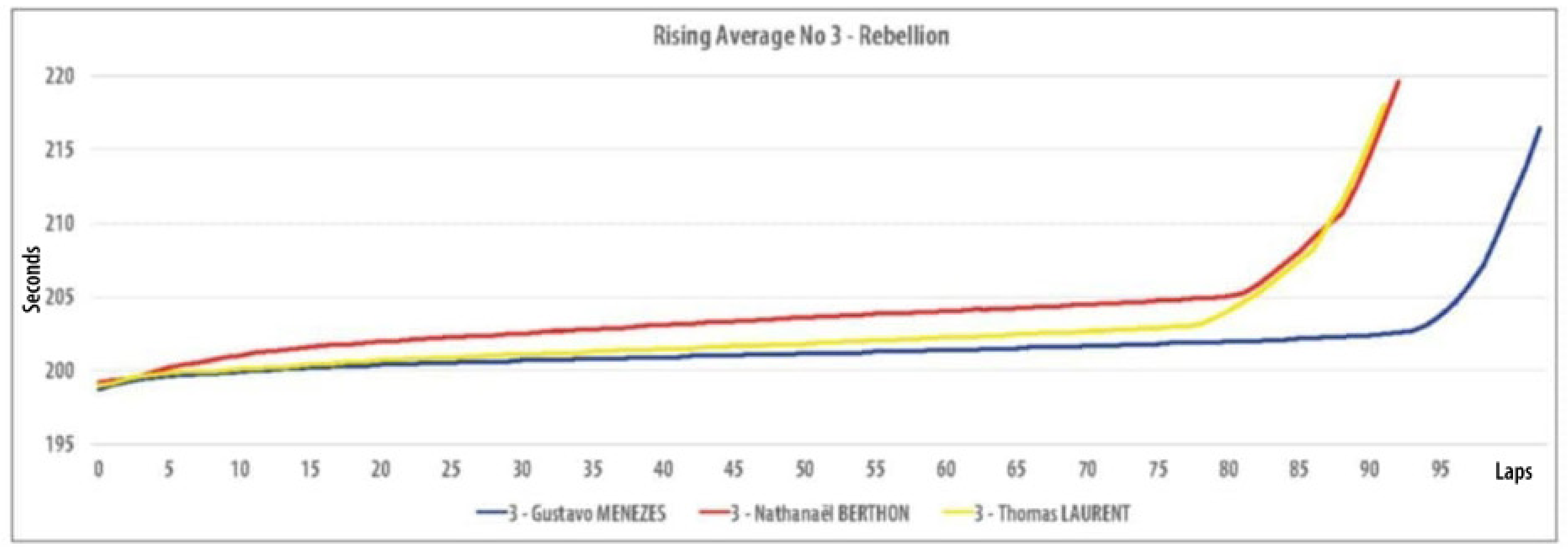
Ultimately, however, with a lap of Le Mans still classed at 13.625km, three safety cars was always going to be a game of chance and so it transpired, as both the LMP2 and the GTE Pro grid were split by their introduction. The overall race lead was also affected on Saturday night, as the No.8 car was in the pits as a full course yellow was called following an accident, while the No.7 car was scheduled to pit a lap later, and so went further at reduced speed than its sister car and lost its advantage.

From the moment the cars started running on the Wednesday evening before the race it was clear that the Toyotas would have a performance advantage over the non-hybrids









Early omens

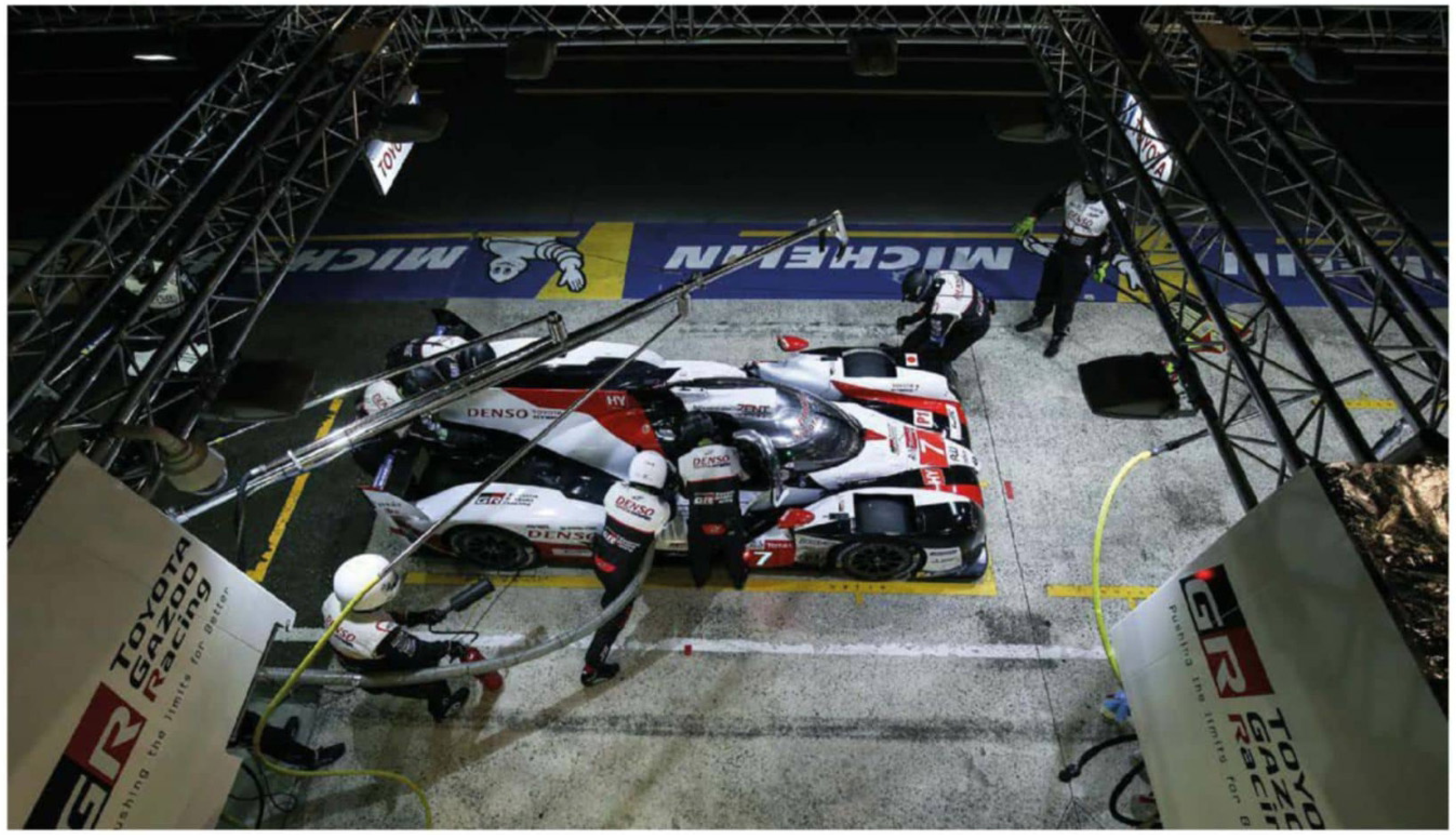
From the moment the cars started running on the Wednesday evening before the race it was clear that the Toyotas would have a performance advantage over the non-hybrids, despite the Equivalence of Technology giving the non-hybrids a mathematical advantage over the factory hybrids (see *Racecar* V29N7). However, it was wasn't all plain sailing for Toyota, and Conway crashed into an LMP2 car that was rejoining the track after a spin. The British driver was briefly airborne and the Toyota team needed a new chassis for the race.

Setting this up was not the work of a moment, and was not that successful either. Despite Kobayashi setting pole position in the car, the team was unhappy with the set-up and so reverted to its settings from 2018, preferring a known quantity as they chased a balanced set up. The choice proved to be inspired, and they had the faster of the two cars during the race.

Buemi, who started the No.8 car, knew within five laps that he would not be able to win

LMP1 laps

Position	No.	Team	Car	Drivers	Laps	Best	Average	Longest stint	S1 - best	S2 - best	S3 - best	Porsche - best	Ford - best	Top speed
1	8	Toyota Gazoo Racing	Toyota TS050 - Hybrid	Buemi/Alonso/Nakajima	385	03:18.397	03:21.209	12	31.935	75.619	90.172	14.298	6.268	342.3
2	7	Toyota Gazoo Racing	Toyota TS050 - Hybrid	Conway/Kobayashi/Lopez	385	03:17.297	03:20.621	12	31.839	75.425	89.540	13.989	6.064	333.9
3	11	SMP Racing	BR Engineering BR1 - AER	Aleshin/Vandoorne/Petrov	379	03:19.785	03:21.966	11	31.669	75.732	91.437	14.302	6.368	350.1
4	1	Rebellion Racing	Rebellion R13 - Gibson	Lotterer/Senna/Jani	376	03:20.605	03:22.965	11	31.767	76.712	91.731	14.056	6.306	343.4
5	3	Rebellion Racing	Rebellion R13 - Gibson	Menezes/Berthon/Laurent	370	03:18.720	03:20.870	11	31.557	75.980	90.545	13.645	6.225	343.4



The No.7 Toyota pits during the night. It was two late pit stops that lost the race for this car late on the Sunday afternoon as a wiring failure incorrectly indicated a right front puncture

on pace alone as Conway consistently pulled away. He was the fastest of the Toyota drivers by some way, nearly seven tenths of a second quicker on the average 20 per cent fastest laps than Fernando Alonso in the sister car, and his fastest lap of the race, a 3m17.297, was a new track record, in race conditions, and four tenths of a second faster than anyone else on the team.

That was all despite Conway racing with a shadow over him, in the shape of a suspended penalty that was a legacy of the Wednesday night crash. Any flag infringement would carry a stop and go of three minutes which, given the pace of the two Toyotas, could have proven catastrophic in their attempt to win at Le Mans. Conway admitted that this played on his mind during the race, but he also reasoned with himself that a flag infringement would carry a penalty anyway, so it would just be more costly.

The car in front

The No.7 Toyota carried a speed advantage throughout the race, while the No.8 ran into an aero problem overnight to do with the driver's door. In 2018 team orders were largely ignored by Alonso, which helped in his bid to close the gap to the leading car in the hours of darkness, but this year there was no repetition of this – instead the former F1 champion was sent to get the tea for the crew on the pit wall.

As it was, it was a slice of luck during a pit stop that finally gave the No.8 a chance to run at the front. The No.8 was in the pits when a full course yellow was called, and this turned a 35 second deficit to the No.7 car into a lead, as the latter was condemned to some slow laps. After this, Lopez, the third fastest of the Toyota drivers in terms of the best 20 laps average, retook the lead for the No.7, but two mistakes handed the advantage back to the No.8 car. He started to rapidly lose time to the sister car, but when he stopped to hand back to Conway he had recovered enough to put his British co-driver out in the lead and they held that advantage for most of the remainder of the race.

Looking at the gaps between the two Toyotas, from lap 170 the No.7 crew simply drove away from their team-mates, the gap increasing to more than two minutes after lap 360, but the No.8 crew had pretty much settled for the championship at this stage. It needed to finish seventh or better and, on pace, the No.7 car was likely to win overall, and No.8 finish second to be champions. There was no communication from the pit wall that this should be the case, but the drivers had privately resigned themselves to the fact – until a fateful call with little more than an hour to run.

Lopez, in for the final stint and with fresh tyres to see him to the end of the race, took over the driving at just after 1pm on Sunday afternoon. His first stop went ahead as scheduled at 13:48, but then at 13:55 he was back into the pits with a suspected puncture. The data showed that the front right had deflated, and so the team changed only that tyre, but the Argentinian went back out still showing a puncture. A slow lap of 5m38s on lap 368 was followed by a second slow lap, a 4m13s on lap 369 and the damage was done. The two-minute lead had turned into a one-minute deficit as it was the rear tyre that punctured, not the front, and the team had not changed all four tyres the first time around.

Lucky number eight

The Toyota team thought about switching the positions back, but stuck to its own regulations, which meant the positions were fixed after the last round of pit stops and the No.8 car of Alonso, Nakajima and Buemi took the race victory, and the world championship title. Lopez closed from a minute behind to 16s at the flag, and Nakajima was forced to do his last few victorious laps at full racing speed to maintain the gap. The only consequence was that the team did not get its photo finish!

'Sometimes we had a better tyre, but most of the time they had the better tyre and we had luck,' said Nakajima. 'For sure, car seven

It was the rear tyre that punctured, not the front, but the No.7 team had not changed all four tyres the first time around

The No.11 SMP BR1 finished in third place, albeit six laps adrift of the two Toyotas. The car showed decent pace but more importantly it ran without a hitch throughout the race

had a better tyre more times than us, and they deserved to win. It is always not very nice to have the race decided by something else than what you do, and especially in the team we are not happy to see it. We had a bad time before [when they lost the race late in the day in 2016], but the race is always tough and hard.'

Non-hybrids

Of the non-hybrid threat, it was actually a more interesting picture than expected. The teams had calculated that they had a lap time deficit to the Toyotas, and that they had fuel for 10 racing laps, 11 if they were gentle on the throttle. At least it gave them strategic options, but the Toyotas likewise could do 11, or 12 if the drivers were careful. Indeed, both the Toyotas did 12-lap runs, and the SMPs 11 laps, in the race.

However, the real killer was the time lost in each pit stop. The non-hybrids had to stop more times (39 stops for the third placed car from SMP Racing, compared to 34 stops for the winning Toyota), and the SMP BR1 spent a total of 53m58s on pit road compared to 38m57s for the winning car. Those extra 15 minutes came not only from the extra stops, but also the time taken to change wheels and refuel, which took longer than the hybrids each time.

The interesting point was the difference between the cars in each team. The fastest of the Rebellions, the No.3 car of Thomas Laurent, Nathanael Berthon and Gustavo Menezes, actually had a better average stint time for the first half of the race than the No.8 Toyota which won the race overall. The non-hybrids did not have to have a fuel lift to complete the lap, which meant they also had incredibly high top speeds, and pace-wise the quicker of the two Rebellions split the Toyotas. But they lost time first when Laurent crashed at the second chicane, and again on Sunday morning when Menezes crashed trying to make up time following a three-minute stop-and-go penalty for a tyre infringement. But speed-wise there was a lot to be optimistic about when looking forward to the new season.

There was a significant difference between the two Rebellions, though. The No.1 car had a nightmare race and was the slowest of the pair in the hands of Neel Jani, Andre Lotterer and Bruno Senna. It lost time first when Bruno Senna had a puncture with less than 90 minutes of the race run, leading to a slow in-lap, but then its race really started to fall apart. Multiple nose changes were made on both cars as drivers hit kerbs, or the noses broke, and at one stage the team admitted that they had no more ready to go on the cars as they were all under repair.

The Rebellion team admitted that it did not deserve a place on the podium, but SMP did, having run through the 24 hours without a hitch, other than a puncture for the No.17 car. According to the rising average graph, the No.11 SMP, powered by the AER engine, steadily lost ground to the Toyota, as expected. Former McLaren driver Stoffel Vandoorne was the quickest of all the SMP drivers, with an average best 20 laps of 3m21.224s, just over four tenths of a second faster than Egor Orudhzev, who then blotted his copybook by crashing his car out of the race in the 11th hour. Of the drivers in the No.17 car, Orudzhev is the only one that does not have Formula 1 experience, yet he was the fastest in qualifying and the race! Slowest of all the SMP drivers was Sergei Sirotkin, Williams' former GP driver who was almost two seconds off Vandoorne's average 20 lap times and the Russian made clear his dislike for the race, saying that if he comes back it will be because he has to rather than because he wants to.

Comparing the fastest of the Rebellion drivers to the fastest of the SMPs, the Rebellion was clearly the quicker of the two racecars, and Menezes was the fastest of the drivers, but the SMP team could see his weakness. The drivers were given instructions not necessarily to pass him, but to worry him, and this was partially successful as Menezes crashed on Sunday morning chasing Vandoorne.

The Dragonspeed car, a BR chassis built by Dallara but with a Gibson engine, continued its season of woe, once again running into gearchange issues. With a crimped loom on

The Rebellion LMP1 outfit admitted that it did not deserve a place on the Le Mans podium, but the SMP team certainly did

The battle for GTE Pro

The GTE Pro category was always going to be the one to watch at Le Mans in 2019. With Ferrari, Chevrolet, Ford, BMW, Porsche and Aston Martin fielding factory-backed cars and 17 cars going for victory in a performance-balanced category, the race would come down to luck or guile.

The speed range between the six different manufacturers was remarkably close; the Porsche was fastest over the 20 fastest laps with an average of 3m51.362, while Aston Martin was the slowest with 3m53.564s.

Rule changes this year were designed to increase the potential for a good race. After the debacle last year – where cars were closely matched on track but a minimum refuelling time was mandated, as was stint length – organisers did away with some of these restrictions for the 2019 race. Cars ran at the test day with fuel flow meters, and the fuel allowance was made such that they could do 14 laps, but if they could go further they were able to do so. This meant there was an element of strategy re-introduced into the class, but the yellows and safety cars could still be a deciding factor.

The No.51 AF Corse Ferrari 488 won GTE Pro after the No.63 Corvette was held in pit-out during a safety car period

The only unknown in the whole Balance of Performance procedure was the level of the Aston Martin Vantage, the British team having been out-performed at Le Mans in 2018 following what it said was a mistake in the initial Balance of Performance. With the BoP changed for 2019, the team then brought a new Le Mans aero kit to this year's race.

After Aston Martin secured pole position, with a 3m48.000 set by Marco Sorensen on Thursday night, the organisers introduced a new balance of performance late on Friday afternoon, which saw power taken away from the Vantages – as much as 15bhp according to estimates.

Weight was removed from all the cars bar the Corvette, which further skewed the Balance of Performance table. With their power reduction, the Vantages wasted no time in going backwards through the field, from pole position at the start to tenth for the No.95 car after the first hour, while the sister car ran 17th and last in class. The Le Mans balance of performance is outside the Auto BoP that governs the rest of the FIA WEC Championship, and was therefore clearly open to mistakes.

Aston Martin led for just three laps before it was passed by the No.63 Corvette, which remained in contention for the win until a safety car late in the race. The Corvette needed to pit for a full service and was held at pit-out for the second safety car. The win was now beyond them, and Jan Magnussen then crashed as he tried to make up the lost time.

That left Ferrari out in front, to the surprise of the team itself. One leading Ferrari engineer had 10 euros on Porsche to win and three euros on a Ferrari victory, before the start of the race, but here was the No.51 Ferrari out front after a perfect race. Alessandro Pier Guidi, James Calado and Daniel Serra had not put a foot wrong, they got lucky with the safety cars and full course yellows, but ultimately won by 49 seconds from Porsche.

GTE Pro laps

Position	No.	Team	Car	Drivers	Laps	Best	Average	Longest stint	S1 - best	S2 - best	S3 - best	Porsche - best	Ford - best	Top speed
1	51	AF Corse	Ferrari 488 GTE EVO	Calado/Pier Guidi/Serra	342	03:50.125	03:51.449	15	36.229	87.897	105.643	17.819	6.662	306.5
2	91	Porsche GT Team	Porsche 911 RSR	Lietz/Makowiecki/Bruni	342	03:49.831	03:51.362	16	35.587	88.112	105.391	17.784	6.560	305.6
3	93	Porsche GT Team	Porsche 911 RSR	Pilet/Tandy/Bamber	342	03:50.279	03:51.664	17	35.717	88.286	105.627	17.832	6.329	302.2
4	68	Ford Chip Ganassi Team USA	Ford GT	Hand/Müller/Bourdais	342	03:50.492	03:51.651	16	36.157	88.035	105.766	17.698	6.562	302.2
5	67	Ford Chip Ganassi Team UK	Ford GT	Priaulx/Tincknell/Bomarito	342	03:50.328	03:51.792	16	36.228	88.046	105.678	17.714	6.584	306.5
6	69	Ford Chip Ganassi Team USA	Ford GT	Briscoe/Westbrook/Dixon	341	03:50.865	03:51.643	17	36.368	88.223	105.675	17.696	6.576	306.5
7	66	Ford Chip Ganassi Team UK	Ford GT	Pla/Mücke/Johnson	340	03:51.247	03:52.188	17	36.336	88.202	105.996	17.690	6.569	303.0
8	94	Porsche GT Team	Porsche 911 RSR	Jaminet/Olsen/Müller	339	03:50.819	03:51.939	16	36.253	88.241	105.720	17.774	6.562	304.7
9	63	Corvette Racing	Chevrolet Corvette C7.R	Magnussen/Garcia/Rockenfeller	337	03:49.958	03:51.372	16	36.191	88.009	105.504	17.728	6.640	303.9
10	92	Porsche GT Team	Porsche 911 RSR	Christensen/Estre/Vanthoor	337	03:49.937	03:51.742	16	36.268	87.783	105.296	17.590	6.522	302.2
11	82	BMW Team MTEK	BMW M8 GTE	Farfus/da Costa/Krohn	335	03:50.702	03:52.943	16	36.326	87.857	106.155	17.650	6.688	298.8
12	89	Risi Competizione	Ferrari 488 GTE EVO	Derani/Jarvis/Gounon	329	03:51.741	03:52.914	15	35.771	88.584	106.403	17.906	6.663	303.9
13	97	Aston Martin Racing	Aston Martin Vantage AMR	Lynn/Martin/Adam	325	03:51.423	03:53.564	16	36.461	88.276	106.442	17.927	6.650	306.5
14	81	BMW Team MTEK	BMW M8 GTE	Tomczyk/Catsburg/Eng	309	03:51.118	03:52.300	16	36.408	88.458	105.794	17.412	6.697	303.9

Thursday and an electronic issue on Saturday, the car then retired in the ninth hour of the race.

The ByKolles had a good run, but a long stop on Saturday night dropped it down the order, and the car was eventually retired with gearbox problems after more than 12 hours of racing.

The new season starts soon with the Prologue in Barcelona at the end of July. While it is clear that the LMP1 privateers were slower than the Toyotas this year, with a new handicap system that is due in next year, there should be proper competition by the time the cars get to Le Mans in June 2020. They were already knocking on the door on pace at Le Mans this year, and more consistency and fewer accidents may have given us a very different story.

There were some stand-out drives at this year's Le Mans, including the efforts of Conway, Menezes and Vandoorne, and what transpired at Toyota was a genuine endurance motor race. It was not a Le Mans that will go down in the annals of motorsport history as exciting, but it certainly was a classic endurance racing in every sense of the expression.

Hyper active

Hypercar regulations have now been confirmed for the top class of the WEC and Le Mans, but what does this really mean and why has it taken so long to put in place? *Racecar* investigates

By ANDREW COTTON

During their traditional press conference at Le Mans on the Friday before the 24 hours the ACO and the FIA finally revealed that the future is hypercar. Both Toyota and Aston Martin are set to compete in this new top class and more manufacturers are expected to join at a later date – James Glickenhaus has also committed to the regulations and ByKolles has stated that it will withdraw from the WEC next year to focus on its hypercar for the 2020/21 season.

All this was confirmed after months of wrangling, but the final regulations do feature some significant changes to those released in 2018, including the option for a manufacturer to build a non-hybrid prototype, or a road car.

Hyper reality

The regulations, which are to come into effect for the start of the 2020/21 season, largely resemble those voted through by the FIA World Motorsport Council in December 2018. The changes include the removale of the moveable aerodynamic devices that seemed from the start to be a bad idea on a dirty road circuit such as Le Mans, and gone too are the weight limitations on the engine.

The option to race a production-based car is now permitted and that is thought to be the reason Aston Martin, McLaren and Porsche are now interested in joining the top category. However, the road car must demonstrate the same safety levels as a prototype LMP1 car, which will lead to some design headaches. A minimum number of 20 road cars must be built in the first year of homologation, says the ACO.

The Aston Martin rumour gained strength at the Le Mans test day. There it transpired that Multimatic, which was already scheduled to produce the chassis for the road car, is now set to also taken over the development of the Valkyrie racecar. Private funding was believed to have been secured to bring the project to the track, and then it was only a matter of restricting the impact of a Toyota's four-wheel drive system. During a meeting late on Sunday night after the test session it was agreed that front-wheel drive may only be deployed over 120km/h in the dry and between 140km/h and 160km/h in the wet. The 120km/h limit was already used in 2012 and 2013 at the start of the WEC project, and this compromise was met with approval in the paddock at Le Mans. It is expected that the Valkyrie will race without a hybrid system, unlike the road car. McLaren and Porsche are also believed to be looking at running non-hybrids.

Toyota, meanwhile, confirmed that it will base its new racer on the GR Super Sport road car. Both the road and the racecar are undergoing design and intensive development at the company's technical centres in Toyota City, Higashi-Fuji and in Cologne. The car, which has Kamui Kobayashi as its lead test driver, will be run by TMG and is expected to be on the grid for the first race in September 2020.

Balancing act

The governing bodies remain optimistic that they can balance the different concepts by bringing their performance close together within set performance windows that will govern weight, power and power delivery. Weight will be set at 1100kg, up from the original proposal of 980kg that was announced at Le Mans in 2018, while power from the ICE is limited to 550kW, up from the 520kW originally announced. The torque curve and hybrid power delivery will also be tightly regulated.

Gone are the fuel flow meters, which were central to the FIA's plans for more efficient engines when they were introduced in 2014. That, and the departure of the regulation regarding Brake Specific Fuel Consumption (BSFC), means that the engine efficiency will take a big backwards step. Aero will be limited by selecting a point on the lift/drag graph, and cars will be expected to hit that efficiency target.

The option to race a production-based car is now permitted and that is thought to be the reason McLaren and Porsche are interested

Aston Martin will campaign its Valkyrie hypercar, developed in conjunction with Red Bull Advanced Technologies, in the new top class of the WEC for the 2020-2021 season

Toyota has announced that it will be joining Aston Martin on the hypercar grid. It will enter its GR Super Sport Concept car

Gone are the moveable aerodynamic devices that seemed to be a bad idea on a dirty road circuit such as Le Mans from the start

Smaller hypercar builders such as Glickenhuas – pictured is its 007 – have already expressed an interest in the new regulations, while WEC stalwart ByKolles plans to make a car

Once the cars are, by design, close together and homologated for five years, a balance of performance will be brought into effect to ensure that each concept is competitive. The BoP system will be automated, as it is in GTE for all races except for Le Mans.

Auto correct

'We want to have the most automatic system that we can have, with the minimum human decisions,' says the ACO's sporting director Vincent Beaumesnil. 'We have integrated into our team new engineers in the last two years, so we have a starting point and will strengthen the team as much as necessary.'

'Concerning the balancing of the road car base and the prototype, we have defined some performance parameters that are the same for both of them, so we will have a close base, and as we now see in GTE Pro, with the BMW M8, the Aston Martin and the Ferrari, if you look at the size and weight of these cars, we can still balance them, so we are confident that we can manage the performance,' Beaumesnil adds. 'It will be only fine tuning because by homologation they must bring their car to an aero and engine performance [that is] the same. When you have done this, it is a big part of the job. We have the principles of the system in place, but the details will come later. We want to bring the manufacturers around the table, and define the process with them.'

One joker package will be permitted within the five-year homologation period.

A single tyre supplier will be nominated for the top category, although both Michelin and Dunlop are against this idea. However, the BoP system will not allow for a tyre war. While the likes of Michelin are crying out for some indication of what demands will be made on the tyres, the ACO has a different plan.

'Our plan is to provide within the single tyre manufacturer different families of tyres depending on the weight distribution,' says Beaumesnil. 'When you build your car, you can choose family A, B or C. Every family will be defined on a specific weight distribution. Here, the difference between the cars is that we will have the same aero, which is not the case in GTE because of the base car; when you have a big frontal area, you need more power. There [in

Front-wheel drive may only be deployed over 120km/h in the dry

hypercar], due to the aero where the windows are closer, the engine performance will be the same so you will not start with the difference in performance that you have in GT.'

The target lap time for the top class around Le Mans is 3m30s, and that means that the LMP2 category will have to be slowed to make room for the new top class. This can be done with fixed rear wing angles, fixed gear ratios and weight, coupled with a reduction of power from the engine. However, the effect on GTE is going to be more significant, with both Aston Martin and Porsche possibly making the switch from this category, which has already lost Ford and BMW in the WEC.

Long time coming

The route to this conclusion has been tortuous, and there have been many alternative options on the table. Right up to the last minute the DPi option, with an LMP2 base and manufacturer engine and aero kit used in the IMSA series in the US, was possible. Had Toyota and Aston Martin not committed for 2020, it seems likely that there would be a global platform based on these cars. Others in the paddock said they could not consider a return to ICE engines only, although that is what the new regulations bring.

The current LMP1 hybrid cars were too expensive, with budgets of an estimated 150-200 million euros, and with the diesel scandal hitting the VW Group in 2015 the loss of both Audi in 2016 and Porsche in 2017 was not surprising. Nissan's 2015 programme was short lived and there were no new prospects on the horizon. The governing bodies had to react.

Along with the manufacturers, the FIA and ACO put together a plan. And cost reduction was very much at the heart of it. A mild hybrid system fitted to a current LMP1 chassis was planned, with power fed through the rear wheels only, but this abruptly changed between January 2018 at Daytona, and March 2018.

At Sebring the FIA announced that the cars would be four-wheel drive, and that manufacturers would have a budget of around €30m. But with no manufacturer commitment, the plan evolved to hypercar, based on the fact that Toyota and Aston Martin had announced just such a car, McLaren and Ferrari needed a new hybrid supercar, while smaller manufacturers might also be interested.

The idea also evolved to make the technology available to customer teams, which had the double advantage of limiting cost, and

Naked Toyota. In the new regulations power from the ICE is limited to 550kW, up from the 520kW originally announced

Toyota's GR is now the subject of intensive development. The hypercars will need to hit a specified downforce/drag target

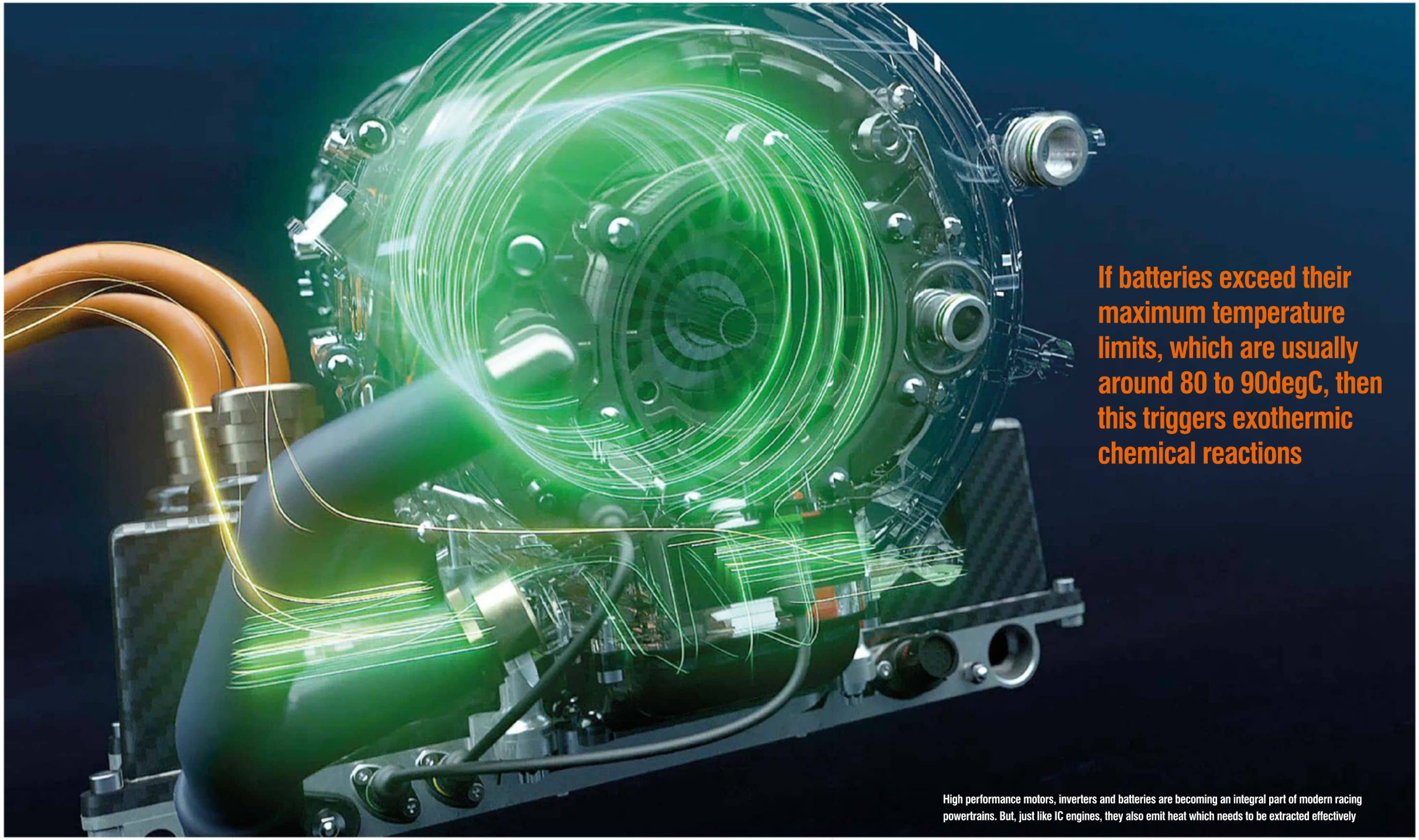
technology. Toyota has said that it would have to re-negotiate its contract with suppliers if it is to supply its system to a customer race team, and that it would need to ensure that that team was also up to handling such a system. The plan was presented to the FIA World Council in December, and was approved.

Hyper drive

Then, late in February, the FIA and ACO held meetings in Paris to establish why there was no public statement of interest from manufacturers that had promised to do so, and they were presented with some bald facts. 'In January a big field of manufacturers were interested to start with a road car for marketing or budget reasons, so they had reasons to ask for this, and we worked on that,' says Beaumesnil. 'In the same period, we had frustrations that there was no announcement and so we had to make sure that this does not happen, so we had another [back-up] plan ready to go. [But] we have never left the direction that we had with hypercar.'

Also, in the background, governments have targeted the internal combustion engine market on the grounds of CO_2 emissions, and manufacturers have reacted by declaring dates that they will stop producing IC engines, leaving consumers with limited options for new cars, and uncertainty over what technology they should buy. Many are choosing to wait, and so the markets in Europe are set to contract. Also, the ACO has already made it clear that it sees a future in hydrogen as a fuel, and has invested in the GreenGT team to enable it to race a hydrogen-powered prototype this year.

Hypercar regulations will be set until 2027, while Bernard Niclot, the former technical delegate of the FIA in the WEC, has confirmed that he expects to have hypercar regulations fixed at the end of 2019, and cars on the grid in a separate class at Le Mans in 2024.



High performance motors, inverters and batteries are becoming an integral part of modern racing powertrains. But, just like IC engines, they also emit heat which needs to be extracted effectively

If batteries exceed their maximum temperature limits, which are usually around 80 to 90degC, then this triggers exothermic chemical reactions

Heat of the moment

With hugely complex systems and restrictive regulations, engineers working in the field of electric racing have been forced to come up with ever-more ingenious methods to cool their motors, inverters and batteries. *Racecar* spoke to those in the know to find out more

By GEMMA HATTON

The concept of cooling for an internal combustion racecar is a familiar one. Ambient air flows into radiators within the sidepods, which reduces the temperature of the coolant flowing within those radiators. This coolant is then pumped around a closed loop system and absorbs heat radiating from the engine and other components. This now hotter coolant flows back to the radiators where it is cooled down, and the cycle begins once again.

However, the top tiers of racing are now either hybrid or electric and consequently running high voltage batteries, motors and inverters. So how does the cooling system work on these hybrid and electric racecars?

Heat is often the number one enemy of any engineer, because when energy is converted into heat it's usually because it hasn't been converted into useful work. Despite 160 years of development, internal combustion engines in road cars are still only around 30 per cent efficient. This means that for an IC engine consuming 200kW of power from burning fuel, roughly only 55kW will be converted into useful motion. The rest is losses; with around 125kW of those losses emitted as heat, either through the exhaust gases or radiators.

Racing engines, on the other hand, are much better, with the modern Formula 1 powerplant reaching 48 per cent efficiency, with some rumoured to be 50 per cent efficient. Yet while this is an astounding achievement – which has been poorly advertised in our modern eco-warrior world – this still means that up to 52 per cent of the energy produced is lost through heat, sound and various other forms.

Electric fan

But what about electric? Well, this newer form of propulsion has made incredible strides towards ultimate efficiency as Formula 1, WEC and Formula E continue to push the boundaries of battery, motor and inverter technology. Formula 1 lithium-ion batteries used in the energy recovery store (ERS) are reported to be 98 per cent efficient, while high spec motors and inverters are now achieving peak efficiencies close to 98.5 per cent. With such high efficiencies you may wonder what progress is left to be made. Well, engineers are now focussed on trying to achieve these high peak efficiencies throughout the wider range of motor speeds, in an attempt to get closer to 100 per cent efficient 100 per cent of the time.

'A very high-end motor will typically achieve a peak efficiency of 98 per cent whereas a modern silicon carbide inverter can probably reach 99 per cent efficiency,' explains Arnaud Martin, chief engineer, motorsport, at Integral Powertrain. 'Therefore, the inverter rejects about half the amount of heat compared to the motor. Using the 200kW example, that's around 2kW of energy whereas the motor would reject around 4kW in rough figures. So, if you want to compare the amount of heat rejection between an ICE and an electric powertrain, even if you include the battery, an electric powertrain has a much higher efficiency. Let's put it this way, chassis engineers and aerodynamicists are very pleased with the size of the cooling requirements from an electric powertrain compared to an ICE.'

Batteries included

Despite this lower cooling requirement for electric and hybrid powertrains, this does not diminish its importance. For example, if batteries exceed their maximum temperature limits, which are usually around 80-90degC, then this triggers exothermic chemical reactions which generate large amounts of heat which in turn then feed these exothermic reactions. The battery enters a continuous loop of destruction – also known as thermal runaway. Furthermore, the performance of the battery is directly related to its operating temperature.

'Normally for a road car battery application you need to keep the batteries within a defined temperature window, in environments ranging from -20degC to +50degC, to sustain the life in the battery across the whole life of the road car,' highlights Anthony Law, head of Motorsport Batteries at McLaren Applied Technologies.

‘There is a trade-off between how much you allow the battery to heat up throughout the race and its efficiency during the first few laps’

‘Whereas in racing we can be more strict about what temperature we need to design the battery to. Normally you can just reject the heat to ambient air, so the upper limits of cells can be 60-70degC or higher in some applications which means you have a decent temperature delta between the cell and the ambient air. The larger that temperature delta, the more heat you can reject. However, battery efficiency drops off rapidly below 15-20degC in most motorsport cases, so in some circumstances you do need to actually warm the battery up. So, there is a trade-off between how much you allow the battery to heat up throughout the race and its efficiency during the first few laps. Also, if you operate the cells at very high temperatures, they will age more so there is another trade-off between how long you want the battery to last versus the performance you want.’

Motors and inverters

Similarly, motors and inverters also need to be kept within a specific temperature window. To understand why this is so, first we need to know the basics of how a motor works. A motor essentially consists of a rotor which has permanent magnets on its outer circumference and a stator which is made up of several ‘teeth’ that surrounds the rotor. Copper coils are wound around each of these teeth and as the rotor rotates so does the polarity of the magnetic field which passes the coils and forces free electrons in the copper wires to move; generating or consuming electrical power depending on the mode used.

‘The magnetic field of the coils and teeth changes from positive to negative in an oscillatory manner,’ explains Martin. ‘This oscillatory waveform effectively pushes and drags the magnet on the rotor and when you rotate this field on the coils, you generate the rotational motion. The more current you generate into the teeth and coils, the more torque you can produce and by increasing the speed of the waveform through the stator coil, the faster the motor rotates.’

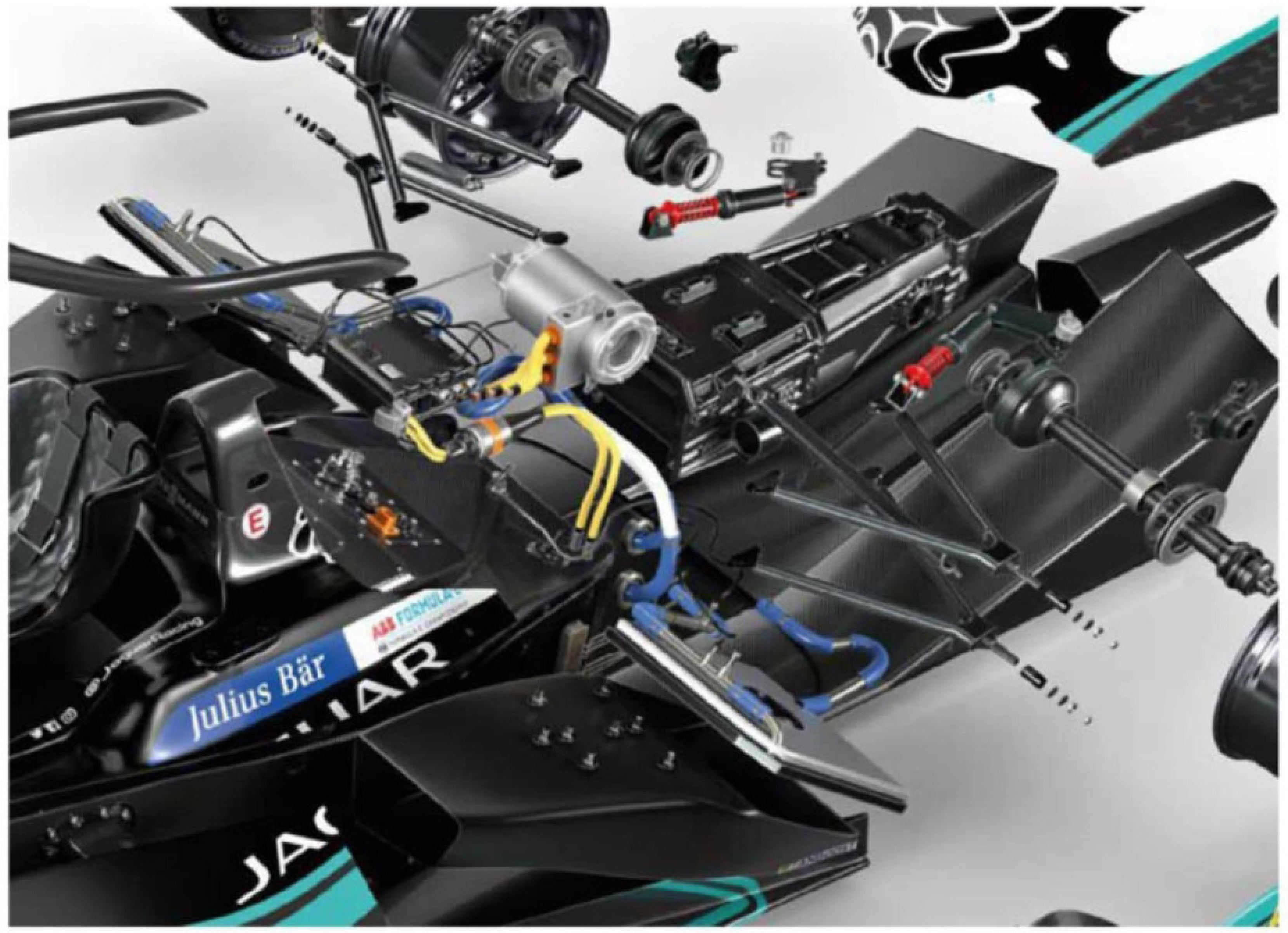
Of course, when current is pushed through wires there is an internal resistance which causes the wires to heat up in accordance with Ohms law. Therefore, one form of electric motor loss is the resistance within the copper coils. ‘As well as these resistance losses you also have some hysteresis losses due to the sinusoidal waveform which is changing the direction of the magnetic field,’ Martin says. ‘The understanding of the way these losses are generated is what allows you to design an efficient motor.’

These various losses within the motor are emitted through heat, which in turn causes a number of further problems. ‘On the rotor side you have magnets which can demagnetise depending on their temperature, their specification and whether you cool the rotor or not. The maximum temperature of a rotor is typically 150degC,’ Martin says. ‘On the stator side the coil windings can sometimes reach peak temperatures of 160 to 180degC. The limiting factor for winding temperature is the deterioration of the insulation on the wires.’

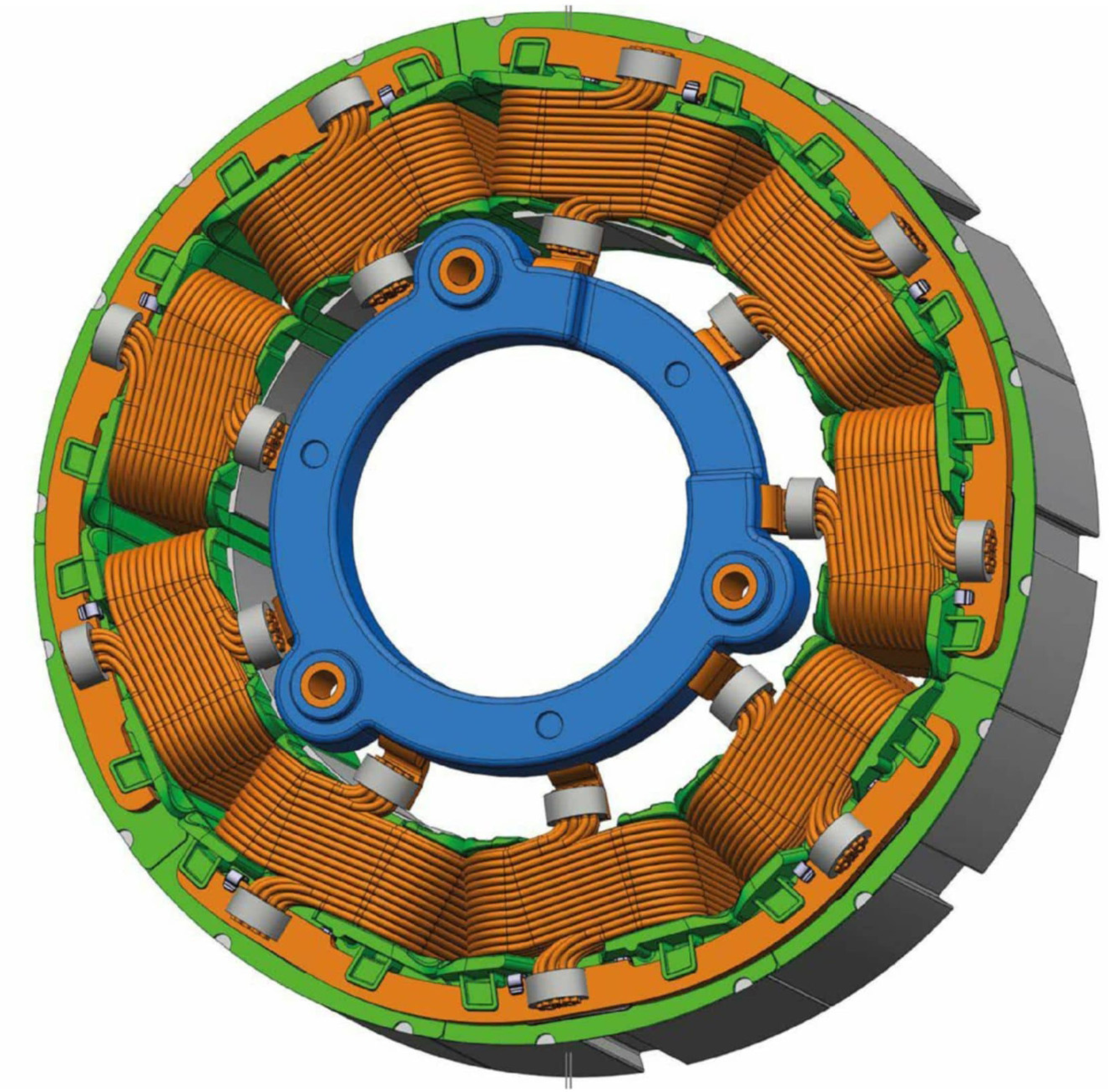
To try and minimise the losses and mitigate the effects of heat, larger wires can be used which have increased cross-sectional area. ‘You can make an efficient motor that is heavy but what becomes difficult is making an efficient motor that is light,’ Martin says.

To try and sustain the batteries, motors and inverters within their specified performance windows, a cooling system is required and there are two approaches: direct and indirect

High performance motors and inverters can achieve efficiencies of up to 99 per cent; much better than an IC powerplant



A Formula E cooling circuit; note the blue piping connecting the two radiators in the sidepods to the inverter and the battery



The stator is made up of teeth wrapped in coils of copper wire. By rotating the polarity of the magnetic field around the rotor electrons are forced to move, generating electricity

cooling. Direct cooling, as the name implies, is where a fluid is in direct contact with the electrical components. So, for batteries the fluid surrounds the individual cells, and for motors the fluid flows around the windings. Of course, water and electricity don't mix, which is why a dielectric fluid is used in these types of cooling systems. These are non-conductive fluids which are typically oil based products.

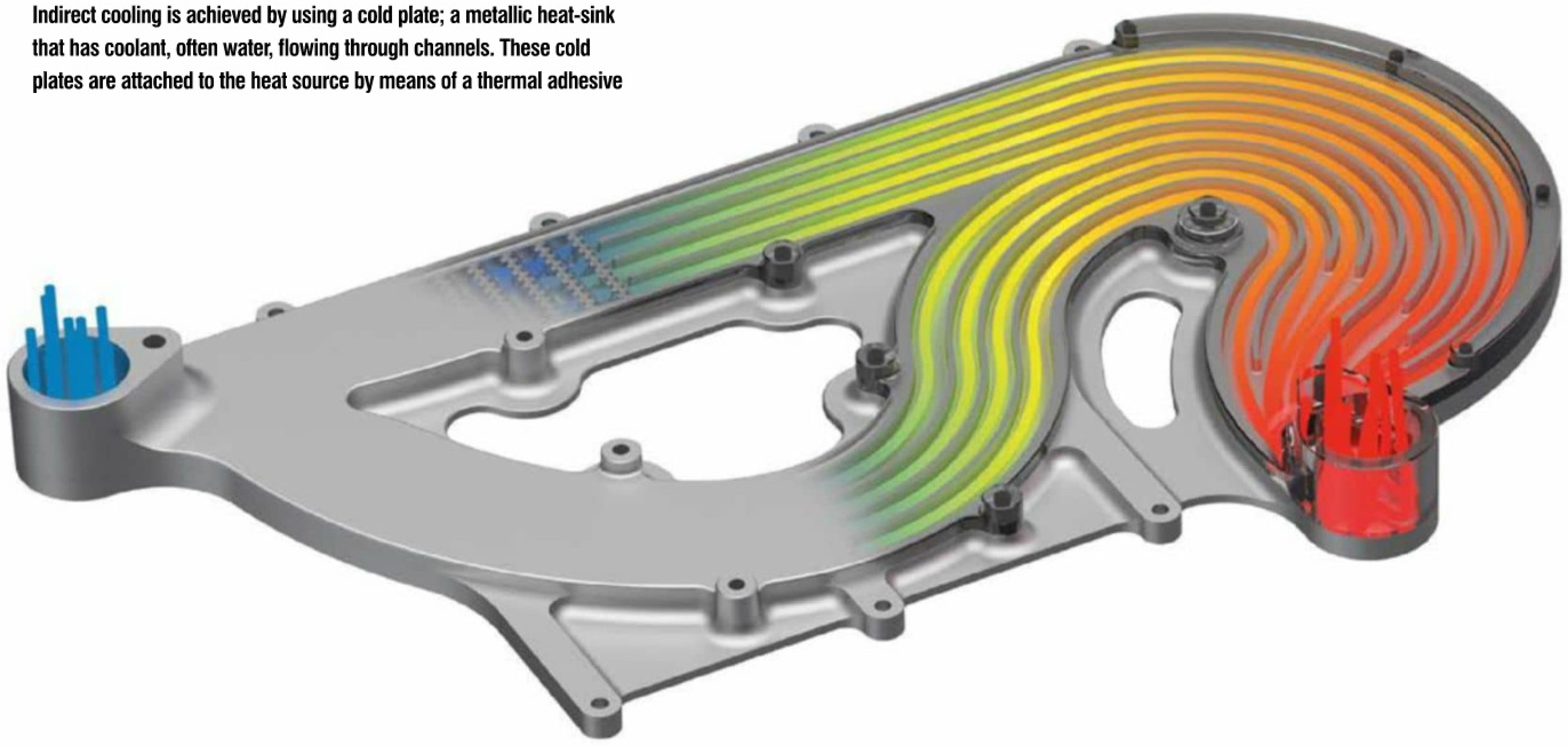
The strategy of submersing electrical components within a coolant and the resulting direct contact between the coolant and the components not only allows heat to be extracted immediately from its sources, but also minimises any further losses or thermal resistance. The problem is, however, that dielectric fluid has typically only half the heat capacity of water. So often this is not the most effective way to cool the components.

Indirect cooling uses cold plates, which are essentially metallic heat sinks that have channels of cooling fluid, such as water, flowing through them. These can be attached to the cells of the battery and the stator of the motor with thermal adhesives. However, separating the coolant and the components with effectively a metallic layer induces thermal resistance and therefore a loss, which is not the case with direct cooling. But, with modern technology now able to manufacture cold plates with extremely thin walls, and the higher heat capacity of water, this means that an effective indirect cooling design can actually achieve similar levels of heat rejection as a direct cooling system. This also means, then, that race teams can achieve high levels of heat rejection, without the weight penalty of filling up the whole battery or motor with coolant.

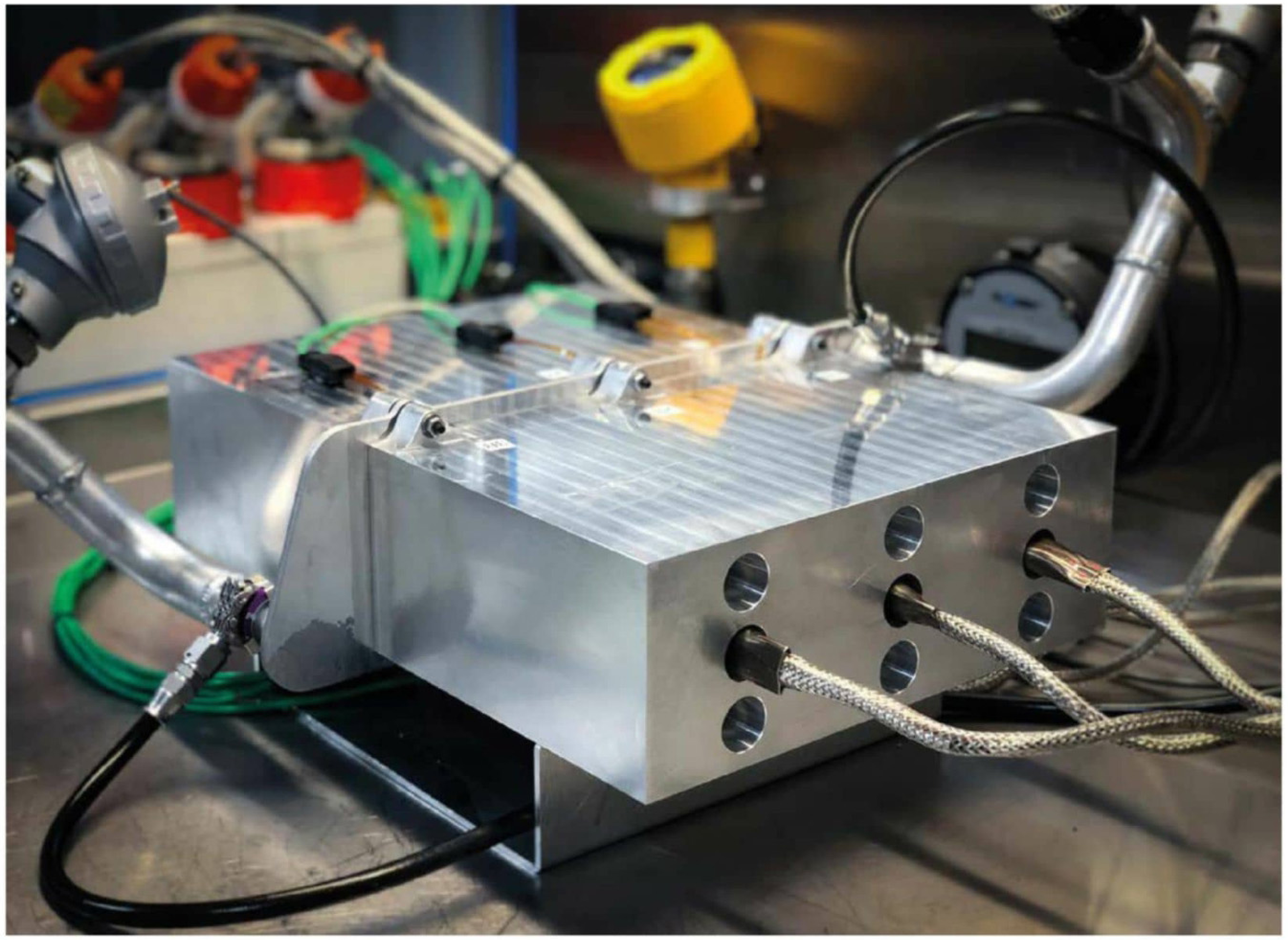
Plating up

'Normally, if you were using the cold plate application, you would aim to use water because, overall, water is a more efficient cooling medium than dielectric fluid and is less dense,' Law says. 'If you use fluid flowing through a cold plate, you can potentially have a lighter weight system because you are not filling every nook and cranny of the battery with dielectric cooling fluid. Whereas, if you just flood the battery, you can end up with a lot more fluid. Furthermore, modern cold plates can be made

Indirect cooling is achieved by using a cold plate; a metallic heat-sink that has coolant, often water, flowing through channels. These cold plates are attached to the heat source by means of a thermal adhesive



An effective indirect cooling design can actually achieve similar levels of heat rejection as those attained by a direct cooling system



PWR has developed a cold plate rig which enables it to test and analyse the flow behaviour of a variety of different coolant fluids in conjunction with a wide range of plate designs

Despite the Formula E championship having to make use of dielectric fluids, the regulations actually forbid direct cooling

with extremely thin walls, yet they are still able to withstand the high pressures.'

Thin walls such as these are only possible due to advances in the manufacturing process. 'In many cases our wall thickness can be down to 0.2mm and the overall extrusion height might only be between 1 to 1.5mm in height,' explains Andi Scott, who is a senior engineer at PWR. 'With packaging space paramount for any racing application, anything we can do to reduce space between the battery cells or electronic components makes the entire cooling solution more compact.'

Surface temperature

There are many factors to consider when designing a cold plate that maximises heat rejection to the cooling fluid. These include the amount of heat dissipation into the cold plate and its corresponding contact area, material type, wall thickness between the heat source and cooling fluid, specific characteristics of the cooling fluid used and the internal geometry of the extruded or vacuum brazed solution. All of these factors dictate the efficiency of the cold plate. In many instances when looking at the temperature delta of the cooling fluid for different plate designs the performance can appear very similar, however it is the surface temperature of the motor, inverter or battery that is more important.

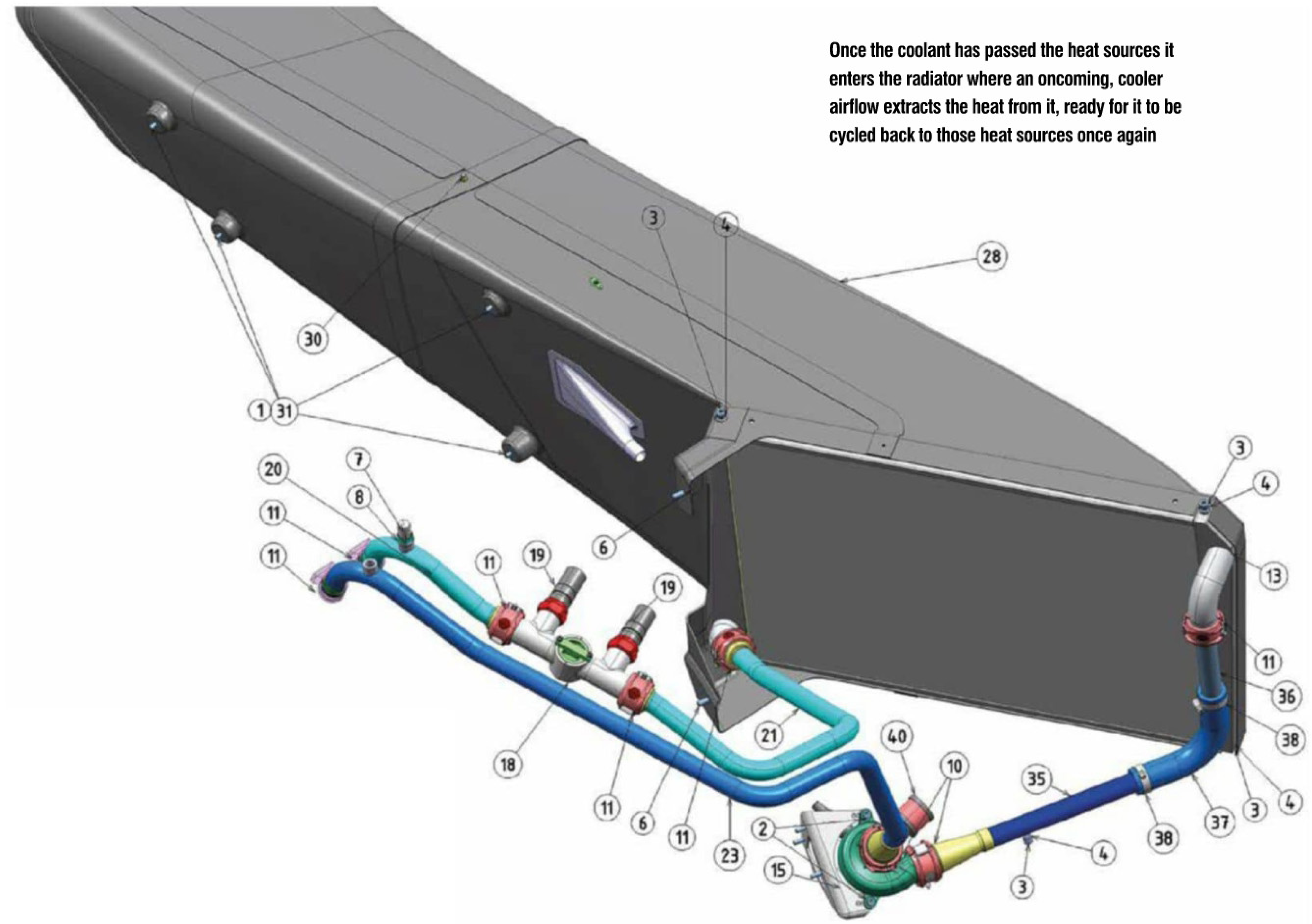
For example, two different plates with the same fluid and identical features, other than internal fin geometry, will have similar heat rejection to the fluid in a steady state condition. But the less efficient plate will have lower convective heat transfer and will require a higher surface temp between the heat source and the plate to reject the same amount of heat.

'The fluid is another challenge for us,' says Scott. 'The different cooling fluids, which can be glycol mixes or dielectric fluids, have varying properties such as heat capacity, density, thermal conductivity and viscosity. All of these properties determine the behaviour of the flow within the cold plate and its ability for effective heat transfer. So, trying to get effective mixing and distribution within the tubes or cavity as well as optimising the flow regime to maximise the heat rejection is certainly important.'

To try and de-mystify these challenges, PWR has developed its very own cold plate rig, where it can physically test different cooling fluids in conjunction with various cold plate designs. This allows its engineers to analyse the different flow behaviours between types of coolant as well as different brands of coolant, in an effort to refine the cold plate design to allow the coolant to extract as much heat as possible. Furthermore, internal simulation tools are also used to create performance predictions. For this, data extracted from the test rig such as pressure drop and heat-transfer coefficients for various flow conditions are normalised to validate the quality of recorded information and are then used in predictive tools for the sizing of new cold plates.

Of course, the choice between direct and indirect cooling very much depends on the regulations of the series. For example, despite Formula E using dielectric fluids, the regulations forbid direct cooling, therefore the battery is cooled via a cold plate but with dielectric fluid running through it rather than water.

'The whole system is fixed at the moment, so the Formula E battery is effectively a black box



Once the coolant has passed the heat sources it enters the radiator where an oncoming, cooler airflow extracts the heat from it, ready for it to be cycled back to those heat sources once again

The cooling system on hybrid and electric racecars will often consist of two separate circuits, as is the case with Formula E

which we hook our radiator up to,' Scott says. 'Sizing a radiator without knowing the intimate details of the battery system is not a problem and no different to sizing any system where we have been given a set of boundary conditions from the customer. We use these specific conditions to produce a radiator core within a certain face area that meets their requirements. Mixed in with the innovative technologies from the manufacturers or teams, the cooling system used in Formula E may appear physically like a conventional cooler supporting that component, however PWR's tube and fin geometries are the real driver in performance. As for inverter cooling, well that is open and an area of development for many customers. The solutions implemented depend heavily on the manufacturer's integration, but our experience with highly complex vacuum brazed cold plates helps us with these challenges. What we specialise in is working in parallel with our customers to achieve the cooling requirements with complex geometric shapes to maximise performance and minimise the packaging space required.'

Safety first

In Formula E, safety has remained the main priority, which as the world's first premier category of electric racing is understandable. This explains why the battery is cooled with an indirect cooling system using dielectric fluids; to avoid any potential leaks and consequent short circuits within the battery, despite the lower rates of heat transfer. However, a water and glycol mix is used to cool the motor and inverter on the grounds that a short circuit from a leak can be mitigated by opening the battery contactors. Therefore, with different fluids used to cool the battery and the motors and inverters, the cooling system on hybrid and electric racecars often consists of two separate circuits, as is the case in Formula E.

'If you have a motor and inverter which are using a water cooled system and by regulation you need to use dielectric fluid on the battery, you have no choice but to split the systems,' Martin says. 'What I've also seen in the past is that you tend to flow more fluid through the battery so as a result you need a different pump. You tend to get less pressure loss, but higher flow-rate for the battery cooling circuit.'

For the motor and inverter cooling circuit there are several schools of thought on the most effective configuration. Typically, trying to make a cooling circuit with a very high heat transfer coefficient often results in a lot of back pressure on the motor, which makes it difficult to cool both the motor and the inverter in series. 'The combined pressure loss is likely to be around 2bar, so if you look at it this way you need a pump which is able to overcome 2bar pressure loss for a flow which, depending on the inverter, can be as much as 20 litres per minute,' Martin says. 'A plus point is that you would flow through the inverter first, then through the motor, to the radiator and back to the pump, so the overall layout becomes relatively simple as all the components are in series.'

Another option is to cool the motor and inverter in parallel but this presents problems in balancing the flows. 'In reality you can make any of the configurations work,' says Martin. 'But personally, I prefer the simplest strategy which is flowing the coolant through the inverter and then the motor. You just need a pump with a reasonably high pressure capability, but these are now commercially available.'

The general principle of cooling remains the same for IC, hybrid and electric powered racecars; maximise the heat transfer between the coolant and the heat source. However, the complexities of electrical machinery such as motors, inverter and batteries have forced engineers to develop new ways of cooling. But the most effective cooling strategy of all is to maximise efficiency to reduce the energy emitted as heat in the first place.

How to make a radiator

Once the coolant, often water, has extracted the heat from the heat source, be that the engine, battery, motor or inverter, it then flows into the radiator through a series of thin channels or 'tubes'. In between these tubes are rows of corrugated shaped internal fins. The heat from the fluid is then transferred through the tube wall and into the fins which then dissipates this heat to the oncoming and cooler air that flows through the core of the radiator.

'Our tubes are either rolled or extruded tubes and some have walls as thin as 0.2mm. Whereas our fins can be as thin as 0.06mm,' explains Andi Scott, senior engineer at PWR. 'Once we've worked out the specification of the core, we will cut the tube and manufacture the air fin to the required density. We will even 'tune' the air fin louvre angles to meet specific thermal and pressure drop targets. As a proof of concept core we will start off with a rectangular core and we'll stack the sandwich layers of tube and fin on top of each other to meet a precise face area that matches the final core, even if it is not the final shape.'

Before the components are stacked and brazed together, they will go through a cleaning process. Firstly, they are washed to reduce any contamination on the components going into the furnace. The core is then fluxed, which is a procedure where a flux and water mixture is applied to the complete core. This then dries off into a powder that encapsulates the whole core, providing a layer of protection before brazing. This is essential because any oxygen that ends up in the furnace through either the environment or evaporated from water that has been left on the core will inhibit the brazing process.

'Then it's the brazing procedure, which consists of several stages of heated braze zones within a furnace,' Scott says. 'Depending on the size and mass of the core, each will react differently because of its thermal inertia, so we have to pick a bespoke recipe to get that core up to the critical braze temperature.'

A selection of the wide range of tube and fin solutions developed by well-known radiator specialist PWR

The brazing process starts off with a drying stage to ensure that any of the remaining flux has been dried off. The materials used in the core will be made mainly from 3000 series alloys. Depending on the core construction, either the tubes or fins will have an additional sacrificial layer which only makes up a small portion of the total material thickness.

'The sacrificial cladding layer has a slightly lower melting point than the parent material so when the furnace takes it up to the critical temperature the cladding layer will liquefy first and it will start to use capillary action to work towards any joints in the core itself,' Scott explains. 'Those are the joints between the fin and the tube and also the joint between the header plate and the tube. It will create a fillet in those joints and once the part drops below the critical braze temperature, it will solidify. Therefore, we end up with a one piece unit which is completely sealed, without any leaks.'

Playing with dyno mights

While dyno results should be treated with some caution, when they're combined with simulation data it all adds up to one very powerful set-up tool, argues *Racecar's* maths guru

By DANNY NOWLAN

One of the most disturbing trends I have seen over the last couple of years has been the emerging view that dyno results, whether they're for engine, tyre or aerodynamics, might be a fax sent from God Almighty himself.

This is particularly apparent with recent graduate engineers, but also surprisingly effects a lot of senior engineers as well. As the principal of ChassisSim one of my main activities is getting correlation on a daily basis, and this puts me in a unique position to discuss this. After all, I have to deal with the fallout from this every day.

To begin, dynos – whether they be engine, tyre or aero – are primarily comparative tools. Don't get me wrong, they will give you a good idea on where the absolute numbers are, but they are never the final word. I learnt this first hand when I worked for an aftermarket engine management company. We used to derive a lot of amusement at the keyboard warriors who would gloatingly post their dyno results. But if you're involved in the engine tuning game you recognise very quickly that the absolute results of an engine dyno will vary. It will depend on your ambient conditions and how long the engine/car has been on the dyno, because it gets real warm real quick. This doesn't mean the numbers you get from the dyno are bad. As a comparative tool they are brilliant, and having been involved in the experience of tuning engines on the road, I know that once you tune on a dyno you will never go back.

Yet while this is all well and good for the engine, what about tyres and aero? Well, first of all, I hate to burst a lot of engineers' bubbles here, but wind tunnel results aren't the panacea that everyone seems to think they are.

To understand this you need to know a little bit about how wind tunnels work and what you are trying to model in them. As can be seen in the picture above, the wind tunnel has a certain cross sectional area and you have a scale model or in this case a car in there, and ideally a rolling road. The first problem comes with blockage effects that will effect the flow around the model or car. Thanks to Bernoulli's equation we know the airspeed will increase around the car. Also,

A wind tunnel is, in essence, a dyno for aero and as such it's a great comparative tool. But it won't give you absolute numbers

when modelling in subsonic flow you match the Reynolds numbers, and in supersonic flow you match the Mach number. The problem with racecar aerodynamics is that thanks to the car's proximity to the ground we have high subsonic/transonic flow coming together. There are certain things we can do to mitigate this, and as a comparative tool and something to help get you into the ball park a wind tunnel is invaluable. However, to claim it will give you absolute numbers to within one to two per cent is foolish. If this was the case why would F1 teams employ engineers to validate their on-track aero?

Taking on fluid

Also, right now CFD is still too immature to give you an aeromap that is within five per cent of the absolute values. The code basis/numerical processing power is simply not there – where CFD is worth its weight in gold is in helping you understand what the flow structures are, as well as illustrating the pitch sensitivity.

But there are some exceptions. As a case in point, TotalSim and TotalSim USA do great work, as well as Andrew Brilliant from AMB Aero. But they are exceptional at what they do; Rob Lewis, Ray Leto and Andrew Brilliant and their respective teams have been doing this for so long they have an instinctive feel for the numbers, while they haven't fallen in love with their own publicity, either.

The next thing to discuss is tyre test rig results and what you get from Pacejka results, because it is something we need to have a serious chat about. If I had five dollars from every Formula Student/FSAE team that thinks that Pacejka results from tyre test rig tests are the last word on tyre performance then I would have retired a very long time ago as a very wealthy man. The thing is, they are wrong. One of the worst kept secrets is how unreliable Pacejka results actually are. **Figure 1** is a Pacejka result from a high downforce category I was involved in, which is a particularly egregious example of something going pear shaped.

Due to confidentiality I can't say where this came from and I have had to block out the scalings, but what this tyre model shows is that as you apply load the peak slip angle will increase significantly. So what this means for vehicle performance is you would have to be applying 10 degrees of steering lock. Given my customers at the time where reporting about two to three degree of steering through high speed corners and the racecars were glued to the track they figured out really quickly that these results left a lot to be desired.

Dynos will certainly give you a very good idea on where the absolute numbers are but they are never the final word

The reason these results can go wrong is down to two factors and the first of these is the inadequacies of the Pacejka model itself. This could be an article in its own right. The other reason is that tyre test machines are very hard pressed to deal with the thermal conditions you will encounter on the race track. This is not to say they are bad, on the contrary they are very useful and as a case in point I would jump at the chance to use the Sova Motion rig in Alton, Virginia in the US, for instance. As a comparative tool they are very useful and have their place. However, you always have to treat tyre test results as a rough starting point only.

Dyno sore

Now at this point in the game I know a few of you reading this will be hitting the rev limiter or suffering from extreme cognitive dissonance. But calm down, for the way you deal with all this is actually quite simple, and I will break this down from the easiest method to the hardest.

Firstly, dealing with the engine is actually very simple, because of all the measurements we're looking at, this is actually very close. What you do here is fix the engine power and use your lap time simulation tools, like ChassisSim, to tune the engine efficiency and global C_DA values. In **Table 1** there are some rough rules of thumb that have worked for us over the years.

Do treat these as rough rules of thumb, though. You typically employ this when your end of straight is a +/- delta of 20km/h. Once you are down under this limit you tune by scaling the total C_DA map, or in ChassisSim speak you play with the C_DA on the rear wing. The goal here is to match the speed at the end of the fastest straight. This is illustrated in **Figure 2**.

In **Figure 2** actual is coloured data and simulated is black. You play with the maximum C_DA values until you are within 0.5 to 1km/h. This is good enough. At this point in the game strictly speaking you may not have an absolute value but you have something much more powerful, and that is a representative environment.

Next task on the list is dealing with downforce. If your wind tunnel is any good it will give you a very good baseline on pitch

Figure 1: A bad Pacejka tyre model

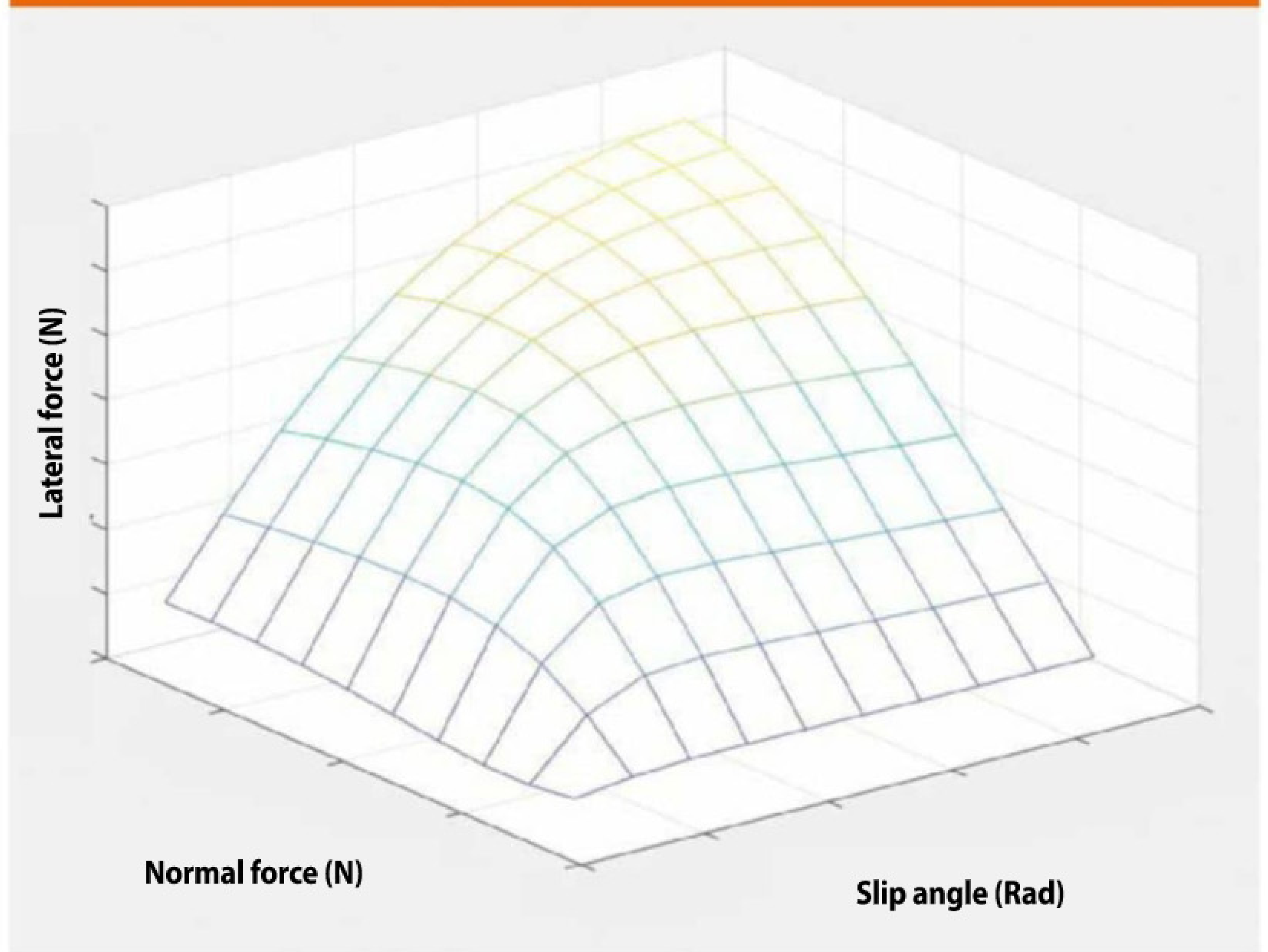


Table 1: Rough rules of thumb for engine efficiency

Transmission type	Engine efficiency
Open wheeler/prototype	90%
GT car/mid-engine	80 – 90%
Touring car/front engine GT car	75 – 85%

Figure 2: Matching the speed at the end of the fastest straight

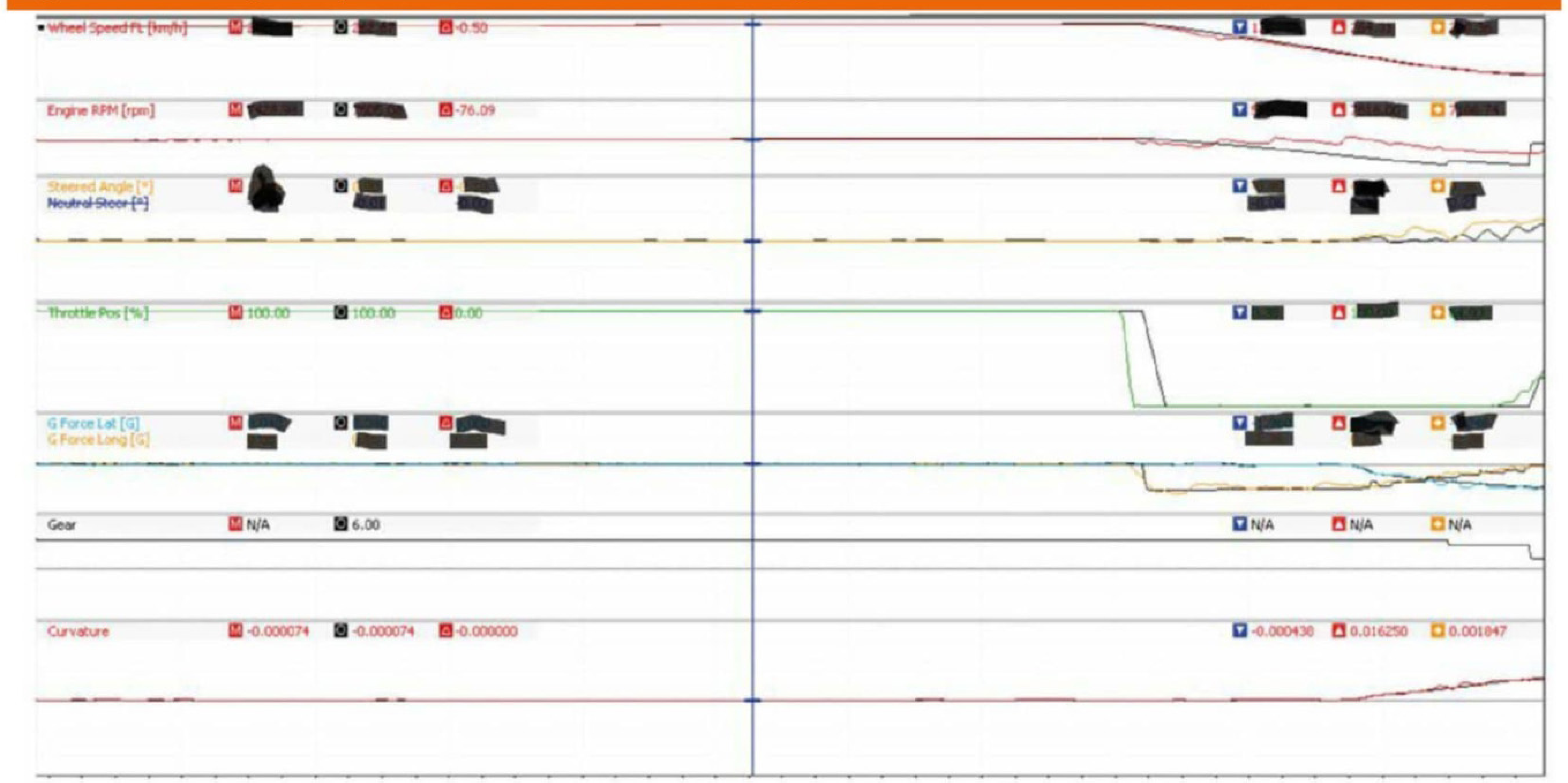


Figure 3: End of straight correlation

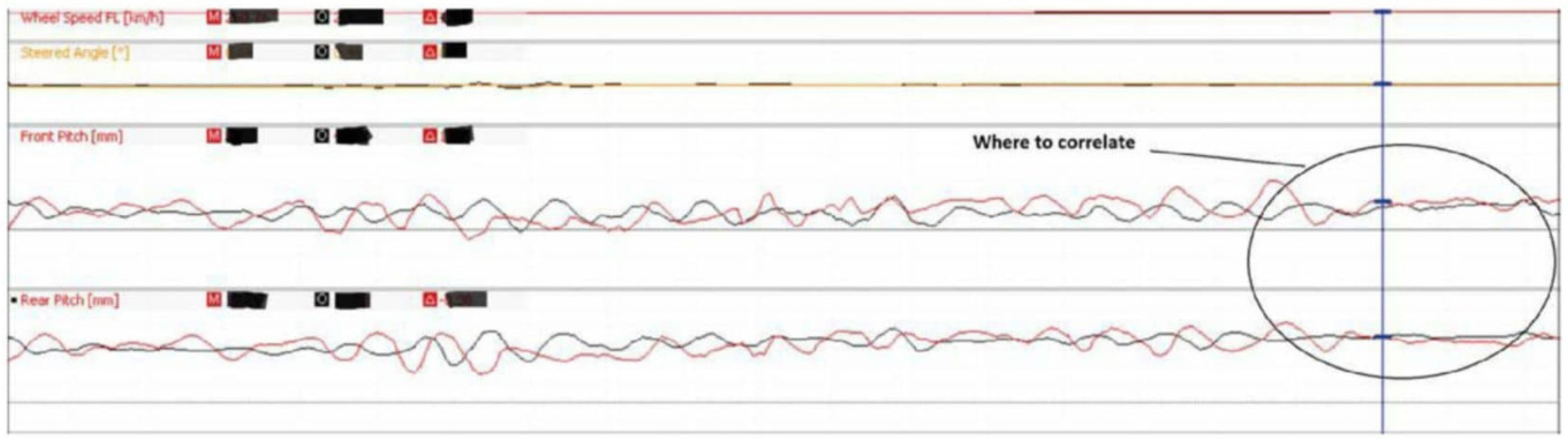
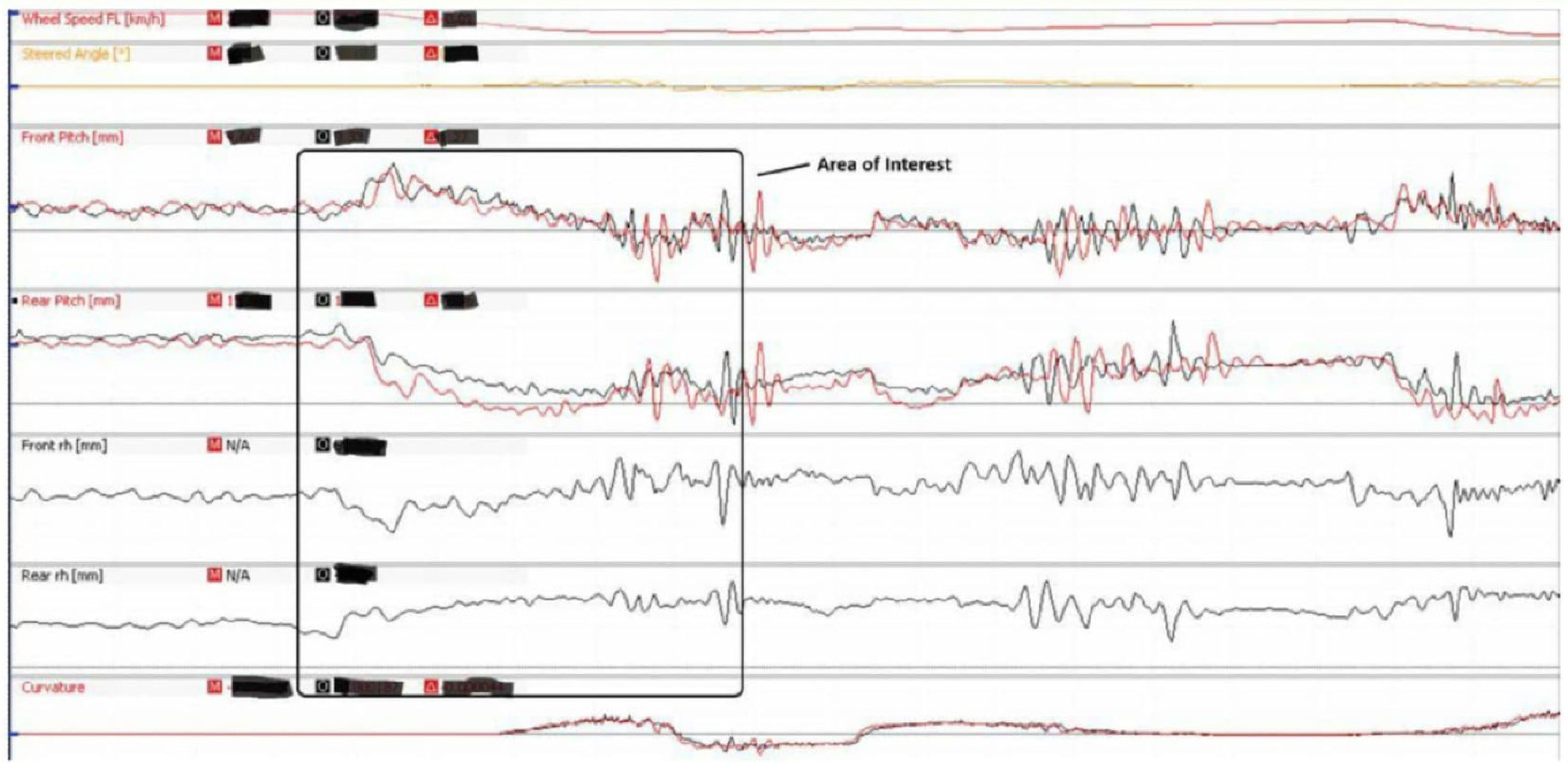


Figure 4: Using the track replay sim to refine the aeromap



sensitivity. Your first port of call, then, is to scale the global C_LA and apply a global aero offset. The great thing about ChassisSim is that if you click on the rear wing by adjusting the C_LA and aero balance offset values then this will be done for you. The goal here is to match the damper positions front and rear at the end of the longest straight. This is illustrated in **Figure 3**.

Again, actual is coloured and simulated is black. The first channel is speed, the second is steering. The third trace is the front pitch, which is the averaged left and right front dampers, and the last trace is the rear pitch, which is the averaged left and right rear dampers. All you are doing is playing with the global C_LA and aero balance to match up the fastest end of straight condition. You can also do this with either lap time or track replay simulation. At this stage of the game it doesn't matter.

The next step in the process is to refine the pitch sensitivity map. This is actually really simple, and as much as I would like to take the credit for this I have to give it to a colleague of mine, JP Sarrazin, who came up with the idea of using the ChassisSim track replay to compare simulated to actual data, as shown in **Figure 4**.

Here you need to look at where the dampers don't match up. Then look at what the simulated ride heights are and that tells you what you need to adjust in the aeromap. In this case what this is telling us is that we need to decrease the C_LA in this area and increase forward aero balance.

EQUATIONS

EQUATION 1

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

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)

Table 2: Typical open wheeler numbers for maximum tyre force with the coefficient of friction dropping off linearly with load

Parameter	Value
k_a	2
k_b	5.0 e-5 (1/N)

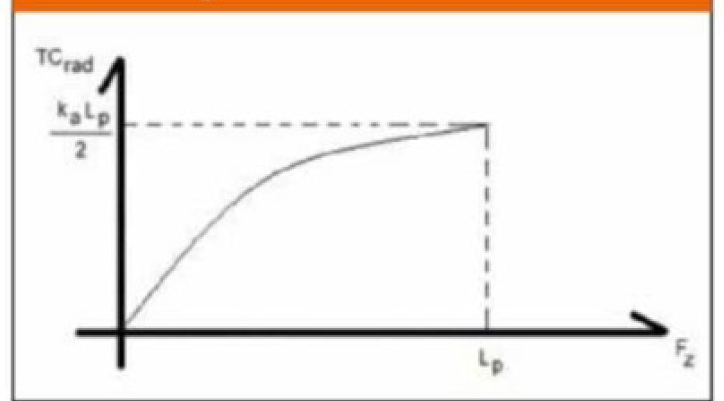
Tyre modelling

The last thing we need to talk about is how to deal with the tyres and to this we need to recap a technique I've discussed before, which involves tyre modelling from scratch. To recap, we are using the form of the traction circle radius that is shown in **Equation 1**, and some typical values for this are shown in **Table 2**.

What is really useful about this is that any tyre can be broken down into a peak load and

Figure 5: Plot of tyre loads for a given lap – simulated

Figure 6: Visualisation of a 2D tyre model



force, as illustrated in **Figure 6** (where L_p is the load at which the tyre generates its maximum force). There are two ingredients to the magic sauce that makes all this work. As can be seen from **Figure 6**, the first method is you need to determine the peak load of the traction circle radius. You can do this by running a track replay simulation or a rough cut lap time simulation, either using ChassisSim or something similar to determine what the tyre loads look like during the lap. This is illustrated in **Figure 5**.

All you then need to do is to take the peak tyre loads and add 100 to 200kg and this gives you your peak load. For Formula Student cars, which are so much lighter, add 50 to 100kg.

Science friction

The final piece of the puzzle is figuring out the initial co-efficient of friction. All you are doing is a static force balance for a given curvature, speed and set-up. Then you change the k_a terms or initial co-efficient of friction to match the corner speeds. The really great thing about this is it can be combined in an Excel spreadsheet such as the one illustrated in **Figure 7**.

Once you have all this you have a tyre model you can put into your simulation package. The only addition to this, if you are using something like ChassisSim, is that for transient simulation you add 20 per cent scaling front and rear, because you need that to offset the bumps.

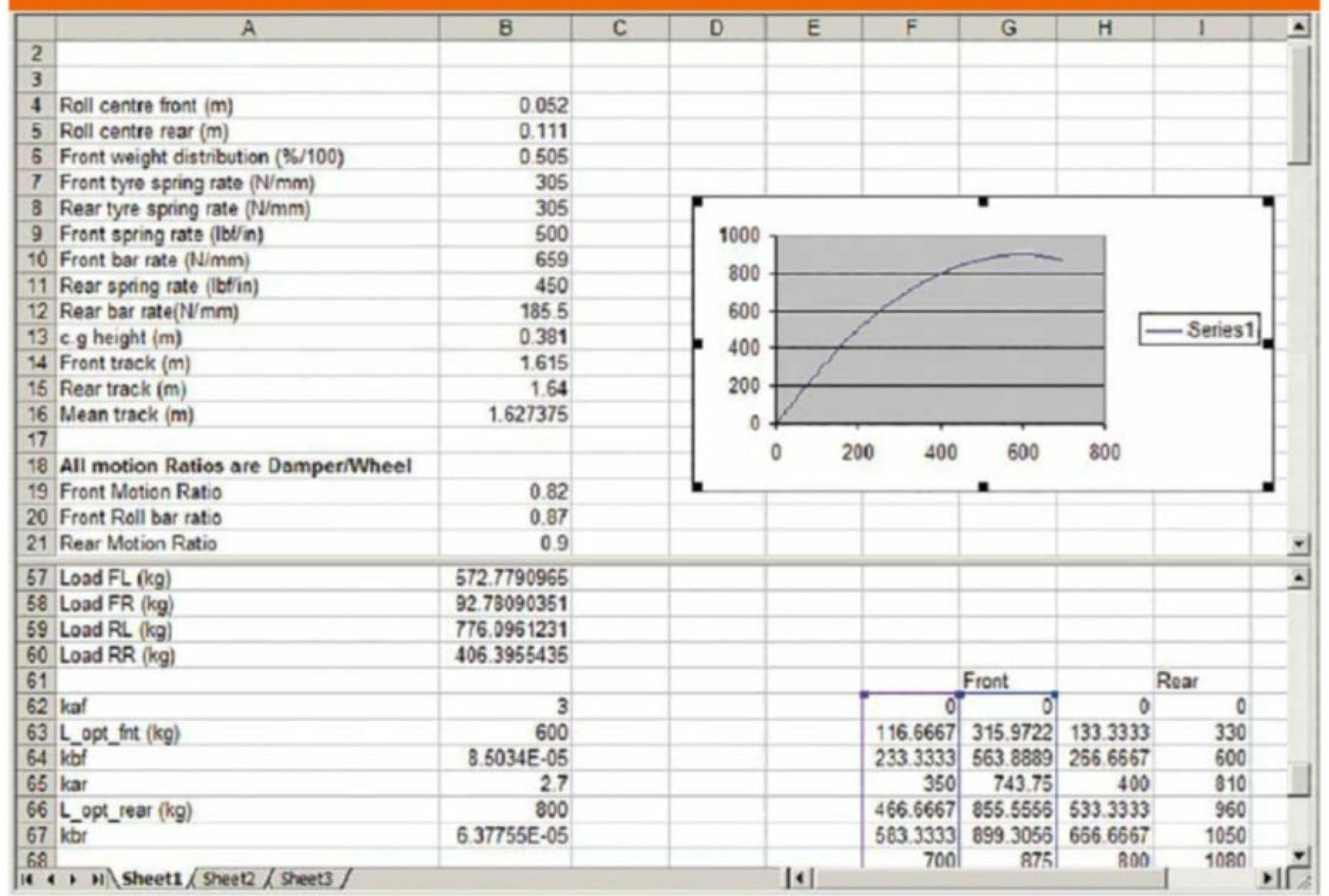
To sum up, what we have done here is use both dyno results and data together. In the case of engine and aero we took our engine dyno and wind tunnel results as our baseline. We then used the data to fine-tune the results.

Lastly, with the tyre results, because tyre test rig results tend to be less reliable we had to be a little creative here. However, as always everything is cross referenced back to the data.

The bottom line is that a well-calibrated data log will always have the final word.

In closing, while engine, wind tunnel and tyre test rig results are valuable points of reference they are never the final word on the numbers you apply to the racecar. To subscribe to this view is naively optimistic at best and downright dangerous at worst. But if you use these numbers as a start point, and cross reference this with the data using the methods we have discussed, then they will become a very powerful tool that will provide you with a model that is representative.

Figure 7: Excel spreadsheet for figuring out the tyre model



	A	B	C	D	E	F	G	H	I
2									
3									
4	Roll centre front (m)	0.052							
5	Roll centre rear (m)	0.111							
6	Front weight distribution (%/100)	0.505							
7	Front tyre spring rate (N/mm)	305							
8	Rear tyre spring rate (N/mm)	305							
9	Front spring rate (lbf/in)	500							
10	Front bar rate (N/mm)	659							
11	Rear spring rate (lbf/in)	450							
12	Rear bar rate(N/mm)	185.5							
13	c.g height (m)	0.381							
14	Front track (m)	1.615							
15	Rear track (m)	1.64							
16	Mean track (m)	1.627375							
17									
18	**All motion Ratios are Damper/Wheel**								
19	Front Motion Ratio	0.82							
20	Front Roll bar ratio	0.87							
21	Rear Motion Ratio	0.9							
57	Load FL (kg)	572.7790965							
58	Load FR (kg)	92.78090351							
59	Load RL (kg)	776.0961231							
60	Load RR (kg)	406.3955435							
61							Front		Rear
62	kaf	3				0	0	0	0
63	L_opt_fnt (kg)	600				116.6667	315.9722	133.3333	330
64	kbf	8.5034E-05				233.3333	563.8889	266.6667	600
65	kar	2.7				350	743.75	400	810
66	L_opt_rear (kg)	800				466.6667	855.5556	533.3333	960
67	kbr	6.37755E-05				583.3333	899.3056	666.6667	1050
68						700	875	800	1080

Interview – Hugh Chambers

At your service

The CEO of Motorsport UK explains how the recent shake-up in the national governing body in Britain amounts to much more than just a name change

By MIKE BRESLIN

'The very clear evidence is that unless we make some changes the future of motorsport, not just in this country but I think worldwide, is threatened'

There's an expression Hugh Chambers likes to use to describe the UK's motorsport governing body, at least as it was until recently, and that's 'The Ministry of Motorsport'. It's a recognition that things were done in a certain way, a way that certainly had its place and time. But it is also a recognition that things have now changed.

Among the more obvious of these changes is the title switch from MSA (Motor Sports Association) to the catchier Motorsport UK, but it's a change at the top which has driven this, with Chambers taking up the post of CEO in September last year – taking over from Rob Jones – and Prodrive boss David Richards becoming chairman at the start of 2018. Chambers' appointment wasn't, perhaps, a surprise as Richards and him go way back, Chambers working at Prodrive through the glory years of Subaru, Colin McRae and Richard Burns, BTCC success and even Formula 1 with BAR. He is a racing man, then – his father was former BMC team manager and rally and race driver Marcus Chambers and he has competed himself – but it's his wider CV that is really interesting.

'When I left Prodrive I was approached to get involved in the Olympics [London 2012], that was a fantastic opportunity to have a touch-point with lots of different sports,' Chambers says. 'Back then it was 26 summer sports and about another 13 winter sports, so over five years I got to see how different governing bodies worked; the challenges they faced and the way that they approached them. I was then invited by Sir Dave Brailsford to get involved in Team Sky [cycling], which was really fascinating. He is an extraordinary individual, and that then in turn led to a position as chief commercial officer at World Sailing.'

Chambers has, then, an eclectic background. Question is, how does that help in his current position? 'I think it's about perspective,' he says. 'I think it's about seeing the way that sport is run, the best practice, the challenges that are faced, and the solutions that you can find. Because there are more similarities than differences. The biggest similarity with the roles that I have held is with sailing, because it involves athletes and it involves big bits of equipment, and also quite high technology.

'This role [with Motorsport UK] is the culmination of all of those different elements,' Chambers adds. 'To me this is the absolutely perfect role and I just can't imagine doing anything more exciting right now.'

Challenges

The change at the top of Motorsport UK has meant change throughout the organisation. But why the rush to fiddle with something that has been working adequately, some would say, for many years? 'The fact of the matter is that motorsport worldwide is facing both short term challenges and long term challenges,' Chambers says. 'And the very clear evidence is that unless we make some changes the future for motorsport, not just in this country but I think worldwide, is threatened. This is probably best defined by the shrinkage in licence numbers and the shrinkage in event permits, which is indicative of a market that is not buoyant, it's indicative of a customer base that is leaving faster than they are coming in.'

Motorsport UK hopes to change this by shifting its focus, Chambers says. 'I think one of the key insights, and like any insight when you have got it it seems blindingly obvious, is that an awful lot of the emphasis of this organisation historically has been on the elite pathway. So it's been focussing on taking youngsters from karting, through single seaters, with the objective of getting them into Formula 1, and that's a laudable objective. But how representative is that pathway for our entire community? How many drivers and co-drivers actually earn a living from motorsport in this country? I'd struggle to believe there's probably more than a hundred. And we've got 30,000 licence holders, so that means you have 29,900 that don't make a living from motorsport. The vast majority are actually doing it for fun. So, is our job managing professional motorsport, or are we in the entertainment business? I firmly believe it's the latter.'

Barriers to entry

Part of the challenge is to attract more 'customers', which means making it easier for people to compete, while also making sure people know that this is not just a sport for the rich.

'What we are looking at very closely is the barriers to entry,' Chambers says. 'Some of the regulations; are they too complicated? Some of it is cost, it's too expensive, or it is certainly perceived that the cost is too high, and some of it is just that people don't know what they can do. It's too obscure, the man and the woman in the street imagine that if you're going to go motor racing then you have got to go and get yourself a Formula 1 car; whereas there's autograss, autocross, hillclimbs, there are so many different facets to this sport.'

Club competitors make up the bulk of the 30,000 UK licence holders. Pictured is 750 Formula

On a practical level Motorsport UK has already started looking at ways it can help competitors to cut costs, including taking some bold decisions. 'One of the first things that David [Richards] did when he arrived, was really challenge some of the safety regulations, something which is very difficult to go back on for all the obvious reasons,' Chambers says. 'But you have got to have fact base analysis, real empirical data, to make these decisions, and all too often, in the absence of data, people just make a very, very conservative decision. So, seatbelts [harnesses], this whole notion that you have got to replace them every five years; based on what? We started to do comprehensive analysis and study, and there is no evidence that after five years a seatbelt, if it has not been involved in an accident and is not damaged, is in any way compromised. So we changed it, and now it's every 10 years.'

Reaching out

But it's not only about competitors and Chambers is keen that Motorsport UK should get involved with the broader motorsport community, and particularly engineering. 'I really want to open up a dialogue with the engineering community,' he says. 'I think previous generations of management here have not really entertained or encouraged an open dialogue with the engineering community, and that's what I firmly want to get across; the engineering community, from the technicians through to the designers, absolutely need to be integrated into all of our thinking and into all of our development.'

Those 'previous generations of management' are what Chambers, with tongue in cheek, refers to as The Ministry of Motorsport, and it's his explanation of this term that really gives an insight into how the difference between Motorsport UK and the MSA is about much more than a mere name change.

'There was a civil service mentality, which meant that it was a lot easier to say no than to say yes,' Chamber says. 'If you are risk averse then you rely on your rules and your regulations, in the same way as a civil servant does; sort of sucking on the teeth and saying the book says you can't do that; and then that propagates a mindset, which is very much about policing things. But, actually, we are a membership organisation and we are accountable to our 720 clubs and our 43,000 members, and what this organisation is about is customer service; we are here to serve our customer base, not the other way round.'

RACE MOVES

Norman Dewis, for many years a Jaguar test driver and a man who helped to develop the first disc brakes, has died at the age of 98. Dewis was the test driver for the C-Type and D-Type Jaguars that won Le Mans five times during the 1950s, and such was his value to the company that his own racing outings were limited, although he did drive a D-Type in the 1955 24 hours. He remained with Jaguar, where he was involved in road car development, until the 1980s, the E-Type just one of the cars he was associated with.

Edward Nelson, a sportscar racer of the 1960s who went on to become a team manager in Formula 5000, has died at the age of 85. Nelson, a member of the British bobsleigh team before he turned his hand to motor racing, spent much of his career driving GT40s and then ran **Jacky Epstein's** Speed International team after he hung up his helmet. He also served on the board of the BRDC.

Roger Andreason, who had been the managing director of racecar constructor Chevron since the early 1980s, has died at the age of 75. A gifted engineer and race driver, Andreason bought Chevron from its founder **Derek Bennett** in 1983, and as well as servicing existing cars he also brought new models, including Sports 2000, Group C2 and a Formula Ford 1600, to the marketplace.

Former NASCAR chairman and CEO **Brian France** has pleaded guilty to drunk driving. France was arrested in Sag Harbor, New York, after the Watkins Glen race in August last year, when he failed to stop at a stop sign and was found in possession of a controlled substance. France's blood alcohol level was 18 per cent. He will now have to complete 100 hours of community service. After his arrest France took an indefinite leave of absence from the sport, with **Jim France** taking his place as chairman and CEO.

Masaru Unno, a senior business adviser at Honda F1, has died. **Masashi Yamamoto**, managing director at Honda F1, said of his passing: 'He was well known to the Formula 1 community and a good friend and adviser to Honda, supporting our Formula 1 programme for many years. He played a key role in motorsport in Japan, particularly the Suzuka circuit's hosting of the Japanese Grand Prix. He will be sadly missed.'

Richard Cleare, who was a sportscar team owner and driver through the 1980s, chalking up a number of appearances at Le Mans, has died at the age of 75. His RC Racing operation won the GT class at the French endurance classic in 1982 with its Group 4 Porsche, Cleare sharing the driving duties with **Tony Dron** and **Richard Jones**.

Wally Willmott, who was the first person to be hired by fellow Kiwi **Bruce McLaren** when he set up his eponymous team in the 1960s, has died at the age of 78. Willmott came to McLaren from Cooper, and he was involved in building the first ever McLaren racecar – while he also shook down cars at Goodwood for the team on occasion. He left the team and returned to New Zealand in 1968.

Wayne Bruce has been appointed director of communications at Bentley Motors. He will be based at Bentley's global headquarters in Crewe and will report to Chairman and CEO **Adrian Hallmark**. Prior to his appointment Bruce was most recently communications director for McLaren Automotive.

Billy Scott, the crew chief on the No.41 Stewart-Haas Racing Ford in the NASCAR Cup, and **Trent Owens**, who fulfils the same role on the JTG Daugherty Racing No.37 Chevrolet, were both fined $10,000 for improperly fitted lug nuts at the Michigan round of the series. Meanwhile, **Randell Burnett**, the crew chief on the No.2 Richard Childress Racing-run Chevrolet in NASCAR's second-tier Xfinity Series, was fined $5000 for lug nut infractions, this was also at the Michigan round of the championship.

NASCAR crew member **Taylor J Morse** has been indefinitely suspended from all NASCAR competition for what has been described as 'behavioural level penalties', which includes violating the US stock car racing governing body's strict substance abuse policy.

OBITUARY – Robin Herd

Robin Herd, best known for his part in the founding of March Engineering and for the many racecars he designed that carried the March name, has died at the age of 80.

After graduating from Oxford with a double first in engineering and physics, Herd first worked in the aerospace industry – including contributing to the Concorde project – before finding a job with McLaren in 1965.

Herd designed the McLaren M2A and the M7A Formula 1 cars, plus others racecars including Can-Am – his M8 ran with ground effect way before F1 cottoned on to it – before moving to Cosworth where he penned a revolutionary four-wheel drive Formula 1 car, which was never raced.

In 1969 Herd teamed up with Max Mosley, Alan Rees and Graham Coaker to form March – which is an acronym of their initials – and by the time of the first grand prix of the 1970 season in South Africa there were five March 701s on the Formula 1 grid.

Over the next 20 years March racecars contested more than 200 grands prix, chalking up three wins, while it was also very successful as a constructor of cars for lower formulae, especially Formula 2, and it also produced sportscars.

In the United States March won five consecutive Indianapolis 500s from 1983 until 1987, and it was during this period that Herd hired a young aerodynamicist called Adrian Newey.

By the end of the 1980s Herd was the majority shareholder of March, but he sold his stake in 1989 and went on to set up his own design office before leaving motorsport for good in the mid-1990s. He then worked on developing an environmentally friendly waste disposal process while he also had a spell as the owner and chairman of Oxford United Football Club.

Robin Herd 1939-2019

Former Peugeot Sport boss takes up post with the FIA

Bruno Famin is now director of operations within the Sport Division at the FIA, with Francois Wales stepping up to replace him as the head of Peugeot Sport.

Famin fills a newly-created role at the FIA, where he will be responsible for the day-to-day running of departments within the Sport Division. He will report to the FIA secretary general for sport, Peter Bayer.

FIA president Jean Todt said of Famin's appointment: 'Bruno brings a wealth of experience across many facets of motorsport to this new position, which has been created to strengthen the development of FIA Sport. His passion for competition and organisational strength will be a great asset in guiding and implementing our strategic vision. I would also like to thank PSA Motorsport for its cooperation during Bruno's transition to the FIA.'

Bruno Famin is now employed by the FIA

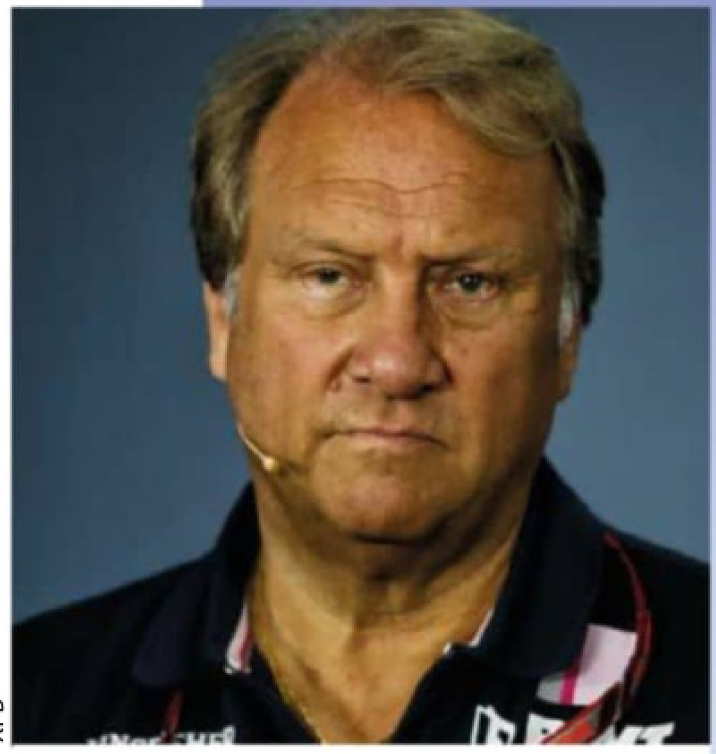
Famin had been at Peugeot since 1988 in a variety of roles, not all motorsport related. As technical director for Peugeot Sport he led the endurance racing programme that culminated in victory at the Le Mans 24 hours in 2009, while as head of the organisation since 2012 he was instrumental in its victory at Pike's Peak in 2013, followed by the three Dakar wins in 2016 to 2018.

Famin has been replaced by Francois Wales at the head of Peugeot Sport.

Wales has worked for PSA since 1989, holding positions as a project and engineering manager in France, China and Spain.

At the beginning of 2018 he moved to PSA Motorsport as manager of the Customer Competition Vehicles Department where he oversaw the development of both the new PSE range of electric sports cars and the 208 R2 rally car.

RACE MOVES – continued



XPB

Robert Fernley has left the McLaren IndyCar operation in the wake of **Fernando Alonso's** failure to qualify the team's entry for this year's Indianapolis 500. The former Force India deputy team principal took up his post at McLaren in November, soon after Force India was acquired by a consortium headed by **Lawrence Stroll**.

Australian Supercars operation Mobil 1 Mega Racing moved its co-team principal **Mathew Nilsson** and technical director **Carl Faux** to race engineer duties for the Winton round of the series in a bid to unlock pace in its struggling Holden Commodores. Both took on the lead roles on the team's cars, alongside regular race engineers **Robb Starr** and **Terry Kerr**.

US PR firm Sunday Group Management has taken on **Amy Greenway**, who has previously worked for SCCA Pro Racing, as its series manager. Greenway will now look after the TransAm series and the MX-5 Cup. She began her media career writing and voicing radio commercials.

NASCAR has announced the inductees who will make-up the NASCAR Hall of Fame Class of 2020, with team owner **Joe Gibbs** and crew chief and engine builder **Waddell Wilson** joining race drivers **Buddy Baker**, **Bobby Labonte**, and **Tony Stewart** (who is also a team co-owner) on the list of the new Hall of Famers.

Edsel Ford II has been named as the recipient of the 2020 Landmark Award for Outstanding Contributions to NASCAR. Ford, the great-grandson of **Henry Ford**, is a member of the Ford board of directors and a long-time executive of the company. He is also a well-known supporter of Ford's NASCAR involvement.

Ian Harrison, a well-known figure in the BTCC paddock, has signed up with BMR Racing to oversee its Subaru Levorg assault for the rest of this season. Former Williams Formula 1 team manager and Triple Eight boss Harrison guided his Vauxhall-equipped team to six titles from 2001 to 2008 and ran the works-backed MG programme up until the end of 2016.

Jaguar has announced that its director of design, **Ian Callum**, has left the company after two decades. **Julian Thomson**, who was the creative design director at the firm, has now stepped into the director of design role. Before joining Jaguar Callum was chief designer at TWR Design, where he was responsible for the Aston Martin DB7 and the DB9.

Brian Pattie, the crew chief on the No.17 Roush Fenway Racing Ford, and **Todd Gordon**, who tends the No.22 Team Penske Ford, were both fined $10,000 after the Charlotte round of the NASCAR Cup series after it was discovered their cars were running with improperly fitted lug nuts.

NASCAR Truck Series team **Kyle Busch** Motorsports (KBM) switched its crew chief line-up around in the run-up to the Texas Motor Speedway race, with **Marcus Richmond** looking after the No. 46 car for two events, while **Wes Ward**, shop foreman at KBM, served as the interim crew chief on the No.4 Toyota. **Michael Shelton** was also set to have a stint as crew chief on the No.4 truck.

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Reflecting on Le Mans

It seemed bizarre to be leaving the final round of the FIA World Endurance Championship at Le Mans with a 'see you next month for the start of the new season', but that's exactly what we were doing. In between the Le Mans race in June and the Prologue, a meaningless but never the less compulsory test day at the end of July, Porsche will launch its new GTE Pro contender at the Goodwood Festival of Speed. It's a tight schedule that adds pressure on the teams and manufacturers who are looking to homologate their new cars for the following season. Bodywork that could normally have been carried through the season can be binned as new and updated aero is introduced for the season that will carry all the way through to Le Mans 2020.

Before we get there, however, the series technical team has to work out how to hobble the Toyotas. Everything is on the table, apparently, from power delivery from the engine, the hybrid system, weight, and fuel flow. Anything that could be considered a performance differentiator, in fact, and all to give the non-hybrids a chance to win. This flies in the face of what motor racing should be about; hobbling the fastest contender is hardly on, or is it? Yet that's the way it is.

Even if you believe hobbling the faster contender is not a bad idea, how much do the hybrids actually need to be pegged back anyway? The BR1, a car designed by Dallara and featuring the AER engine for the Russian SMP team (Gibson in the Dragonspeed car), qualified in 3m16s at Le Mans, faster than the hybrids from Porsche and Audi in 2017. Only Toyota in 2017 went faster, and has done so since. Now, I am aware that the rules are different, and that the non-hybrids should have an advantage by virtue of maths, but let's just take a minute to raise our hats to the suppliers of this car, and the Rebellions, which are travelling at this pace in their first full racing season.

> **'If you want to bring the people to Le Mans, you need to bring the cars they want to see'**

This is no mean feat; the cars are designed to take multiple engine installations, and while the engines have been around for a good few years now, they are being carried faster than ever. These cars have not had the same development time as the manufacturer cars; they have not even used up their full allocation of test days in the 2018/19 season.

Michelin has new tyres to bring to the party next year (well, this month, as the season runs from July to next June) which will bring the LMP1 cars closer, so I could imagine that Toyota is looking at fettling rather than large-scale changes. And remember, this is only to get through the next year before hypercars arrive in July 2020.

The announcement at Le Mans may not have been what many wanted; DPi and a global programme was clearly the preferred option for teams and manufacturers, which rather begged the question why the hypercars needed to be brought to Le Mans. Support came in the unlikely form of Stephane Ratel, suited and booted at Le Mans and holding high-level meetings. 'If you want to bring the people to Le Mans, you need to bring the cars they want to see,' he said. Startling clarity in an otherwise murky world.

Immediately the announcement came, the rumours followed. McLaren was the obvious choice to follow Aston Martin and Toyota into the category, while an outside bet also needs to be placed on Porsche, which was reported in German press to be looking at the new top class. With the option of a non-hybrid prototype, this could drag in others looking for that 'cheap' Le Mans win that has not been available for more than 10 years. One estimate for a three-year programme was around €27m, or about €9m per year.

Suddenly other manufacturers found their names linked to it, including Kia, while FIA president Jean Todt also lobbed in the possibilities of Ferrari and Lamborghini, both of which have looked at the new regulations. Ferrari is almost certain to say 'no', but Lamborghini has always said it needs to see a final set of rules before it could make a decision. And there's the crux of it; there are none. They are needed before the engineers can try to rip them apart and see where the weaknesses are, and then present their ideas to their board of management. It's not a fast process, but it will need to be if they are to make any firm commitments. Porsche has already said that it will need two years to get ready, even if it got approval in August of this year.

This was the interesting point; once the rules were fixed, the beetles came out of the woodwork and started to talk in positive terms. It remains to be seen if any of them will actually take the plunge and race in the top class at Le Mans, but good news rumours are a welcome relief.

There is still the small matter of balancing the new hypercars, though, and more than one 'seen it all before' engineer doubted that this could be done. But then, who would have thought that a 3.4-litre V8 with a super capacitor and 6MJ of stored energy could compete with a diesel featuring a mechanical flywheel in the same class? The ACO and FIA achieved the impossible once before.

ANDREW COTTON Editor