
180 MPH WITHOUT MOVING AN INCH

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# EXtreme E

## Innovative electric SUV series puts engineers to the test in the Saudi desert

**ALTERNATIVE FUELS**
Bio and synthetic set to extend lifespan of the ICE

**FUTURE OF BRAKE TECHNOLOGY**
Are carbon-ceramic brakes ready for Formula 1 in 2025?

**ROLLCAGE ANALYSIS**
FIA declares new standards for testing safety structures

**WILLIAMS FW43B**
Under the skin of Grove's latest grand prix car

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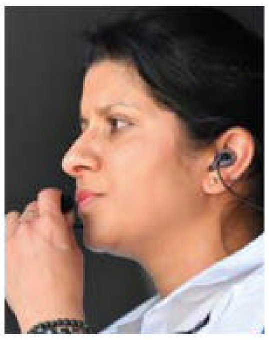
The FIA has announced technical regulations for a new Electric GT series, designed to bring road car relevance to the racetrack



# Fuel for thought

## Are OEMs and the motorsport industry missing a trick?

I write this sat on an aeroplane to Charlotte. In my cabin there are three other people, 10 in Economy, none in Business and maybe some in First Class. Mid-pandemic, there is now a daily flight from London to Charlotte and, instead of the usual nine hours, the reduced payload means it's done in seven and a half hours. That's not progress. The 'plane still burns one of earth's most precious resources, albeit a bit less when it's not full, and still owns an impressively large carbon footprint.

Now before anyone thinks, and then says it, I care deeply about my impact, and that of the motorsport industry, on the environment for a variety of reasons. Yes, I am aware I work in an industry that also burns a precious and finite resource, using transportation that isn't clean and with materials that can be toxic. But that doesn't mean I don't care and that we don't have a moral responsibility to our children.

I struggle with anyone that tells me my impact is minimal, or it's hypocritical to work in racing and then try to be greener, especially industry insiders. It's a bit like saying why bother using the toilet when you can just throw it out of the window, Middle Ages style. No!

Humans are resourceful and, in the case of transportation, we have seen a revolution in less than a century that was driven by the need to progress.

### A new chapter

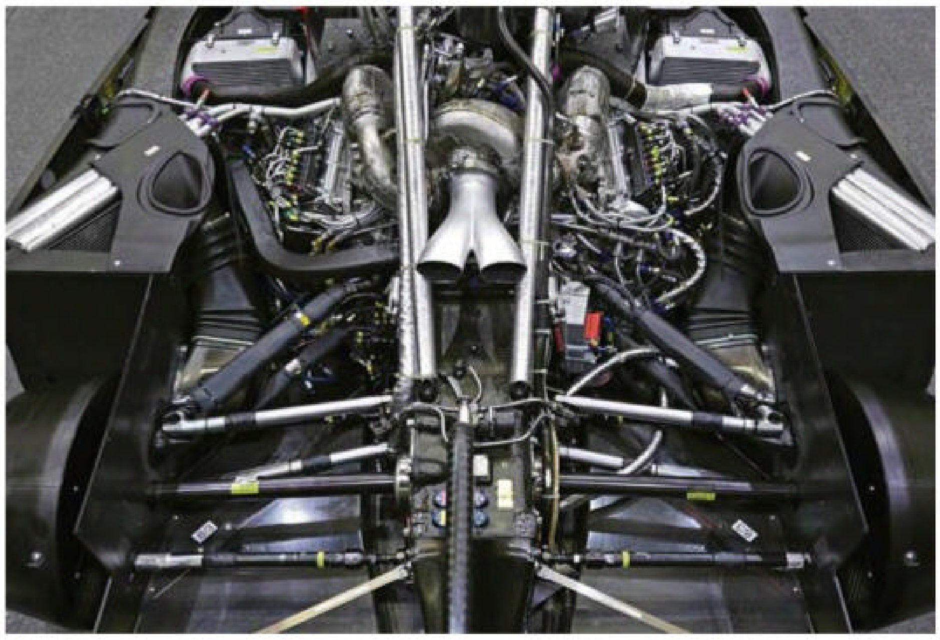
Alongside Formula E, now seven seasons in, this year has seen the debut of Extreme E, an electric World Touring Car Series and, for 2023, a new electric GT series, which aims to bring pure electric racing into an endurance racing format. All of this is great. It's a bit like 2006 when Audi introduced Le Mans to diesel and a new chapter in racing history was written.

Many at the time were appalled that such a fuel could even be considered in racing but, once you sift through the pessimism, you see progress was made in bringing a new technology to the track (nine overall Le Mans titles between Audi and Peugeot). However, I don't think electric racing alone is enough.

An infrastructure is developing that is bringing electric technology to many Londoners, allowing them to move around the city in less noxious gas-emitting vehicles. I don't believe the London bubble is representative of anywhere else in the UK, though, and other areas are years away from enjoying the luxury of electric transportation.

For many smaller places, it simply won't be economical to introduce electric charging structures because there isn't local authority or central government investment available.

Thirty years ago, on a two-week placement in an engineering firm, I wrote an essay about a hydrogen car as part of a project on possible future projects. I'd been taught about climate change at school so this was exciting for me.



Ferdi Kräling Motorsport-Bild GmbH

**Audi diesel technology was a revolution at Le Mans. Motorsport needs its next fuel revolution**

Sadly, that car was just a young engineer's dream, and the options today are still too few.

My interest in clean alternative fuels was spurred by a research paper written by Aquafuel who provided Formula E with fuel to use in generators to charge the batteries. It looked into the use of glycerine from naturally occurring algae to power ICE, and with some success.

It doesn't provide the same power and performance as petrol, but also doesn't produce any NOx, CO or $CO_2$. So, while it might not power the next Le Mans winner, it does have cleaner credentials for everyday use.

Except for electric, there is likely no other fuel source out there that provides torque and power with the same expectation of fossil fuel.

So how about combining that fuel into a hybrid to achieve that? We haven't done enough to find fuels that could be used in our current cars. I say this because in 2030 when no new ICE cars are sold, there are going to be lots of people stuck with 'dirty' cars paying high tariffs because they can't afford an electric alternative, and without viable public transport because it is expensive and still being scaled back.

### From race to road

Why does any of this apply to racing? Well, around 100 years ago, OEMs used racing to validate their road products and technology. But in the last 20 years, racing's prowess hasn't always revolutionised mainstream automotive engineering. In fact, on the powertrain front it could be argued that road cars are *more* advanced. Where OEMs might not want to commit to fully investing in alternative fuels for future models, they could finance niche racing products to explore alternatives on a small scale.

There are plenty of specialised engineering firms experimenting, and using their expertise could be an opportunity to develop a racing certified system.

This argument exists because we all want cars for movement and that is not likely to change anytime soon. So as a society, and an industry, we need to show what is possible. There can be options that still remain true to the art of racing, whilst perhaps sparking complementary technologies using fossil fuel alongside the battery industry.

To be clear, electric has its own controversial and moral issues, so it isn't the golden ticket to all our green, ethical and sustainable transport.

I feel the governing bodies are moving too slowly, with a hang up on equivalence and the past. There are so many clever minds in this business, it would be refreshing to see a partnership between racing and automotive bring a new perspective on our every day. It's never too late to try something new!

*Leena Gade is race engineer at Multimatic Engineering UK*

**While OEMs might not want to commit to fully investing in alternative fuels for future models, they could finance niche racing products to explore alternatives**

# Punch to the glut

One *can* have too much of a good thing

While understanding Liberty's financial desire to increase revenues by staging 23 F1 World Championship events in one year, it seems to me they have failed to consider the negative effect this may cause. Arguably, even 20 GPs are two too many. Exclusivity often defines an image. Dilute this and you potentially risk a devaluation of brand value and prestige. It pays to keep devotees hungry for more.

I suspect, with a race almost every other weekend and a number back to back between late March and mid-December, the dedicated TV audiences worldwide will find it difficult to follow every round – certainly live – because of the sheer time required. Especially so at the time of year when people are being tempted to enjoy outside activities, and are under pressure to not compromise these family pleasures. It's a problem even for the nerds among us who find the Saturday practice and qualifying a key part of each event.

Yes, there are those who just watch F1 occasionally, but I imagine Liberty's business model relies more on the regular viewers to boost their TV income. Missing one race makes it easier to miss another one, and quickly the chain is broken.

## In the trenches

Just to add to the concern, after every race now one car will be selected at random and subjected to a deeper level of inspection. This will result in an extra day at the circuit for the team personnel concerned. If this isn't enough, F1 sprint races are now about to be trialled. So, reduce free practice sessions by 30 minutes on one hand, and then add one hour of racing on the other. Has anybody asked those who actually fight in the trenches what they think regarding the extra workload?

At least drivers and senior staff earn sufficient wedge to compensate, capable frequently of avoiding the hassle of commercial air travel etc. It may be that a staggered rota, or shift, system will have to be introduced for less fortunate personnel, but this is far from ideal when it comes to continuity, pit stop sharpness and keeping up with race-by-race developments.

One should also not overlook the myriad of FIA employees that will be similarly affected.

Despite all of this, I am glad that Stefano Domenicali has ruled out two-day F1 weekends. Apart from the business advantage to the promoters and other event stakeholders, there are the fans who cannot afford Saturday and Sunday ticket prices but can just manage Friday's. I have defended these before and it's good that their voices have been heard.

## Stellar entry

Given that the idea of the Sprint Races is to liven up the show, much better surely would be to consider re-introducing a successful concept from the past. The BMW M1 Procar Championship ran in 1979 and '80 as a support event to the European rounds of F1. There was a stellar entry from F1, and other top drivers, and the titles were won by Niki Lauda and Nelson Piquet, no less. The big attraction to fans was seeing drivers with less experience, or those struggling in uncompetitive F1 teams, going wheel-to-wheel with the current heroes, crucially in equal machinery.

XPB

**Procar demonstration at Hockenheim in 2008. It was a good idea at the time, but are the drivers all too precious now to put themselves forward for such a series?**

I imagine this to be even more attractive now. A minimum amount of practice and qualifying would encourage pure talent to shine through, allowing it also to fit into F1's tight schedule. The spectacle might well attract a manufacturer with a suitable performance car to promote – right up Elon Musk's street? Sadly, wrangling over sponsorship and contracts could knock this on the head, as might reluctance among some drivers to be tested in this way.

With the stratospheric earnings now of those whose reputations stand to lose the most, financial incentives would have to huge to tempt them. Unfortunately, I can't see the F1 hierarchy being able to make participation mandatory.

It would be a great levelling spectacle, though, wouldn't it? And with no issues for the 'proper' F1 races with devious tactics, politics, grid penalty impositions, effects on championship final results and all the complicated baggage that sprint races bring. Perhaps, where there's a will, there might be a way?

Netflix is now brilliantly proving how alternative coverage can work with the regular media in boosting F1 recognition worldwide, of whichever gender and generation (despite revealing that the favourite word in F1 also seems to begin with f…).

## Big Tech money

At least as important is the investment in the sport the popularity of the screen series is helping to draw from Big Tech companies, a huge step towards the ideal of making F1 teams potentially self-supporting, profitable franchises. This is how professional sport *should* be, with the caveat that new blood is not deliberately barred from entering by unrealistic financial and other barriers put in place purely out of self-interest by the incumbents. Closed shops are not healthy and team name changes are not the same as new teams.

Away from the broader picture (relief!), proof of the complexity of the systems integrated in current F1 cars and the drivers' (and engineers') understanding of how to maximise their advantages is revealed in recent comments by Alonso, Perez and Ricciardo. Despite their experience, all have admitted it will take four or five races for them to be 100 per cent confident in their new cars and teams. Light years away from the 'jump-in-and-drive-the-wheels-off-it' approach that used to occasionally stir up the established order.

Yet Yuki Tsunoda, with the least experience in racing *anything*, hops into his AlphaTauri and stuns everyone with his pace. There's either *much* more to come from him or he hasn't had to unlearn brain-embedded information.

**Given that the idea of the sprint races is to liven up the show, much better surely would be to consider re-introducing a successful concept from the past**

# Fresh blood


**Williams Racing's new team principal, Simon Roberts, gives *Racecar Engineering* an exclusive insight into its 2021 challenger**

**By STEWART MITCHELL**


Simon Roberts, pictured here at the 2021 pre-season test in Bahrain, is confident Wiliams Racing is back on track

The Williams FW43B is considered a high-rake car, by nature of the static ride height of the rear axle being significantly higher than the front


**We've tried to do as much development on our car as we can with one hand tied behind our back**

Photos: XPB


Like the rest of the 2021 Formula 1 paddock, Williams opted to design its side impact structure in the mid-height position to allow for a more efficient sidepod intake design


As per 2021 technical regulations, the floor of the Williams FW43B is 100mm narrower at the trailing edge and features no sealing slots down the side, or tyre jet controlling holes at the back

It's no secret that Williams Racing has struggled in Formula 1 for the last few seasons, finishing last in the Constructors' Championship three years in a row running up to 2021.

Technical and business management re-structuring has unquestionably caused some trials for the team in recent years, but the challenges the team has been facing are multi-faceted.

Formula 1's current revenue structure, introduced in 2012, formed the origin of its financial issues, solved only recently by the American private investment firm, Dorilton Capital's, acquisition of the team in August 2020.

This transaction received the unanimous support of the board at Williams, including Sir Frank Williams.

He determined the transaction delivers the best outcome for the company's shareholders, and secures the long-term success of the Williams Racing Formula 1 team.

With that, Sir Frank Williams and Claire Williams stepped down from their roles as team principal and deputy team principal, respectively, in September 2020.

Williams Racing's managing director F1, Simon Roberts, then became team principal, following the appointment of a new CEO, 40-year motorsport veteran, Jost Capito.

With the appointments out of the way, *Racecar Engineering* can concentrate on Williams Racing's 2021 challenger, the FW43B.

## Evolved development

The 'B' in the 2021 car's nomenclature denotes an evolution of the 2020 FW43, carrying over the same chassis, nose and a series of other parts from its predecessor.

'We've tried to do as much development on our car as we can with one hand tied behind our back, the token system limiting us on what we could do to the car,' notes Roberts.

'The car is an update on what we had last year, and it has evolved a lot.

'We've spent the tokens wisely, opting not to get a new nose like some other teams because we decided to use a token elsewhere, and you need two tokens for the nose.

'As for the car's rear end regarding the new regulations on the floor area, diffuser and rear brake aero devices, the aero team did an outstanding job in minimising the losses.

'When we put the changes on the car, we, like everyone, lost a lot of downforce, reducing rear-end stability. We've tried to recover as much as we can in aero, but whether we've done enough to finish higher up the order this season, who knows?'

According to Roberts, the detailed engineering in the car saw the most investment, despite retaining much the same regulations from last season.

'It's much more refined than it was in 2020,' he says. 'We have managed to save weight in many areas by re-positioning and tidying up many systems inside the car.

'Anything we can do to improve it, and make it more reliable and competitive, we've done.

'Although it's a highly homologated carryover car, with not much scope for change, if you saw the 2020 and 2021 cars back-to-back, it's a big step.'

The FIA targeted a 10 per cent reduction in downforce with the changes made to the floor, rear diffuser and rear brake winglet regulations – most of that affecting the back end.

It is thought the high-rake design philosophy, which Williams had used for many years and carried on for 2021, is less affected by the changes compared to the flatter running cars of Aston Martin and Mercedes.

'We, like many other teams, relied on the interaction of the rear brake aero furniture and the lower edges of the diffuser strakes, because that had been relatively stable in the regulations for many years.

'Due to the homologation, there's only so much you can do to mitigate the changes. You can't change the wheelbase, you can't fundamentally change the geometry of your car.'

## Slot machines

Also introduced by the FIA for 2021 was a ban on enclosed holes and slots in the floor area. Previously, these slots were used to control the aerodynamic consequences of the varying sidewall bulge of the rear tyre and contact patch squirt (loss ejected by the tyre as it contacts the ground).

'We had all the slots and holes down the side of the floor, and you're trying to do two things with them – you're trying to seal the edge of the floor to generate more suction, and control the flow to the rear of the car,' explains Roberts.

'Controlling the jet of air you get coming out as the tyre rolls forward [tyre squirt] is an area that made a huge difference in car behaviour. Removing the holes and slots changes all of those flow mechanisms and subsequent flow structures.'

**We have managed to save weight in many areas by re-positioning and tidying up many systems inside the car**


**The Mercedes 2021 PU has a larger plenum system than its predecessor. Consequently, the Williams FW43B has a wider engine cover**


**The bodywork surrounding the sidepod-mounted heat exchangers on the FW43B has been sculpted to drive airflow over and down its upper surface**

Although the FIA was hoping the regulation changes would act as a calming measure for the tyres, and reduce engineering and financial costs with most of the car homologated for another season, it wasn't the case.

'It meant a huge amount of re-working of the front end of the car to mitigate some of the losses and optimise the flow over the car with the new package,' remarks Roberts.

'Optimisation starts way up front. You're looking at interactions between sidepods and the front floor and its interaction with the rear and so on. Small changes in sidepod and front floor sections go a long way to adjust the behaviour of the aero further back.

'The barge boards have seen a lot of development too, as we are still trying to manage front-wheel wake.

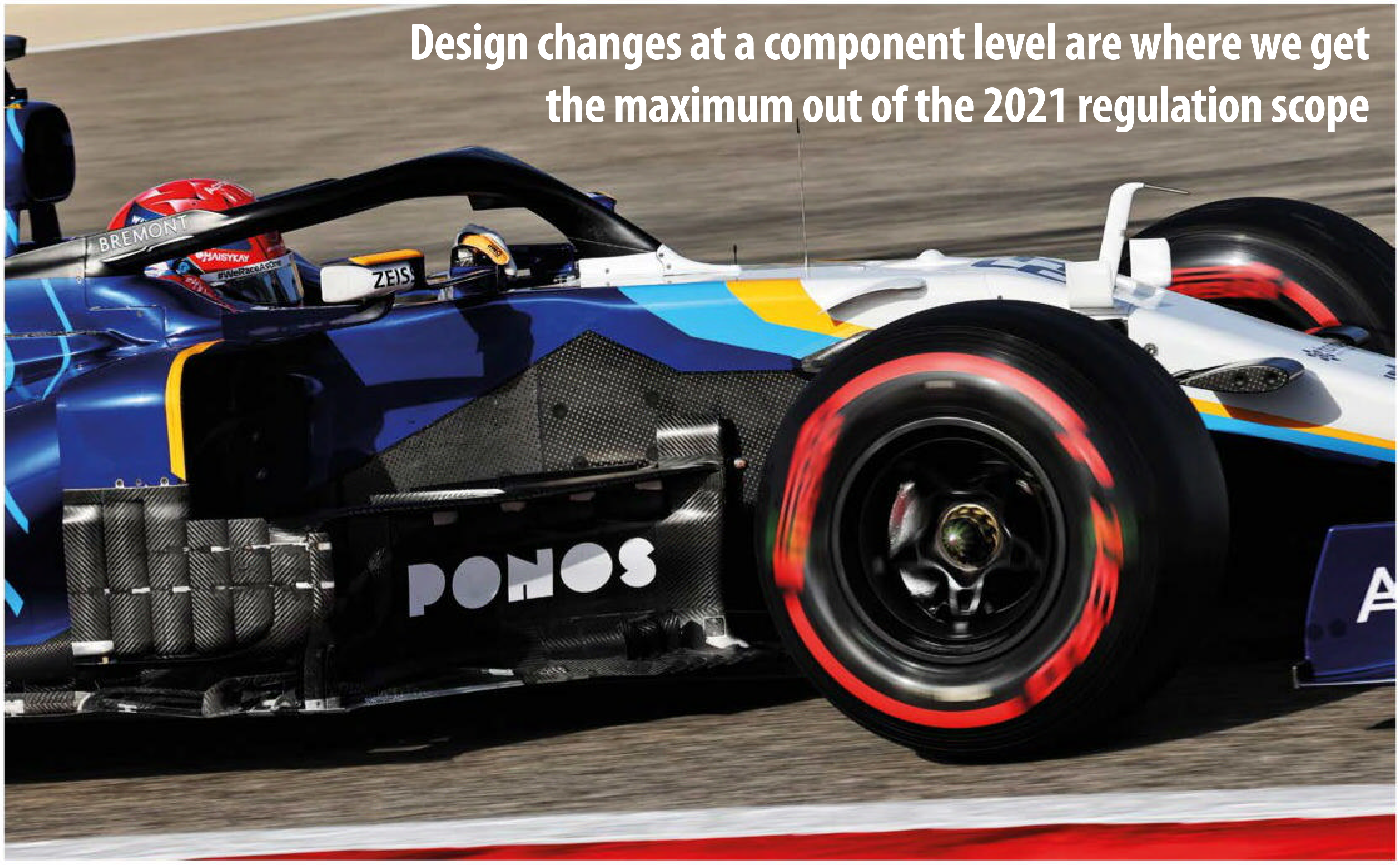
'Although the changes from the FIA were around the rear of the car, it just meant we've got to be even better at managing the front-wheel wake because as that encroaches on the back of your car, that's one of the things that gives you a stability problem.'

## Power unit management

Mercedes HPP, the power unit supplier to Williams, brought some significant updates to its power unit package for 2021, providing Williams with an opportunity to subtly develop the car.

'We've reviewed all our cooling,' says Roberts. 'That's been a big part of the tidy


**The FW43B's diffuser showing the vertical dividing strakes, which are 50mm shorter than those used on the 2020 version of the car, again as per FIA-implemented changes to the technical regulations ahead of the 2021 season designed to reduce cost**



**The barge boards are a very open area in the current generation of Formula 1. Williams has continued to refine this area on the FW43B to, as much as possible, control front tyre wake**

up of systems at a component level, and we have a much better solution now.

'Design changes at a component level are where we get the maximum out of the 2021 regulation scope, and cooling has been one of the significant changes we've looked at in detail for the FW43B.

'Although essentially the architecture is very similar, in detail, we've moved a few things around, and we've got more performance out of the cooling pack on the car.

'Fundamentally, we all run the power unit as hot as we dare and the charge cooler as cold as we can. Cooling is therefore exceptionally effective in developing car performance as the more efficient the cooling package, the tighter the bodywork can be, the less drag you have and the higher the potential for more downforce.

**We're not just trying to cool everything as much as we can, we're trying to operate in a window, and you need to make sure your system can cope with that**

'These cars are so aero sensitive that it always comes back to that.'

Although the Mercedes grand prix team is a competitor, as a supplier Mercedes HPP supports its power units and, by regulation, all Mercedes HPP-powered cars must run the same code, physical parts and performance as the factory team. How a customer team manages its cooling package, though, is up to them, and it's of note that all Mercedes customer teams use a different charge air cooling technique to the Mercedes F1 team.

'When it comes to charge air cooling, essentially, we're all trying to extract as much heat out of the air as possible, and reject the heat extracted from any heat exchange away from the car as cleanly as possible without generating drag,' explains Roberts. 'Our solution for some time has been air-to-air, and we've stuck to that coming into 2021, even with a huge revision to the car.

'This opposes the ethos Mercedes carry on their car as they use air-to-liquid for charge cooling. Despite the different philosophy, each seems to work well for the Mercedes power unit.

'[Mercedes' solution] is efficient, but there are some downsides to it. You have to consider in far more detail the pressure drops on all the systems. If you have too much pressure drop, or too little temperature extraction, then you're in a world of pain.

'Additionally, you have to consider all the scenarios on track for base engine cooling, which is also air-to-liquid. For example, the cars are very different in green flag laps compared to when running behind the safety car, which is an entirely different set of cooling issues compared to running in qualifying, and overcooling isn't great.

'These engines and gearboxes are designed to run in very tight limits, so we're not just trying to cool everything as much as we can, we're trying to operate in a window, and you need to make sure your system can cope with that.

'The current engines seem to respond better to narrow temperature windows, which aren't necessarily as cold as possible.

'You don't want to run your water jacket too cold, you want it to run at the right temperature and get the lowest charge temperature you can.

'Every year that goes by, we start engineering it to another level. If you go back 10 years, it wasn't that the engineers didn't care, it's just the tools they had, and the technology they had around them, gave a different solution.'

## Volume control

Air-to-air cooling requires a significantly larger volume than an air-to-liquid cooling solution, and the team must place that volume somewhere, while air-to-liquid designs must consider boundary efficiencies.

The size and layout of all cooling packages must consider overall system efficiency.

'Every time you have a heat transfer boundary, you get some inefficiency,' notes Roberts. 'If you go air-to-liquid for charge cooling, then you've got an extra boundary to cross as the heat goes from air to liquid to air.

'From a pure air cooling point of view, air-to-air is more efficient if you can make it work, but you've got an extra cooler on the car. If your bodywork and aero philosophy have enough space to stand that, and you're happy to deliver that compromise, then you can gain by going that way.

'If you look at Mercedes, it's a very tight, very tucked bodywork package. Some of that they achieved through using a liquid-cooled heat exchanger for their charge cooler.

'They know they're getting rid of area from that in their car design, but it's not easy to do. You've still got to package the air-to-liquid charge cooler somewhere, and you have to take the weight [penalty]. It's weight and complexity vs space and volume.'

Williams opted to position its air-to-air charge cooler above the engine using the stream of high mass flow air that enters through the roll hoop over the driver's head.

'You get a nice clean, solid, typically laminar flow coming in over the top of the car, whereas the flow to the sidepod coolers can have less capacity, especially if you are in traffic, making them a little bit less efficient,' explains Roberts. 'We look at the overall car design to get an overall picture of how well it will all work. We don't want to have all our big coolers high up on the car as it'll start making the top body and engine cover too large, so there is a split between the efficiency, weight and location as a function of vehicle dynamics, and we have to accept compromise there.'

The main engine radiators are in the sidepods. The central cooling above the engine is for charge air and some ancillaries but, because it is efficient, it means said coolers are very small.

'This concept also allows us to tune the cooling a lot more from track to track, or different ambient ranges. We've got some flexibility between the sidepod and the centre options, and we're not the only team that does that. Quite a few teams have coolers in two or three places, and then you can play around with it.

'There is a divide amongst the teams as some use coolers for solo systems, while others use a split core. That's as much as anything to do with your engine design and what the pressure drops are. We use a singular unit for each system including charge cooling, engine coolant and engine oil.'

Along with the 2021 technical rule changes, the FIA also introduced a sliding scale of wind tunnel and CFD testing time for each team. The winner of the previous championship is allowed the least amount of wind tunnel time, and the last place constructor offered the maximum time.


With a token system in place for 2021 technical developments, Williams opted not to make any changes to the front wing and nose

For 2021, Williams has the maximum wind tunnel testing and CFD allowance of all the teams on the grid, 112 per cent of the nominal 40 runs per week, giving them 45 runs per week as a function of them finishing 2020 as the last-placed constructor.

In comparison, Mercedes, the first-placed constructor in 2020, has just 36 runs per week.

'It's still less than we had before [around 65 runs per week in previous seasons],' notes Roberts, 'but this structure will allow for a better balance up and down the grid.

'We are aware we've got more than the other teams and don't want to waste that. It certainly makes you conscious of being effective and efficient with what you do. Every wind tunnel run, every CFD run, is precious.

## Parallel development

'This will come into play when we consider the next-generation car. All the teams will go from splitting their design and R&D on this [2021] car and the 2022 car to a total effort on the 2022 car at some point in this season. We're doing both in parallel, and we have an excellent plan that we've been working on for over a year.

'The FIA stopping development entirely on the 2022 car in 2020 gave us time to think about how we're going to do it. We used the opportunity to work on the current car, and we will be bringing updates to the track this season.

'[The] 2021 [season] is just as crucial as any in Formula 1, and we don't want to lose sight of that. We must keep that competitive spirit in the team. We want to keep working on 2021 and pushing and making life difficult for our competitors by getting better and better as they turn their efforts over to 2022.'

**We are aware we've got more [wind tunnel testing and CFD allowance] than the other teams and don't want to waste that… Every wind tunnel run, every CFD run, is precious**

Williams was around 3.4 per cent off the nominal race lap time performance of the championship-winning Mercedes throughout 2020, and consistently within 0.75 per cent of its closest rivals, Haas and Alfa Romeo.

As to whether the two and a half per cent extra wind tunnel time will translate directly to on-track performance, Roberts is positive: 'It *will* make a difference in tiny marginal gains at the start, and then it *will* add up.

'But what overrides that, unfortunately, is whether the stuff you're working on is the right stuff. If you're following a good development thread, and you're finding good downforce and performance, that will have more impact in the short-to-medium term than whether you've got two or three per cent more wind tunnel and CFD capacity.

'Over the long term, it will help even the teams out because the more runs you do, the more CFD you do, the more data you've got and the better decisions you'll make.'

With its new structure and leadership, helped by aspects of the new regulations, Williams Racing may well be fighting for F1 glory again in the not-too-distant future.

**The sporting regulations are as complicated as nuclear physics, with shootouts, crazy races and fan-induced voting for a favourable grid position**

# Sand and deliver

**A new electric racing series kicked off early April in Saudi Arabia, and proved a steep learning curve for all involved, including the Andretti United Extreme E team**

**By ANDREW COTTON**


Photos: Extreme E

It was history in the making when nine electric SUVs lined up to contest the inaugural Extreme E series in Saudi Arabia earlier this year. For the race engineers involved in the running of the cars, it was a completely new experience.

Combined with the desert sand racing surface, on which few teams had actually tested prior to the cars being shipped to the event, there were high temperatures to contend with, which played havoc with the strategies for the two qualifying sessions and multiple race format.

The Odyssey 21s, built by Spark Racing Technology, comprise a common package of standard parts, including a niobium-reinforced steel alloy tubular frame, crash structure and rollcage. Teams are able to design their own bodywork, or work with an automotive partner, but the exterior shell of the Odyssey is made from BComp's natural flax fibre in a bid to be more sustainable.

The SUVs weigh in at 1780kg and put out a maximum of 400kW (550bhp) through drive to both front and rear axles. The 800V battery, which has 40kWh of useable energy, and which weighs less than 400kg, is produced by Williams Advanced Engineering. Tyres come from Continental.

## Environmental impact

Extreme E's purpose is to highlight the environmental impact on natural resources due to human activity and, as such, the

Cars were shipped to the event in Saudi Arabia. Next stop Senegal

### TECH SPEC: Odyssey 21

| | |
|---|---|
| **Overall length** | 4401mm |
| **Overall width** | 2300mm |
| **Overall height** | 1864mm |
| **Front track** | 1998mm |
| **Rear track** | 1998mm |
| **Ride height** | 450mm |
| **Wheelbase** | 3001mm |
| **Weight** | 1780kg |
| **Battery capacity** | 40kWh of useable energy |
| **Power source** | Twin 250kW motors (550bhp equivalent) |
| **Torque** | 920Nm |
| **Gradient capability** | 40 degrees on an 80 per cent slope<br>53 degrees on a 130 per cent slope<br>(estimated, depending on surface) |
| **Suspension travel** | 385mm |
| **SPEC PARTS** | |
| **Chassis** | Tubular frame constructed of niobium-reinforced steel alloy |
| **Suspension** | Double wishbone with three-way adjustable mono damper; hydraulic bump and rebound stop |
| **Braking** | Six-piston Alcon caliper; iron disc and pads |
| **Steering** | Electrical PAS system |
| **Battery** | Built by Williams Advanced Engineering |
| **Tyres** | Engineered for the extreme terrains by Continental Tyres |

Ambient temperature and sand ingression were the two main predicted problems engineers would face, but in fact neither proved a big issue in the race, battery management being the more significant challenge

**'I think the battery thermal management was the most challenging aspect of the first race'**

*Brice Gaillardon, race engineer at Andretti United Extreme E*

series has to remain as environmentally friendly as possible, using the latest available technology. To that end, it has signed a deal with AFC Energy to use its hydrogen fuel cell technology to enable its race fleet to be charged using zero-emission technology.

'AFC Energy is the leading provider of Alkaline Fuel Cell systems for the generation of clean energy,' says series founder, Alejandro Agag. 'It has developed a wide range of technologies to enable sustainable off-grid power generation, which is easily transportable, offers high efficiency and emits water as its only by-product, which we can utilise elsewhere on site.'

The sporting regulations are as complicated as nuclear physics, with shootouts, crazy races and fan-induced voting for a favourable grid position, but ultimately boil down to qualifying in a single-car format, a semi-final where cars race against each other for the first time, and a final. Driver pairing regulations stipulate one male and one female driver, although there are no such regulations in the pits.

## Eat my dust

What was noticeable in the opening race was that the multi-car races were pretty much decided by who was ahead as the cars stretched their legs on the long straights between the gates that demarked the track. The dust cloud behind made it difficult to challenge the leader, despite the freedom in terms of available space between gates to each competitor.

The Saudi event showed the cars were strong and safe, but also that race conditions were harsh on equipment. Both Stéphane Sarrazin and Claudia Hürtgen crashed in single-car qualifying, the former unable to continue due to rollcage damage.

Although the cars supplied are pretty much standard, there is still plenty of scope within the software for the engineers to extract performance. With a variation between power delivery to the front and rear axles, traction control and thermal management all coming into play during the competition, it was a steep learning curve for the race engineers.

**The multi-car races were pretty much decided by who was ahead as… the dust cloud behind made it difficult to challenge the leader**

'I think the battery thermal management was the most challenging aspect of the first race,' said Andretti United Extreme E's race engineer, Brice Gaillardon. With a compressed schedule, the two qualifying sessions – one for each driver – were held on the same day, which led to problems for the teams.

'When we charge the batteries overnight, that's fine, we have plenty of time, but the problem is when we have two sessions in the same day,' confirms Gaillardon. 'The second one is tricky, and that is why we had to reduce the power. Between qualifying one and qualifying two I was trying to do some simulations to see how we could finish the race without the battery getting too hot.'

Teams must comprise one male and one female driver and the sessions are a mix of single and multi-car challenges

## Keeping cool

It might be natural to assume any overheating was due to the high ambient temperatures, but they were less than 30degC, and in fact air temperature had a very limited impact on battery temperature.

Each of the teams was able to run air conditioning for their battery packs, maintaining them at a steady eight degrees, but it took a long time and energy to drop the temperatures that far, certainly too long for the two sessions in the same day.

'There is a lot of stuff in a black carbon box, and it gets really hot,' says Gaillardon. 'You have no way to cool it. We only have air conditioning, but it takes hours to cool to the right temperature, and then there is so much inertia and it is a huge mass.'

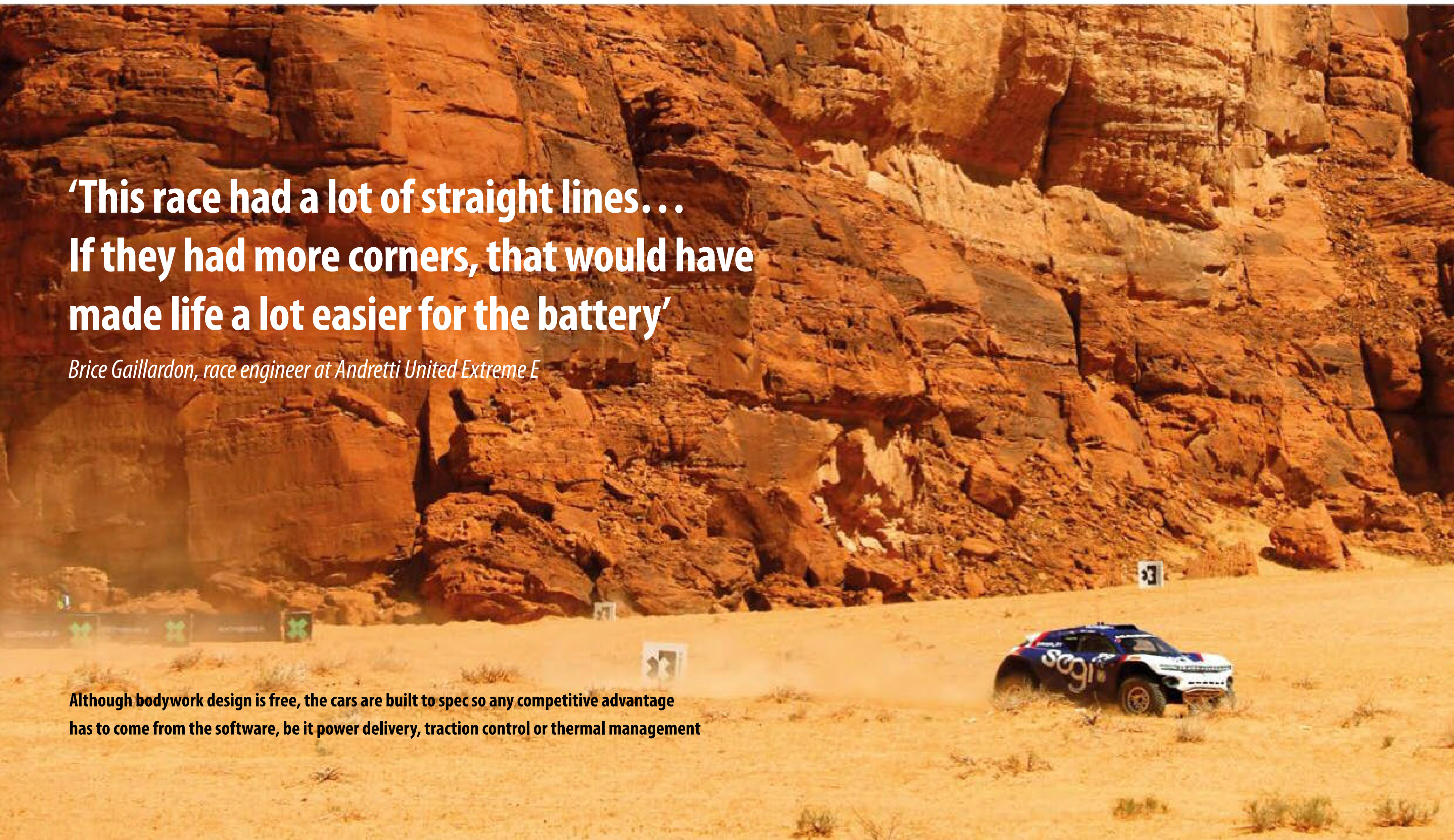
The decision taken by the organisers to reduce the power between the two qualifying sessions might have cost them track time, but actually Andretti United Extreme E had rather larger problems that are more typically associated with traditional rallying. Catie Munnings, the former European Rally Championship ladies champion in 2016 and former WRC driver, suffered a spectacular right rear puncture and had a job to even get the car to the finish line. Hers was the slower of the two sessions anyway, due to the power reduction.

'We ran the first qualifying session at 285kW, and then the second at 225kW,' says Gaillardon. 'We lost something like 20 per cent of the power. The issue was more the track layout than the temperatures. This one had a lot of straight lines, and I think it was 70 per cent flat out. If they had more corners, that would have made life a lot easier for the battery.'

The team has not yet seen the route for the second round, but they are hoping for a change in the layout, or to the timing. 'I think they need to adjust the timetable more than anything,' says Gaillardon.

## Surface tension

It was a big ask to take brand new cars to the extreme conditions of the desert, but that is kind of the purpose of the series. More of an issue was the fact they had little testing prior to the event, and none of the teams actually tested in the sandy conditions of the race.



**'This race had a lot of straight lines… If they had more corners, that would have made life a lot easier for the battery'**

*Brice Gaillardon, race engineer at Andretti United Extreme E*

Although bodywork design is free, the cars are built to spec so any competitive advantage has to come from the software, be it power delivery, traction control or thermal management

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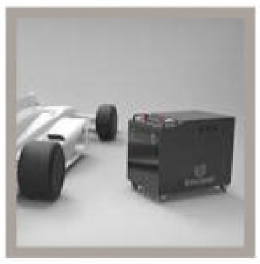

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**The sand is constantly changing and so, therefore, were the track conditions**

Aside from damage sustained in some spectacular crashes, the racecars themselves stood up to their first test well, but the conditions at round two in Senegal will offer a new set of challenges

'We only had one test of two days, in Motorland Aragon, and there [we ran] 360kW of power on gravel,' explains Gaillardon. 'Suddenly, for the first race we are in the sand with 285kW and there was still a lot of adjustment to the software that we had to make.

'We still had a lot to play with for the different conditions, but nobody tested in this kind of sand before. That was the biggest challenge for us, the change of surface.'

Despite the depth and dryness of the sand, teams were pleasantly surprised that the cars kept the particles out of the cockpit and battery.

'I think Spark did a couple of days of testing before the [race] weekend on the actual course, so I think they learned a lot here,' notes Gaillardon.

On such a surface, clearly traction control is a performance differentiator and here, too, the engineers had plenty to play with in order to get the fastest times. The teams have three options within the software, including how to distribute the power over the terrain, the maximum power you want to deliver to the front axle and a balance map, a 3D map based on lateral g forces and steering angle that provides traction control to the front axle.

'For example, you can have 285kW split by 200kW at the rear and 85kW at the front, or 140kW rear and 145kW front if you want, so you can choose, and this makes a big difference.

'Then you also have traction control at the front. Basically, the front motor cannot exceed a speed you can set with maximum rpm. You have a rear motor that is set at 10,000rpm and you can say okay, I am only going to allow 12,000rpm at the front. You then have a delta between the two and that is how you control the front wheelspin.'

If that sounds complicated, there were additional issues thrown up by the fact the sandy surface the teams were racing on is constantly changing and so, therefore, were the track conditions. Guessing what the track conditions would be for the session was an unexpected challenge, as was lining up on the start for the initial dash to the first gate.

'You had to change the power level from one session to another, and we had to be quite dynamic and reactive to the changing conditions,' explains Gaillardon.

## A question of balance

As with all multi-driver formulae, balancing the needs of both drivers who share the car in the race, with a strictly controlled changeover, is also key. Munnings is partnered with Timmy Hansen, the 2019 World RX Drivers' Champion and winner on the FIA World Rallycross Championship tour.

'The more time we spend together, the more you understand what they need,' says Gaillardon. 'Catie and Timmy, as far as I am concerned, need completely different things. I think Timmy will be fast

**'We are not able to change springs between the two drivers, so we have to use the maps and be clever with the settings, and then see'**

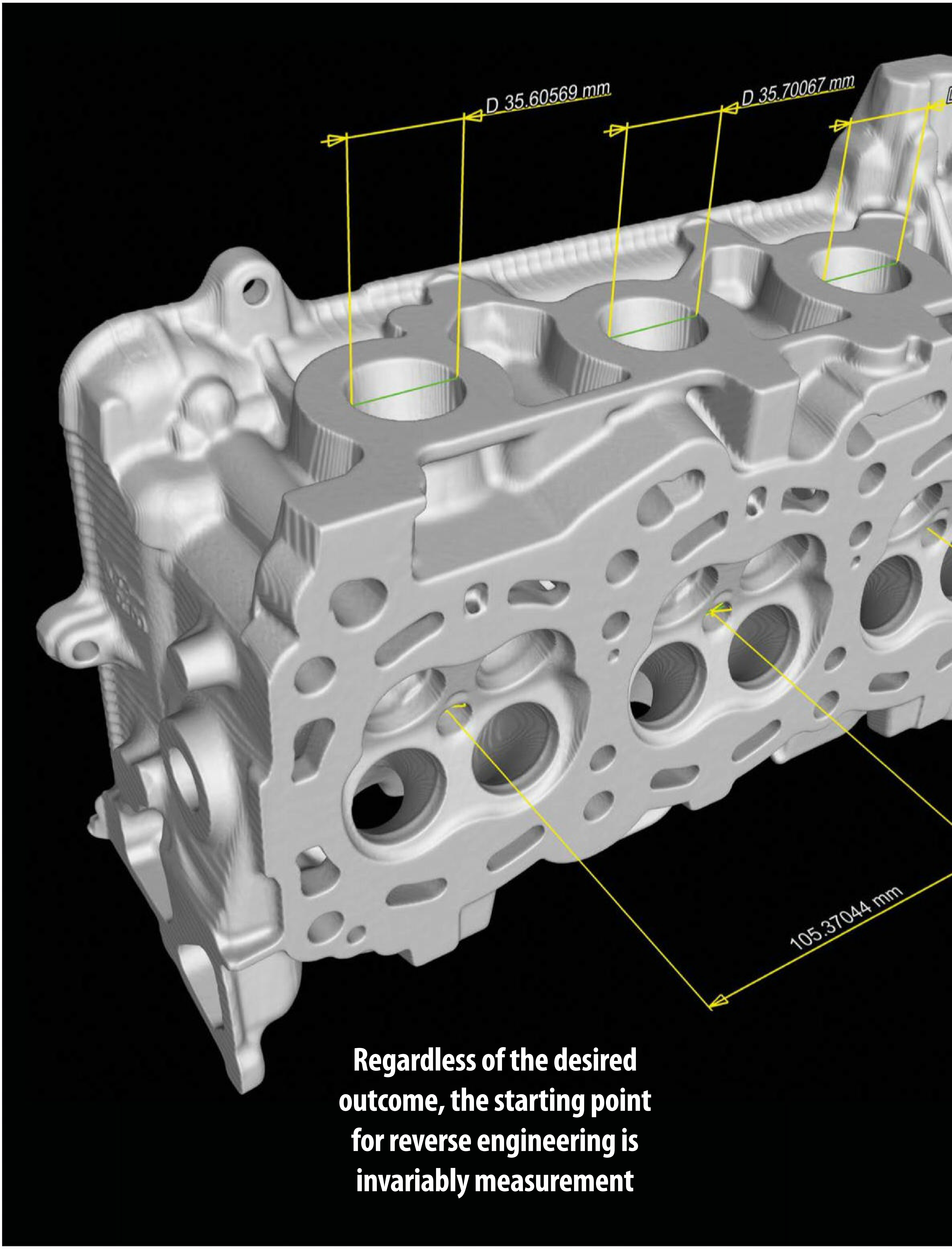
*Brice Gaillardon, race engineer at Andretti United Extreme E*

with anything you give him, but to be ultimately fast he needs precise settings. Catie is from a different racing background in front-wheel drive cars, and therefore will have different needs to be quick.

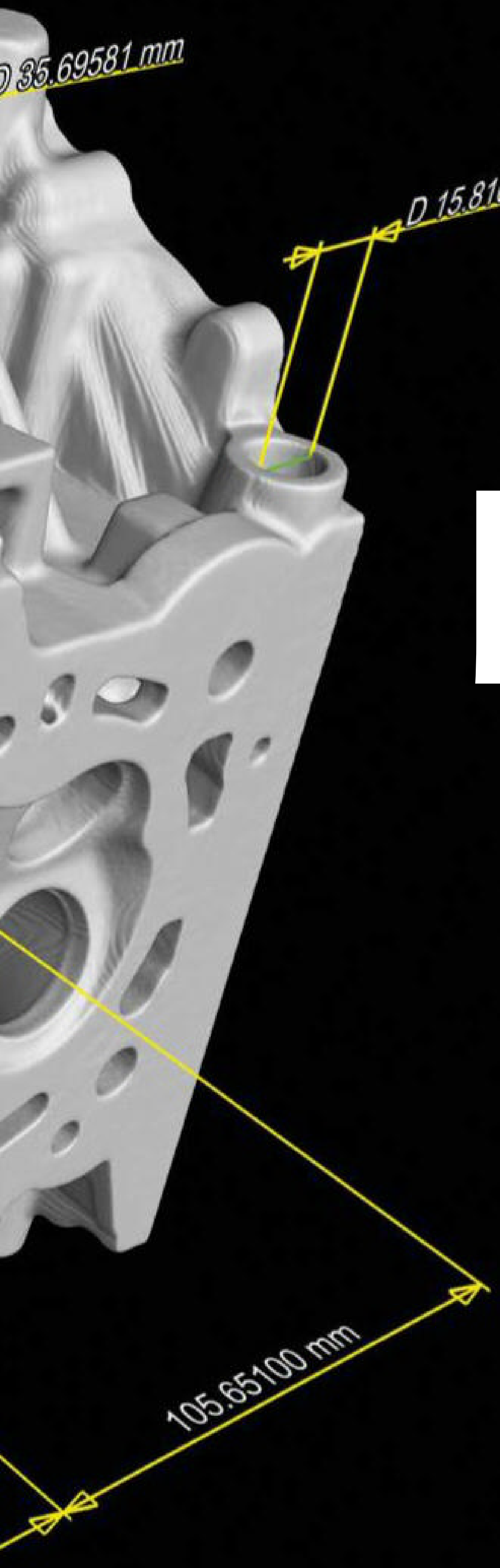
'Obviously, we are not able to change springs between the two drivers, so we have to use the maps and be clever with the settings, and then see.'

The next round, scheduled to be held at the end of May at Lac Rose, Senegal, is also going to be sandy, but the team is less concerned about that one.

'It is a sand bar, but the conditions will be very different to the Saudi race because it is close to a beach and it will not be dry sand everywhere,' notes Gaillardon. 'That will change a lot of things. I haven't seen the course, obviously, so I don't know what they will come up with, but it will be a fresh and interesting challenge.'




**Regardless of the desired outcome, the starting point for reverse engineering is invariably measurement**




# The backwards evolution

**Reverse engineering may now be banned in F1, but the technology involved has far wider reach than simply copying one's competitors. *Racecar* investigates**

**By LAWRENCE BUTCHER**

The FIA's recent ban on reverse engineering practices in Formula 1 brought the subject into motorsport headlines after the arrival of the 'Pink Mercedes' in 2020, courtesy of the then Racing Point, now Aston Martin team. Outside of such high-profile cases, the uses for reverse engineering techniques within racing are many and varied, with the technology to aid the process constantly evolving.

There are a host of reasons why one might want to reverse engineer a part, and the desired outcome – be it simply creating a surface form or generating CAD data for a mechanical part – will dictate the processes used and subsequent data manipulation. For example, one could be working without easy access to CAD chassis data, as is often the case for Touring Cars based on a roadgoing platform. In this situation, being able to create a model of the 'shell is very useful when developing bodywork or revised suspension components.

Alternatively, one might have the case of an irreplaceable historic racecar, where it is desirable to create a 'digital twin' so if parts are damaged, or rendered unserviceable, they can be more easily replaced.

Regardless of the desired outcome, the starting point for reverse engineering is invariably measurement. This can be as simple as noting down with a pencil readings taken with a string line and a tape measure, through to gathering millions of data points using a 3D scanner.

With both approaches, the quality of the end product is only as good as the initial inputs.

What can be achieved with simple manual measuring devices should not be underestimated. The CAD renderings of a Dirt Late Model shown in **Figure 1** were initially generated from measurements gathered by entirely analogue means. Created by engineer, Matt Furman, who currently works for Siemens in North Carolina, each component of the car was measured and then modelled individually in CAD, with hard points on the chassis recorded and cross referenced to each other until, eventually, an entire car could be constructed. The end goal of this particular reverse engineering process was to create a multi-body physics model of the car for simulation purposes, as well as CFD studies.

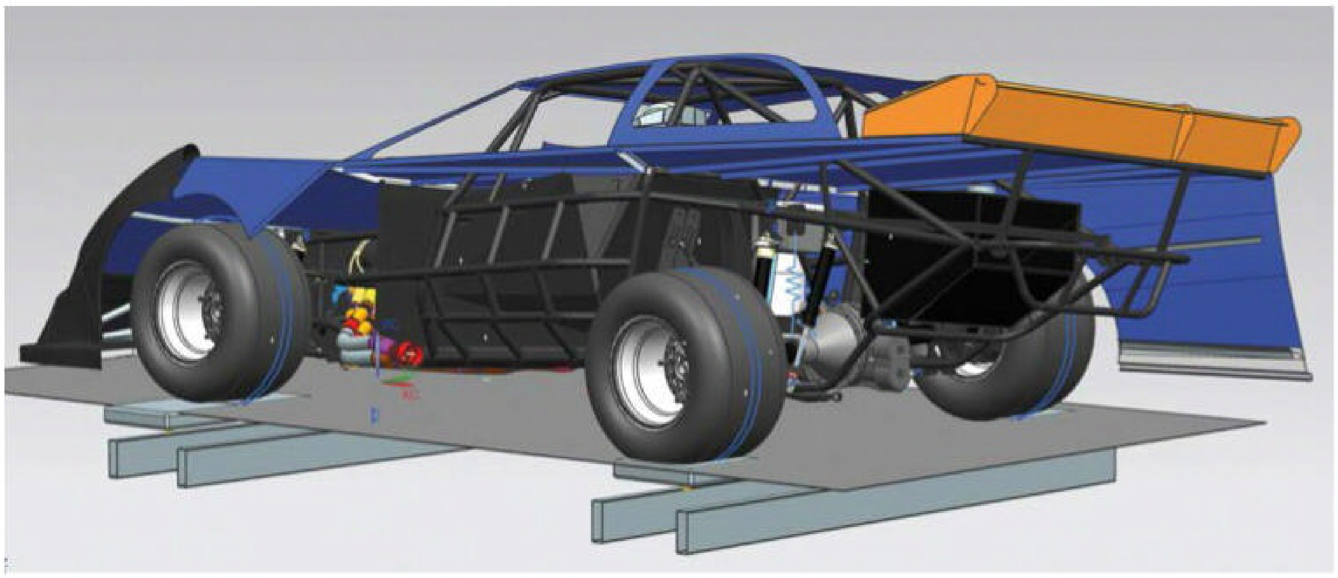
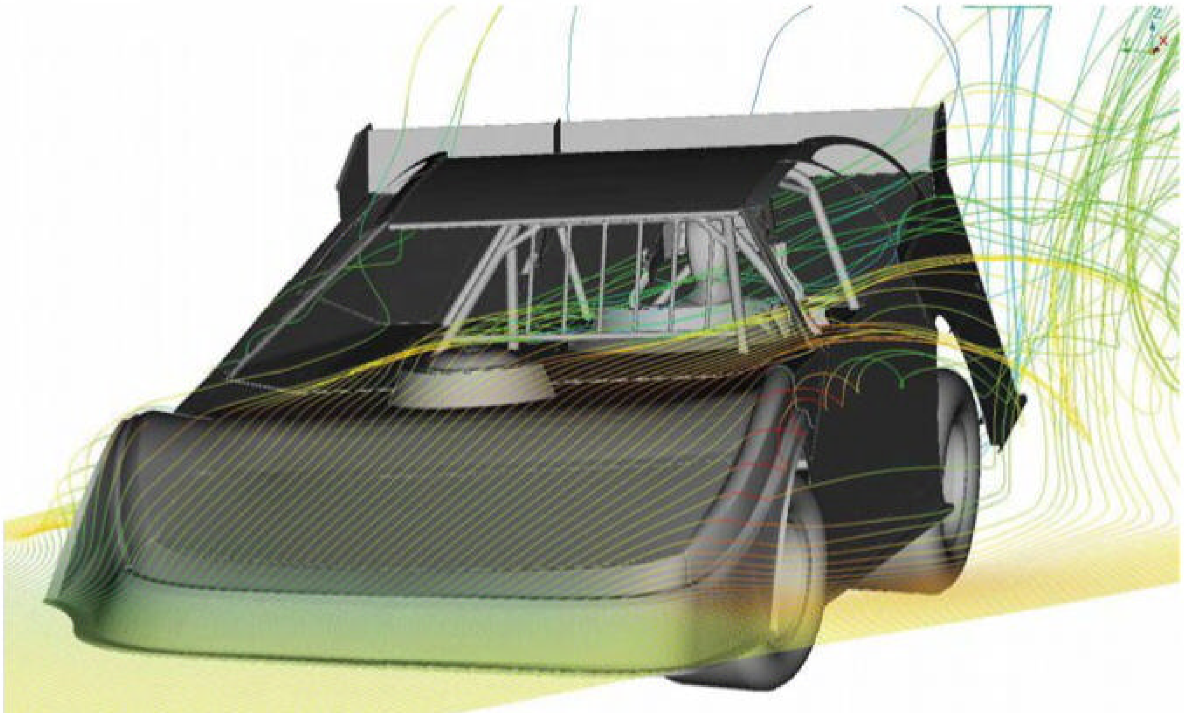


**Figure 1: CAD renderings of a Dirt Late Model created from analogue measurements for CFD and simulation studies**



## Metrology technology

Make no mistake, such an approach is long winded and far from ideal in most situations, and it is better where possible to leverage modern metrology technology. The most commonly found example of this is a Coordinate Measuring Machine (CMM), which has become a regular sight at many racecar constructors.

Though seemingly a new technology, CMMs have been around since the 1950s, with the first exhibited by British company, Ferranti, at the International Machine Tool exhibition in Paris in 1959. However, it wasn't until the advent of the touch trigger probe, developed by Sir David McMurty to solve a very specific problem, that CMMs began to see widespread use. The need in question was the Concorde supersonic airliner, with Rolls-Royce requiring a means to inspect the components of its Olympus jet engines to a high degree of accuracy in an automated way.

CMMs work along three orthogonal axes, x, y and z, on a 3D coordinate system. Each one has a scale that indicates the position of that axis. The machine reads the input from a touch probe as it contacts the part being measured, as directed by the operator or a computer program. It then plots the x, y and z coordinates of each discrete point, creating a point cloud to precisely determine the size and position of the component being checked.

**Though seemingly a new technology, Coordinate Measuring Machines [CMMs] have been around since the 1950s**

It is the touch trigger probe that allows for automated (or manual) measurements to be taken accurately and repeatably. The probe generates an electrical signal when it touches against the part being measured. The probe tip, or stylus, can move about its axis and the point at which it touches the object can be determined by a variety of methods. The longest serving of which is the kinematic resistive method, where the stylus is located on a spring-loaded mount with an arrangement of balls and rods (see **Figure 2**) that allow the stylus to return to the same point over and over again.

An electrical circuit runs through these contact points and, as the stylus moves on contact with a part, the resistance of this circuit varies. When the resistance reaches a certain threshold, the probe is triggered (at a defined point in its travel) and a

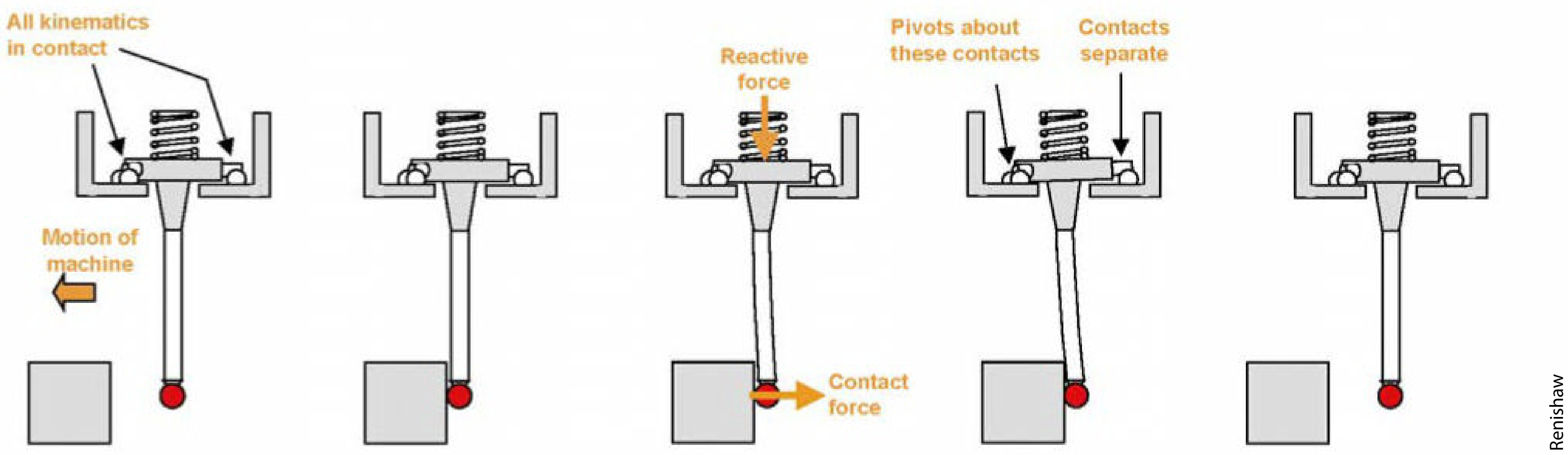



**Figure 2: Kinematic resistive probe operation. The stylus is located on a sprung mount that ensures it returns to the same point and the varying resistance in the circuit measured**


Optical scanners are often used in conjunction with CMMs for more complex measurement processes


CMM arms come in many shapes and sizes, operating in up to seven axes of movement

measurement is recorded. Provided they are properly calibrated, such probes are capable of accurate, repeatable measurements.

## Strain gauge probes

More recently, strain gauge-based probes have come into use. These still use a kinematic mechanism, but the trigger signal is not based on resistance. Instead a series of strain gauges measure force against the stylus and record a measurement at a given threshold value.

The advantage of this type of probe is that as the sensing is not dependent on the kinematics of the device, consistent characteristics can be guaranteed in all axes. They also have a much longer service life than resistive probes due to not being reliant on an electrical contact between moving surfaces.

Traditional CMM machines will normally operate on a gantry to which the probe is attached, providing freedom of movement in up to five axes (if the probe head itself is articulated), with the part to be measured placed on a flat reference plate. This type of machine is generally suitable for the measurement of smaller parts, such as engine components. For larger parts, a portable CMM on a remote measuring arm can be used.

Portable measuring arms (generally referred to as Romer arms after the first company to produce them), were first created in the 1970s to make it possible to measure bent and curved pipes in 3D. As with fixed CMMs, they use a touch probe, but instead of only being able to move within a fixed envelope, the probe is attached to the end of an articulated arm. Each joint of the arm, of which there are usually six, features an encoder disc capable of logging the exact rotation of the joint. From the information gathered by all six encoders, the probe's location can be calculated.

CMM arms will be constrained by their movement envelope (the maximum arc of the arm), usually between two and 6ft, and machines are classified by their maximum working volume. In general, the shorter the arm, the more accurate the machine, because there is less mechanical error caused by factors such as flex in the arm sections.

Arms can also be classified by the number of rotation axes, typically six, but if an arm has a handle at the end of the unit to control a rotating wrist, it is considered a seven-axis arm.

There is much that can be achieved with a CMM when it comes to measuring parts for reverse engineering, though they are best suited to relatively conventional geometries, and tasks where a high degree of accuracy is needed.


Portable measuring arms are now commonly referred to as Romer arms after the company that developed them

## Optical measurement

When it comes to recreating complex forms, such as bodywork, or internal ducting, optical scanning processes may be more appropriate. Of course, there are also CMM arms which also incorporate optical measurement systems as well.

For example, if one is trying to create a CAD model of an engine, with a view to recreating it, a combination of CMM data on

**When it comes to recreating complex forms, such as bodywork, or internal ducting, optical scanning processes may be more appropriate**


# Revolution with infusion

Carbon monocoques have proven their safety status over the past decades in motorsport and, up until recently, have all been produced using pre-preg and aluminium honeycomb technology.

But now Dominik Dierkes from DD-Compound, a specialist in infusion technology, has developed a process to produce a one-shot carbon monocoque, including all layers, structures and inserts.

The inserts are made from 7075 aluminium, either machined or square. To ensure perfect adhesion and avoid electrochemical corrosion, the inserts are given a special surface treatment prior to being positioned and infused in cut-outs in the core. As the foam used in the process holds its shape during and after CNC cutting, the inserts remain precisely located.

Another benefit of the structural design is less vibration due to the damping effect of the special foam core which, in combination with the resin, offers inherent damping without any loss in stiffness or strength.

A further advantage of this technology is no fibres are damaged in post-processing as everything is placed in one step in dry fibres, so no additional machining of the core is required.

## Energy saving

Not only do unimpregnated fibres not need to be stored in a frozen state for use with this technology, but also production times are dramatically reduced and less energy is required in the process as curing is achieved in one cycle, without the need for an autoclave.

As a combined result of all this, DD-Compound claims a cost saving of 30 per cent compared to that of a pre-preg monocoque.

**One-piece, infused carbon monocoque technology offers dramatic cost and time savings in the manufacturing process**

In partnership with Hexion, DD-Compound is using a resin system that gives the best results in bonding and strength, and also reduces operating temperatures for the infusion and curing processes to as low as 60degC, compared with up to 140degC with standard pre-pregs.

Revolution Racecars joined with DD-Compound to prove the technology by building the first FIA-approved infused monocoque.

After several material investigations, the monocoque passed the FIA test and are are now in serial production and racing on tracks around the world, with proven safety and performance.

DD-Compound is now working with Cunningham on an infused Hypercar chassis, and also on a revolution for the next Revolution.

**FIA approval means infused tubs are now in production and out racing, with a Hypercar design currently in development**

**No autoclave required, meaning significant energy savings**

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# Optical comparators have long been used both to check parts against drawings and to reverse engineer them


For high accuracy measurement of smaller parts, such as individual engine components, the item to be measured is placed on a flat reference table with the probe attached to an overhead gantry

key dimensions such as bearing locations and cylinders coupled with optical scan data of features such as the block could be used. If, on the other hand, you only need to model the engine in order to ascertain where it sits in a chassis, to create engine mounts or work out exhaust routing, optical scan data would be sufficient.

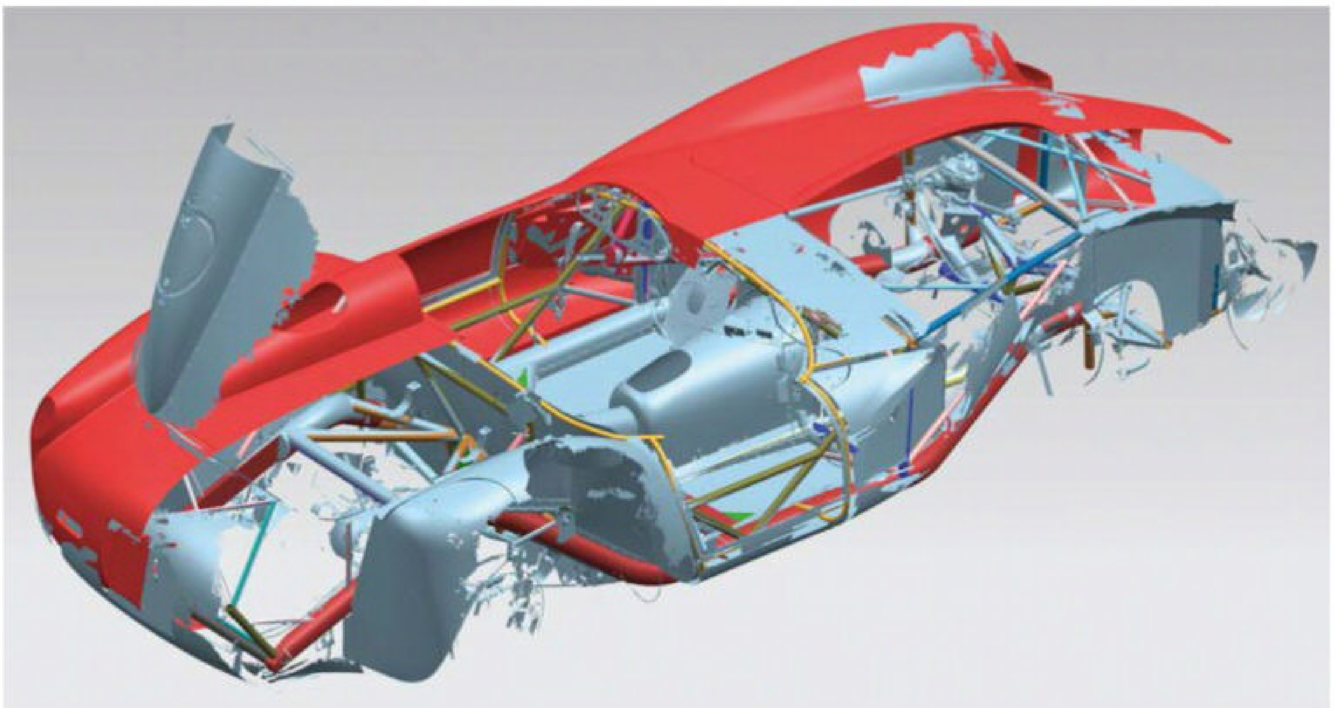
The use of optical processes has been around for centuries. For example, optical comparators have long been used both to check parts against drawings and to reverse engineer them. A comparator projects a magnified silhouette of the part being inspected onto a viewing screen. The screen includes graduated markings for direct measurement of features. Alternatively, an accurate dimension drawing of the part can be overlaid onto the screen (correctly scaled of course) and compared to the projection. The inclusion of a coordinate table onto which the part is placed also allows for relative measurements between features to be taken, with either micrometre scales or a digital readout recording the movement of the table.

## Automated processing

Optical comparators are still in use today, though the current digital systems are far more versatile than their analogue predecessors. Through a combination of high-resolution imaging sensors and processing algorithms, the laborious task of manually recording each dimension is removed and, in some cases, a part can be dimensioned entirely automatically in a matter of seconds. The integration of either contacting or non-contact probes also allows for height measurements to be taken, removing the 2D limitations of traditional machines.

Of greater interest in most motorsport applications are optical scanning systems. The most rudimentary scanning systems rely on a process of triangulation to obtain measurements. Designed for scanning relatively small parts, they feature a rotating platform on which the part to be scanned is placed, and a laser / sensor unit.

A laser line, or single laser point, scans across the object and a sensor picks up the laser light reflected off the object. Using trigonometric triangulation, the system calculates the distance from the object to the scanner. The system's software can also measure the angle at which the reflected light is returning to the sensor, and therefore the distance from the laser source to the object's surface. In this way, a point cloud of measurements can be collected and, from this, a 3D surface generated.



Here, the bodywork of a Ferrari 250 GTO Testarossa has been scanned and overlaid over a CAD model of the chassis

## Structured light scanners

More advanced scanners use a process known as structured light (white or blue light), and are likely the most commonly encountered systems in the realm of racecar engineering. Structured light scanners also use trigonometric triangulation but, instead of employing laser light, they project a series of linear patterns onto an object. By examining the edges of each line in the pattern, software algorithms can calculate the distance from the scanner to the object's surface. This type of scanner is generally mounted on a tripod-type mount at a set distance from the item to be scanned.

From there, one then moves onto hand-held scanners, which also use the triangulation method. A laser dot or line is projected onto an object and a sensor, typically a charge-coupled device (CCD) or position-sensitive device, measures the distance to the surface.

Datum points are recorded in relation to an internal coordinate system incorporated into the scanner. In order to


Structured light scanners project a series of linear patterns onto the article to be measured and use trigonometric triangulation and software algorithms to work out their distance from the object


An optical comparator projects a magnified silhouette of the part under inspection onto a viewing screen with accurate measurement scales marked on it

collect data when the scanner is in motion, the position of the scanner needs to be determined, either via the scanner using reference features on the surface being scanned or an external tracking method.

External tracking of the scanner can be in the form of a laser tracker (to provide the sensor position) with an integrated camera (to determine the orientation of the scanner). Alternatively, a photogrammetric solution can be used, with three or more cameras providing complete six degrees of freedom for the scanner. Both techniques usually use infrared LEDs attached to the scanner, which are seen by the cameras through filters, reducing the impact of ambient lighting on accuracy.

## Data handling

Once the data is collected, it must then be subject to various post-processing stages to make it useable. For example, there will be holes in the point cloud that need to be filled, and erroneous recorded points that need deleting. Depending on the end use, the data set can be thinned out to make it more manageable, with software applications available to do this in an automated way. For example, software may remove points of features with low curvature while retaining detail in complex areas.

It must be remembered that the point cloud, and resulting polygonal mesh generated from a scan, cannot easily be manipulated in a standard CAD package. Reason being, scan data is not geometric and is under defined. For example, the software has no way of knowing that an area of a part is flat. However, if one is simply creating a model to check the location of a part within an assembly, such as the aforementioned engine, this is not a problem. In this case, a NURBS (Non-Uniform Rational Basis-spline) is created, effectively by wrapping a surface around an .stl file created from the mesh data generated by scanning. The limitation of such a model is that it cannot be easily manipulated.

In order to create a useable CAD model, the scan data is simply used as reference from which a model with full dimensional properties is created. Fortunately, there are a number of standalone software programs and plug-ins for common CAD packages that make this process easier. One example is Geomagic from 3D Systems, which works with SolidWorks to allow CAD models to be rapidly created from scan data. This makes it relatively straightforward to build geometric features from a scan.

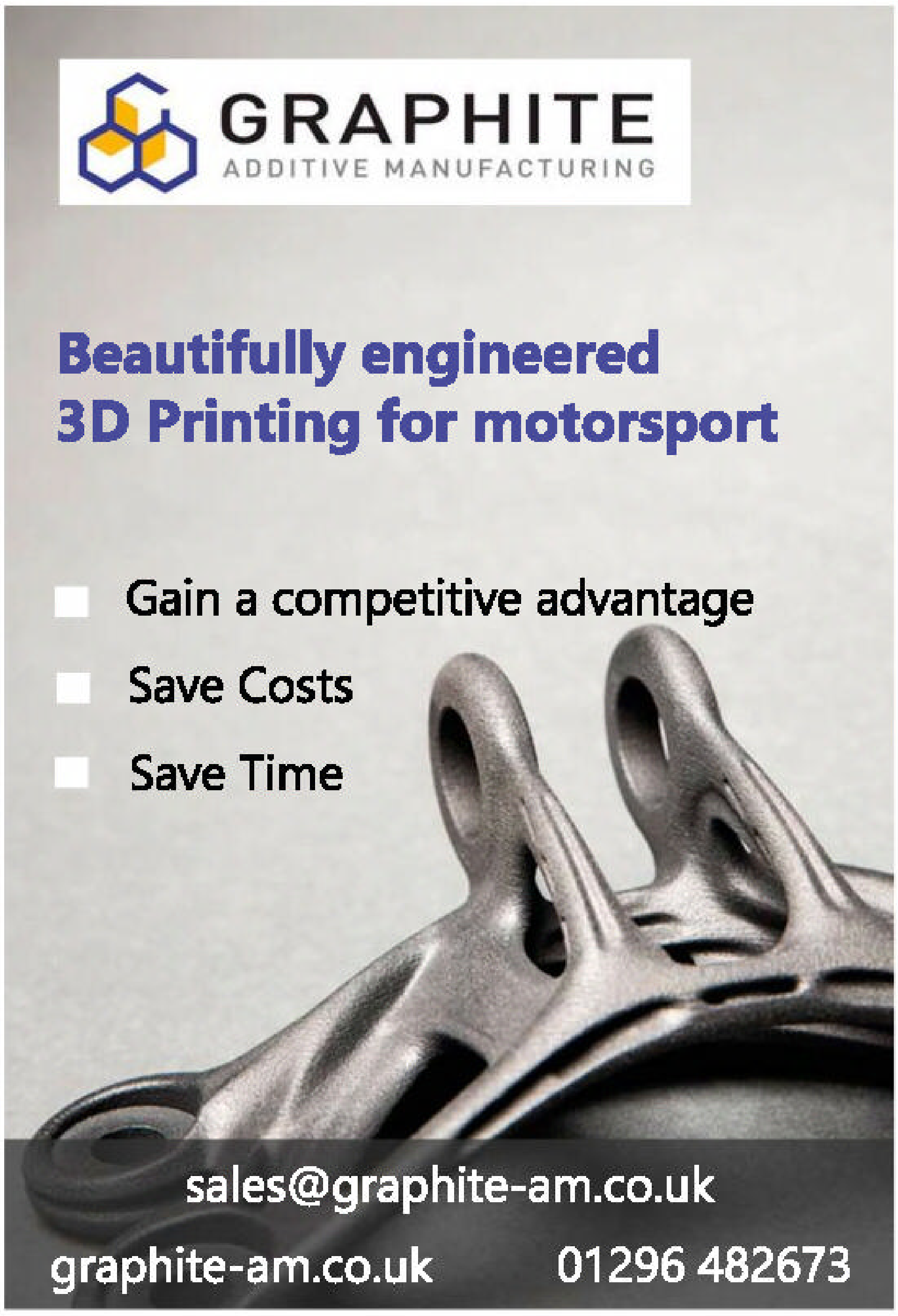
**Software capability in this area is advancing at a considerable rate, and a convergence is emerging between how scan data (polygons) and CAD can be used**

Software capability in this area is advancing at a considerable rate, and a convergence is emerging between how scan data (polygons) and CAD can be used. There is also scan-to-CAD software available that does not require any user intervention. In theory, one simply drops in a mesh file and it will create a CAD model, but such systems have their limitations. They work perfectly well for simple geometries, but struggle with more complex parts.

## Specialist services

Unsurprisingly, there is an increasing number of specialist companies offering 3D scanning and reverse engineering services. Given the cost of high-end scanning equipment, and the considerable time needed to become proficient both with the hardware and software to ensure efficient workflows, outsourcing such work to these specialists can be a boon for smaller outfits in need of such capabilities.

However, with ever-greater integration of the relevant add-ons into commonly used CAD packages, and the variety of tasks that can be achieved using the technology (not only reverse engineering, but QC checking of finished parts or, for example, assessing chassis for deformation after a crash), more and more racing outfits are finding it beneficial to have in-house scanning and data manipulation capability.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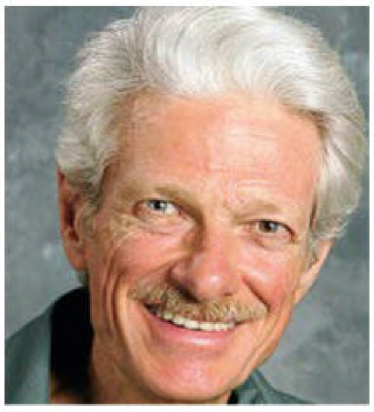

# Heave ho!

Considering the case for heave springs and dampers on road and race cars

By MARK ORTIZ

**Q** **A recent *Road & Track* email newsletter featured a link to a video describing F1 suspension operation (see here: www.youtube.com/watch?v=6Mxm_Vb25lI&t=30s).**

**Except for some specialised racing elements, the layout seems essentially similar to a double wishbone suspension found on many cars, but heave springs and heave dampers are new to me. I was a little uncertain if these are separate or combined parts, as in a coilover shock, but they are arranged to interconnect the right and left sides of the front suspension.**

**From what I can make out, these components work in an opposite way to an anti-roll bar, in that they are activated when both wheels are simultaneously in bump or droop, but not in roll.**

**My questions are firstly, what purpose do they serve? And secondly, since it looks like the device(s) would not be too difficult to add to a wishbone-equipped car, would they be of any benefit on a street or track day car?**

## THE CONSULTANT

**A** These are what have long been called 'third springs'. They are generally combined with a damper, often with a snubber on the shaft, and have been common on high-downforce cars with pushrod suspension for at least 30 years now.

It is common to use one just on the front suspension, but they are fairly often used on the rear as well. I don't think I've ever seen one used on just the rear. No, wait, I have, but in a somewhat different form. We'll come to that in a moment.

Before I go any further, it will be helpful to review some vocabulary. First, what is heave? It's, er, nauseatingly ambiguous and complex. As used in the referenced discussion, it means motion of both wheels of a front or rear pair, with respect to the sprung structure, in the same direction at the same speed or in the same amount. I call this synchronous suspension motion (as opposed to oppositional motion, which occurs in opposite directions at the same speed, or in the same amount). Any displacement, velocity or acceleration of a wheel pair can be described as some amount of oppositional motion and some amount of synchronous motion.

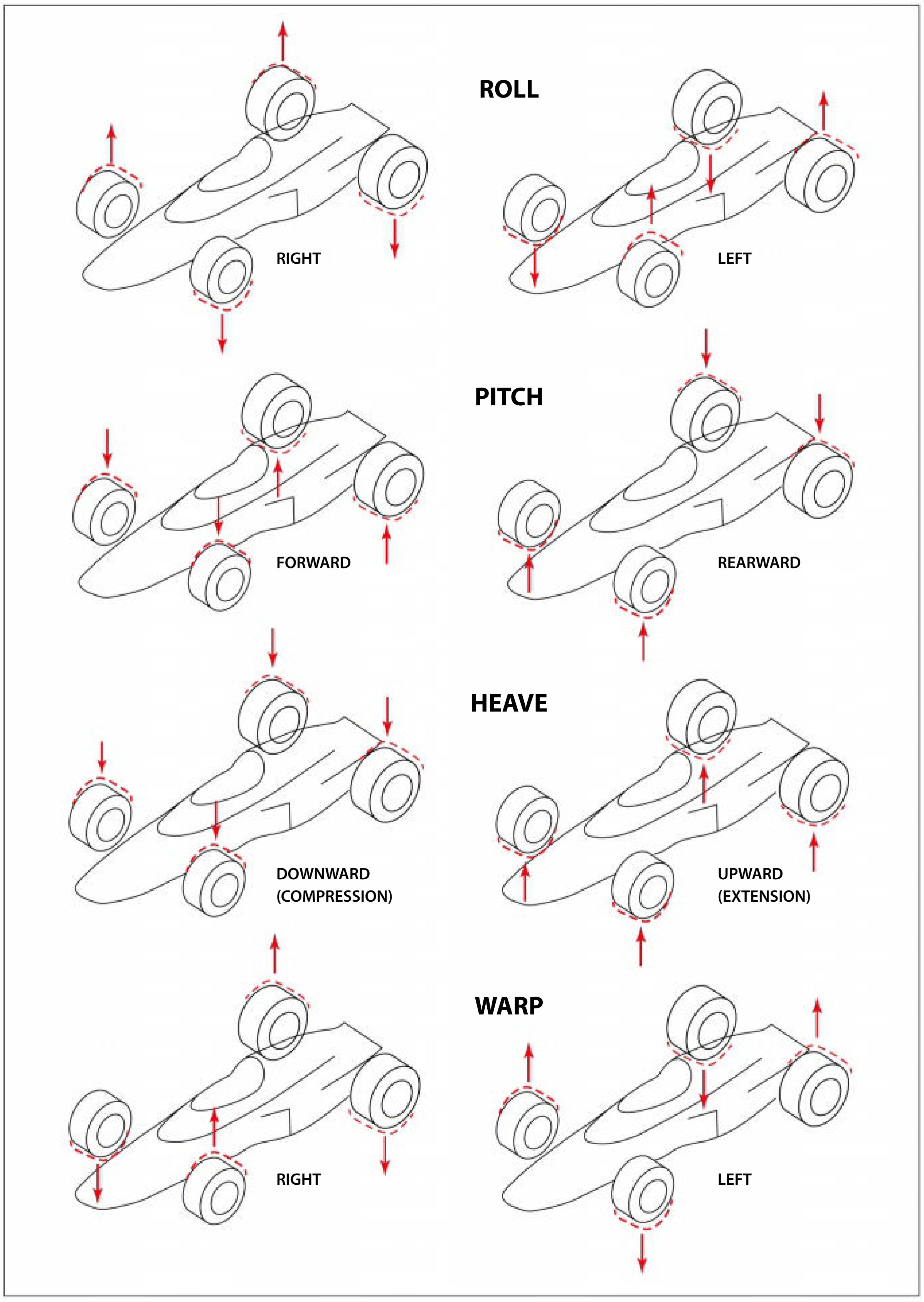


**Figure 1: the four modes of motion for a four-wheel suspension system**

That's simple enough, but complexity and ambiguity arise from the fact there are other uses of the term heave, in the context of vehicle and suspension motion.

**Complexity and ambiguity arise from the fact there are other uses of the term heave, in the context of vehicle and suspension motion**

# A third spring, or heave spring... is an anti-synchronous elastic connection between two individual wheel suspensions

Most of the terminology we use to describe suspension system motion derives from that used to describe motion of the sprung structure, and that in turn comes from words used to describe the motion of ships at sea, and then aircraft, and finally wheeled vehicles.

A water craft, aircraft, or car has six degrees of freedom: it can translate along, or rotate about, three axes.

- The longitudinal (front to rear) axis is conventionally the x axis. Rotation about the x axis is roll, and movement along it is simply forward or rearward vehicle travel.
- The transverse (right to left, or starboard to port, offside to nearside) axis is conventionally the y axis. Rotation about the y axis is pitch, while motion along it is side slip.
- The vertical axis is conventionally the z axis. Rotation about this is yaw, and motion along it is heave.

All of these apply identically to a ship, an aeroplane or the sprung structure of a car. When the object is fluid borne, and all its parts pretty much move as a unit, we only need to describe the motion of the whole assembly. But a car has multiple wheels that can move with respect to the main structure. The motions and loadings of these, and their interaction with the road surface, are crucial to the behaviour of the machine as a whole.

## Describing motion

Consequently, there is a need to describe the motion of the wheel set with respect to the sprung structure, and nautical / aeronautical vocabulary does not supply this. Rather than invent entirely new words, people have applied the vocabulary for sprung mass motion to suspension system motion. As a result, we have terms used somewhat differently depending on whether they are applied to the suspension system or the sprung mass, and the terms have to be understood in context.

As shown in **Figure 1**, roll, pitch and heave denote movements of a four-wheel suspension system, as well as movements of the sprung structure. For a particular vehicle, on a flat surface, these correspond to the movements of the suspension when the sprung structure moves in the corresponding ways. However, these motions can also be caused by road irregularities.

Yaw is not applicable to four-wheel suspension system movement, but there is one additional mode that does not correspond to any sprung structure movement, and needs a name of its own. That is warp, which is caused only by uneven road surfaces.

I have only recently encountered 'heave' used to denote synchronous motion of only a front or rear wheel pair. Note that when heave denotes synchronous motion of all four wheels, it corresponds to the sprung mass motion of the same name, absent any road irregularity. Heave of only a front or rear pair of wheels could correspond to sprung mass heave if it's synchronous at both ends, or it could correspond to pitch if it's oppositional.

To get around this confusion, I have used the term 'ride' to denote synchronous motion of a front or rear wheel pair. Unfortunately, that is problematic too, because ride is also used to denote total displacement of suspension and tyre combined. 'Ride rate' is change in load per unit of vertical displacement of the contact patch and sprung structure with respect to each other, and 'wheel rate' is the same, but for relative displacement of wheel and sprung structure, tyre compliance not included.

Anyway, returning to the original question, a third spring, or heave spring, or ride-only spring, as described in the video, is an anti-synchronous elastic connection between two individual wheel suspensions. It elastically resists synchronous motion but not oppositional motion. And that is indeed opposite to an anti-roll bar, which is an anti-oppositional elastic connection.

So why use both together? The answer is that this way we can get different amounts of rising rate in the two modes. We can make the anti-synchronous element highly progressive, or rising rate, and the anti-oppositional element more linear, or constant rate.

Why is that desirable? Because when cars started developing large amounts of aerodynamic downforce, it became apparent that rising-rate suspension could preserve at least a bit of compliance at lower speeds, where downforce was modest, while preventing excessive bottoming and maintaining close control of ground clearance and rake at high speed. However, if the individual wheel springing was made highly progressive, the car's elastic roll resistance distribution would vary dramatically with small amounts of pitch. If the elastic roll resistance has more linear characteristics, this problem is ameliorated.

With push-rod suspension, it is quite possible to eliminate individual wheel springs entirely, and have just ride-only and roll-only springing, as in monoshock systems. With a second set of links from the rockers to an anti-roll device, it is possible to incorporate damping into the anti-oppositional system, either with a single through-shaft damper diagonally connecting the links or with two conventional dampers.

## Street application

Would it make sense to use highly progressive heave-only springing on a production-based street / track day car? Probably not, if the car has only modest downforce and enough ground clearance to be practical for road use. However, there are applications of anti-synchronous, two-wheel springing that do make sense for road cars. One we've covered recently is a 'camber compensator' on swing-axle rear suspensions. On such systems, we want the anti-synchronous springing to be either linear or digressive, although we are trying to keep the suspension from jacking up, rather than squashing down excessively.

We can also connect the front and rear wheels on the same side of the car with an anti-synchronous springing system, as on the Citroën 2CV or various Packards.

One rule that applies to all such systems is that any two-wheel interconnective springing system springs two of the four modes, and leaves the other two entirely, or at least relatively, unaffected. To spring only one of the four modes requires interconnection of interconnective systems eg front / rear interconnected hydraulic anti-roll bar links.

This means if we have dedicated springing and damping systems for synchronous and oppositional motion at each end of the car, we can interconnect these front to rear and achieve stiffness in roll, pitch and heave with softness in warp. Since warp is only created by road irregularities, we can produce a passive suspension system that can traverse irregular surfaces with smaller variations in tyre loading, while still providing desired control of ground clearance, aerodynamic properties, roll angle and camber.

This is useful for both road and racecars, and *very* useful for off-road vehicles.

### CONTACT

**Mark Ortiz Automotive** is a chassis consultancy service primarily serving oval track and road racers. Here Mark answers your chassis set-up and handling queries. If you have a question for him, please don't hesitate to get in touch:

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# Load transfer

## Understanding the 'necessary evil' and how and why it is detrimental to performance

BY CLAUDE ROUELLE

Before we go any further, let us first discuss why load transfer is 'bad'. In **Figure 1** we can see the evolution of the left front and right front tyre vertical loads, slip angles and induced lateral forces as we enter a corner.

To keep things simple, we only look at the front tyres, and imagine that the speed, and therefore the front downforce, is constant so the sum of the two front tyre vertical loads that is 3776N x 2 = 7552N will stay constant. In this simplified presentation we also ignore the effect of camber and initial slip angle due to static toe. That is why all lateral force vs slip angle curves have no lateral or vertical offset at their origin.

The initial vertical load (load + downforce) on each front wheel is 3776N. With lateral load transfer, this evolves to 7208N on the right (outside) wheel (bottom right legend on **Figure 1**) and to 343N on the left (inside) wheel (top left legend). The inside wheel has barely any vertical remaining load as we are probably close to the maximum lateral acceleration that will keep it on the ground.

Meanwhile, the slip angle goes from zero to 5.8 degrees on the inside wheel, and zero to 6.9 degrees (showing an anti-Ackermann steering kinematics, just as a side note as this is not the main point of this explanation) on the outside wheel.

With each front tyre not far away from their peak slip angle, we get about 800N of side force (bottom left, red horizontal line, again on **Figure 1**) on the inside wheel and about 11,800N on the outside wheel (top right, green horizontal line), so a total of 12,600N.

In the theoretical case of no lateral load transfer (for that we need a c of g on the ground, good luck!) and, providing that we would be able to get each tyre operating at its peak slip angle, we would get about 7200N of lateral force on each tyre (dash red and green horizontal lines), so a total of 14,400N on the front axle. Compared to the total lateral force of 12,600N with load transfer, that's a gain of 1,800N, or 14.3 per cent, which is really consequential on the car's performance.

We gained 11,800 – 7200 = 4600N on the outside wheel and we lost 7200 – 800 = 6400N on the inside wheel.

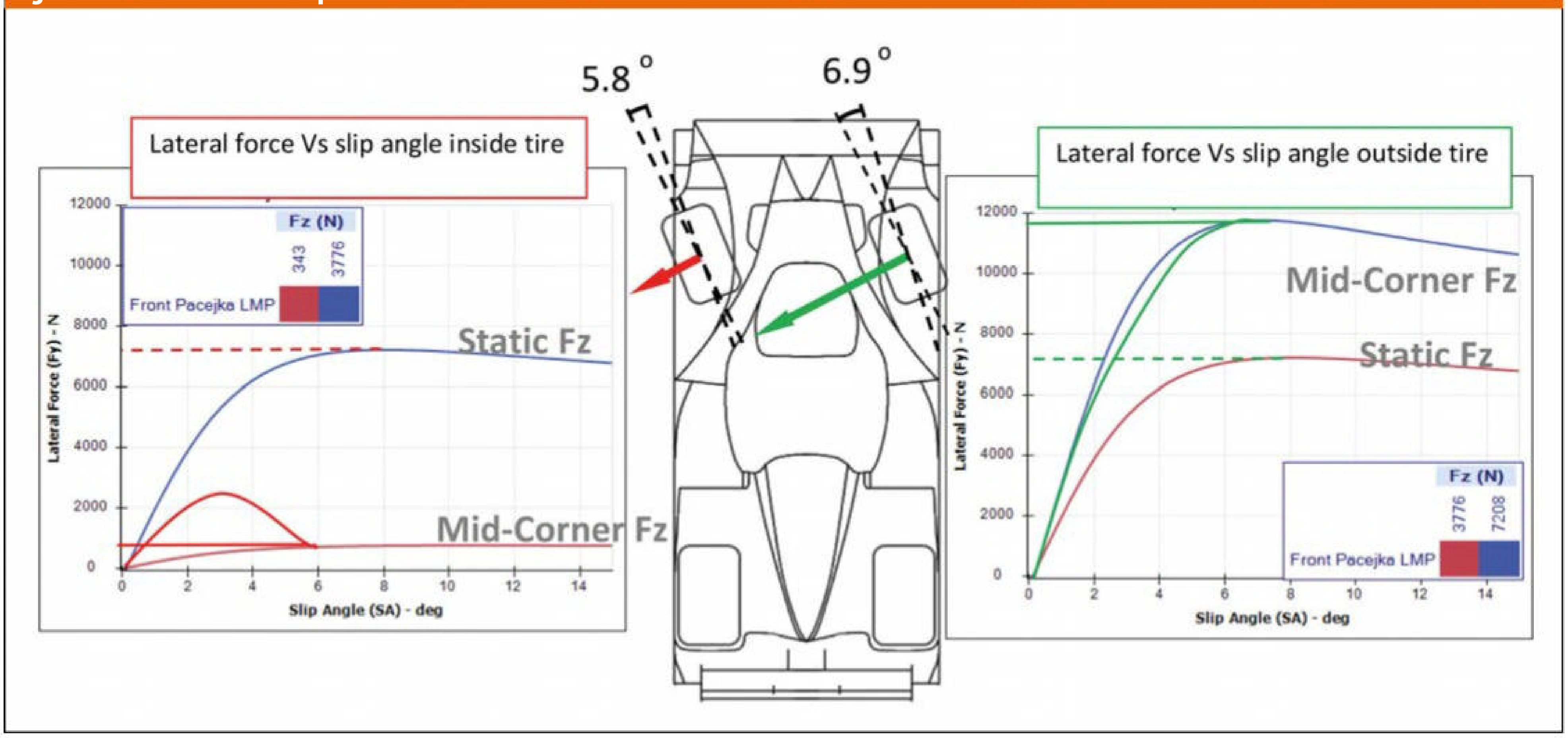
The lateral load transfer made us lose 40 per cent more grip on the inside tyre than we gained on the outside tyre. In other words, load transfer is 'bad' because we are a bigger loser on the inside than we are a winner on the outside. All because of the non-linearity of the tyre lateral force with its vertical load.

In correct vehicle dynamics language, we should not speak about weight transfer, or mass transfer, but about load transfer. Major misconceptions come from the incorrect understanding of the word 'transfer', which is often assimilated to 'mass movement'.

### Common misconception

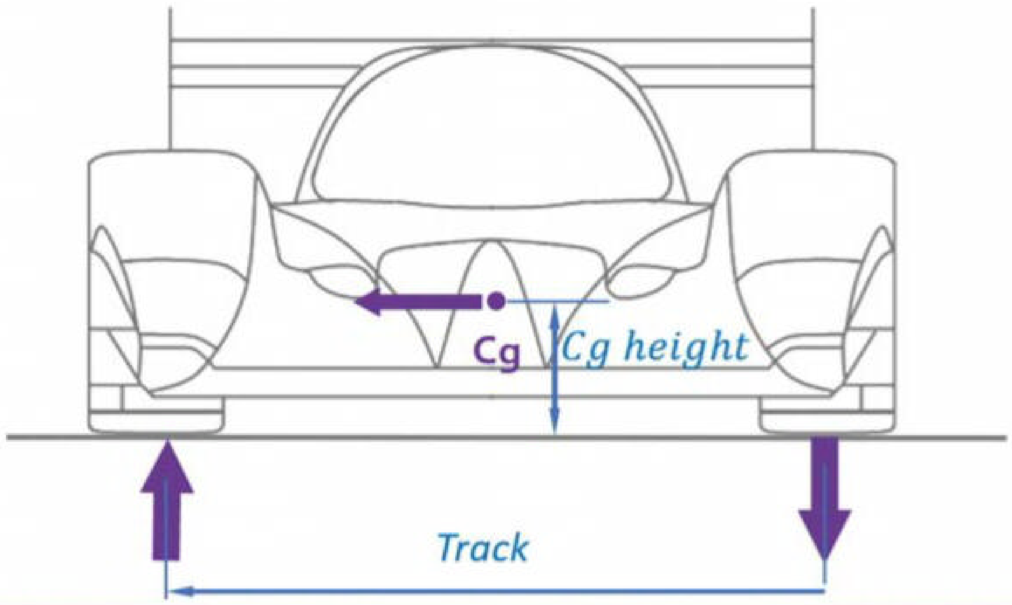
Some students and amateur racers often mistakenly think the variation of inside and outside wheel vertical loads under lateral acceleration in a corner is due to the lateral movement of the suspended mass c of g induced by the roll angle.

**Figure 1: Load transfer description**




**Load transfer is 'bad' because we are a bigger loser on the inside than we are a winner on the outside**

**Figure 2: Simplified 2D (front view of one axle) load transfer equation**




$$Lateral\ force = Mass\ \times lateral\ acceleration = Mass \times V^2/R$$

$$Lateral\ load\ transfer = Lateral\ force\ \times Cg\ height/Track$$

The basic equation of load transfer in a simple 2D front (one axle), as shown in **Figure 2**, is:

*Mass * V2/R * c of g height / track*

Where mass (*M*) is in kg, speed (*V*) in m/sec, radius (*R*) and track in metres and load transfer in Newtons.

The roll angle is not part of that equation.

In steady state, the roll angle (in degrees) is the roll moment,

*Mass * V2/R * c of g height (Nm)*

divided by the roll stiffness (Nm/deg) due to the springs and anti roll-bars that are in parallel, themselves is series with the tyre vertical stiffness.

For simplification of the demonstration, we will neglect others kinds of spring that we call compliance here, although in reality compliance could have a dramatic effect on the car's behaviour.

Now let us get real. On a racecar, the roll angle rarely exceeds three degrees. Most racecar suspended mass c of g heights are around 250-350mm. With a suspended mass c of g height of 300mm and three degrees of roll, the suspended mass (g) will move laterally by 16mm.

Let us consider a simple example of a 1000kg car with an equal front-to-rear mass distribution, so 250kg of mass per wheel. If each non-suspended mass is 50kg, the suspended mass is 800kg. With three degrees of roll and 16mm of suspended mass c of g lateral movement, the static weight on each wheel would only change by 4kg (or 40N if we more correctly speak of load). That is 1.6 per cent. In racing, 1.6 per cent of tyre vertical load variation is not negligible. But we also know that the lateral load transfer under two,

**A side movement of the c of g will influence the tyre load just as much as grandma would when she moves from one side to the other of the rear seat**

or three, or more *g* of lateral acceleration will contribute to a much bigger extent to each tyre's vertical load variation.

A side movement of the c of g will influence the tyre load just as much as grandma would when she moves from one side to the other of the rear seat. A change of static load distribution is not a load transfer.

Imagine a car perfectly rigid, tyre and suspension infinitely stiff, no compliance. You could have enough lateral acceleration to get the inside wheels off the ground, but only by a fraction of a millimetre. The roll angle would be negligible. So would the c of g side movement. But the whole car load would be on the outside wheels. That is the proof that load transfer is not roll angle dependent.

In a serious magazine like *Racecar Engineering*, we should not really even be discussing this, but I chose to because in my many years of meeting with racers I too often hear that misconception, even from so-called professional vehicle dynamics engineers.

## Transient load transfer

Of course, with detailed calculations, the effect of the lateral movement of the suspended mass c of g on dynamic wheel load could be considered.

Some other considerations could be made, especially in transient load transfer:

- Change of front and / or rear track width due to the camber and track variation in heave, roll and steering.
- Change of front and / or rear track width due to the tyre side deflection. Most of the time the side load defection will be bigger on the outside tyre than the inside one. That will result in a reduction of the track change, and therefore more load transfer. Usually, the increase of load transfer due to a tyre's deflection is bigger than the one due to the suspended mass lateral movement.
- An additional load transfer that considers the lateral acceleration of the suspended mass can be considered.
- Similarly, wheelbase change due to suspension anti-dive and anti-squat kinematics, tyre longitudinal deflection, and possible longitudinal acceleration of the suspended mass c of g could be considered for longitudinal weigh transfer.

If, on the other hand, we want to decrease load transfer, we have several solutions:

**1. Lower the c of g.**

In some racing series, regulations impose a specific height under which the c of g for the whole car and / or some components, such as the engine, cannot be found. And yet car designers, while respecting these rules, will play with ballast placement to modify the weight distribution (which, within some windows, is sometimes regulated, too) as well as the roll, pitch and yaw inertias.

In absence of such c of g height regulations, professional racecar manufacturers often design cars *under* the weight limit and then add ballast at the lowest point of the car to bring it up to weight. At this level, everything is considered – engine and data acquisition looms, ECU, even the driver's water bottle – for the suspended mass.

In recent racecars, uprights have even been designed to have the brake calipers attached at the bottom, whereas 15 years ago they were to be found at the height of the wheel centre, ahead or behind the brake disc. Such innovation was mostly dictated by aerodynamic constraints: the higher the lower wishbone, the cleaner the airflow for the under wing.

In any case, such design leaves room for a lower mounted brake caliper with an appreciable advantage of a lower, non-suspended mass c of g.

In Formula Student, the minimum allowed wheelbase is 1525mm, and the driver could represent as much as one third of the total mass. A few teams successfully found good compromises between the ergonomics of the driver in his cockpit, low c of g and low yaw and pitch inertia. Here are a few ways it could be achieved:

**2. Increase the track.**

Larger is better. Usually, teams use the largest possible front and rear track widths allowed by the rules. We need to remember, though, that the larger the track, the more yaw inertia. Inertia ($kgm^2$) of an object has two components: a) the mass (kg) multiplied by the square of its own radius of gyration (m2) and b) the distance of the c of g of that object multiped by the square of the distance between its own c of g and the centre of rotation of the object (parallel axis theorem).

In Formula Student competitions, circuits are mainly made of tight, low-speed corners where control is more important than stability. Some teams have found that the lower yaw inertia achieved with small tracks and wheelbase improved the response and gave more lap time gain than bigger lateral and longitudinal load transfers. At least one successful team uses track as small as 900mm.

Also remember, the bigger the track, the bigger the frontal area, which is generally good for downforce but bad for drag.

**3. Mass.**

Formula Student is not motorsport. It is a design and project management exercise based in the design and running of a racecar that helps students experience the human and engineering challenges they will face in their future job, that will not necessarily be in motorsport. That said, Formula Student is probably the only 'racing' category where there is any minimum weigh limit. Less mass means less load transfer and less loss of grip due to load transfer.

**4. Decrease lateral acceleration.**

Asking the driver to go slower in order to have less load transfer is not going to win a race. But in fact, to a certain extent, this is what drivers do, as shown in **Figure 3**. If the driver follows the outside line (red) with a larger radius, they minimise load transfer but make the circuit longer.

I remember engineering an Indy Light car on the Michigan Speedway. Handling was not an issue, but minimum drag was, and we won because of a huge rear wing reverse Gurney flap. But we gained 0.3 second a lap just by asking the driver to take the inside (green) line.

**Figure 3: Optimal line for minimising load transfer and trajectory length**

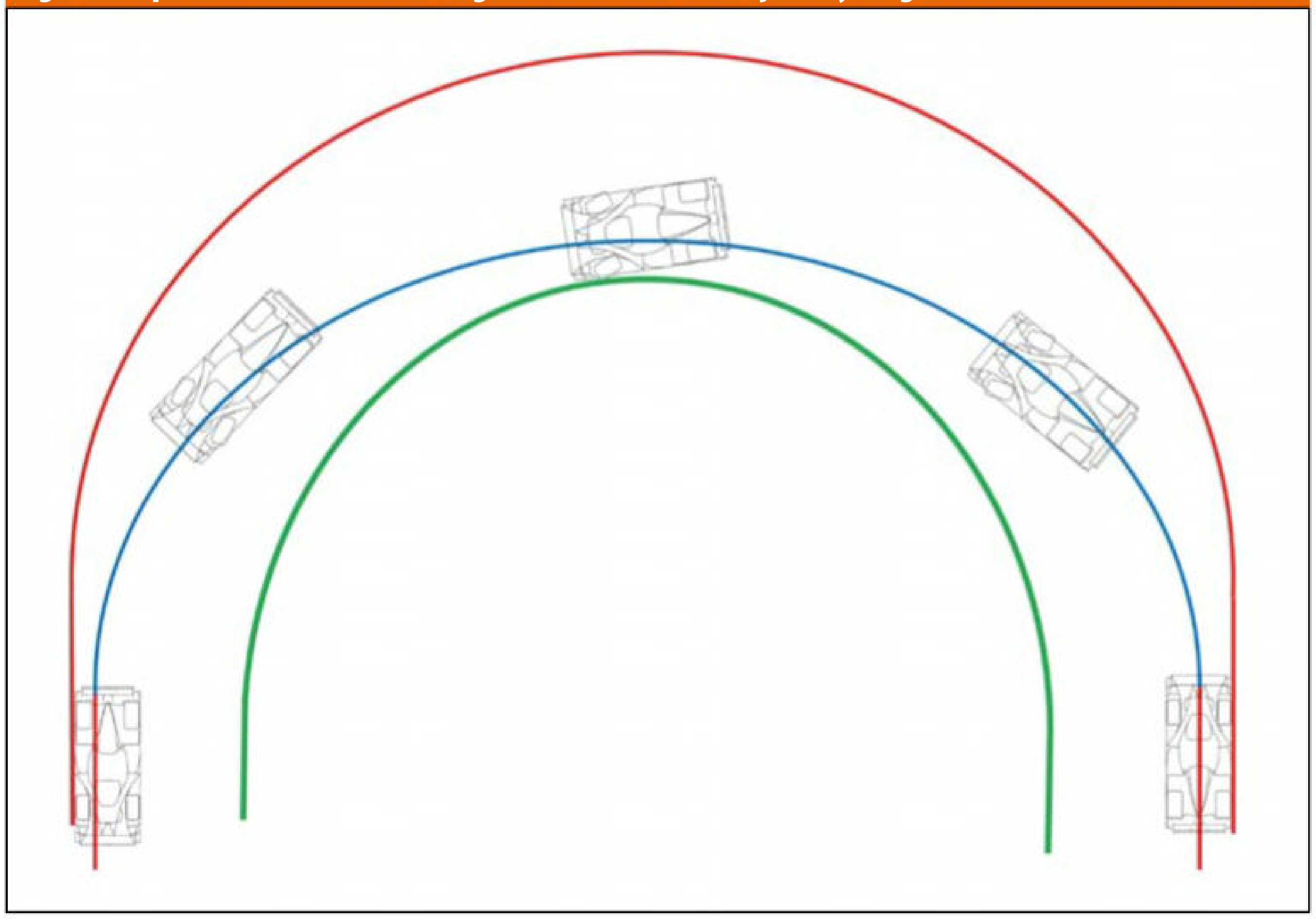
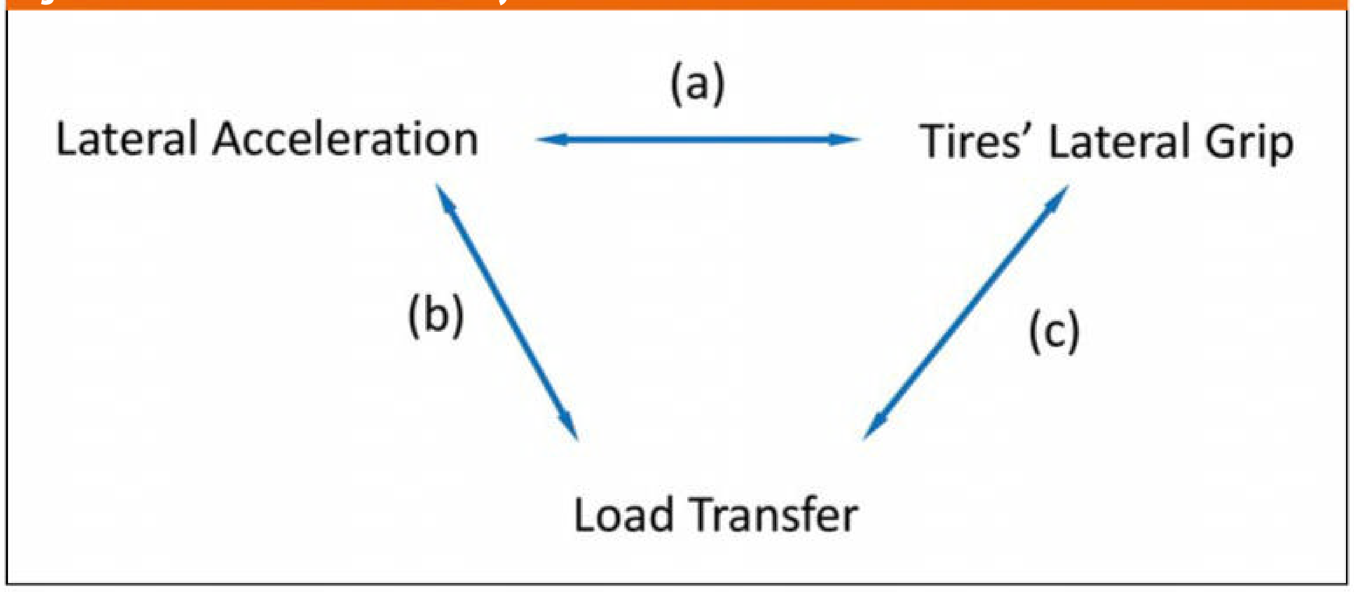


**Figure 4: Load transfer: the necessary evil**




The shorter radius meant a shorter circuit and more load transfer but, in this case, that had no effect on the handling.

By following the blue line, the driver has the best compromise between minimising load transfer and trajectory.

## Conclusion

All the considerations lead us to the conclusion shown in **Figure 4**. You can achieve lateral acceleration unless you lose grip. Use bad tyres, or drive the car on a wet surface, and you will not get as much lateral acceleration. And *vice versa* (a).

But, unless you achieve the impossible of a c of g on the ground, if you have lateral acceleration, you *will* have load transfer (b). It's inevitable.

Now people are a bit more surprised by (c). You cannot have lateral grip *unless* you have load transfer. In other words, load transfer is a bad thing, but it is a bad thing that needs to happen. It is, as we said at the beginning of this article, a necessary evil.

**Slip Angle is a summary of Claude Rouelle's OptimumG seminars, which are held worldwide throughout the year.**

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OPTIMUMG

# 'Cage fighters

## On the 50th anniversary of the mandatory introduction of rollcages into closed-cockpit racecars, we look at the safety cage homologation procedure and compare some typical design alternatives

**By DEJAN NINIC**


Fifty years have passed since the FIA mandated the installation of the 'Safety Cage' in closed-cockpit racecars, as set out in Appendix J to the International Sporting Code of 1971.

Since then, the regulations have evolved from a simple set of guidelines to a strict list of rules governing design, manufacture, installation and testing of the structures.

In 2004, the FIA introduced Technical List no. 35 (TL35), a list of testing houses permitted to test 'cage structures that do not abide completely to the regulations, but could still be accepted thanks to the homologation process. In this anniversary year, we take a close look at the safety cage homologation procedure, and compare the performance of some typical design alternatives.

Article 253 of Appendix J (J253) has, for decades, been the reference regulation for 'cages in motorsport. J253 has described the minimum requirements for one to be fabricated and installed without the need for separate testing and homologation – any 'cage made according to these rules would be accepted for competition without proof of strength.

Any design that deviated from J253 could be proposed to the FIA for homologation, upon which a new set of regulations would apply, namely the Homologation Regulations for Safety Cages (HRSC). The HRSC is a set of regulations separate to J253 and are only available upon request from the FIA or an ASN.


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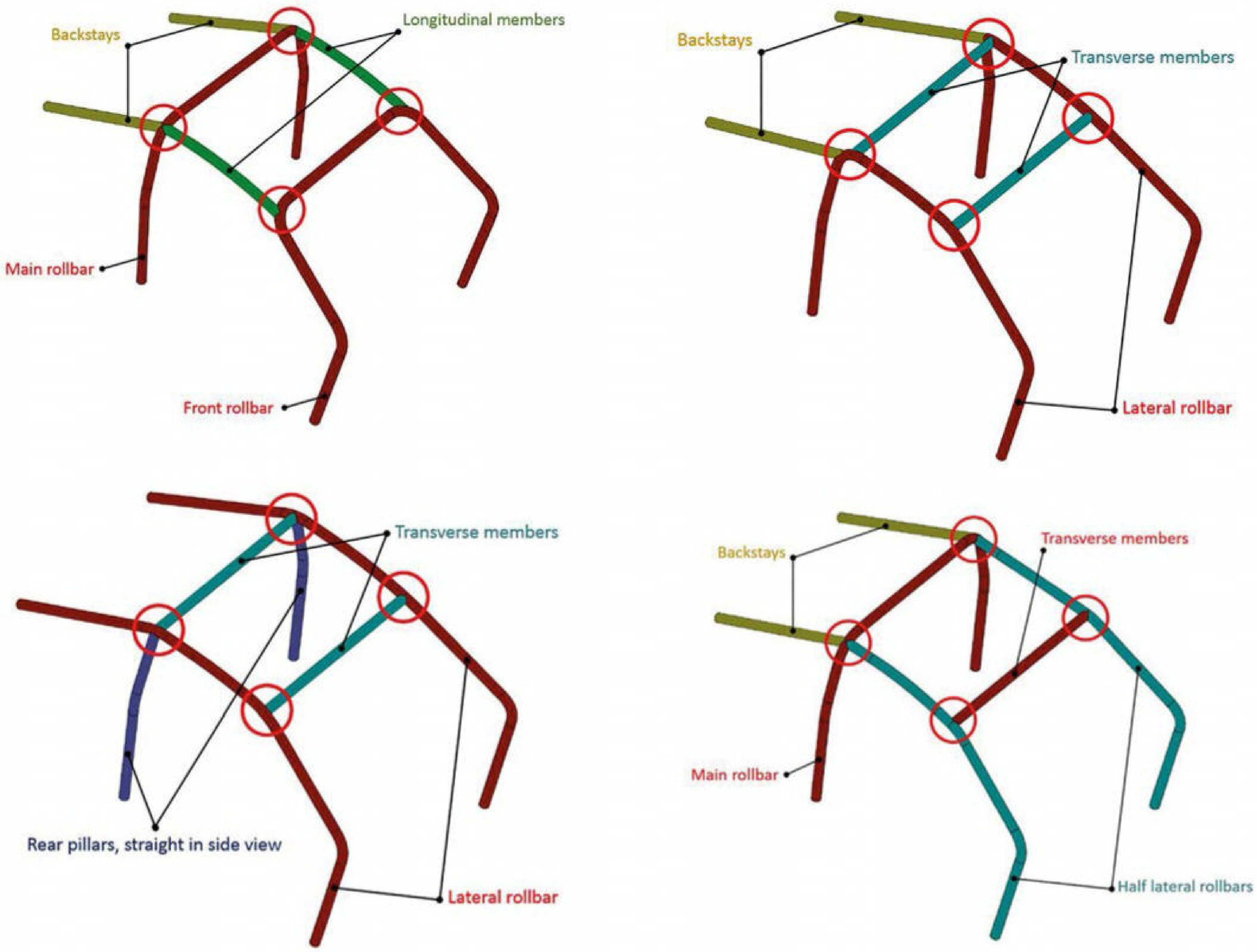
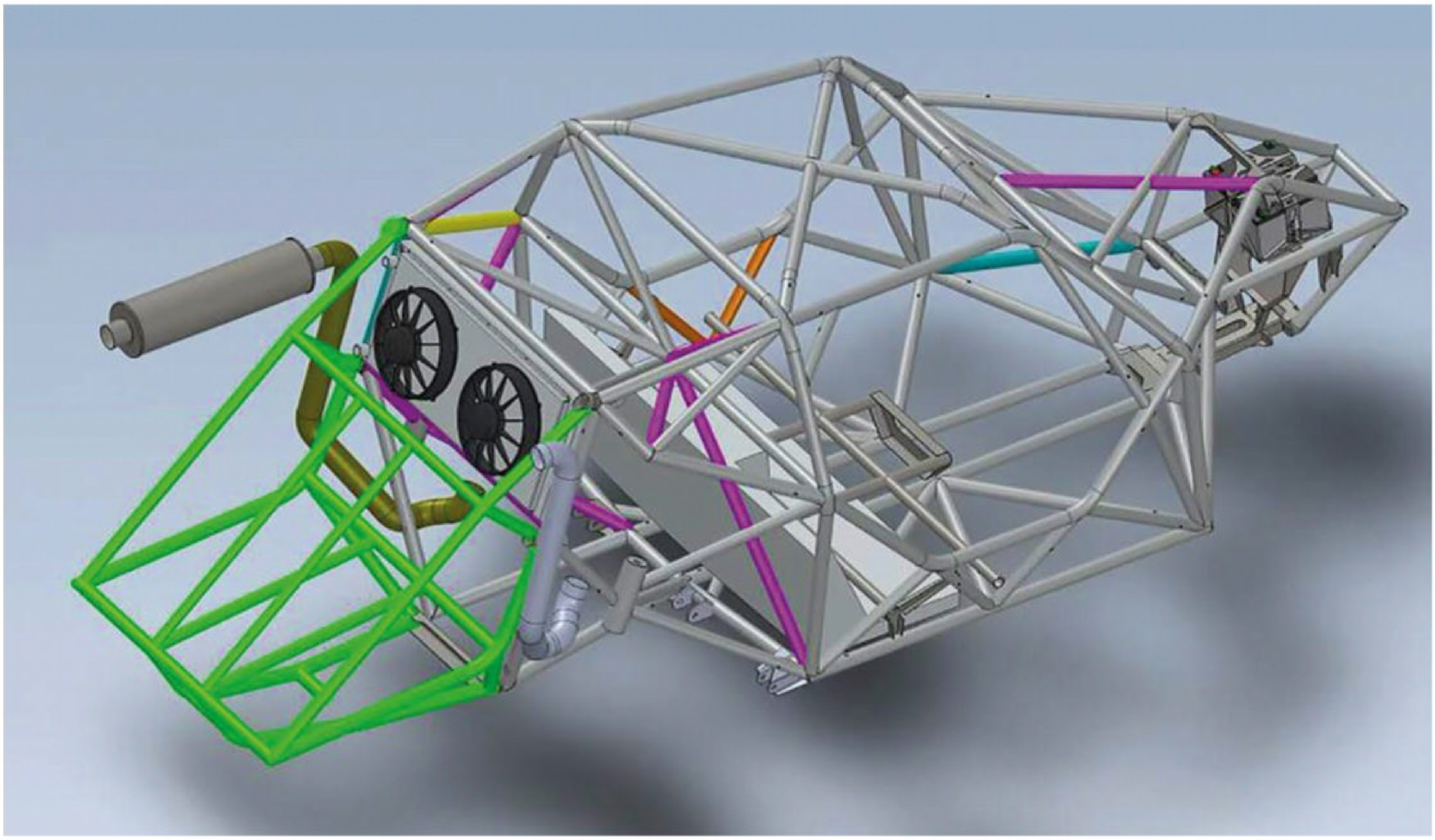



(Source: FIA 2021 HR for safety cages)

**Figure 1: The four accepted variants of 'base structure' of an FIA-approved safety cage**



**In all cases, regardless of category (Glickenhaus Baja Boot shown here), the rearmost section of the cage structure must not extend beyond the rear suspension mounting points**

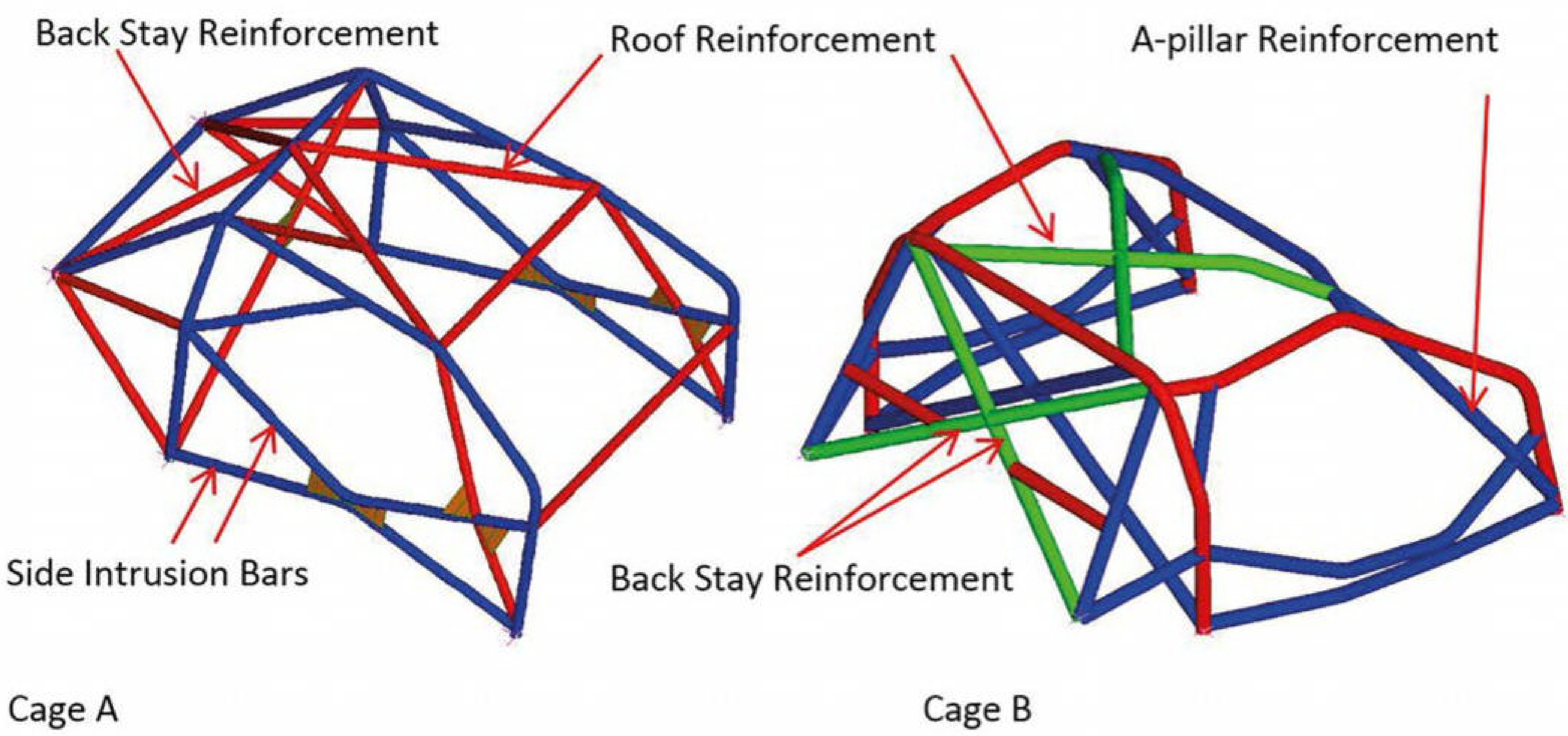



**Figure 2: Examples of safety cage additional member layouts to further strengthen the base structure**

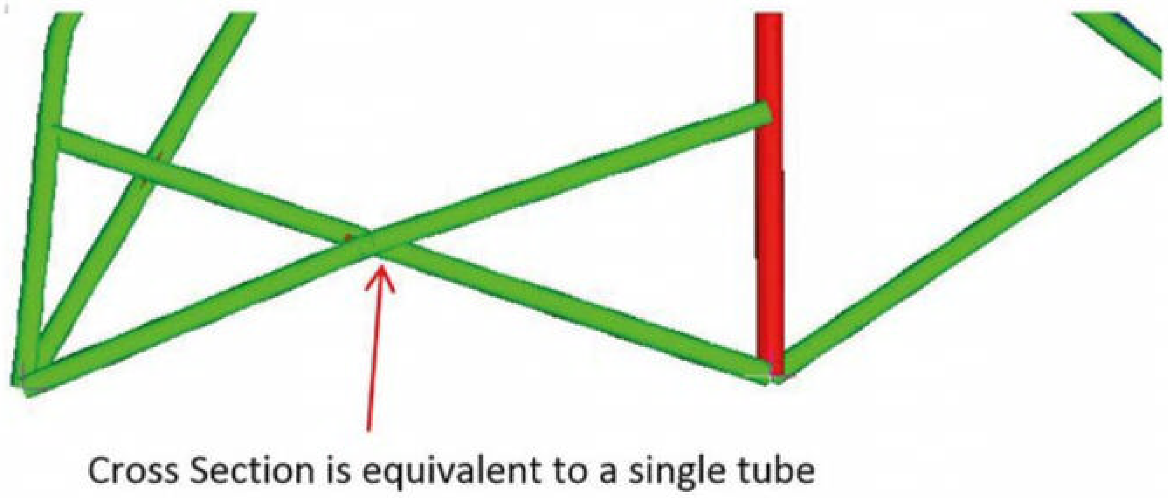



**Figure 3: FIA acceptable side intrusion cross brace, though those shown in Cage A and Cage B in Figure 2 are better**

**It is worth highlighting here that the most common configuration of side intrusion bars is flawed**

Other than that, they are quite similar in their requirements and appearance.

From the beginning of 2021, however, J253 now declares all 'cages must be homologated according to the HRSC, unless stated otherwise in a category's technical regulations.

## Concept approval

The first step in 'cage homologation requires the approval of the concept by the FIA or an ASN. A 3D sketch or CAD rendering showing the tube arrangement, listing the tube dimensions and material is submitted to the FIA. The second step is to engage a company on TL35 to perform the tests outlined in the HRSC. If the 'cage concept passes the tests, a draft report is supplied to the FIA / ASN and a certificate number is issued to finalise the report. Finally, a dossier is completed with the test report attached to create the homologation document.

**From the beginning of 2021, J253 now declares all 'cages must be homologated according to the HRSC, unless stated otherwise in a category's technical regulations**

A common misconception regarding the homologation process is that, since the 'cage strength will be verified as part of the process, it can be of 'free' design. On the contrary, the HRSC defines a 'base structure', of which there are just four variants, as shown in **Figure 1**. There are strict rules on the form of this structure and limits to the positioning and angular orientation of the various rollbars. The design must have a main rollbar, a front rollbar (or two lateral roll bars), transverse members and a pair of backstays. These are absolutely mandatory.

Thereafter, there is a list of 'compulsory members and reinforcements, depending on the intended use of the vehicle. Together these combine to define a base 'cage. **Figure 2** shows a series of typical examples with the reinforcements highlighted. 'Cage A uses an opposing v configuration in the roof and backstays, which is most common these days because it is believed the v junction offers better support in the main rollbar. 'Cage B has a double cross arrangement, with a cross in the roof and another in the backstays. This arrangement provides better protection for intrusion via the roof in a roll over situation. The double cross is an evolution of the single diagonal reinforcement that was the minimum reinforcement required throughout most of the 1980s to 2000s.

In addition to the reinforcements in the roof and backstays, both examples have a pair of side intrusion bars on each side of the car. For events with only a driver in the car, the passenger side can be a single tube member only. It is worth highlighting here that the most common configuration of side intrusion bars is flawed. The HRSC allow for the two side intrusion bars to cross and meet at the centre, provided one of the tubes is a single piece along its length. However, as shown in **Figure 3**, a close inspection of the assembly shows the two tubes eventually become one – only in cross section – exactly where the bending moment, induced by an impact on the side of the car, is the greatest. The better solution here is to form both side intrusion bars into a v shape and allow them to come together but not cross (as evidenced in both 'cage A and B in **Figure 2**).

## Mandatory gussets

A relatively recent introduction to the mandatory reinforcements is the a-pillar support, which is required if the roof-level bend of the lateral rollbar is more than 200mm rearward of the floor-level attachment of the front leg. Gussets are also mandatory, and their locations are shown in **Figure 2**. Additional gussets and reinforcements are allowed, and usually these are added to provide continuity of the tubes to the attachment points to the chassis. 'Cage A shows how the upper side intrusion is extended rearward to meet the backstay attachment point. This member adds to the lateral impact strength of the chassis.

Further extension of the 'cage to the front suspension is permitted in some categories, but in all cases the 'cage cannot extend beyond the upper suspension mounts at either end of the car.

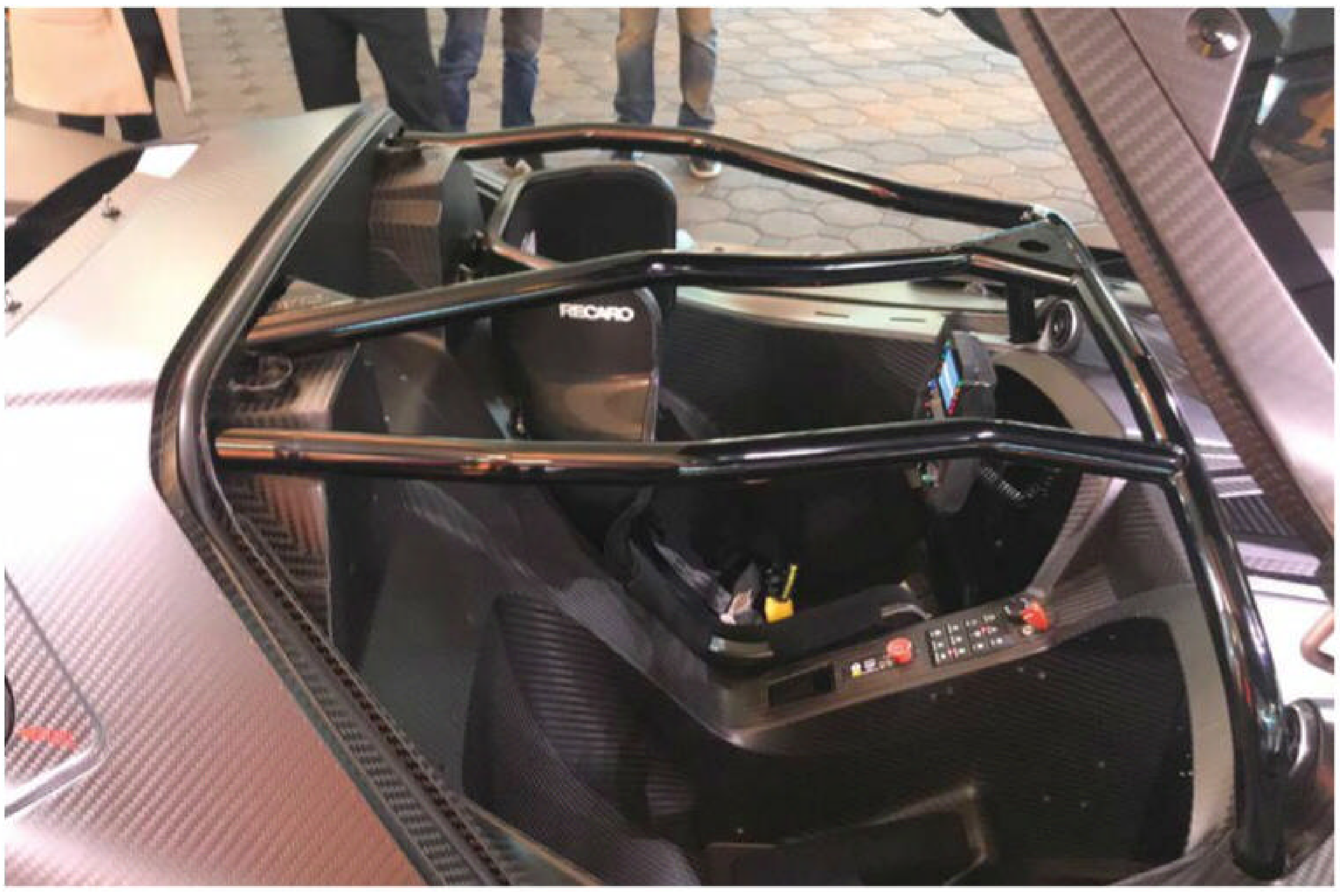
**These days, most manufacturers aim to use 40mm x 2mm for all 'cage members except the main rollbar, which is often 45mm x 2.5mm**

After all the tubes are formed to conform to the inside of the cockpit, the HRSC defines two templates to be inspected. The first ensures the tubes do not impede vision through the windscreen, the other that there is sufficient room in the door aperture for ingress / egress.

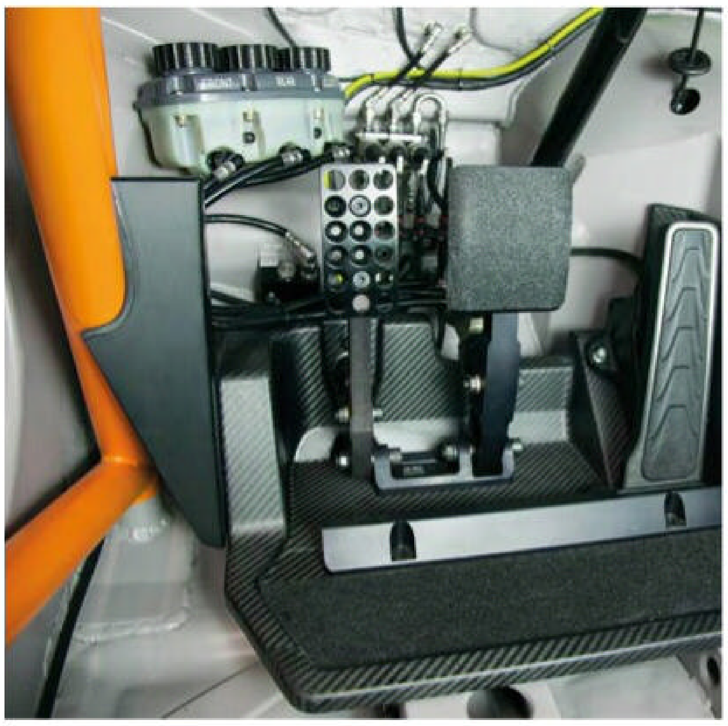
## Material usage

While the configuration of tubes undoubtedly plays a fundamental role in the stiffness of any safety cage, the most significant factors regarding strength are the tube dimensions (diameter and wall thickness) and material. In the 1980s, some alternative materials to steel were briefly allowed, with many Touring Cars and Rally cars featuring aluminium 'cages.

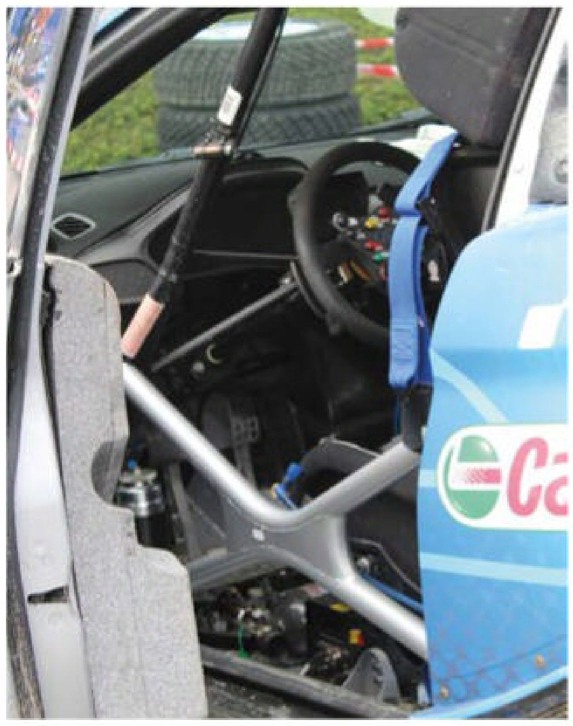

Kalle Rovanpera made full use of the rollcage in his WRC when he crashed on Rally Croatia in 2021. Driver and co-driver were unhurt




This shot of a GT2 KTM Xbow upper 'cage structure shows the use of additional gussets for tube continuity at attachment points



Regulations also cover spreader plate dimensions at floor level



Side intrusion bar gussets are now mandatory

## A stress-strain curve must be derived from the yield strength and tensile strength of the material used

However, poor performance of aluminium welds in big impacts forced the FIA to limit materials to steel only from 1986, and eventually J253 mandated only CDS 350MPa steel (low alloy, low carbon, cold drawn seamless steel).

The HRSC limits the total length of tubes of diameter less than 40mm to 15m, and the minimum wall thickness of any 'cage member is set at 1.5mm. In the past, the most common size used was 38.1mm (1.5in) diameter, 2.54mm (100thou) wall thickness CDS 350. These days, though, most manufacturers aim to use 40mm x 2mm for all 'cage members except the main rollbar, which is often 45mm x 2.5mm.

Despite 2021 J253 now requiring all safety cages be homologated, many national series still have their own version of J253, which do not mandate 'cage homologation. As part of the national regulations, CDS 350 steel can be used without requiring the 'cage to be tested, though in such cases the minimum dimensions for the main rollbar are 45mm x 2.5mm (or 50mm x 2mm) and for other tubes 38mm x 2.5mm (or 40mm x 2mm).

## Alloy steels

It doesn't take long to determine that by using a higher-grade steel with a smaller wall thickness, significant weight savings can be found. Alas, national competitors have also taken advantage of the HRSC by choosing to fabricate safety cages from higher grade, 'chrome-moly' steels such as AISI4130, 25CrMo4 or BS4 T45, despite the additional cost of the analysis and homologation. Compared to CDS350, which has a tensile strength of 350MPa, alloyed steels can be as strong as 900MPa, with elongation of greater than 15 per cent. It should be noted here, though, that welding alloy steels must be done with great care to avoid embrittlement of the material near welds. Excessive heat and rapid cooling can cause this, as well as poor toughness at the junctions. It is therefore not uncommon to hear people say that a good 350 'cage is safer than a poor chrome-moly 'cage.

For accurate simulation, the materials must be modelled with non-linear material properties. This means that a stress-strain curve must be derived from the yield strength and tensile strength of the material used. In many cases, the suppliers of the tubes can supply reports of mechanical tests performed on tube specimens. These reports provide yield strength, tensile strength, elongation at break and the composition to prove the alloy elements exist.

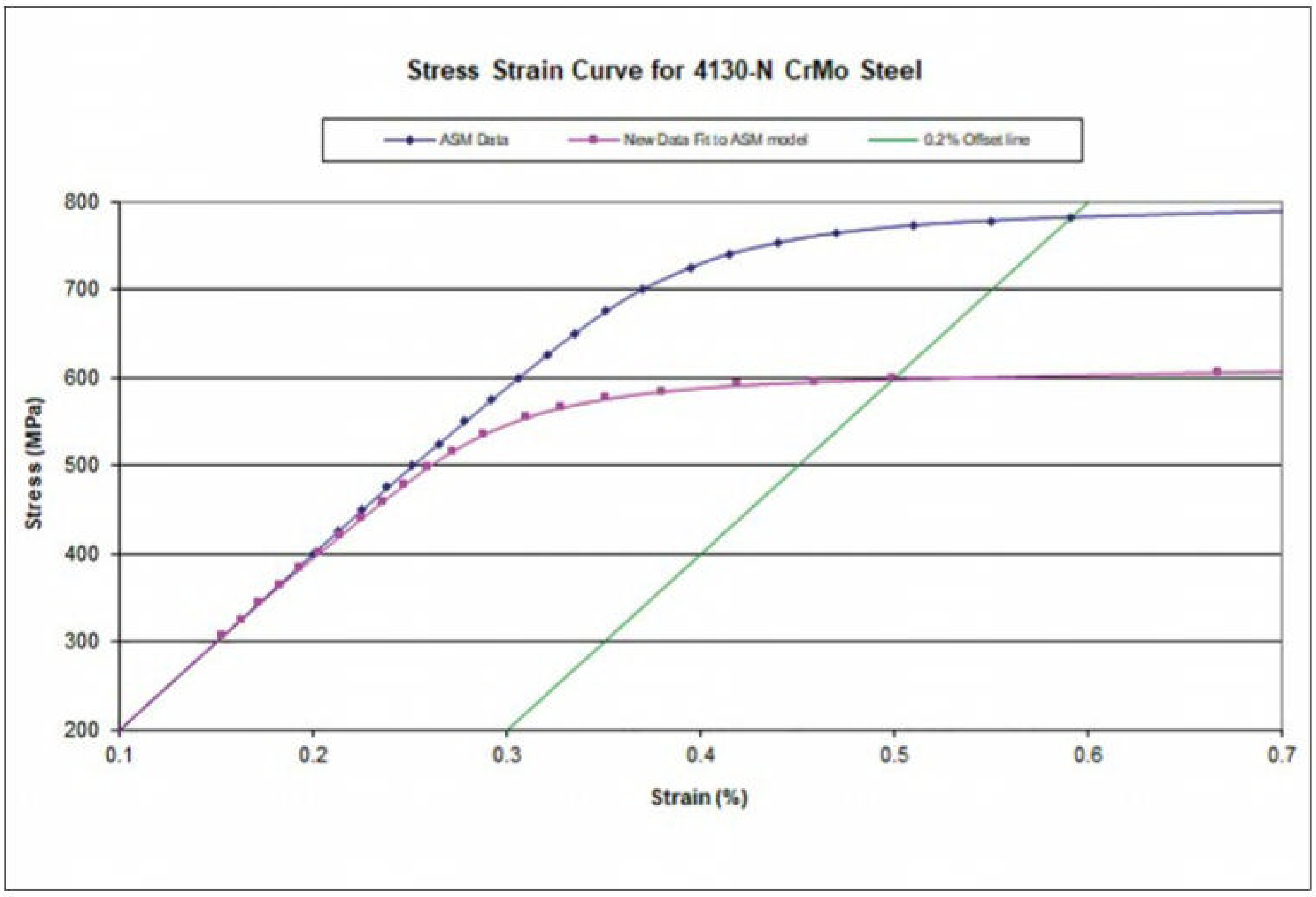



**Figure 4: Typical stress-strain curve for AISI4130 steel**

**Table 1: The three load tests introduced by the FIA with the advent of TL35**

| Test | Load direction | Load Magnitude (daN) | Pass criterion |
|---|---|---|---|
| 1. Main rollbar | Vertical down | 7.5 x w | No breakage or distortion of more than 50mm in the load axis |
| 2. Front rollbar | Down, offset 5 degrees longitudinally, 25 degrees laterally | 3.5 x w | No breakage or distortion of more than 50mm in the load axis |
| 3. Main rollbar | Lateral inward | 3.5 x w | No breakage or *plastic* distortion of more than 50mm |
| w = vehicle mass (without occupants) + 160kg | | | |

**Compared to CDS350, which has a tensile strength of 350MPa, alloyed steels can be as strong as 900MPa, with elongation of greater than 15 per cent**

## Simulation and testing

**Figure 4** shows a typical stress-strain curve for AISI4130 steel. Where manufacturers intend to produce multiple versions of the same 'cage, the minimum material properties, specified in the material standard, are used. Typically, tested samples exceed these minimum requirements.

With the advent of TL35, the FIA introduced three tests, which can be performed physically on a full-scale 'cage model, or simulated using FEA. **Table 1** summarises the three load cases. The principal criterion for acceptance is based on minimising intrusion. The belief is that occupants will be well restrained and wearing helmets, so the 'cage is there to stop the chassis from crushing.

Whilst the first two tests are evident, the third test has been modified for 2021: the criterion is not measured during the load phase, rather the remaining *plastic* deformation in the structure is assessed, after the load has been applied to maximum and then removed. This small change forces the FEA to be non-linear.

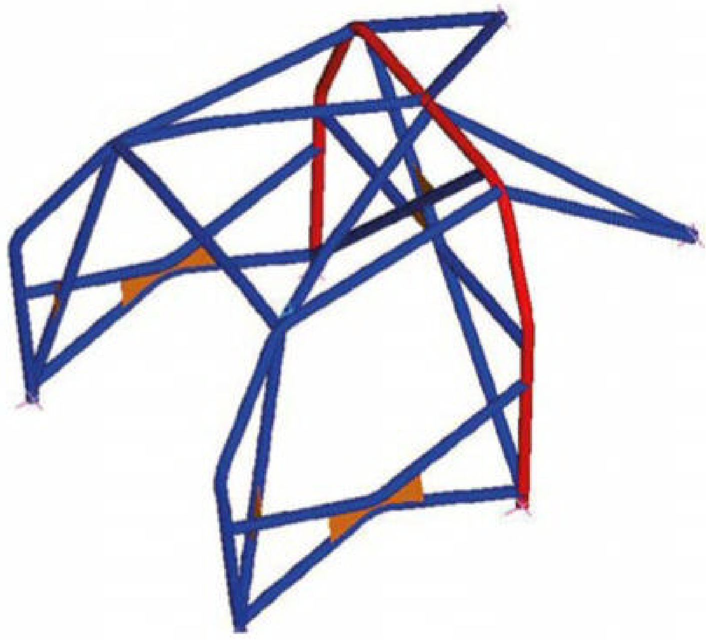
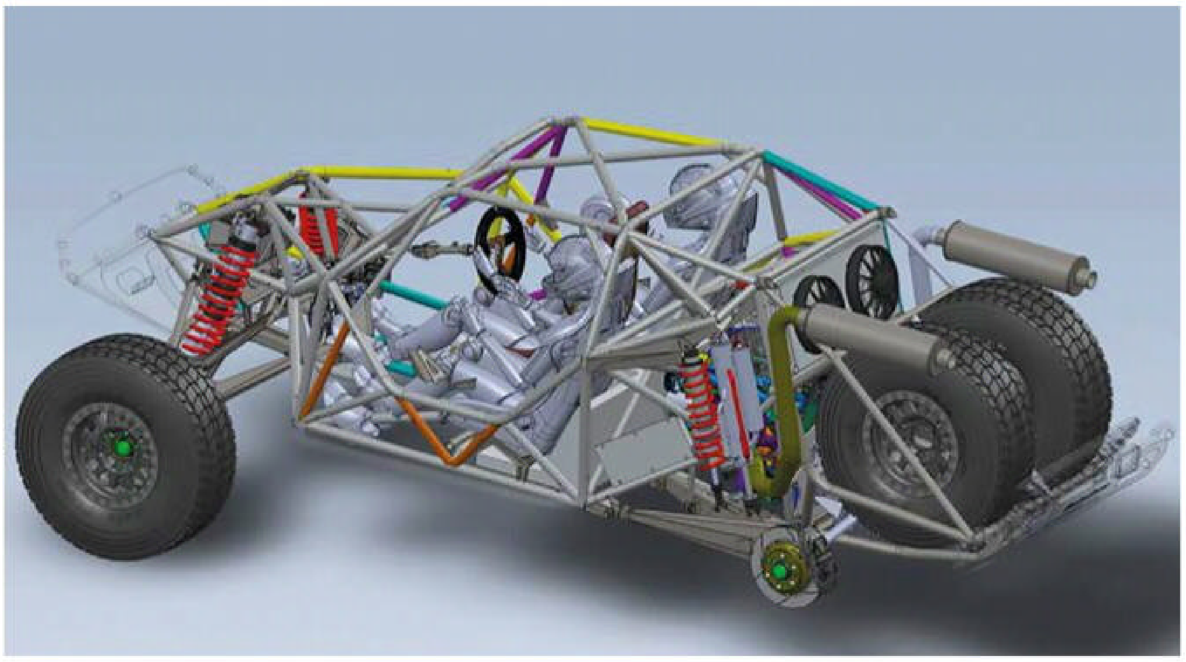


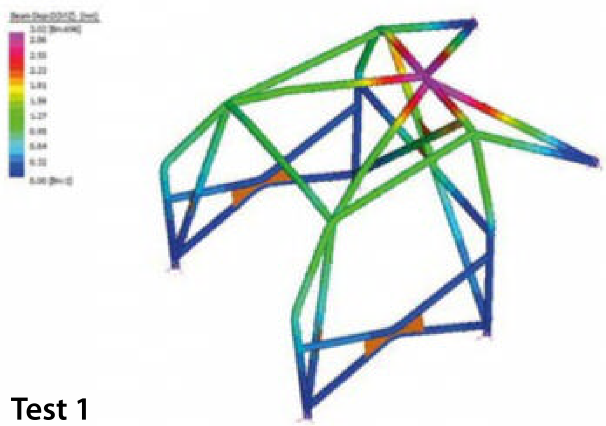
Figure 5: Typical test comparison 'cage



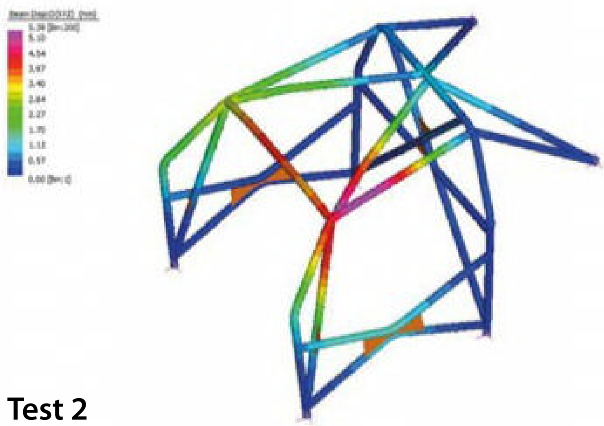
Safety Cage test procedures are regularly updated, with the latest revision focussing on reducing plastic deformation

Table 2: Material options

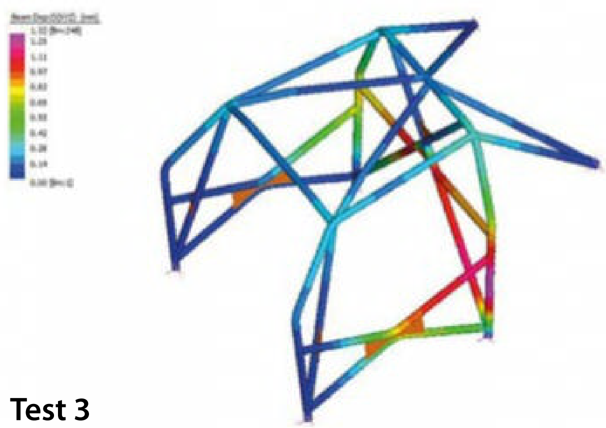
| Case | Material | Yield strength (MPa) | Tensile strength (MPa) | Main rollbar (mm) | Other members (mm) | 'Cage mass (kg) | Result 1 (mm) | Result 2 (mm) | Result 3 (mm) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | CDS350 | 300 | 350 | 45 x 2.5 | 40 x 2.0 | 47.9 | 3.02 | 5.39 | 1.32 |
| 2 | 25CrMo4 | 450 | 700 | 45 x 2.5 | 40 x 2.0 | 47.9 | 3.01 | 5.10 | 0.47 |
| 3 | 25CrMo4 | 450 | 700 | 45 x 1.5 | 40 x 1.5 | 34.9 | 3.79 | 6.97 | 1.22 |
| 4 | BS4 T45 | 620 | 700 | 45 x 1.5 | 40 x 1.5 | 34.9 | 3.75 | 6.73 | 0.66 |
| 5 | BS4 T45 | 620 | 700 | 40 x 1.5 | 40 x 1.5 | 34.3 | 3.99 | 6.83 | 0.79 |



Test 1



Test 2



Test 3

Figure 6: Deformation output for case one, CDS350 steel

To better understand the nature of the tests, and the relative importance of tube selection, let us compare a typical safety cage, as shown in **Figure 5**, with the material options listed in **Table 2**.

The car mass is 1400kg, so w = 1560kg. The load for test one is 117kN and the load for tests two and three are 54.6kN. **Table 3** displays the results and **Figure 6** shows the graphical output of deflection for case one.

Firstly, we notice that in all cases, the tubes selected would pass the tests. For high-strength steels, we may not expect to see high values of deflection (more than 30mm) as fracture occurs shortly after yield. Indeed, as we can see in test three, all cases resulted in a small amount of permanent deformation, therefore all saw some amount of plasticity.

For the readers' interest, each of the test one cases reached yield at 80-90 per cent of peak load, and 70-80 per cent of peak load for test two.

Also note that for cases one and two, despite the difference in strength, the deflection for test one is almost identical, which indicates the maximum stress in both cases would have been less than the yield stress for case one.

## Weight saving

Of particular interest is the weight saving, with very little reduction in strength, to be had from switching from CDS350 to chrome-moly – some 13kg. A further saving of 0.6kg can be found by reducing the main hoop diameter. Additional weight saving can be made by removing any non-compulsory tubes, though most 'cage manufacturers tend to priorities safety over optimising the 'cage to the letter of the HRSC. Frequently, a well-placed tube that adds a small amount of weight offers a large gain in safety. An example of this is the gusset tube adjacent to the driver's ear / shoulder, joining the main rollbar to the lateral rollbar.

**Frequently, a well-placed tube that adds a small amount of weight offers a large gain in safety**

Since the introduction of mandatory safety 'cages for closed racecars, the FIA has made steady progress in improving occupant safety. The recent Homologation Regulations for Safety Cages have given 'cage manufacturers the opportunity to optimise designs and make weight savings with little effect on the 'cage strength.

For readers interested in more detail, please contact your local ASN or find the author at Human Impact Engineering (email: enquiries@humanimpacteng.com).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# The heat is on

## How motorsport out-performed traditional brake technology and led to the introduction of carbon-carbon braking systems

By JAHEE CAMPBELL-BRENNAN

AMR

**Iron braking set-ups are still used exclusively in GT racing due to their lower cost, strength, longevity and more friendly and predictable thermal characteristics**

From sliding tectonic plates to the honey in beehives, the conversion of kinetic energy into heat energy through friction is a universal process that's been going on for millennia. It wasn't until we figured it could be used to our advantage in the ignition of fire, though, that it started to become useful to us as a species.

Friction features extensively in the automotive world, where it is both useful and not so useful. By far and away the largest generator of friction in an automobile originates in the action of the braking system.

Up until the last few decades, motorsport braking systems solely used cast iron discs as the frictional medium. It's cheap, has good longevity and good thermal characteristics, making it perfect for most applications.

Traditionally, brake discs for road cars and motorsport alike were manufactured from grey cast iron, differentiated from standard cast iron in that it contains around three per cent carbon by weight, and has higher sulphur and manganese content. This gives it some useful properties.

The microstructure of grey cast iron endows it with a number of useful properties. It has relatively high thermal conductivity, resists thermal fatigue well and has better corrosion performance than many other ferrous alloys. It also has higher hardness, which makes it more wear resistant.

Iron in all forms has a relatively high thermal mass (or heat capacity in chemistry terms), which means it takes a lot of energy to increase its temperature, reducing the rate of temperature increase during each braking application. Once hot, it has a high thermal conductivity, which means it will lose heat to the air through convection relatively easily.

### Surface temperature

Bringing an 800kg F1 car down from 200mph to 60mph dissipates approximately 2900kJ of kinetic energy as heat into the braking system in just a few seconds. To give you some perspective, that's roughly equal to the heat generated by an average kettle if left on for 20 minutes.

Sure, there are four brake discs, but it's enough energy to result in surface temperatures of over 1000degC in extreme cases. This takes cast iron systems way above their comfortable temperature range, which ceilings around 750degC with today's materials.

The problem with absorbing energy on this scale using cast iron discs centres on the changes it brings to the material properties and thermal expansion. These temperatures are close enough to its 1200degC melting point that the material properties are altered, becoming ductile and reducing in hardness, which leads to faster wear.

Traditionally, it was the pads that would limit the upper temperature range of these systems and fail first but, in the last decade, pad material has progressed to the point that these temperatures


Alcon

As brake calipers don't have to withstand the same heat cycles and wear patterns, exotic aluminium alloys can be used in their construction, using CAE to optimise the design

**Bringing an 800kg F1 car down from 200mph to 60mph dissipates approximately 2900kJ of kinetic energy as heat into the braking system in just a few seconds**

are no longer a problem and the discs themselves are the limiting factor.

'Even in its normal temperature range of 400-750degC, you get a significant amount of dimensional change with iron discs, which we have to design caliper clearances around,' explains Garry Wiseman, chief engineer of motorsport projects at brake manufacturer, Alcon.

'The typical sign of an overheated pad is a drop off in friction coefficient, so the driver has to generate more pressure in the system. At these elevated temperatures, wear tends to go up and also the risk of 'taper wear', where pads wear in a wedge shape, is increased.'


BMW Team RLL

Although the working range of iron discs is 450-750degC, it is not uncommon for them to see spikes of up to 1000degC on occasions

In the motorsport domain, the weight of the braking system is especially important due to its contribution to unsprung mass. That has a large input into tyre performance, which, in a world of weight watching, makes it a decisive target for improvement.

## Rotational velocity

Brake discs are unique amongst braking components in that they also possess rotational velocity. From the physics of rotational inertia, you'll appreciate the dynamic affect this has on braking and throttle applications, where having to overcome this inertia blunts the wheel's angular acceleration somewhat. Another penalty incurred with cast iron. It's a very dense material.

Brake calipers don't have the constraints of being wear resistant, nor are they exposed to such high temperatures due to their isolation from friction surfaces. As such, caliper manufacturers are afforded the luxury to explore non-ferrous alloys in efforts to reduce weight and optimise performance.

'Calipers are largely made of aluminium alloys. If budget and regulations allow, an aluminium-lithium alloy is used, which is of a slightly lower density and higher stiffness than standard aluminium, allowing us to optimise designs to a further degree,' notes Wiseman.

## Carbon entry

But when carbon braking technology arrived in F1 in the mid-1970s, it was another notable advancement through motorsport's relationship with aviation. The technology was borrowed from

**Manufacture of carbon-carbon discs and pads involves months, multiple lengthy temperature cycles at four-digit temperatures and five-figure price tags**

the aerospace industry – Concorde to be precise – and adapted for racing.

Today, the types of braking systems associated with super high-performance racing such as F1, LMP1, DTM (notice the trend with high aero) are carbon-carbon systems, based around carbon fibres held within a matrix of carbon atoms. These differ quite significantly from the carbon-ceramic technology traditionally seen in high-performance road car applications.

The introduction of carbon-carbon technology bought with it the dual benefits of light weight and the ability to withstand very high operating temperatures without failing in the same ways that iron systems do, allowing leaps forward in braking performance by being able to withstand much higher energy inputs.

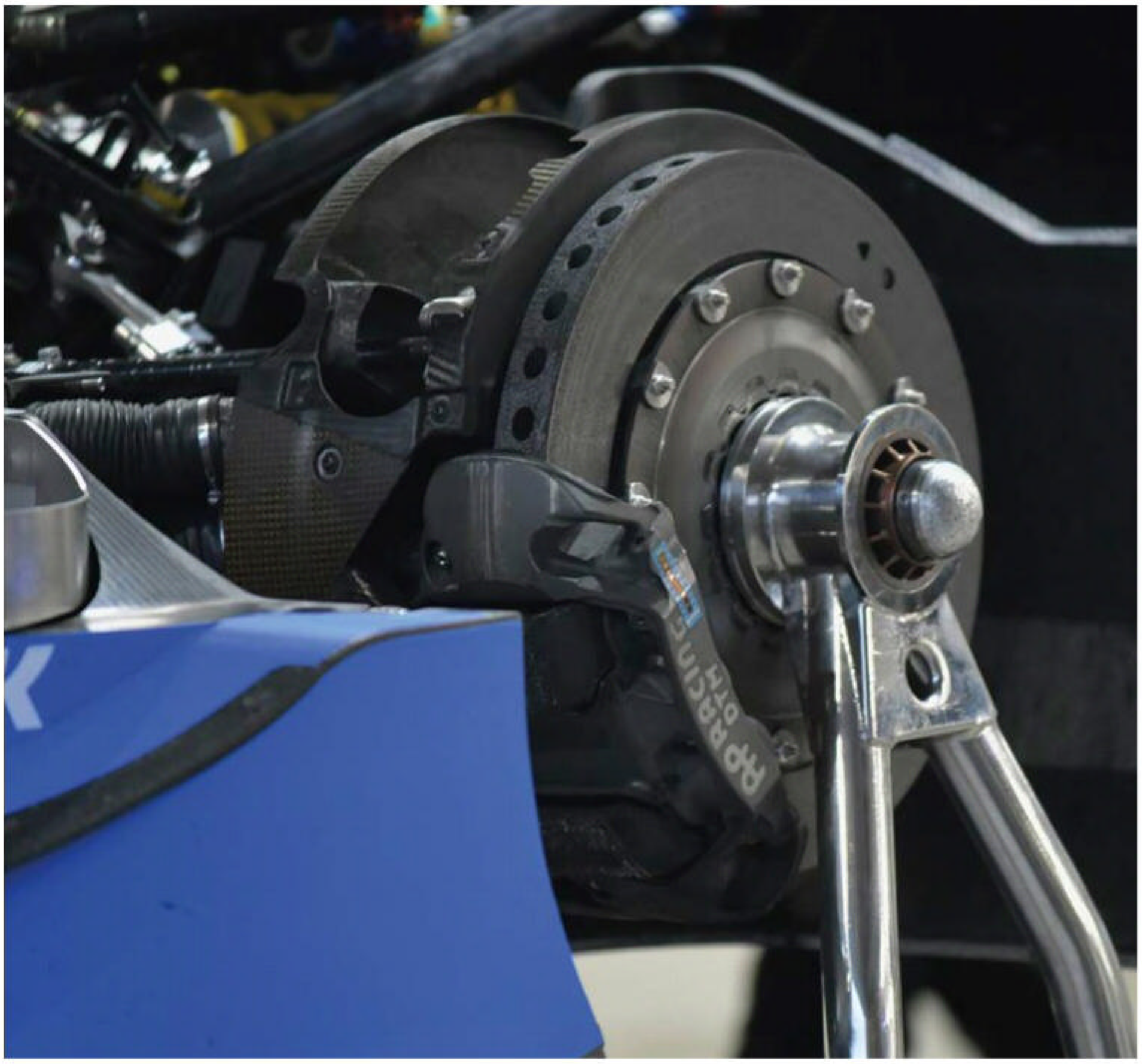
Add in the much harder friction surfaces of carbon-carbon systems, and the consequent lower wear rates, which reduce servicing requirements and the time penalties they incur, and they are very attractive to endurance racing especially.

Of course, they are also very expensive.

The manufacturing process of these systems (see box out on p57) is hugely different to pouring a homogenous molten metal into a cast. Manufacture of carbon-carbon discs and pads involves months, multiple lengthy temperature cycles at four-digit temperatures and five-figure price tags.

'The length of manufacture can be a little tricky if you're waiting to verify a change, so it can add some complexity to development,' notes Jason Carpenter, trackside and product support engineering at AP Racing. 'At times you might want to explore various design routes, which means you need to produce all the part options in parallel. There's no getting round it, it's a long-winded process.

'You can play around with the construction and orientation of the fibres. For example, designing a three-dimensional fibre lay-up offers a certain




AP Racing

Carbon-carbon brakes offer a number of advantages over their iron counterparts, but at a significant cost penalty

level of heat conductivity in certain directions, while a more 2D-based construction might offer greater consistency in terms of material behaviour.

'There are different targets depending on the particular application, so you have freedom to really specialise carbon-carbon to the application.'

## Tailored pads

Brake pads are made of the same material as the disc with these systems, but their exact construction is another area of design freedom that can be used to tailor the system's performance.

'You could tailor the friction couple and combine a 2D disc with a 3D pad construction, for example,' continues Carpenter. 'That means the pad material can have a proportion of fibres oriented in the car's y axis [left to right across the centreline], increasing thermal conductivity in that direction to aid heat rejection from the friction surfaces.'

Carbon-carbon discs still need to be attached to a metal brake hat for strength purposes, but nonetheless emerge around one quarter of the weight of their iron counterparts. This can be a huge percentage of the unsprung weight, saving up to 10kg per corner in some cases.

The frictional coefficient between the pad and disc for both iron and carbon-carbon

**Producing a consistent CoF characteristic over the entire temperature range of the system is much more desirable than it is to achieve the highest peak CoF**

systems isn't particularly high by most standards, at approximately 0.5. This means that for each Newton of compressive force applied between disc and pad, you'll get 0.5N of braking force. Force is then multiplied by the disc radius to give braking torque.

For comparison, the coefficient of friction (CoF) between a racing tyre and the track surface fluctuates at approximately 1.5.

Producing a consistent CoF characteristic over the entire temperature range of the system is much more desirable than it is to achieve the highest peak CoF, especially when durability and maximising system life is a priority.

'The main point for development currently with pads is a consistent frictional coefficient over the widest temperature range.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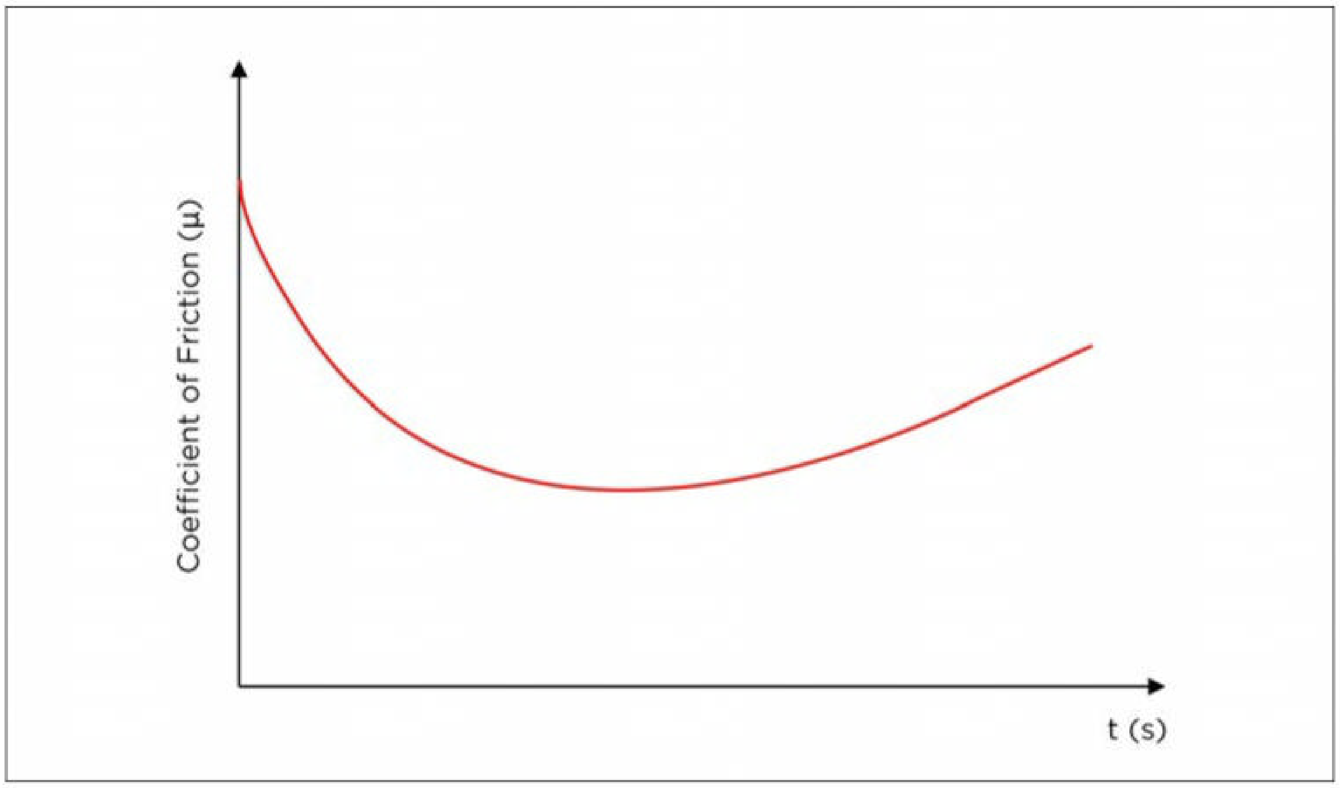
'In-stop' friction characteristics are an area that also gets a lot of attention, as this is what drivers want for a confident braking feel,' notes Wiseman.

'Initial bite is important for drivers, as well as having a relatively flat profile as it heats up, though sometimes there are advantages to digressive pad materials, which lose friction as the pad heats. This can be useful in the rear axle, especially as the car slows and loses downforce. Having this means the rears are less inclined to lock up as speed falls.'

Driver feel is an important consideration, and generally where carbon-carbon technology shines is in terms of repeatability and consistency. Carbon-carbon is a very stiff material, so there is less energy compression in the discs and pads, which is an energy loss. This creates a very stiff pedal.



**The coefficient of friction throughout the braking phase of a typical carbon-carbon braking system**


**Oxidative damage to a disc can usually be visually spotted, as Jason Carpenter at AP Racing (left) demonstrates**

AP Racing

## Upper limit

Of course, with friction comes temperature, so while the upper limit for operating temperature of carbon-carbon is much greater than iron systems, the technology does still have its limit.

As temperatures approach 1000degC, the discs and pads begin to chemically oxidise in a process known as thermal decomposition.

In terms of chemistry, the carbon atoms undergo a chemical reaction with oxygen atoms in the surrounding air, resulting in a loss of electrons and a change in the mechanical properties of the material. This change can be objectively measured through a reduction in weight.

Many of you will be familiar with the sight of F1 cars with plumes of black dust flowing out from the wheel after an extended period in the wake of another car. This is overheated friction material being lathed away as the brakes are applied. It's not wise to keep that up for long!

Short spikes of high temperature aren't so bad for the system in terms of wear as oxidation is a cumulative phenomenon. More important is the average temperature of the system over a race.

'Generally, you can easily identify how oxidised disc material is just by looking at it,' adds Carpenter. 'A clean, healthy disc is visually quite distinctive, so there are things to look out for as signs of excessive temperature in friction materials – a shinier finish, or banding around the radius, for example.

'Evidence of porosity would be the most worrying to find, and would indicate there's something to investigate on the set-up. The type of track and / or braking that has been done may influence how this damage presents itself, too.'

In most cases, oxidative damage can be recovered by skimming the affected material from the disc face. Often it only penetrates 1-2mm deep, leaving plenty of material to recover and allowing the disc or pad to be re-used without issue.

'I've experienced an occasion where brake cooling ducts have been taped up by a team during an installation lap and the tape wasn't removed before a full-speed run,' recalls Carpenter. 'The whole system was fried when it got back to the pits. Discs, wiring, brake drums and all had seen very high temperatures and a lot of damage had occurred.'

Most issues with carbon-carbon braking systems are due to temperatures going outside of range, so teams are quite responsible with this and know the dangers. And costs.

Discs, calipers and pads are therefore supplied with ample fresh air via ducting. F1 has the highest energy dissipation requirements in motorsport, so the discs can feature as many as 1400 cooling holes extending from the inner radius to the outer radius. This maximises the surface area available for heat exchange. With this approach, air is pumped through the disc by its rotation, absorbing heat on the way through.

## Lower limit

Temperatures fall by as much as 700degC between braking zones, which presents a nice segue into another thermal

**As temperatures approach 1000degC, the discs and pads begin to chemically oxidise in a process known as thermal decomposition**

phenomenon unique to carbon-carbon systems – their minimum temperature limit.

In today's era of endurance racing where you have to manage fuel and hybrid energy recovery, it's common to see teams implement some coasting, or periods where drivers are a bit easier on the brakes. This, however, can be a difficult problem to manage from a thermal point of view.

'If you fall below 300-400degC on carbon-carbon systems, the frictional coefficient drops to literally around half of the normal operating conditions, as low as 0.2. It can really be a very sharp gradient. This is a problem that iron systems don't suffer from,' notes Wiseman.

This not only presents problems in terms of braking power, and can make it difficult to get heat back into the system, but if one axle falls out of the temperature window before the other it can dramatically change the braking balance. In race conditions, that can be very hard to recover.

**'If you fall below 300-400degC on carbon-carbon systems, the frictional coefficient drops to literally around half of the normal operating conditions, as low as 0.2'**

*Garry Wiseman, chief engineer of motorsport projects at Alcon*

Likewise, warm-ups have to be done in a structured way to prevent one axle reaching temperature before another.

## Thermal management

Temperature management isn't just focussed on disc and pad either. Calipers are also part of the equation due to their heat sensitivity, due to their proximity to the brake fluid and the polymer piston seals used.

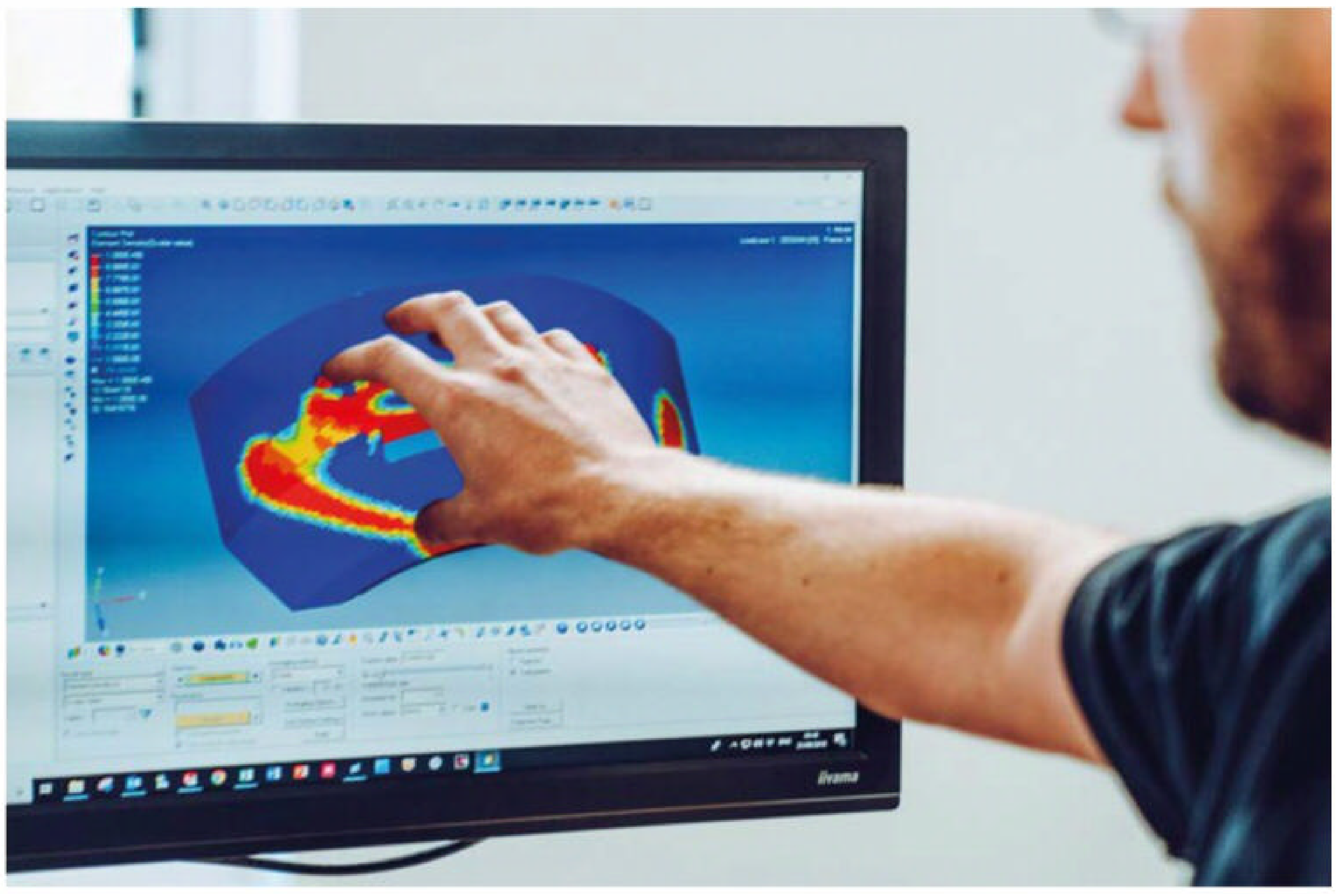
Caliper design is optimised to minimise heat transfer into the fluid, so fluid volume in the caliper is kept as small as possible and various ducts used to regulate the system.

'The temperature gradients in the calipers aren't anywhere close to the same as the discs and pads,' says Carpenter. 'Over a stop, the friction surfaces might see a 500degC heat increase, while the caliper will only increase around 50degC. They are quite isolated in that sense, and stay between approximately 150-200degC at the top end.

'This is important to protect the brake fluid and prevent the piston seals going over their limit. But another aspect is that pedal stiffness can start to be affected if the fluid and caliper gets too hot.'

Thermal management is therefore critical to racing with carbon-carbon systems, and much energy and resource is spent on finding that optimum temperature window for performance and longevity. When it's right, even today's iron systems can last the entire duration of a race as arduous as the Le Mans 24 hours without a disc or pad change. This was previously a luxury only afforded to carbon-carbon systems.

Wiseman: 'Temperature management over the whole system is so important. The key thing is understanding your friction package and figuring out the best operating window, then maintaining that over the whole race.



Alcon

**Calipers are designed to optimise structure and meet deflection targets, but also have to account for thermal changes in discs, too**

## The making of a carbon disc

### Fabric manufacture

The discs start life as standard PAN (Polyacrylonitrile) carbon fibres. Before use, the fibres are oxidised, which involves heating them under tension to align the molecular structure in such a way to maximise their strength.

The fibres are then chopped and mixed up to create a felt-like layer, which is spun onto rolls for later use.

### Carbonisation

To further refine the PAN felt, the material is placed in a furnace at over 1000degC. This carbonisation process liberates any contaminants. Anything non-organic (not carbon) evaporates. This process takes place in an oxygen-free gas, often nitrogen, to ensure the PAN is not combusted.

### Pre-forming

The fabric is then cut into disc shapes resembling the final product and stacked in layers to reach the desired thickness. Weight is measured at every stage to ensure the correct density.

Once the 'disc' is built up, it is placed in a hydraulic press and compressed with upwards of 20 tonnes of pressure to make the 'preform' substrate for the next process.

### Chemical Vapour Deposition (CVD)

Perhaps the most important, intricate and mysterious phase in carbon disc manufacture is the CVD process.

In this stage, the still porous carbon fibre preforms are loaded into a furnace under partial vacuum and heated again in excess of 1000degC. Carbon atoms, often liberated from methane, are deposited onto the fibres of the preform to form a dense, very low porosity matrix of carbon and encapsulated fibres.

This process can be repeated up to six times, in cycles of up to four weeks' duration, to mature the material. Each cycle increases its density and further reduces porosity.

### Graphitisation and final machining

Graphitisation is a further heat treatment process performed above 2000degC in order to change the molecular structure of the carbon fibres, increasing their modulus of elasticity. This makes them stiffer, but more brittle.

Finally, the components are machined to their final dimensions and tolerances.

The entire process can take around six months, from initial oxidisation of the PAN fibres through to the production of a ready-to-race disc (or carbon pad).

'Being quick and consistent over the whole race is what's really important. This is what made our brakes on the Aston Martin so successful at the 2020 Le Mans 24h.'

Nonetheless, parts do wear over the course of an event. Carbon-carbon systems lose up to 10mm of disc material in endurance events, and slightly less for sprint races. Considering they can cover over 5000km in an event such as Le Mans, those wear rates are actually quite low.

Outside of the combustion cylinder, there is no harsher environment for a component. Through extreme heat, vibration, tension and clamping forces, brakes have to operate time and time again without scope for failure.

With pressure to create lightweight, durable and reliable systems, material scientists, chemists and brake manufacturers have to be commended for their finesse in understanding the boundary conditions and engineering components to perform flawlessly within them.

## The next developments

With electric / hybrid motorsport being implemented in an ever-growing number of championships, and regenerative braking thrown in the mix too, those boundary conditions are now changing.

As braking power is a tyre friction-limited quantity, and a proportion of braking power is now provided by electric motors (MGU-K) in these championships, the requirements of the friction braking system become less demanding.

Effective and reliable braking in these cases can only be implemented through brake-by-wire (BBW) systems, which de-couple the driver's pedal input from the brake master cylinder and instead use electric actuation to engage friction braking on the rear axle, allowing it to be merged constructively with regenerative braking systems.

'In our Formula E systems, the capacity for regenerative braking is the key input to managing the relative contributions from each system. We have a pressure target interface so, based on the regen' capability at any specific moment, the car's management system performs the complex calculation to work out the remaining braking torque required from the friction brakes. This is then communicated to the brake-by-wire system,' comments Simon Zollitsch, motorsports lead at LSP Innovative Automotive Systems.

'To be able to provide BBW technology to further race series in the future without introducing high costs, our next generation BBW has the functionality to run these regen' control calculations onboard, removing software complexity from a teams' workload.'

Maximising regenerative braking to race as efficiently as possible means there is less energy going into the friction braking system. It certainly allows for smaller, more compact and lightweight braking systems, but does this open the door for lower performance friction braking technologies?

Carbon-ceramic technology has been present on high performance road cars for many years now. It's less robust thermally, but it is cheaper and less energy intensive to manufacture, which gives it a lower carbon footprint. As such, in F1, under the spotlight of sustainability and road relevance, it's starting to receive some attention.

'We have a lot of experience with application of carbon-ceramic systems on fast road cars, but in my view at the moment that technology isn't quite there for motorsport. It's too limited in terms of the energy input it can accept,' states David Hamblin, AP Racing managing director. 'It's very good technology, but it's not ready yet for F1 without taking a huge step back from what they have at the moment. The [braking] energies are on a different level.'

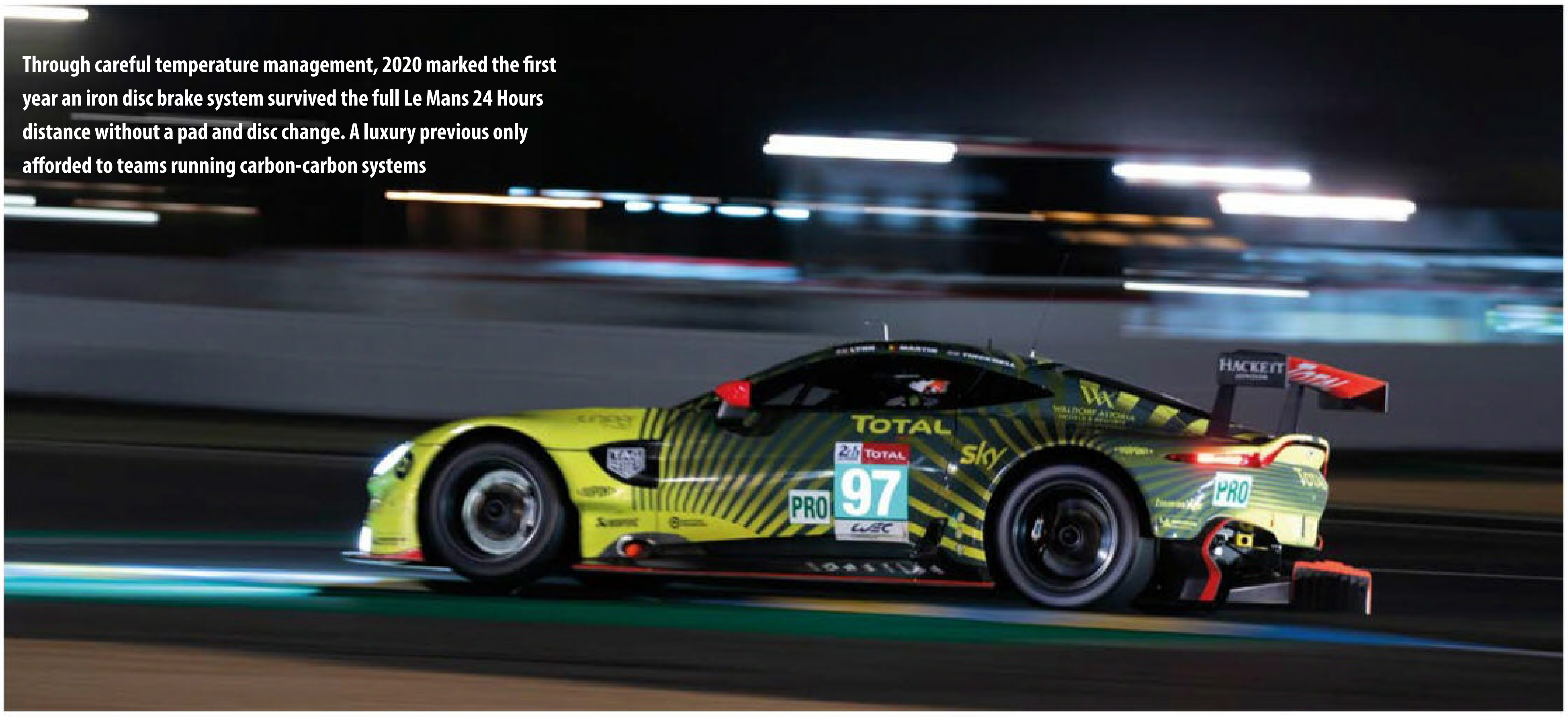
**Thermal management is critical to racing with carbon-carbon systems, and much energy and resource is spent on finding that optimum temperature window for performance and longevity**

Carbon-ceramic braking technology suffers from degradation in a similar manner to carbon-carbon systems, albeit through a slightly different process and, crucially, at a lower temperature.

'In its current state, carbon-ceramic braking systems are significantly heavier. Lighter than iron of course, but still way heavier than carbon-carbon,' adds Hamblin.

Still, with the ever-increasing pressure on high-level motorsport to stay relevant with road car technology, and to develop environmentally friendly solutions, there's no doubt there will be an increased and sustained R&D effort into both carbon-ceramic and BBW systems in the coming years.

Motorsport has proven time and again that, with the right motivations, some very special and creative engineering can take place. In that environment, braking technology is certainly not standing still. Pun intended.




Through careful temperature management, 2020 marked the first year an iron disc brake system survived the full Le Mans 24 Hours distance without a pad and disc change. A luxury previous only afforded to teams running carbon-carbon systems

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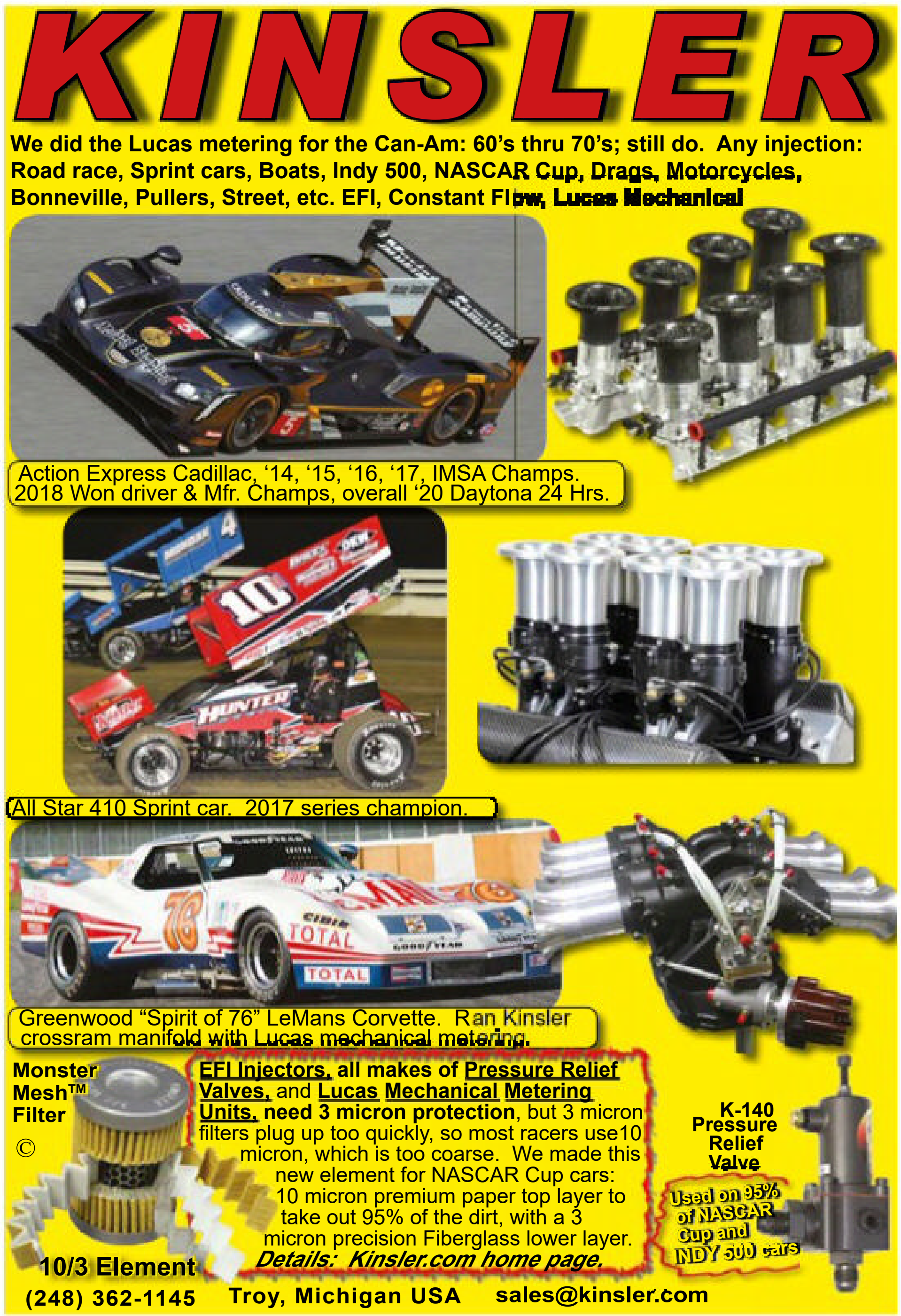
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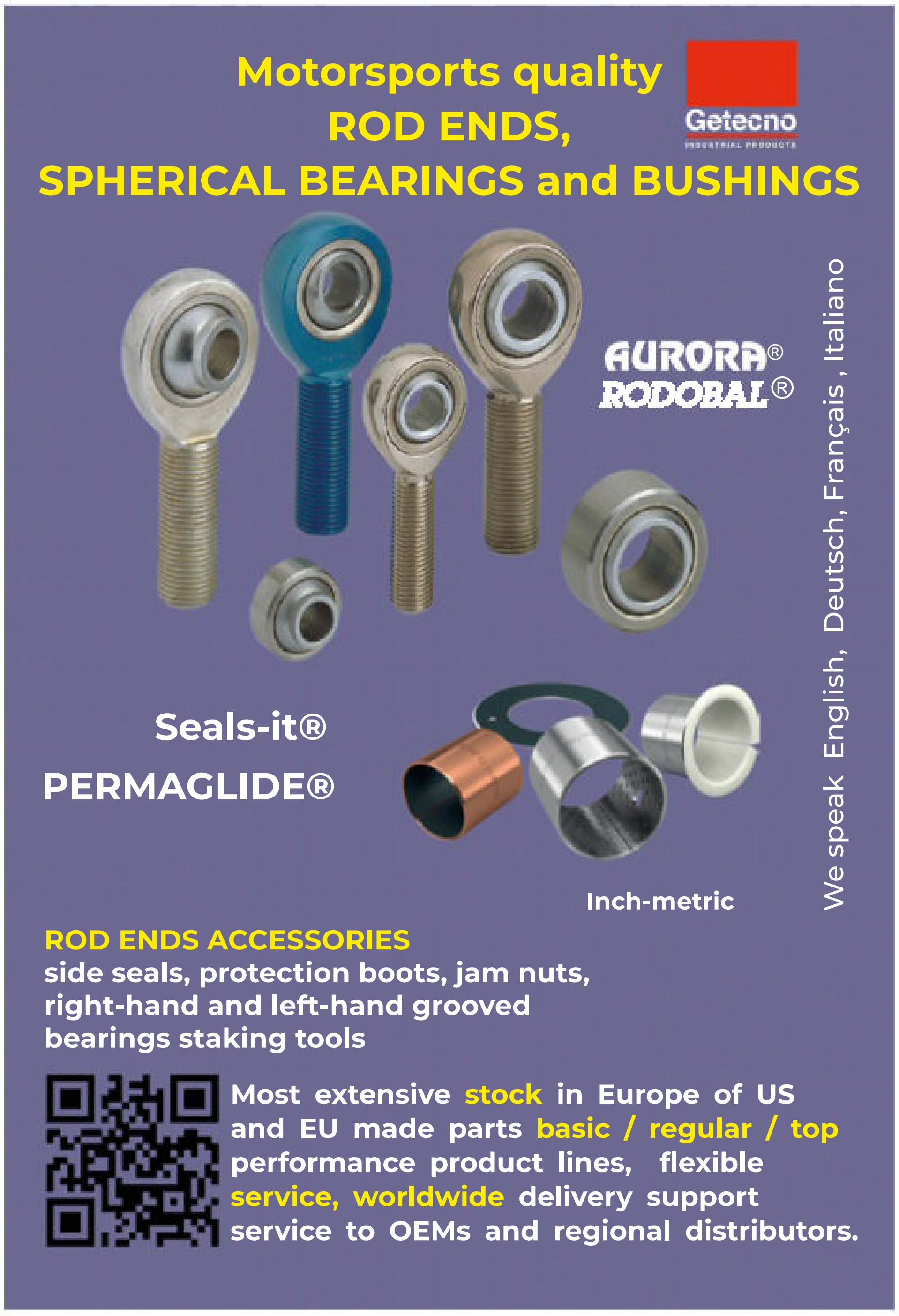
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# Networking

## How data transmitting services have evolved to work effectively and reliably in today's congested airwaves

**By STEWART MITCHELL**

Racecar telemetry and data transmitting systems have come a long way since the days of huge data logging boxes mounted inside the cockpit collecting analogue sensor input data at low resolution. The information back then was crude and challenging for engineers to decipher after the car came back to the pit lane.

Data logging technology's evolution saw it move to digital sensors and smaller data storage boxes uploaded to static computers in the pit lane when the car came back to the garage.

Then came radiotelemetry, which could transfer data from the car wirelessly to the pit lane. This was a true revolution for the racecar engineer. Radiotelemetry is still used extensively today, but has its limitations – fundamentally, coverage and bandwidth.

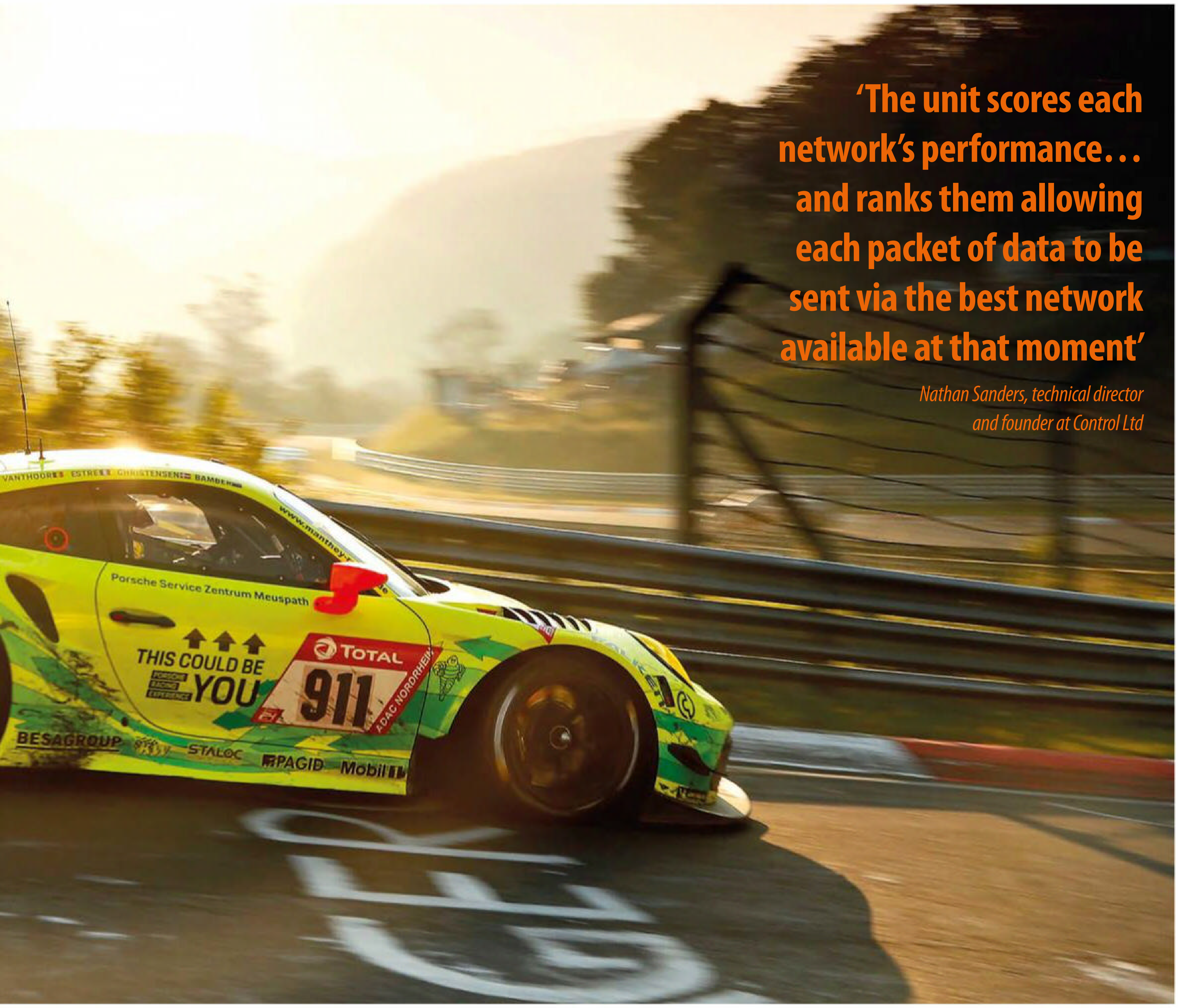
The challenges of coverage are a function of the distance over which radio transmitters can transfer signals and data. Radio doesn't go very far and causes major signal issues at large circuits, especially those with significant gradient changes such as the Nürburgring or Spa Francorchamps.


The Nürburgring is one of the most challenging race circuits for telemetry data transfer, but with multiple modems attached to a number of different mobile networks, the whole track can now be covered

Porsche


Control Ltd

**The Control TLM-P1 Cellular Telemetry Modem features three global modems attached to multiple mobile networks. The technology allows for ultra-high coverage resilience whilst delivering live data using the best network available at any point on the track**




## ‘The unit scores each network’s performance… and ranks them allowing each packet of data to be sent via the best network available at that moment’

*Nathan Sanders, technical director and founder at Control Ltd*


XPB Images

For events attended by hundreds of thousands of people, multi-modem systems can choose the best cellular set up to transfer car data while simultaneously sharing bandwidth with the crowd

Without a repeater, complete radiotelemetry coverage at these circuits is impossible.

As for bandwidth, most radiotelemetry systems run at 9600 bits per second, which, for engineers in the upper echelons of motorsport, isn't sufficient capacity to give a complete picture of a car's performance.

## Cellular modems

Since cellular networks have become more widespread, especially in rural areas where racetracks frequently are, it solves both radiotelemetry challenges.

As cellular coverage reaches further than radiotelemetry, repeaters all around the track are no longer required. The available bandwidth is also much greater. However, public cellular networks can be unreliable and, despite the available bandwidth, must be distributed between all users of that network.

Suppose a race team uses a public cellular network for sending data from the racecar to the pit lane and the team's factory, it is merely a passenger on someone else's infrastructure. If there is inadequate coverage at the circuit on the day, or that coverage breaks, they are left blind.

Even if a team has examined a cellular network on test day and deemed it sufficient for the race, because public cellular networks distribute capacity to all devices on the network, there will be undoubtedly be a surge on race day with everyone at the circuit fighting for connection. Consequently, the connection and bandwidth impact on everything up and down the pit lane.

## Multi-modem systems

In the last few years, cellular data transmitting systems have evolved to combat this in the form of multi-modem units.

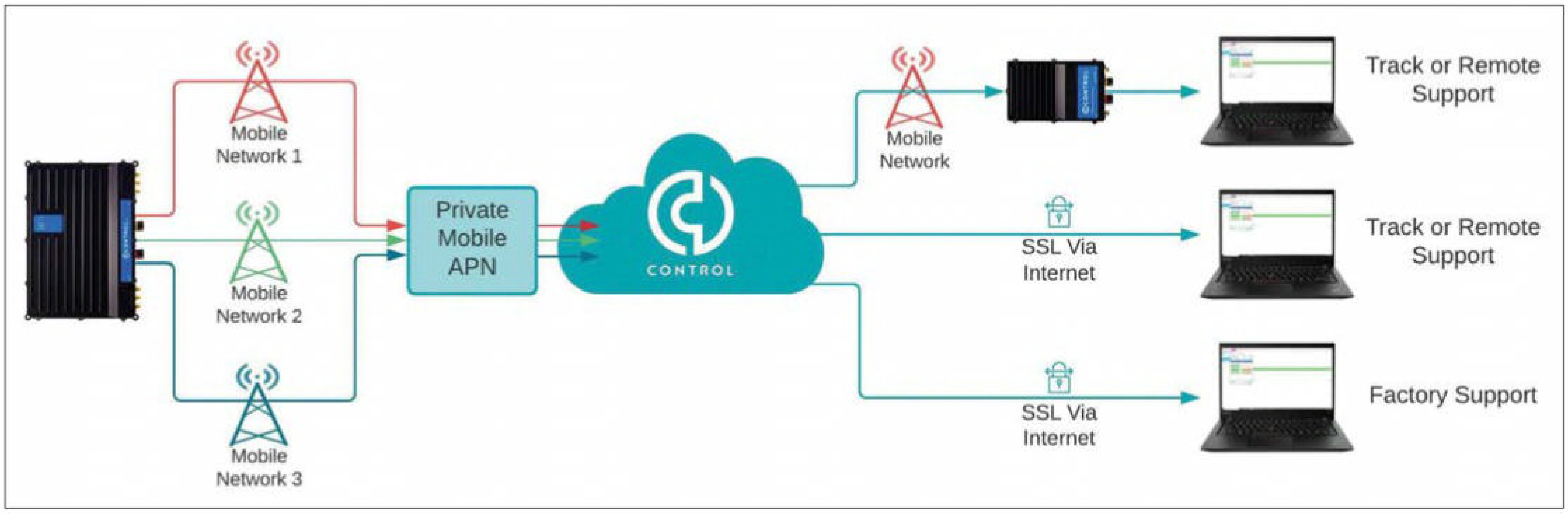
Basic cellular data systems use an industrial modem designed to send serial data between one machine and another, but the latest motorsport telemetry transmitting systems feature bespoke PCBs and a complete software stack specifically designed for the application, which enable it to use multiple SIM cards to connect to numerous networks at once.

**The connection and bandwidth impact on everything up and down the pit lane**

They can also switch between modems connected to different networks, which allows the telemetry units to deliver live data to the garage using the best network available at any point on the track. They can also transmit across the three modems at the same time.

The TLM-P1 Modem from Control Ltd is currently the only example of a multi-modem telemetry unit for motorsport with three modems connecting to different cellular networks.

'The unit scores each network's performance, including speed, latency and jitter [the variation in latency] and ranks them allowing each packet of data to be

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Flow chart explaining the data transfer infrastructure within the Control TLM-P1 Cellular Telemetry Modem

sent via the best network available at that moment,' explains Nathan Sanders, technical director and founder at Control Ltd.

'It also transmits this network information via CAN to the vehicle logger, allowing teams to generate graphs of signal strength around the track to understand where coverage is good and bad on different networks.'

This tool allows on-the-fly switching of networks as the car moves around the track, which can be crucial in a highly congested network, for example, at Le Mans. The driver can push a button to send a CAN message from the logger onboard the racecar to change the modem's behaviour to send data through all three connected networks at the same time, or to switch to a lower bandwidth 'data set' to maximise the limited connectivity.

The data is then de-duplicated before it is passed onto the consuming telemetry server. Some telemetry transmitter system firms even offer private mobile networks behind the scenes for security. The SIMs use the public radio area network to connect, but then come back through the roaming agreement into a private network.

## Data management

As the information coming off modern racecar data loggers can be vast, contemporary data transmitters with multi-modem can send data to multiple places from the ethernet, serial or CAN connections inside the car.

Should the team / driver want to, they can change where the data is sent using a switch in the cockpit. The Control telemetry system can receive data via its private APN cloud service and stream it over a VPN connection, or receive data directly from an additional modem connected to the telemetry server in the pits. This allows teams to switch to an alternative, non-internet connectivity reliant connection.

Products such as the TLM-P1 Modem also have a feature to suppress transmission to prevent data transmitting all the time the unit is powered up. Not only does this make it easier to control costs, it prevents the system from consuming vast amounts of the data quota at times when the engineers don't want to collect data from the car.

Further 'space saving' techniques include real time, over-the-air compression, whereby the modem compresses the telemetry data stream, and then decompresses it at the receiving end to improve coverage and reduce cost by lower data consumption.

With motorsport's drive for a more sustainable future, cost saving and consumption in every element of the sport must be analysed, and systems like Control Ltd's TLM-P1 offer both significant cost savings and efficiency gains across the board.

Sanders explains: 'The industry is starting to understand that sophisticated telemetry systems are critical for motorsport's sustainability.

'For example, if a damage occurs and the driver hasn't noticed, but an engineer sees it in data, calling the car to stop, or telling the driver to slow down and bring it back into the pits, could be the difference between the pit stop time lost vs destruction of the car.

'Direct cost savings during races, car development on a test bench or track during a test day can also be enormous.

'Teams use engineers at the circuit to make decisions on things like wing adjustments, engine maps and suspension damper changes. With sophisticated modems on board the car, the engineers can see all the data live, analyse it and make decisions about set-up changes, without the traditional delays incurred in uploading and distributing data, all while the car is out racing on track.

'Then, when the car arrives back in the pit box, as it's taking on more fuel and new tyres, the engine engineer can upload a new engine map, and the wing and damper mechanics know exactly how many clicks they're going to change.

'By the time fuelling is complete, engineers can finish all set-up changes and recalibrations, and the car is ready to go out again. It's transformative.

'These systems allow teams to arrive at set-up optimisation earlier, and the time engineers can save could amount to huge savings in track time, days in the season's testing schedule and tens of thousands of pounds.'

As cellular modem users use internet access to receive the data, the equipment they need is nothing more sophisticated than some software installed on their computer. That's it.

**Allows on-the-fly switching of networks as the car moves around the track, which can be crucial in a highly congested network**

Porsche

**With some race grids, such as the Nürburgring 24 Hours, contested by as many as 150 cars, engineers need to know that data transfer from every individual car will be fast, reliable and secure**


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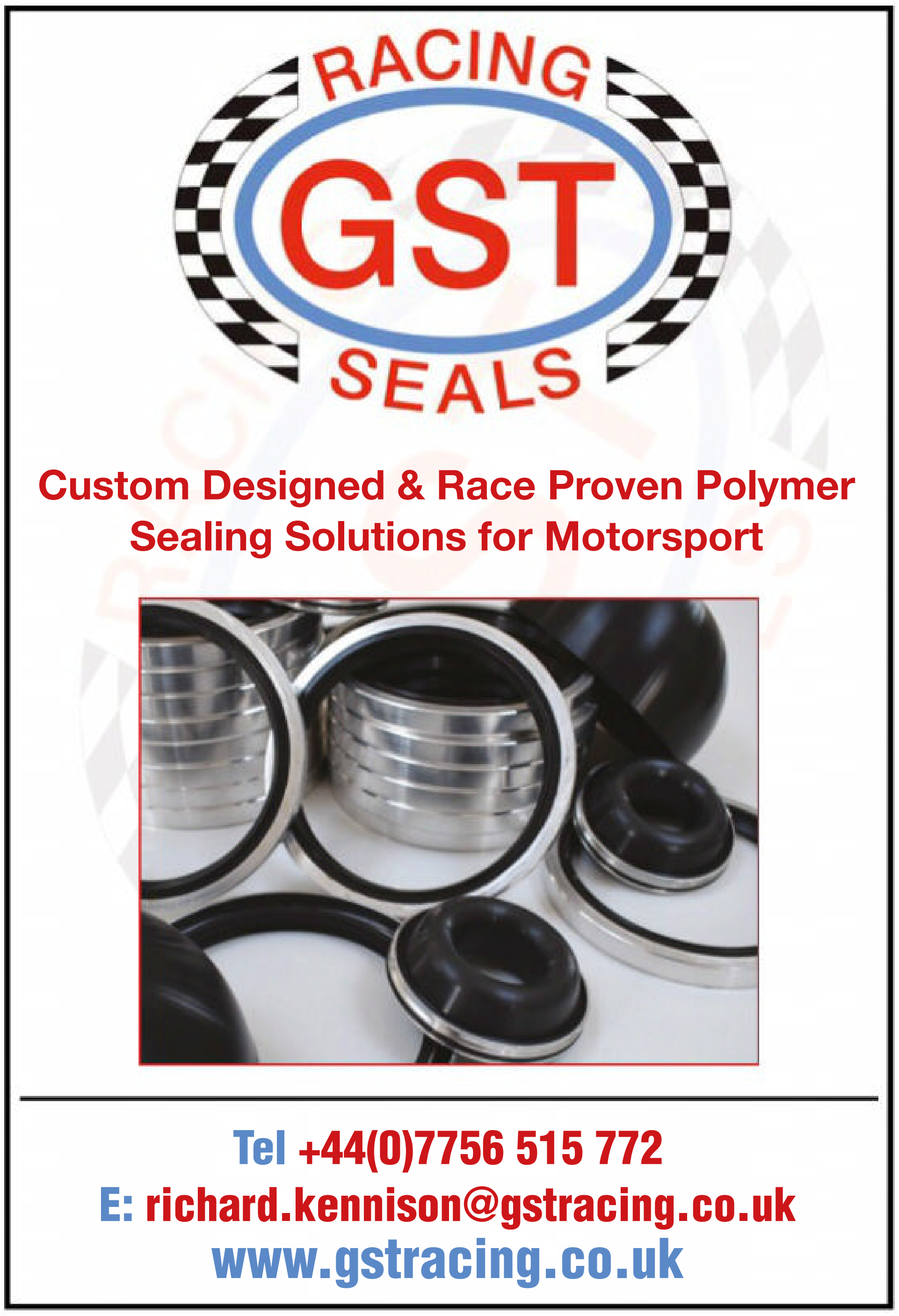
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'As is the nature of internet access, said computers could be anywhere in the world, and in multiple different places, so you can have data coming into the garage and the factory simultaneously,' remarks Sanders.

'The engineering team can be scattered around the world, minimising the number of personnel required at the circuit, and in turn reducing the team's expenses and carbon footprint.'

## Race strategy

Today's upper echelons of motorsport, such as Formula 1 and Le Mans Prototype racing, feature regulations that are forcing contenders to become increasingly more efficient, and

without live, reliable data, teams can be at a fairly significant disadvantages in terms of race strategy. Things like understanding the car's fuel burn can make a difference, especially in changeable conditions such as slow zones, safety cars and changeable weather conditions.

Here, ultrasonic flow measurement devices are used to provide consumption data. These must integrate with the car's onboard telemetry and data logging systems, and engineers calibrate them with the type of fuel used, target flow rates and prevailing conditions.

In a series where ultrasonic technology is financially and technically inaccessible, race engineers can investigate fuel consumption using the fuel injectors' performance information table, calculating the fuel volume that passes through the nozzle at any rpm. Software can then total the fuel used based on how often and how long the injector nozzles are open. Together with the fuel pressure, this can form a basis for calculating fuel consumption.

However, this technique has a margin of error, as nozzle characterisation must be calibrated against all fuel types, duty cycles, fuel pressure and temperature. As temperature and density are inversely proportional, fuel temperature is critical to accuracy. But the coefficient of thermal expansion is not a constant over the full range of temperatures at which fuel might find itself in a racecar, and additives such as ethanol have differing expansion characteristics to the base fuel.

The higher the fuel's temperature, then, the lower its density, and so a higher volume must pass through the injector to supply the desired mass.

Some software types use open-loop exhaust gas temperature and oxygen sensor inputs. These calculate fuel consumption as a function of the exhaust gases' constituents. The proper air / fuel ratio, and the absolute amount of fuel used per cycle, are extrapolated from these sensors.


Control Ltd

**The Control TLM-P1 Modem installed in a modern racecar alongside a logging unit, ECU and power distribution modules**

Engineers can then use this information to amend the air / fuel ratio based on the exhaust gas temperature, oxygen sensor readings, air temperature and moisture levels.

Engineering the car and engineering the strategy are closely linked and rely on accurate, fast, reliable and complete telemetry. If this data is transferred in real time and tailored to be easily understood by strategy engineers, or strategy software, it can be a game changer.

'Strategy software linked to data coming in from the car can tell the team that, at a given pace and taking into account all the telemetry off the car, the best time to pit is on x lap,' notes Sanders.

'Together, the high-quality telemetry data, combined with strategy software, can assist in changes in preparation for the next stint.'

Teams in high-level series often use proprietary software implementations linked to onboard telemetry units to pull fuel burn information out and pass it into the strategic tool to provide another parameter it can use to form those predictions.

These predictions have only one goal – finding the quickest way to the finish line.

'Doing predictive analysis on when your competitors will stop, understanding traffic management and how the car's potential and behaviour changes as the fuel load drops

**If this data is transferred in real time and tailored to be easily understood by strategy engineers, or strategy software, it can be a game changer**

and the tyres degrade are primary inputs into race strategy,' says Sanders.

'Delivering telemetry is the biggest part of the strategy as it allows the team to know how the car is functioning *now* so they can know what to do *next*.'

## Safety considerations

In some branches of motorsport, especially today's hybrid and electric classes, if telemetry isn't connected and running, teams won't even run the car because it's not considered safe to do so for the driver, or because of the sheer cost of damaging the car should something so wrong.

With telemetry, engineers can work around many problems that could be

terminal for the car if left unchecked. In endurance racing in particular, the victors aren't always the fastest competitors, but the ones who mitigated the problems that occur during the race the quickest. Monitoring your own car's behaviour for performance and pit stop strategy is vital, but so is observing its state for longevity. And as many race series now have limits on the number of parts consumed throughout the season, ensuring the use targets can be met is critical to championship success.

Likewise, being able to remotely monitor and report back on electrical safety, especially at a series level, will become more critical as motorsport's future will likely see more electrification and hybridisation of cars.

Suppose a car crashes, knowing the electrical systems are okay might be the difference between telling a driver to get out or stay in the cockpit and not touch anything. Or to inform marshals whether or not it is safe to approach a car. In all safety-critical conditions, real-time data from the car is vital.

## Machine learning and AI

Control Ltd's products use machine learning running in the background.

'Our modems send up information every two minutes to our cloud platform about what percentage coverage they've got, what their signal strengths are and what network they're on,' explains Sanders. 'We can work out the race track they're at based on the cell towers they can see.

'We put all of that into a machine learning model, and it works out the best network or combination of networks for a given racetrack. It also carries out diagnostics like antenna anomaly detection.

'If, for example, there are 50 modems at one racetrack on one network, the machine learning algorithm clusters the signal strengths. If there's a modem with signal strength consistently outside the cluster, it will automatically fire an alert to us, allowing us to notify our customer.

'It's not yet AI levels capable of making decisions based on the information, but that's not impossible for the future.'

The major challenge related to using machine learning and AI in motorsport, as elsewhere, is the volume of data required to be analysed before the computer can make an accurate decision. The more parameters an AI system has inputs for – and in a racecar, there are hundreds – the harder it is to accept and process the data. The accuracy of this data is also critical, as it is for a human interpreter. And like a human, an AI system is only as smart as its inputs.

Easy access to vast computer processing power and memory via cloud services and data processing centres has been a critical enabler for AI that makes it more suitable now than in the past.

Although direct AI control of racecar parameters is currently outlawed, investigating the conditions that could lead to power unit failure is an application that is already an area acceptable for AI.

> **'It's not yet AI levels capable of making decisions based on the information, but that's not impossible for the future'**
>
> *Nathan Sanders, technical director and founder at Control Ltd*

For example, where an engineer would analyse the data from a power unit failure to identify the failure's instantaneous moment, an AI system could explore all the engine parameters when the engine failed and potentially identify the cause, too.

For this kind of system to work, each operating parameter of the power unit, each parameter's operating window, the factors that influence any parameter and the influence any one parameter has on another must all be 'taught' to the AI system. The AI's ability to then prioritise each dynamic operating parameter analysed is vital to the system's success.

AI is currently extensively exploited in simulation, testing and developing race strategy before a race using previously collected data. It's safe to say, then, that AI has its place in motorsport, and it's all based on reliable telemetry transmission.


XPB Images

**Like all the other electronics in modern-day motorsport, telemetry systems must be robust to withstand all racing and environmental conditions, including occassional airborne moments**

# Keep it simple

## The Damper Workbook applied to a real-world case study

**By DANNY NOWLAN**

One of the most popular racecar articles I have ever written, and one of the most downloaded items on the ChassisSim website, is the Damper Workbook. Not only does that show this to be a hot button topic, but also that there is a lack of genuine information on this important matter of racecar tuning.

One trap I see people regularly fall into with racecar damping is over complicating things when they really don't need to. What we'll be doing in this article is applying this knowledge and showing how simulation tools enter the equation using the example of a car I recently worked on.

The car in question, and shown in **Figure 1**, is the Scorch Racing Silvia S15 Time Attack car, raced by Tominoko 'Under' Suzuki in the Pro class at World Time Attack Challenge at Eastern Creek raceway in Australia.

This car is a fire-breathing monster. We are talking 900bhp and CLA numbers well north of seven. If you were to put DTM slicks on it, over the course of a lap it would make most circuit cars look rather modest.

The joker in the pack here, though, is the tyres used in this class are a halfway house between a performance road tyre and a racing slick. Consequently, this makes a great case study for just how effective the approach we are about to discuss can be.

The other thing to note here is that the way the damping curves were deduced on this car was not rocket science. Basic high school maths got us into the ballpark, and then the simulation software took us the rest of the way. This is how you use simulation properly, rather than as a magic wand.

**Figure 1: Scorch Racing Silvia S15 Time Attack racecar**


### Quarter refresh

As always, your start point is the quarter-car model. To refresh everyone's memory this is illustrated in **Figure 2**.

The quarter-car model is the most basic building block of racecar damper analysis. Yes, it is simple, and in order to use this you cut corners by assuming the body rate is much less than the tyre spring rate. This is an assumption that leaves a lot to be desired for high-downforce cars because of the high spring rates you need to hold the car up.

However, the power of the quarter-car model is exactly that simplicity and, when used intelligently, it gets you a fair way down the road. I've done the derivation to death in my previous articles, but **Equations 1** and **2** need to be committed to memory.

$$\omega_0 = \sqrt{\frac{K_B}{m_B}} \tag{1}$$

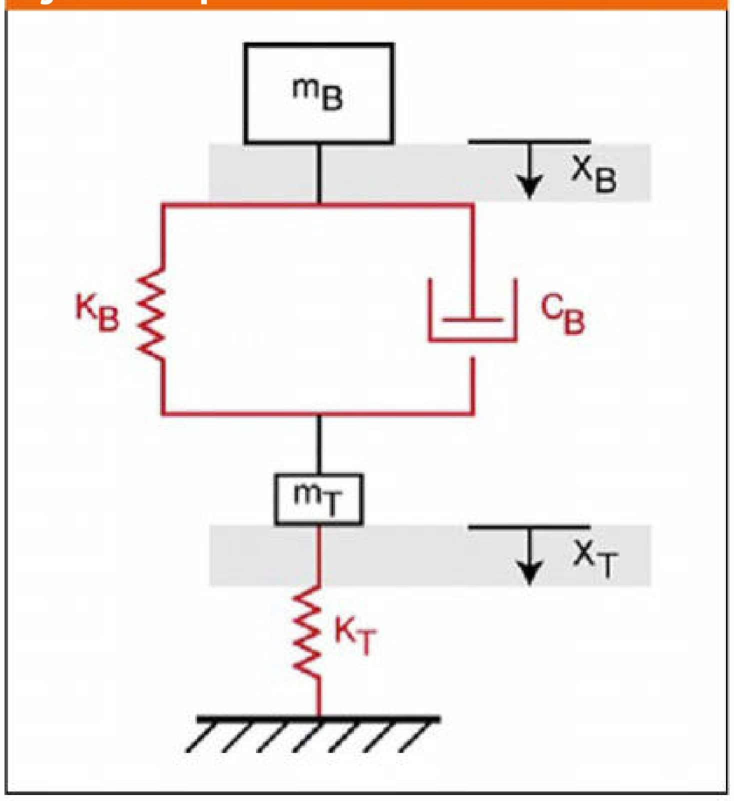
$$C_B = 2 \cdot \omega_0 \cdot m_B \cdot \zeta$$

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

Here,

$\omega_0$ = natural frequency in rad/s
$K_B$ = spring rate of the quarter car in N/m
$m_B$ = quarter car mass in kg
$\zeta$ = damping ratio
$C_B$ = damping rate in N/m/s

**Figure 2: The quarter-car model**




There are a couple of traps for young players here. Firstly, all the wheel and damping rates are wheel rates. We'll chat about what they look like at the damper shortly. Also work this in strict SI/metric units. I know this annoys my American readers, but you'll get over it.

**This is how you use simulation properly, rather than as a magic wand**

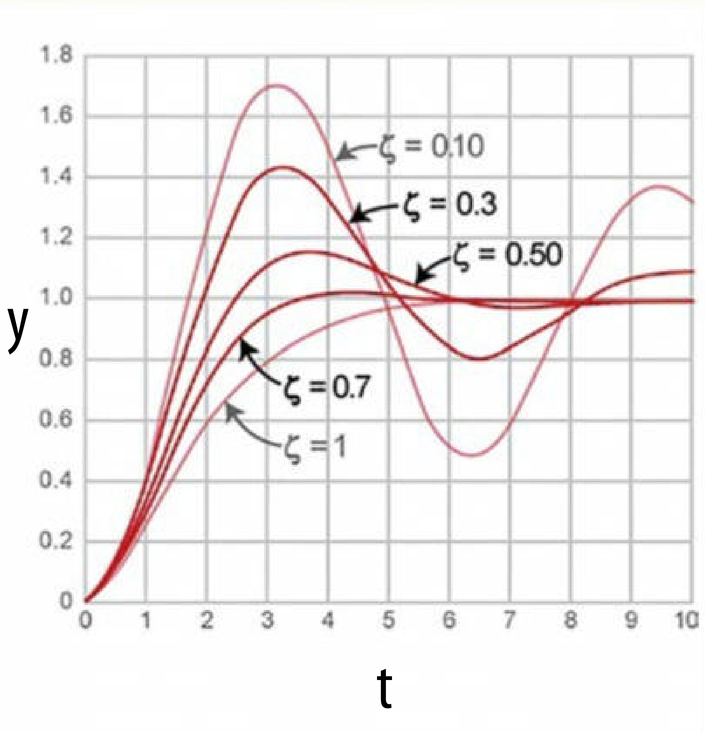
Now, there is one thing to note about what we have done here with the quarter-car vehicle model. The equations effectively treat the tyre spring as infinite and approximate the car as a simple spring damper unit at the sprung mass. While this is not theoretically correct, for road cars it's a very good approximation, and for high-downforce racecars it's a good start.

Because this is so numerically simple, it gives you a quantitative basis to start talking about your damping and, as we are about to discuss, this is brutally effective as it takes you into a much larger and more precise world (a side note to those of you looking for perfection, you have chosen the wrong line of work).

## Second order response

The next step in this process is to understand what you want the damping ratio to do. For this, we need to consider a typical second order system response, as shown in **Figure 3**.

**Figure 3: Second order system response**




The reason the second order damping response is so important is it closely resembles the quarter-car model. As we can see from the figure, when the damping ratios are quite low, about 0.3-0.4, we have a lot of oscillatory behaviour. This is not great for body control, but is really good for riding bumps.

When damping ratios are greater than 0.5, damping response is quite good. This is bad for bumps but great for body control.

If you can understand these two principles, you are well on your way to specifying a damper curve. For those of you who have a problem with the curve shown in **Figure 3**, it comes from *Linear Systems Control Analysis and Design* by D'Azzo and Houpis, the go-to textbook for aerospace and electrical engineers designing flight controls.

These guiding principles about bumps, body control and damping ratios segue into the damper selection guide presented in **Figure 4**.

For low-speed damping, body control is paramount. Consequently, for mechanical cars we are talking damping ratios of 0.7, and for high-downforce cars we are talking damping ratios of at least one. My hard limit is 1.4, but you get the idea.

In low-speed rebound for mechanical cars, you are talking damping ratios of 0.4-0.5. For high-downforce cars, you are looking at damping ratios of 0.7. There is an outlier on this, but we'll come back to that in a future article.

## Guiding principle

So, with this as our guiding principle, let's work through an example of how you figure out the damping rates and put together a damper curve. To start, let's consider the quarter-car parameters shown in **Figure 5**.

**Figure 5: Quarter car parameters**

| Parameter | Value |
|---|---|
| Quarter-car mass | 250kg |
| Motion ratio | 0.8 |
| Base spring rate at damper | 300N/mm |

Now we have this, we need to work out the natural frequency, as shown in **Equation 3**.

$$\begin{aligned}\omega &= \sqrt{\frac{K}{m}}\\ &= \sqrt{\frac{MR \cdot MR \cdot K}{m}}\\ &= \sqrt{\frac{0.8 \cdot 0.8 \cdot 300 \times 10^3}{250}}\\ &= 27.7 rad/s = 4.41Hz\end{aligned} \qquad (3)$$

Then we need to calculate the base damping rate, denoted by CBR, as shown in **Equation 4**.

$$\begin{aligned}C_{BR} &= 2 \cdot m \cdot \omega_0\\ &= 2 \cdot 250 \cdot 27.7\\ &= 13856.4 N/m/s\end{aligned} \qquad (4)$$

Now that we have the base damping rate, we can choose the actual damping we need. For the low-speed rates, we'll choose a damping ratio of one, and for high speed we'll choose a damping ratio of 0.5. It can then be shown as in **Equation 5**, where CLS and CHS are the low and high-speed damping rates respectively.

$$\begin{aligned}C_{LS} &= C_{BR} \cdot \zeta_{LS}\\ &= 13856.4 \cdot 1\\ &= 13856.4 N/m/s\\ C_{HS} &= C_{BR} \cdot \zeta_{HS}\\ &= 13856.4 \cdot 0.5\\ &= 6928.2 N/m/s\end{aligned} \qquad (5)$$

**Figure 4: Damper selection guide**

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

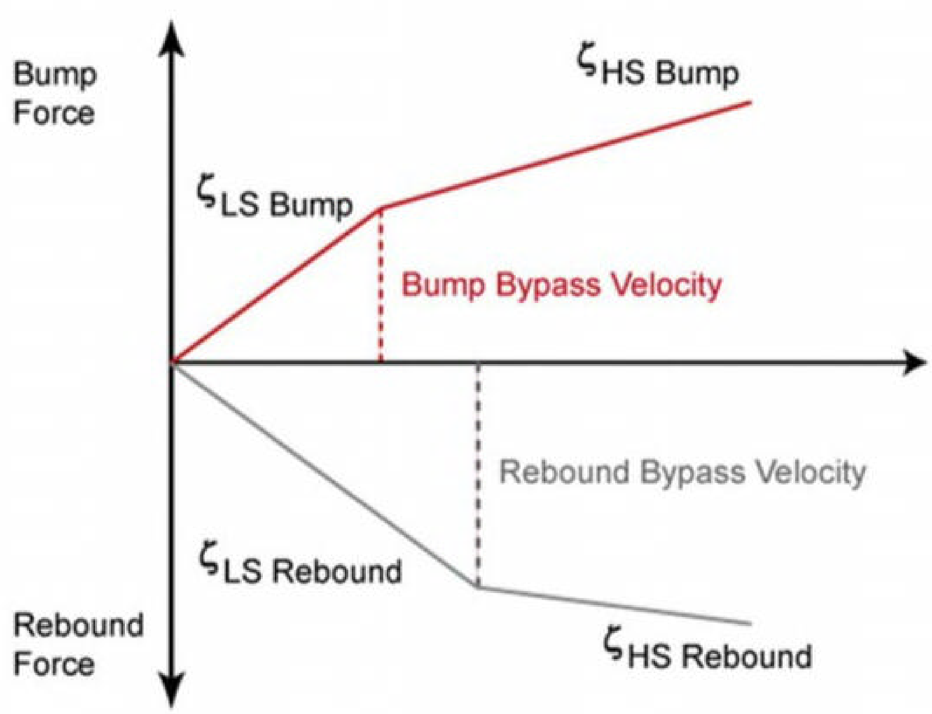
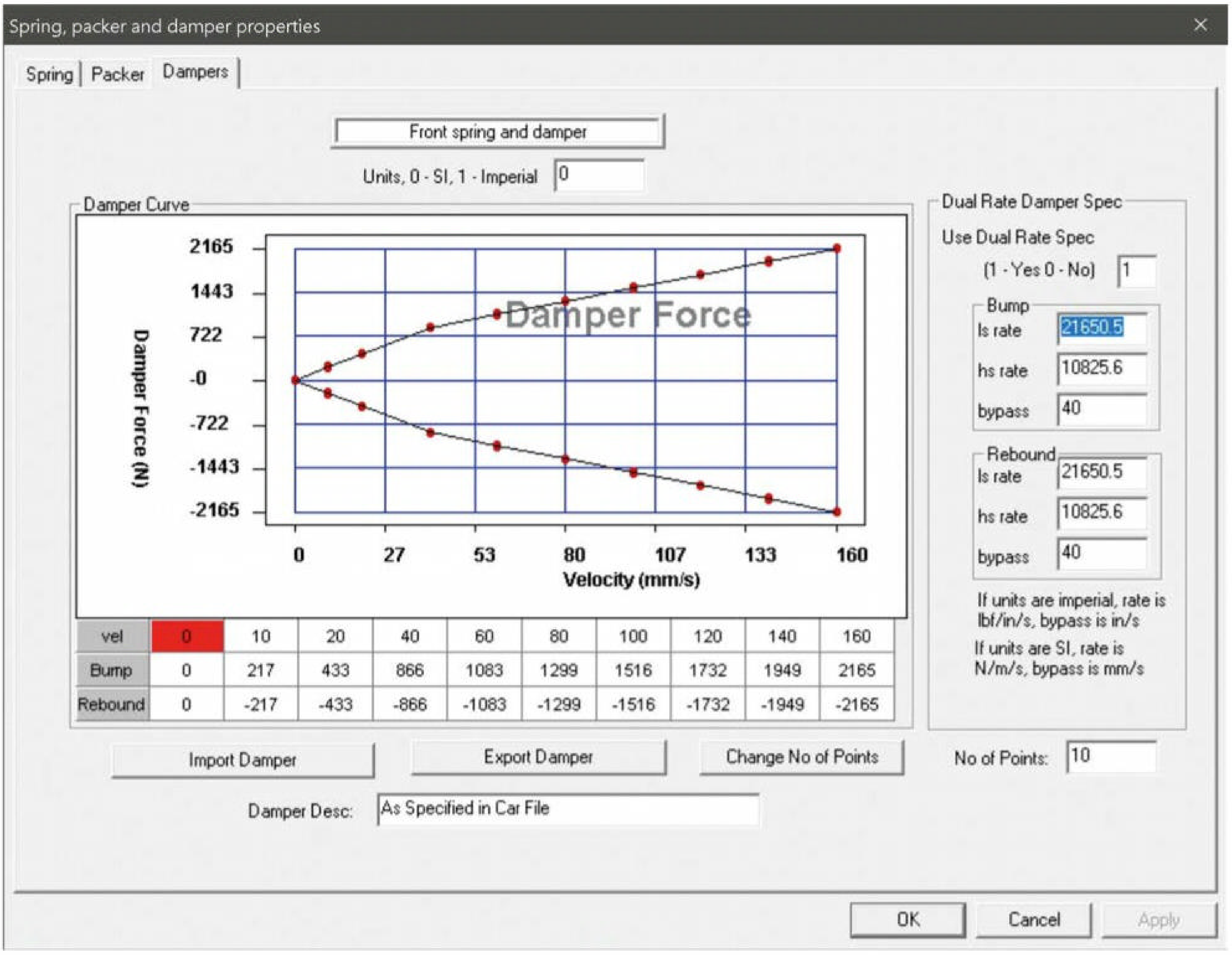


**Figure 6: Entering a dual rate model in ChassisSim**




The last step is working out the damper rates at the damper. To do this, all we need to do is to divide by the motion ratio squared, assuming the motion ratio is damper movement / wheel movement. Crunching the numbers, we have the results shown by **Equation 6**.

$$\begin{aligned} C_{D\_LS} &= \frac{C_{LS}}{MR^2} \\ &= \frac{13856.4}{0.8^2} \\ &= 21650.6 N/m/s \\ C_{D\_HS} &= \frac{C_{HS}}{MR^2} \\ &= \frac{6928.2}{0.8^2} \\ &= 10825.2 N/m/s \end{aligned} \quad (6)$$

Now, at this stage you might be thinking this is all great, but how do we get a damper curve? Here is where the dual rate model in ChassisSim is about to become your friend. If you already have ChassisSim, all you have to do is click on the damper tab, choose the dual rate model, fill in the numbers and press OK. When you do, you'll have something similar to that shown in **Figure 6**.

When this process is done, you'll have a base damper curve, but still work to do.

The next step is to use the ChassisSim shaker rig tool box. Usually, for a mechanical car, I'll focus on minimising contact patch load variation and then tune the frequency response. For a high-downforce car, the frequency response, and in particular minimising the cross pitch mode, becomes dominant because controlling the aero platform is your number one priority.

## Key challenges

However, when this was applied to Suzuki's car, a number of key challenges were faced. Firstly, due to the nature of its tyres, you couldn't muscle it out with big main spring rates. That was a non-starter. Significant support had to come from the third spring and, when you do this, you have to factor this into the natural frequency and damper calculations we showed earlier.

Add the high aero load in with the nature of the tyres and both the aero response and contact patch load variation become equally important.

What all this translated into was a lot of simulation work, the end result of which is shown in **Figure 7**.

Here, the initial damper spec is black and the final damper design is red. As can be seen, the contact patch load variation has dropped by 4kg at the front and 0.8kg at the rear, while the cross pitch mode response has dropped by nearly 20 per cent. When you see results like this, you put that set-up on the car.

Sure enough, when this was applied to Suzuki's car, to say it was a step change in performance would be an understatement. The net result of this work is seen in **Figure 8**.

**Usually for a mechanical car, I'll focus on minimising contact patch load variation and then tune the frequency response**

**Figure 7: End result of the shaker rig analysis work**

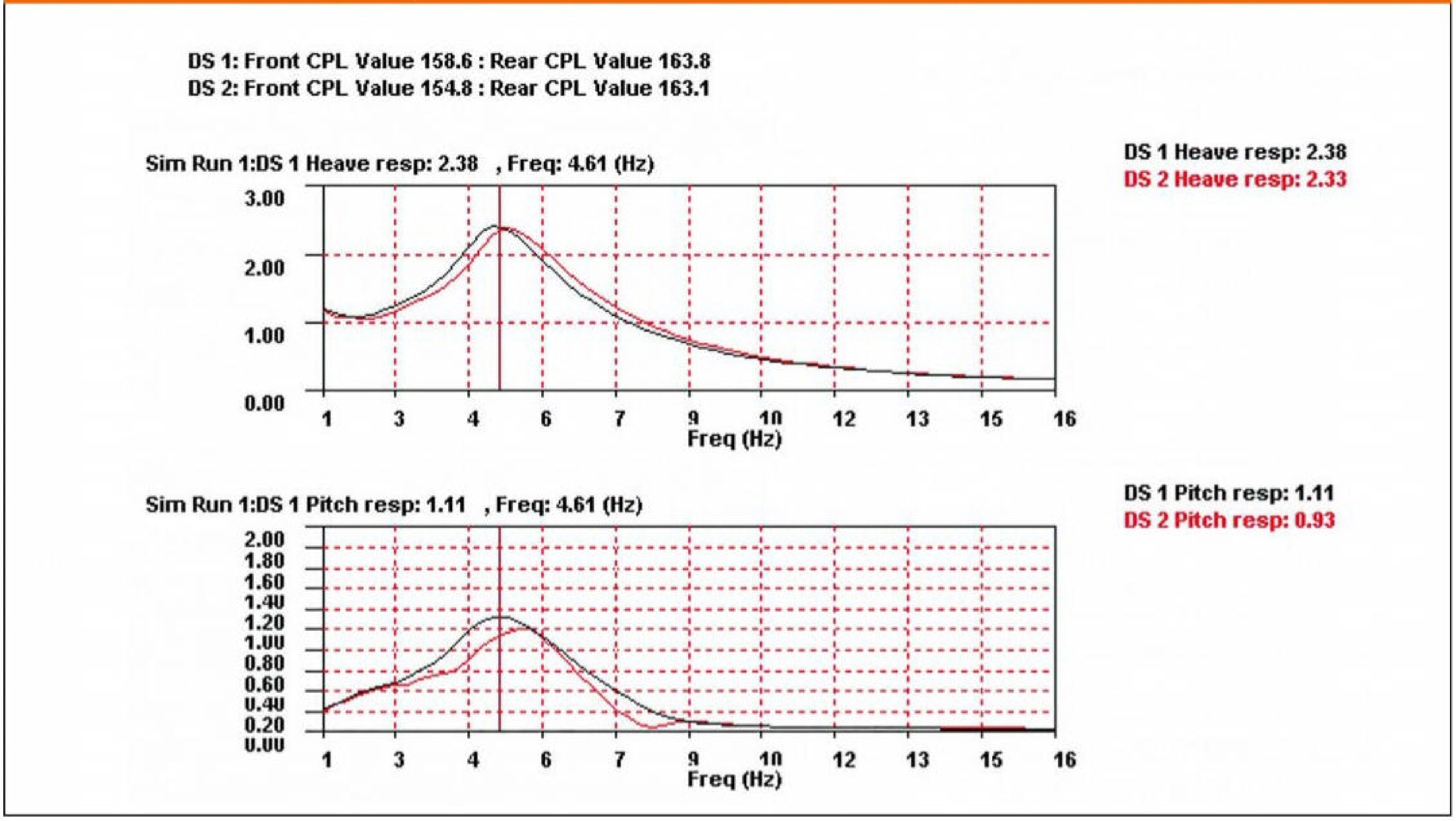
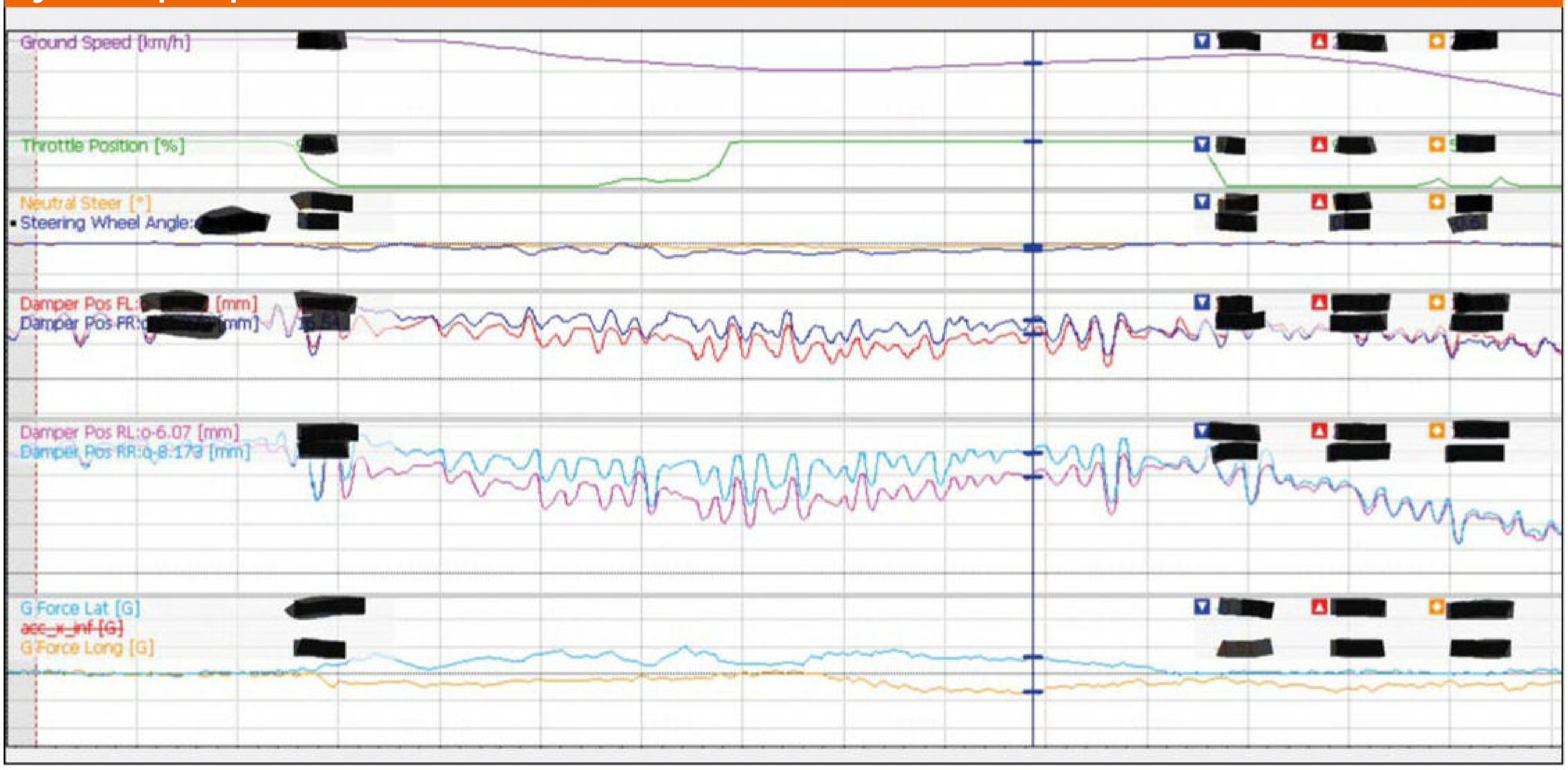



**Figure 8: Damper response at Eastern Creek**




Due to confidentiality, all scalings have been blanked out, but the traces are speed, throttle, steer, front dampers and rear dampers, followed by longitudinal and lateral *g*. In the low-speed section, the car response was now excellent, but there were still issues at high speed, though I have no doubt some of this was due to technicalities being lost in translation. That said, the issue was resolved by going up in the high-speed damping.

The real nail here, though, was this translated into improved car performance (Suzuki recording a lap time of 1:22.3s) on tyres that were over 12 laps old. What's so significant about that is that Pro class Time Attack cars are brutal on tyres. They are lucky if they last three laps, so this sort of performance improvement is unheard of.

Unfortunately, a subsequent accident in morning practice put the car out of commission for the rest of the event, so its true pace has yet to be seen.

In closing, what we have just outlined is a very powerful technique and case study of how to tune dampers. While this method is not perfect, it is practical, simple and gives you a feel for the numbers. When we combine this with simulation, and use it as a calculator, the end results will take care of themselves.

## IN BRIEF

**Porsche** and its partner, **ExxonMobil,** will test advanced biofuels and renewable, lower-carbon eFuels as part of a new agreement to find pathways towards potential future customer adoption.

The first iteration of the fuels have already indicated their potential to significantly reduce greenhouse emissions. The liquid fuel and products will be tested in the 2021 and 2022 Supercup series. The company says it remains committed to electrification of its fleet, but the development of eFuels will extend the life of the internal combustion engine.

**RallyX Nordic** will debut a new, sustainably produced, high-performing biofuel produced by **P1 Racing Fuels** this season as the championship aims to lead the way in going 100 per cent fossil free by 2022.

Tech-focused investment bank, ICON Corporate Finance, has advised UK-based Retrac Group to enable its employees to acquire the business in an eight-figure deal. Former McLaren motorsport director **Dan Walmsley** has been appointed as the company CEO, leading the Group's two divisions, Retrac Productions Ltd and Retrac Composites Ltd. Co-owner **Andy Carter** has stepped into the role of Chairman of the Retrac Group.

**Pennzoil** has signed a multi-year agreement to become the official motor oil and lubricant partner to IndyCar and the NTT IndyCar series. It will sponsor the Technical Inspection area and technical inspection transporter, as well as stumping up a $50,000 prize for Best Mechanic, which will be awarded to the chief mechanic of the winning team.

Leading international travel company, **TUMI**, has unveiled a new collection of capsule luggage developed in partnership with McLaren Formula 1. The company is warmly invited to send samples to *Racecar Engineering's* head offices in London.

# WRC gains hybrid support

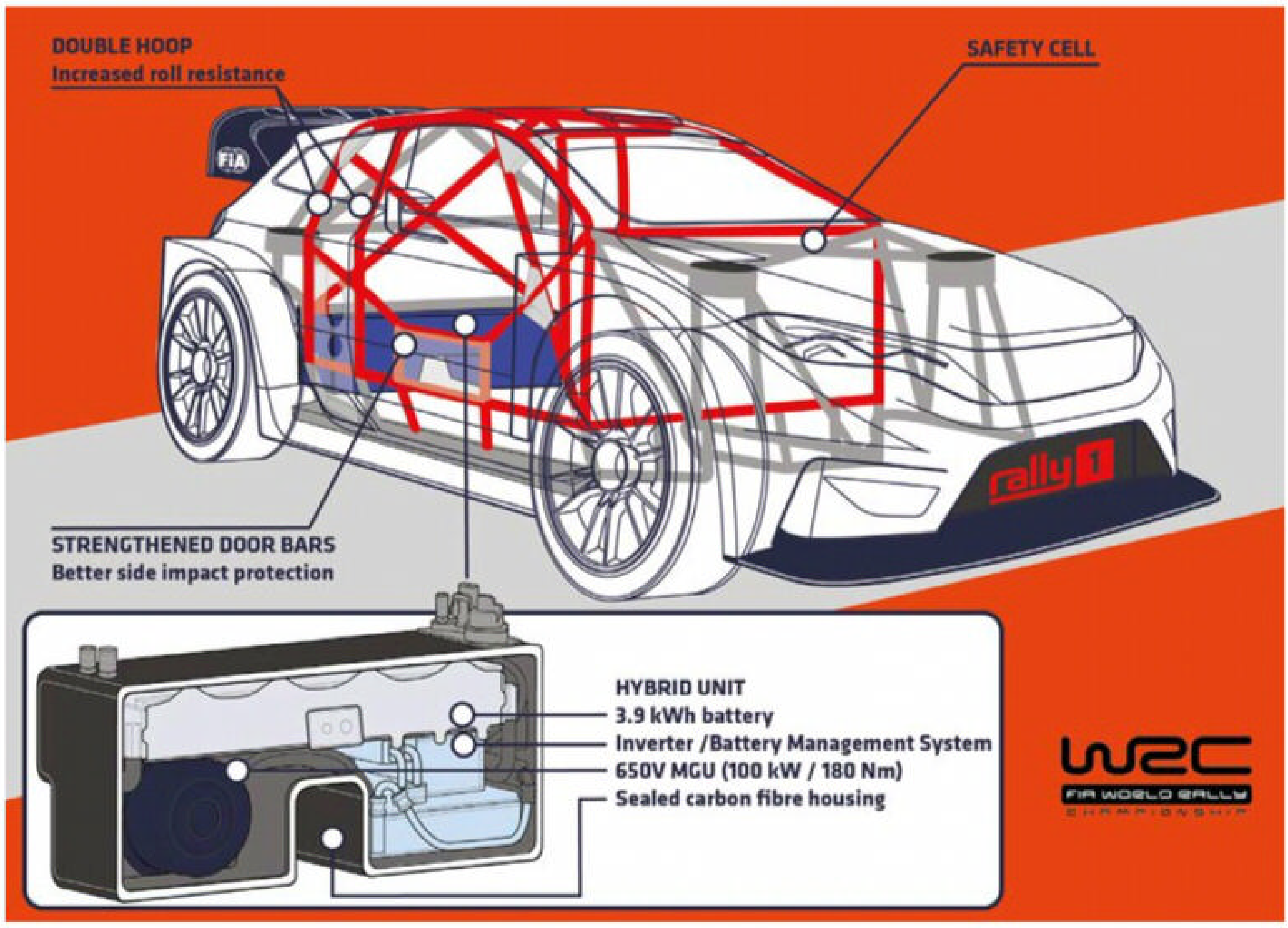
**Three manufacturers entered into the FIA World Rally Championship have agreed to share the burden of cost to develop a hybrid system for the future of the sport.**

Hyundai, M-Sport Ford and Toyota will each make an equal contribution along with the FIA for the system that will be introduced in 2022 after gaining approval for its technical regulations from the FIA World Motorsport Council in March.

The three manufacturers have all committed to the WRC until 2024, but the FIA remains committed longer term to developing new, stable and cost-effective solutions, even during Covid-affected times.

The joint initiative, which will be incorporated in the next generation Rally1 cars, will be part of a partnership model based on a three-year cycle, unlike the current annual commitment, which the FIA hopes will offer better stability and planning opportunities, as well as new marketable assets for all parties.

'Along with the FIA and the manufacturers, WRC Promoter is committed to the introduction of greener cars,' said Jona Siebel, WRC Promoter managing director. 'The hybrid powertrain forms an integral part of the automotive industry as the world moves towards a more sustainable future and it's essential the WRC is aligned with this evolution.'




The World Rally Championship will strengthen its commitment to a more sustainable future by introducing a hybrid system in 2022

# GCK lead Dakar development programme

**French company, Green Corp Konnection (GCK), has joined forces with FEV, a leading global engineering supplier, to design, develop and integrate its own high-performance fuel cell.**

The hydrogen-based fuel system will be showcased in motorsport on the Dakar Rally in 2023, before being deployed across other industrial areas.

Fuel cell system development is a key component to GCK Motorsport's breakthrough project, that was itself launched during the Dakar Rally last January. Led by Guerlein Chicherit and now supported by FEV, GCK motorsport will become the first team to present a hydrogen-powered cross-country vehicle at Dakar 2022 before competing in the race in 2023. Other alternative fuel vehicles will also be presented as motorsport continues to seek sustainable mobility.

'We are delighted to have a leading partner in FEV to join us on this huge challenge,' says Eric Boudot, CEO of GCK. 'This historic step in the life of our company perfectly illustrates our mission to develop technological solutions to meet the growing demand for integration of green energy in the field of mobility.'

That sentiment was backed up by Nadim Andraos, executive vice president for FEV in France, Spain and North Africa. 'Thanks to [our] experience in the field of hydrogen-related technologies, FEV is driving numerous projects on a European and global level when it comes to the transformation of the mobility sector towards $CO_2$ neutrality.

'We are facing one of the great human and technological adventures, and will make sure to support GCK's participation in the Dakar Rally with a hydrogen-powered vehicle with our passion, expertise and infrastructure.'

# Bentley's green race to the clouds


mattwoodsphotography.com

**Dwarfed by its enormous rear wing, the FastR Bentley Continental GT3 will make its assault on the Pikes Peak Time Attack 1 record this June**

**Bentley has confirmed it will enter a modified GT3 Continental on biofuel in its latest Pikes Peak campaign.**

The project is being run by Bentley's customer team, Fastr, and the campaign will promote Bentley's plan to offer its entire production car range with hybrid variants by 2023, and to be all-electric by 2030.

The Continental GT3 Pikes Peak, developed by technical teams from Bentley, Fastr and M-Sport in Cumbria that built the GT3 Continentals, will compete with assistance from US team, K-Pax Racing, and will be driven by New Zealander Rhys Millen.

Millen has already captured two other Pikes Peak records for Bentley, the Production SUV record in 2018 with the Bentayga W12, and the outright Production Car record in 2019 with the Continental GT, so is well placed to put this attempt into the record books, too.

The car will be built to compete for the Time Attack 1 record at the Colorado competition, where the car will have to average more than 78mph up the 5,000ft climb in order to beat the record of 9m36s.

Final specification of fuel has yet to be determined and the company is working through various solutions with possible greenhouse gas reductions of up to 85 per cent compared to standard fossil fuel. The fuel will be designed to compensate for the reduction in power due to altitude.

The car features the largest rear wing ever fitted to a competition Bentley, a standard 4.0-litre V8 engine with short side exhausts and cooling scoops in place of the rear window.

The Pikes Peak hillclimb takes place on 27 June 2021.

## HYUNDAI WTCR


**Hyundai has confirmed it will switch to the Elantra N TCR model for the 2021 FIA World Touring Car Cup this season. The new car is based on the roadgoing Hyundai Elantra N and has been developed from the i30, which won the teams' title in 2018, but features a brand new 2.0-litre turbocharged engine. Hyundai also confirmed its participation in the Pure ETCR series with the Veloster N ETCR, the company's first all-electric racer.**

## IN BRIEF

The **SRO Motorsports Group,** which runs GT-only races around the world, has stepped up its efforts to meet the 2023 carbon neutrality target though new initiatives surrounding lower impact travel, reduced carbon race fuels and more environmentally-friendly tyres from **Pirelli**.

'Carbon reduction is one of our absolute priorities for the years ahead,' said SRO Motorsports group CEO, **Stéphane Ratel**. 'Working with experts such as Futerra and Permian Global has allowed SRO to make quick progress and set ambitious goals.'

The **ByKolles** team has signed two drivers, **Tom Dillman** and **Esteban Guerrieri,** to develop its new Hypercar that the team intends to debut in the FIA World Endurance Championship in 2022.

The LMP2 cars will compete in the FIA and ACO endurance championships with new performance parameters to make way for Hypercars that are expected to be around 11s per lap slower than the old LMP1 cars at Le Mans.

The LMP2 cars will race with 400kW of power, down by 50kW compared to last year, 20kg heavier at 950kg and with Le Mans-specification bodies at each of the races, estimated to be between 10-12 per cent lower downforce compared to the Sprint package.

**AP Racing's** latest state-of-the-art noise, vibration and harshness (NVH) dyno is now fully operational at its Coventry, UK facility. The dyno allows the company to ramp up development and testing of high-performance braking systems for race and road vehicles, and also includes an environmental control chamber capable of performing temperature and humidity controlled tests from -40degC to +70degC.

**Metis Engineering** has unveiled a CAN-based sensor designed to detect the early onset of catastrophic battery failure. The sensor works by detecting a range of environmental parameters, including volatile organic compounds, hydrogen, pressure and humidity. It then places that information into a small sensor with a configurable CAN interface.

**Lotus Engineering** has joined forces with **Jenson Button's** Extreme E team as technical partner. The world-renowned British engineering consultancy is part of Group Lotus.

Interview – Peter Riches

# Bounce back

**The British Touring Car Championship kicks off in May, with a full grid and bright future ahead. The tin-top series' technical director guides us through the forthcoming season**

**BY ANDREW COTTON**


Riches admits to being 'staggered' by the 2021 grid

Following a challenging 2020 season, the motor racing world is slowly starting to open up fully this year, but few have done so quite in the same way as the British Touring Car Championship (BTCC).

A grid of 29 full-season entries line up for the 2021 campaign, with 11 new cars that have been built over the winter, nine manufacturer / constructor entries and 20 campaigning for the Independent trophy, as well as a hybrid system doing on-track testing prior to it being introduced for next season.

It's an extraordinary achievement even for a series that, despite being a domestic one, has consistently held its place on the global stage.

This is the final year of the current technical regulations, which makes the build of so many new cars all the more surprising. Despite the freeze in development for this year, there are two major changes compared to the compressed 2020 schedule.


Some of the older, established cars such as the Honda Civic, BMW 1-series, Mercedes A class and Volkswagen's CC will bow out gracefully, with plenty of new cars already built to replace them


**Entries from Toyota, BMW, Ford, Vauxhall, Infinity, Hyundai and SEAT will contest the 10 scheduled events of the 2021 British Touring Car Championship, with a hybrid system testing alongside**


**We left Brands Hatch at the end of last year thinking we would lose some cars, but things started to build and we have 11 new cars on the grid**

The Goodyear 'Option' tyre will be phased back in at four of the 10 scheduled events, following a hiatus last year on the grounds of cost savings for the teams. It was also agreed between organisers and teams that maximum success ballast will be increased back up to 75kg, given that cars now demonstrably carry their extra weight far more capably and competitively than before.

'Both Alan [Gow] and I are staggered that the numbers have gone up,' admits series' technical director, Peter Riches. 'We left Brands Hatch at the end of last year thinking we would lose some cars, but things started to build and we have 11 new cars on the grid. The NGTC concept allows you to move components from an old car to a new one, but there are still new shells that were built.'

## Out with the old

'We thought we were getting to a point that we needed to do something about the old cars… but then they left already. The old Honda Civics have gone, as has the Audi A3s, the BMW 1-Series, the Mercedes A Class and the VW CC, yet we actually have *more* cars on the grid this year.'

Amongst them are entries from Infinity, BMW, Ford, Toyota, Vauxhall, Hyundai, while Team HARD has four Cupra Leons. Going for the manufacturers' / constructors' title are BMW, Toyota and Motorbase Performance Ford.

'In some ways, the delayed start to the season was a bonus for the teams because Willie Pool – who does a lot of the shells – said what he really needed was the start to be put back four weeks because of the amount of work he was being asked to do. So it is really amazing that we've got all these cars, and that the BTCC technical partners have produced all the parts during lockdown to get them to the grid.'

Producing the parts with such a short winter was hard for suppliers that were subject to lockdown restrictions in the UK, but the like of AP Racing, RML, ATL, Cosworth and Xtrac were nevertheless ready by the end of April with the full grid supplied.

'All of those on the technical partner list have come up with the goods,' confirms Riches. 'One or two were touch and go on delivery, but they all got there.'

## Hybrid test car

Another exciting prospect for the 2021 series is the hybrid test car. This will serve as a test bed for the Cosworth-prepared hybrid system ahead of the 2022 season when it will be introduced across the entire grid.

Although it is not yet scheduled to take part in any races this year, a test programme is lined up for the season and the car will run alongside the regular competitors at the planned two-day tyre test at Oulton Park in

July, when it is hoped the British summer will provide warmer ambient temperatures.

The Cosworth-developed system will use a 60V, gearbox-mounted electric motor that will provide around 40bhp extra power and will replace success ballast altogether, with leading cars restricted by their use of the additional power. The system will weigh around 64kg and cost teams £20,500 per season, which comprises 10 race weekends, on a fully maintained lease basis, making it an affordable system.

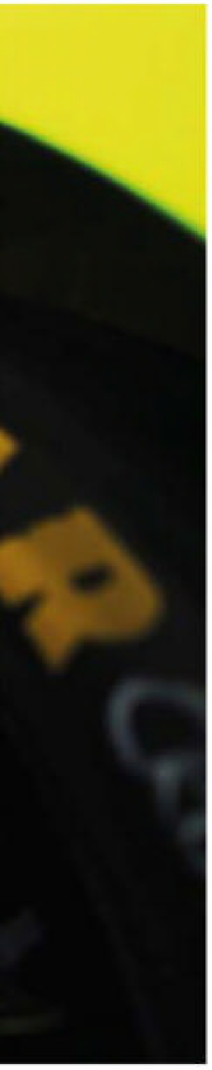
Meanwhile, internal combustion engine development work has progressed over the winter in the workshops of MSport, which will supply the TOCA engine for the 2022-2026 seasons to those teams that don't wish to do their own engine programme.

'We have run a season on MSport's transient dyno so we have already done 10 full [race] weekends,' says Riches. Each race weekend comprises three races, so a total of 30 races. 'We did out laps, in laps, qualifying laps, included heat soak and so on. It was really complex programming, not just achieving the mileage of a race weekend, so it was a proper full race weekend simulation.'

**The idea of the hybrid is it will be used for up to 15s per lap in race conditions, but it is not a push-to-pass system**

With Goodyear having recently extended its deal to supply the BTCC, further tyre-related news saw the re-introduction of the 'Option' tyre for selected rounds of the 2021 season

Although the BTCC has lost some of the car makes, its grid has actually increased in size for the 2021 season with 29 full time entries




Toyota, BMW and Motorbase Performance Ford will all contest the manufacturers' / constructors' title


## The BTCC has opted to introduce hybrid power designed to help bring cars alongside each other

The engine is now in the Toyota Corolla hybrid test car, and will run with the hybrid system that is also still under development, though real-world testing is still needed to confirm the dyno figures. 'You also can't do things like sump surge on the dyno,' confirms Riches.

### Driver skill

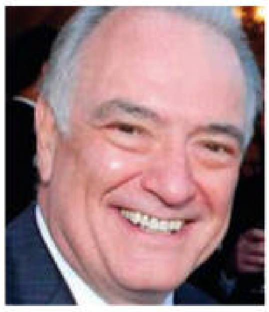
The idea of the hybrid is it will be used for up to 15s per lap in race conditions, but it is deliberately designed *not* to be a push-to-pass system. With Formula 1 experiencing high closing speeds thanks to its DRS system, the BTCC has instead opted to introduce hybrid power designed to help bring cars alongside each other. That will still leave room for driver skill to make the difference.

'We haven't run the new cars and the old one together yet, and actually lap time is not what we are looking for,' confirms Riches. 'We want to prove the hybrid does what it is supposed to do in terms of boosting the car and gaining the distance. We are using it more for the development than in race terms. In the race it will be used for up to 15 seconds per lap, but on the long laps [in testing] we can probably regen' three times for 14-15 seconds, and that speeds up the durability testing.

'If you can do three complete cycles in a lap, you are effectively doing three races in the length of one race.'

Testing of the hybrid system has not yet taken place in hot weather, but so far there has been no issue with it during tests around Anglesey, Oulton Park and Donington circuits. If anything, the system is over-spec'd for the BTCC needs, giving plenty of headroom for the series to make changes in the future if required.

The 2021 BTCC season starts in May at Thruxton, to be held behind closed doors to comply with existing government guidelines. It will comprise 10 events on eight circuits around the UK. Fans are expected to be able to return to the series from the second race onwards, provided infection rates remain low in the UK.



# Now, the fun starts!

## Act now, and act fast, as this is a once-in-a-lifetime opportunity

In Motorsport Valley, a year since Covid brought business to a halt, the sun is out, spring is here and motorsport is preparing to welcome spectators in the next few weeks. Early, fast-paced decisions and proactive solutions stood many companies in good stead.

The FIA, series promoters, race teams and amateur racers all worked to keep our business and sport active and alive. Thankfully, most initiatives have proved successful, keeping many in employment and TV-based fans happy.

Some uncomfortable weeks lie ahead, but positivity is everywhere again. Unemployment is static and, with £124 billion in excess lockdown savings available, we can expect fast growth in amateur and private sport.

Most motorsport suppliers have survived reasonably successfully, helped by generous government support, though sadly there will be some job losses as cashflow becomes paramount.

Some sponsors will be replaced by others eager to reach our audience, but the determined, can-do attitude of motorsport will see us through.

Good orders from UK, Europe and the USA for 2021 are already being placed and suppliers are eager to get started on 2022, when many series require changes, upgrades and even new cars.

Martin Meiners

**The Aston Martin Rapide S that ran on a hydrogen / fuel mix at the Nürburgring in 2013 was the first car to do a zero emission lap of the famous circuit. Technology has moved on rapidly since then**

## Fast innovation

From the recent MIA Energy Efficient Conference, it is clear suppliers will see demand from technology advances prompted by climate change. Innovative solutions are needed fast, as pressure mounts from governments around the world. They want reduced emissions from automotive, mobility air travel and marine in the next five to 10 years. That's good for motorsport as we know engineering competition drives innovation.

World media picked up Pat Symonds at the Conference saying: 'While many might think the internal combustion engine is dead, I would argue it's far from dead. Sustainable fuel is our big push in Formula 1.'

It is said opportunities only come to those who are ready for them. The optimism and confidence of the business leaders speaking at EEMS was powerful. They know how to deliver results fast and on time – ideal capabilities to meet and benefit from the demands of climate change. If your business wants to be in the race to 2030, you need to make the right decisions *now*, and to pay close attention to what is going on. And move quickly.

Interest in climate change will escalate leading to the globally important COP 26 conference in Glasgow in November, hosted by the UK government. The FIA's deputy president for world motorsport, Graham Stoker, recognised that motorsport uses advanced disruptive engineering to provide sustainable solutions, which will benefit society.

James Grainger of Grainger & Worrall concurs. 'Spread your bets,' he says. 'Engage with as many technologies as you can, and move fast.'

Iain Wight of Williams Advanced Engineering likewise urged motorsport suppliers to develop technologies that offer growth in adjacent sectors who are ready to seize on them.

Andy Cowell, one of the most successful motorsport engineers for many years at Mercedes F1, agreed with this. 'Our engines are not miraculous, just the result of relentless, obsessive hard work across the value chain,' he said. 'Motorsport is a mighty innovator of energy efficient systems [and] we need to closely align with other industries that can benefit from that knowledge.'

Ulrich Baretzky felt that motorsport will play a big part in promoting eco-friendly fuels to a wide audience. He's right. Sustainable fuels will be a complementary solution to batteries, and competition can show the value of sustainable fuel solutions, from hydrogen to bio and synthetic fuels.

## The power of influence

Motorsport has the power to influence the public on a large scale through its TV and online presence. The *Drive to Survive* success on Netflix, for example, has attracted millions of new fans.

When the cars use sustainable fuels, demand will explode for similarly powered day-to-day transport, as proven by the popularity of Formula E for batteries and diesel in its day.

Toto Wolff, CEO of Mercedes F1 team is a long-time investor in technology-based companies. Mercedes, with INEOS, has set up its Applied Sciences subsidiary, so expect growth there, which will require new suppliers.

Wolff said legislation should set a date and a target for $CO_2$ emissions levels, but then allow the experts to deliver the solution. Just as American President Kennedy simply set the goal of being first man on the moon, and then handed the challenge to engineers to decide how to achieve it.

This will be the most exciting decade in motorsport for years. Energy-efficient diversity will attract new sponsors and partners wanting to link with the 'best technology of tomorrow'. And there will be substantial rewards available for those ready to move quickly and effectively.

Membership of the MIA will help you capture those rewards as we are proactively setting up introductions to new business. We are determined to help our motorsport industry succeed and overcome this awful past year. We would love to have you with us so contact us at www.the-mia.com. We are here to help.

**The most exciting decade in motorsport… Energy-efficient diversity will attract new sponsors and partners wanting to link with the 'best technology of tomorrow'**

Racecar Engineering
The International Journal of Motorsport Technology

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**Publisher** Simon Temlett
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**Editorial and advertising**
*Racecar Engineering*, Chelsea Magazine Company, Jubilee House, 2 Jubilee Place, London, SW3 3TQ
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**Printed by** William Gibbons
**Printed in England**
ISSN No 0961-1096
USPS No 007-969

THE CHELSEA MAGAZINE COMPANY LTD

www.racecar-engineering.com

# Shape shifters

## Have we already found the silver bullet, but not yet realised it?

Motor racing appears to have embraced alternative fuel technology with a vengeance, judging by the raft of series that have now committed to moving away from fossil fuels and instead adopt synthetic and natural liquids. This is all designed to extend the life of the internal combustion engine yet, as mentioned in last month's column, it's still just a holding pattern.

At the end of April, the FIA launched the latest vision of its electric future, Electric GT. Once again, as is the *modus operandi* for this administration, manufacturers are at the heart of the regulations and it is with their development clout that the series has set its ambitious future. It will race at full-length permanent circuits and will set new standards for performance and range, apparently.

There are immediate red flags. Manufacturers involved will mean the smaller companies on which motor racing was built are sidelined, and the major circuits on which F1 races tend to be dull. As yet, there are no manufacturers that have been willing to put their name to the venture, and no promoter either. There's also no start date.

### Electric GT

As revealed in *Racecar Engineering* a couple of years ago when the idea of an electric GT series was first mooted, the cars will have a similar performance window to the current GT3 cars, in terms of acceleration and qualifying pace. They will run shorter races, of course, and it remains to be seen what the performance parameters will be over the course of a full race distance. Extreme E, for example, tested on gravel with around 400kW of power from the battery, but at the first event lost a quarter of that and for the second qualifying session, due to timing issues and course layout, the maximum power was near halved.

Minimum weight will be 1490-1530kg, and maximum power will be 430kW. So Electric GT cars will be around 200kg lighter than Extreme E cars and produce similar maximum power. The cars will go the same speed as current GT3 cars but weigh signifcantly more, so an accident has potential to hurt a lot more than a standard car, and crash testing is going to need re-evaluation.

Weight is, of course, the flaw in electric cars at the moment. There are certain bridges over the Thames in London that some electric cars with four people on board may not cross due to the structural weight limit.

None of this is particularly promising, but never mind. As batteries reduce in size, so weight will drop, range will extend and the cars will become more viable. Right now, though, they are also so expensive compared to their ICE variant they are only for the committed, and the wealthy.

The electric GT cars, however, will not rely on standardised batteries, a brave move by the FIA but one I hope will work for the series. 'It will accommodate cars of vastly different architectures with different spaces available to install key components,' says the FIA's press release.

The batteries will be built to manufacturer-specification by Saft, a subsidiary of Total, using Saft-supplied, lithium-ion cells optimised for the needs of the new class. The cells were designed for 700kW peak regen' and 700kW of fast recharging, which will enable them to replenish 60 per cent capacity within a few minutes during a pit stop.

### Pushing hard

This is all designed to reduce the $CO_2$ footprint of motor racing, and reflect current trends within the automotive industry. They are pushing electric hard, no doubt with an eye on the European directive to bring the fleet average of its products down to 95g/km of $CO_2$, and down further by 2025 and again by 2030. Despite the environmental impact of building *any* new car, electric or otherwise, electric is classed at zero due to output at the tailpipe, so manufacturers are obviously heading this way.

**I have to say this is the first set of regulations for electric racing that really make sense**

With that in mind, I have to say this is the first set of regulations for electric racing that really make sense. It's hardly a shock to see Leena Gade, the multiple Le Mans-winning race engineer currently working for Multimatic, and president of the GT Commission, is at the heart of this.

'We've held regular discussions with GT manufacturers through our Technical Working Groups and there's a keen interest in the new category,' she says in the press release. 'It also widens the FIA's GT portfolio, coexisting alongside GT3, which will remain the focus of the customer racing market worldwide for the time being.'

With synthetic fuels seemingly moving forward to sort out the short and medium-term needs of racing, and electric helping manufacturers avoid large fines, we are still looking for that silver bullet that will sort out our transport needs. I am starting to wonder if we already have it.

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