>> In-cylinder pressure measurement explained p54

# Racecar engineering™

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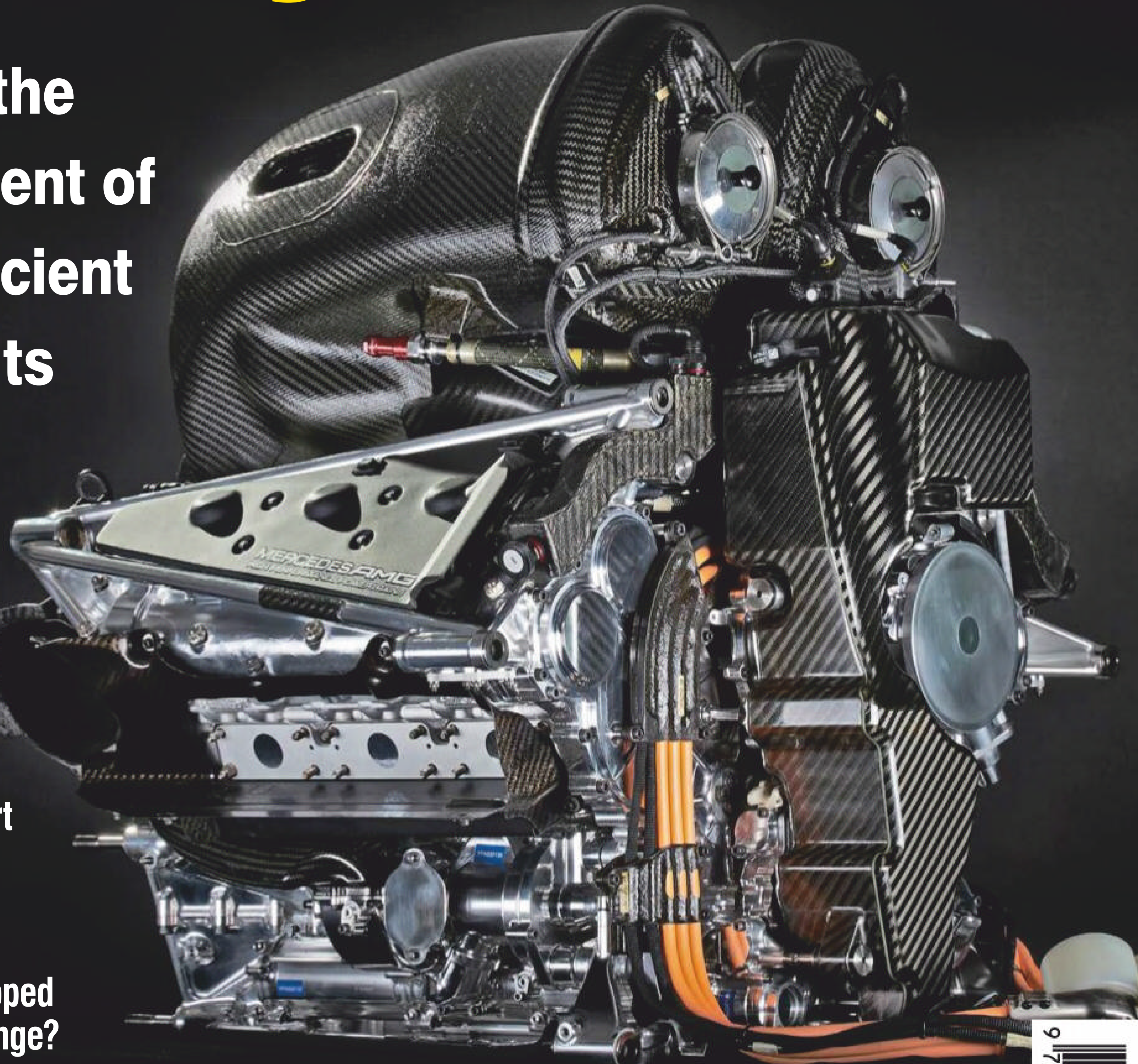
# F1's hybrid era

## We trace the development of super-efficient power units



**AERO TESTING**
Historic Ford Escort in the wind tunnel

**SPOTLIGHT**
Is Drifting an untapped engineering challenge?

**High speed future**
How Bloodhound is paving the way for sustainable LSRs

**Shift change**
Why F1's spec gearbox plan for 2021 could not work

**Ferrari revolution**
A look back to the debut of paddle-shift technology

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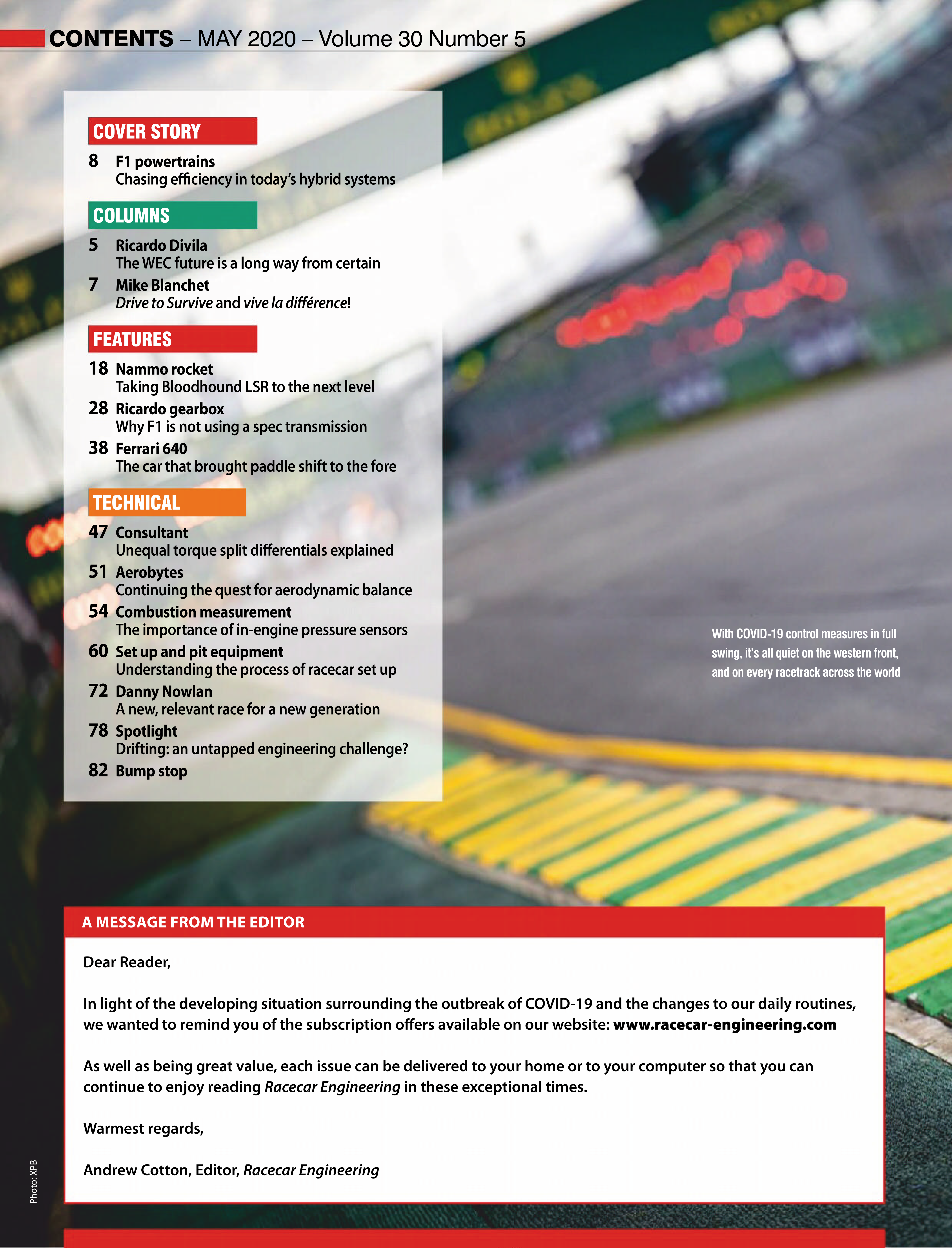


With COVID-19 control measures in full swing, it's all quiet on the western front, and on every racetrack across the world



## A MESSAGE FROM THE EDITOR

Dear Reader,

In light of the developing situation surrounding the outbreak of COVID-19 and the changes to our daily routines, we wanted to remind you of the subscription offers available on our website: **www.racecar-engineering.com**

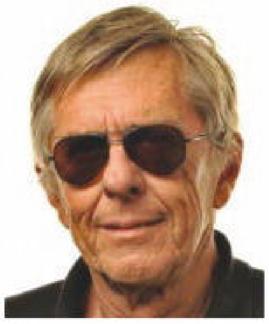
As well as being great value, each issue can be delivered to your home or to your computer so that you can continue to enjoy reading *Racecar Engineering* in these exceptional times.

Warmest regards,

Andrew Cotton, Editor, *Racecar Engineering*

Photo: XPB

Contact us with your comments and views on Facebook.com/RacecarEngineering



# Consolidation time?

There's light at the end of the tunnel, but it just might be a train coming

Endurance racing has had its ups and downs in the last couple of decades, much as most of racing, but the highs and lows span a bigger range of dates. Consider the fact that Le Mans is more dependent on factory campaigns than F1, for example, and we have gone from 1999's five manufacturers to today's one.

Endurance racing is close to my heart and the announcement that IMSA and the ACO will have a common platform was promising (it's something I have been promoting for years), much like the convergence of Japanese Super GT and DTM.

It makes sense to have similar rules and equipment in the name of reduced costs and wider global coverage. Niche championships are fine for regional sport and school series, but they do not make commercial sense on a global stage.

Comments from Porsche saying it would be 'evaluating all the details' of the common ACO / IMSA LMDh proposals could conceivably mean the German manufacturer making a return to the top prototype class, having withdrawn at the end of 2017. After all, Porsche had previously been in the preliminary working group meetings on the Hypercar and DPi.2 classes.

## Due diligence

On the other hand, we saw endless reports of DPi programmes being evaluated and then going nowhere, and it was the same story with Hypercars, where the rules have been bubbling in a pot since 2018, different flavours regularly added and then stirred in response to various manufacturer input.

Any company that has any interest in international road racing is going to evaluate a possible programme. Of course it is! Call it due diligence. They'll check the proposed rules, look at the series, estimate costs, consider potential ROI and decide if it suits their sales / marketing goals.

So, Porsche? Yes, but also Audi, Ferrari, Bentley, Mercedes, Ford, Lamborghini, BMW and others are busily evaluating away. It doesn't mean they will come, of course, evaluation is nothing on its own.

**New LMDh rules will take over from DPi and last 10 years, giving teams opportunity for return on their investment. Sadly, all endurance racing will focus on BoP or EoT**

Mixing a new type of IMSA contender into the WEC is clearly a good practical move on the part of the ACO. It seems we now have an 'in' for IMSA competitors into WEC races, but the converse – Hypercars being accepted into IMSA – is unclear. And will there be Hypercars at all when the LMDh prototypes fall into a very similar category? If there is a BoP or EoT of some description, why doesn't it cater for both arenas?

## Step back

It is a step back from the concept of the top class being the ultimate technology demonstrators, but there is a general consensus that the business environment for car manufacturers is becoming increasingly difficult, with pollution and emissions targets growing in political weight, plus the push to alternate propulsion methods.

WEC, therefore, definitely needs cars, while there is uncertainty over Le Mans' future. The coy confirmings and retractions over this last period by manufacturers makes it the equivalent of vapourware, although we know that another Peugeot sportscar is due some time in 2022, albeit no longer in partnership with Rebellion. We don't yet know which rule set it will follow.

With IMSA having three manufacturers racing and WEC currently only one, the promise of two more 'possibles' is easy and valuable to announce, but not so simple to implement.

From this initial announcement we could have a common rulebook. No BoP, no EoTs and the same cars running in several championships. Think economies of scale, and it being easier to push through the board. In the worst case scenario, let's hope it is a bandage to help WEC's survival. In a similar way to the IRL was with the Indy 500, Le Mans is the main reason for racing in it.

But any set of rules must have a minimum lifetime. Nobody will invest in long-term programmes that can fizzle out due to lack of interest, or public attractiveness. As a corollary, what about getting rid of the GTE class and adapting SRO's GT3 rules? These already have wholehearted support from many manufacturers, cost half as much and offer similar performance although there is significant resistance for that plan from various quarters.

Suc a move might offer a carrot for BMW; Le Mans in place of the WEC entry it cancelled to go to IMSA. It could see Aston Martin returning to the top rung without the costs of Hypercars and would potentially bring GM's CR8 programme to both classes, rather than just as a GTE, and possibly some others besides.

## Slow down

Which just leaves the problem of LMP2s – basically a spec car that will have to be slowed to fit in the new hierarchy. I suppose it would make a nice back up, with grandfathered cars but its a shame to geld the cars when they are so successful around the world.

Some years ago, while comparing the cost of a WEC LMP2 and GTE programme, I was surprised to find the cost of a two-car GTE Ferrari 458 Italia team was roughly the same as LMP2. With mission creep the GTE programme is likely more expensive.

In all, the results will take at least five years or more to reach fruition, and at a time when the world is experiencing strange times, socially, economically and politically. Maybe that is what the ACO is thinking about primarily?

**Nobody will invest in programmes that can fizzle out due to a lack of interest, or public awareness**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# Going viral

The world may be temporarily on hold, but the ducks are still paddling under the water

Having been relieved in recent months to no longer hear Brexit mentioned every time the TV or radio is switched on, we now have Coronavirus instead. I suspect if it had been described as a flu epidemic instead of COVID-19, fewer headlines would have ensued, but clearly it has become highly concerning and, to certain vulnerable people at least, potentially fatal.

I'm writing this to meet publication deadline just before the Australian GP was due to commence. Instead, it has been cancelled. Immediately, a great deal of criticism has been doing the journalistic rounds, backed up by some drivers and others, about the race not having been called off before the teams departed their various HQs.

Easy to complain if you are not one of those in the hot seat being forced to make the decision, especially based on information available in preceding weeks. I'm very sure I wouldn't have wanted that responsibility.

What is rapidly becoming apparent is the uncertainty worldwide is going to have severe repercussions in motorsport overall, not just Formula 1.

## A bit of a yawn

But for now, back to racing, thankfully. New season F1 cars – bit of a yawn, really. Apart from Mercedes' DAS introduction and some suspension arrangement innovation, there's not much to excite anyone other than a tech geek, or rival teams' engineers. The cars are mainly variations on a theme, although this is not to decry the intensity and ingenuity of the detailed work that has gone into these increasingly complex machines.

Racing Point is possibly the exception to the rule, as it has effectively copied last year's Mercedes W10. Generally, attempted copies of winning racecars result in them being unsuccessful as designers' egos, and the need to justify their positions, mean they try to put their own stamp on the design, which unknowingly screws up the overall package.

Or financial issues cause manufacturing compromises, with a similar effect.

In the case of Racing Point (a relief, surely, when this anodyne identity gives way to Aston Martin's next year) the design team seem to have avoided these pitfalls. Partly, I suppose, because of the already close relationship the team has with Mercedes as supplier of permitted parts.

Claims Ferrari were sandbagging in pre-season testing by turning down its power units puzzles me because surely the performance and, more crucially, the reliability, of its PU is one of the key reasons for testing. Even the most sophisticated dynos and simulation cannot replicate the effects of being launched over kerbs, various vibrations (not least from the tyres) and 5*g* mechanical loads from masses of downforce. The ultimate test is on the track, as Mercedes' engine failures highlighted. So why would the reds sacrifice this vital aspect of preparation in order to play mind games?

Anyway, after all the tantalising speculation, it seems we may have to wait longer than anticipated to find out who's got their sums right as, while virus containment measures inevitably ramp up, it won't stop work completely.

So will teams use this 'extra time' to focus on 2021? It appears Williams already has, its 2020 offering seemingly a warmed-over version of last year's disaster which, though better, is not likely to drag them further up the grid. For the sake of all the loyal Team Willy guys and girls, I hope I'm wrong.

To begin with anyway, and maybe for the duration of next season – viruses permitting – F1 in 2021 should see some genuine technical diversity in response to the forthcoming regulation changes. That is until the inevitable development curve and optimising of design features, along with regulation constraints, distils down again into a grid of cars distinguishable only by relatively minor surface variations. Until then, *vive la différence*!


XPB

**The 2020 F1 cars are largely variations on a theme, though Racing Point's car varies least of all**

## Drive to Survive

I held off subscribing to Netflix's *Drive to Survive* series as I'm not a great fan of fly-on-the-wall documentaries, until general vibes suggested I might be missing out. On viewing the latest series, the producers appear to have arrived at an acceptable compromise between fact and drama, with some entertaining insights. One was the lack of man-management skills displayed within some teams.

Surprising, this, given the degree of professionalism F1 prides itself on. I really can't see that the otherwise characterful and resourceful Guenther Steiner's continual swearing and shouting achieves anything positive at all. This much-valued American F1 outfit needs to succeed, and firm actions, rather than cursing, are required to do so.

Equally negative is continually telling your driver to 'push, push!' lap after lap (Pierre Gasly's Red Bull engineer) when, clearly, he's at his mental limit. Cue the old adage of 'no point in flogging a dead horse'. Better surely to soothe him into a couple of laps of cooling tyres, gathering his composure and then having another go with less pressure. Let the guy drive like he can, naturally, as Gasly proved when at Torro Rosso.

Looking forward, in the overall scheme of life all sport is secondary, but it will be a joy when we can return to enjoying our passion.

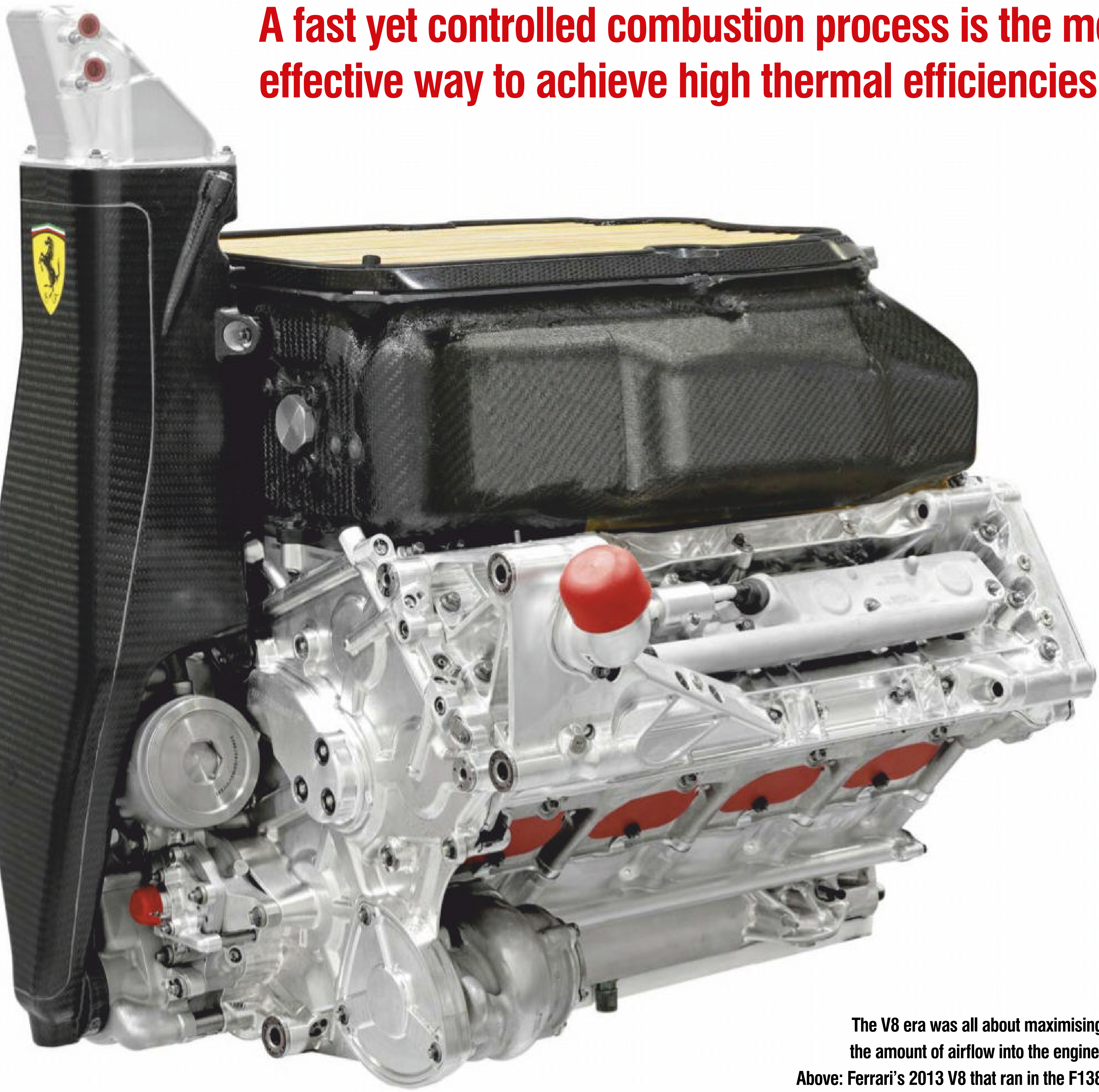
**Uncertainty worldwide is going to have severe repercussions in motorsport**

# Optimal burn

**What we aspire to do is put those [fuel] droplets in exactly the right place within the combustion chamber**

## How Formula 1 powertrain engineers have made the engines used in the series the most efficient in the world

**By GEMMA HATTON**



## A fast yet controlled combustion process is the most effective way to achieve high thermal efficiencies

**The V8 era was all about maximising the amount of airflow into the engine. Above: Ferrari's 2013 V8 that ran in the F138**

Since Formula 1 entered its V6 turbo-hybrid era in 2014, the series' internal combustion engines have been improving on thermal efficiencies of around 40 per cent at the start of the rules cycle, with the latest now exceeding 50 per cent. Add in the contribution of the hybrid system, and the overall efficiency of modern F1 power units is now at an extraordinary 55 per cent, whilst power output has also increased over the last eight years, now crossing the 1,000bhp barrier.

Why has this engineering achievement not been better promoted by teams or F1, particularly in today's environmentally-aware arena? 'One of the tragedies of the current formula is that when we went to Melbourne in 2014 we should have been saying, "look at these engines, they're now using two thirds of the fuel they used to a few months ago!" But someone said they didn't like the sound of these V6s, and instead that became the topic,' says Pat Symonds, F1's chief technical officer.

To fully understand the depth of this achievement, we first need to comprehend what 'efficiency' actually means. 'We use a regular unleaded gasoline that is optimised for this power unit and, if you combust that, you turn it from hydrocarbons into heat energy,' explains Andy Cowell, managing director of Mercedes AMG High Performance Powertrains.

## Mechanical work

'If you could capture all of this heat energy and turn it into useful mechanical work, that would be 100 per cent conversion efficiency. Thermal efficiency is when everything is at a constant self-sustained level so, in other words, when a racecar is going down the straight at full throttle with the engine at peak power and at 100kg/h fuel flow rate, which only occurs at 10,500rpm.

'The simplest way to describe it is, from the heat released from that bonfire [combustion], over 50 per cent of that energy is turned into useful work to propel the racecar.'

During the V8 period of F1, before 2014, the regulations controlled engine performance by restricting the capacity and maximum rpm. This encouraged teams to develop high-power engines rather than high-efficiency engines. In this hunt for power, teams focussed effort on maximising the amount of air they could get into their engines, regardless of how much fuel they needed to burn along with it. This led to rich air / fuel mixtures and high-revving engines.

'Traditionally, racing engines were all about getting as much air into the engine as possible. Then you match that with more fuel and burn it to increase power,' says Nick Hayes, power unit specialist at F1. 'This resulted in engines running much faster because more bangs per minute equals more power. So, the race was always to get your engine to run faster, survive at those higher rpms and then try to reduce losses – and you used however much fuel you needed.'

Unsurprisingly, this high-power, high-fuel philosophy was not the most efficient.

Below: Toyota's 2008 RVX-08 that powered the TF108


'Typically, for the V8 engines we raced in 2013, we turned about 29 per cent of that heat energy into useful work, with a huge amount going down the tailpipe of the exhaust,' recalls Cowell. 'How internal combustion engines were explained in the good old days at universities 30 years ago was that a third of the heat energy would be turned into useful work, a third would go down the tailpipe and the final third would go into the cooling fluid.'

**We need to maximise what we have, whilst minimising waste; the definition of efficiency**

As the world's resources continue to deplete, we need to maximise what we have, whilst minimising waste; the definition of efficiency. With F1 providing a perfect testing platform to showcase innovative technologies to the wider world, F1 revolutionised its powertrain regulations in 2014. Not only did the architecture change to turbocharged V6s, but direct injection was permitted and the 100kg/h fuel flow limit introduced. Whoever could extract the most energy out of the fuel allocation would generate the highest power. Therefore, each droplet of fuel has to be burnt with as much air as possible, which led to engines running lean mixtures of around 20:1.

'The 2014 regulations maybe didn't sound much to the outside world, but they absolutely turned everything on its head because now you had a fuel flow limit,' highlights Hayes. 'So you can put as much air in as you want, you can have more boost, you can do what you like, but you only have a certain amount of fuel.

'All of a sudden, the game to get more power becomes an efficiency game because you've only got so much energy in the fuel and you need to extract as much as you can out of it, and that's the definition of efficiency. It transformed the approach of the engine suppliers and the teams because they had to develop a completely different combustion system.'

## Process management

With the combustion process at the very heart of this conversion from heat energy to mechanical energy, unsurprisingly teams have focussed every possible effort on optimising the characteristics of the combustion chamber, as well the dynamics of how the combustion process itself takes place. The aim is to achieve a fast yet controlled combustion process because this is the most effective way to achieve high thermal efficiencies.

With direct injectors also permitted alongside the V6 turbos, teams now have the capability to precisely control how fuel enters the combustion chamber to achieve that optimal burn. 'Previously [pre-2014], we were only allowed port fuel injection, whereas these engines now have direct injection,' says Cowell. 'We use high pressure injectors with many nozzles on the ends because this permits us to inject very small fuel droplets over a short period of time. What we aspire to do is put those droplets in exactly the right place within the combustion chamber.'

Combusting the fuel and air as fast as possible leads to extremely high cylinder pressures, and the current Formula 1 engines are experiencing cylinder pressures in excess of 35bar. Managing these high pressures presents further challenges, as Cowell confirms: 'Well controlled combustion is thefirst challenge, which does push cylinder pressures up. As they do, if you're not careful, the heat rejection through the combustion chamber also increases. So, the higher the pressure of the fluid, the greater the heat transfer through the adjacent surfaces. Unfortunately, you do also release some energy from the combustion chamber through the exhaust port and into the exhaust stream.'

## Energy recovery

However, the post-2014 regulations have given teams the opportunity to recover this wasted energy, and consequently boost efficiency. Not only was the MGU-K introduced, but so was the MGU-H. The former works similarly to the pre-2014 KERS – recovering wasted heat energy from the brakes and converting it into electrical energy, which is then stored in the energy store. The MGU-K can also act as a generator, deploying energy from the energy store to either the drivetrain, providing up to 160bhp of additional boost, or to the MGU-H to support the turbocharger.

Similarly, the MGU-H together with the turbocharger recovers any wasted heat energy that is in the exhaust stream. The exhaust gases from the engine drive a turbine wheel that is mechanically connected to a compressor via a shaft. So when the turbine spins, so does the compressor, which consequently sucks in large amounts of ambient air, feeding the inlet port with dense, high pressure oxygen. This works just like a conventional turbocharger, then.

What makes modern Formula 1 engines different, though, is that in between the turbine and the compressor is the MGU-H, an electrical motor generator unit. Therefore, when the turbine spins, so do both the compressor of the turbocharger and the MGU-H.

The electrical energy generated from the MGU-H can then be used in three ways: it can be stored in the energy store; deployed to the MGU-K via the inverters or used to spin up the compressor to minimise turbo lag, as well as carefully control the compressor to improve torque delivery and driveability.


Post-2014 regulations have given teams the opportunity to recover this wasted energy

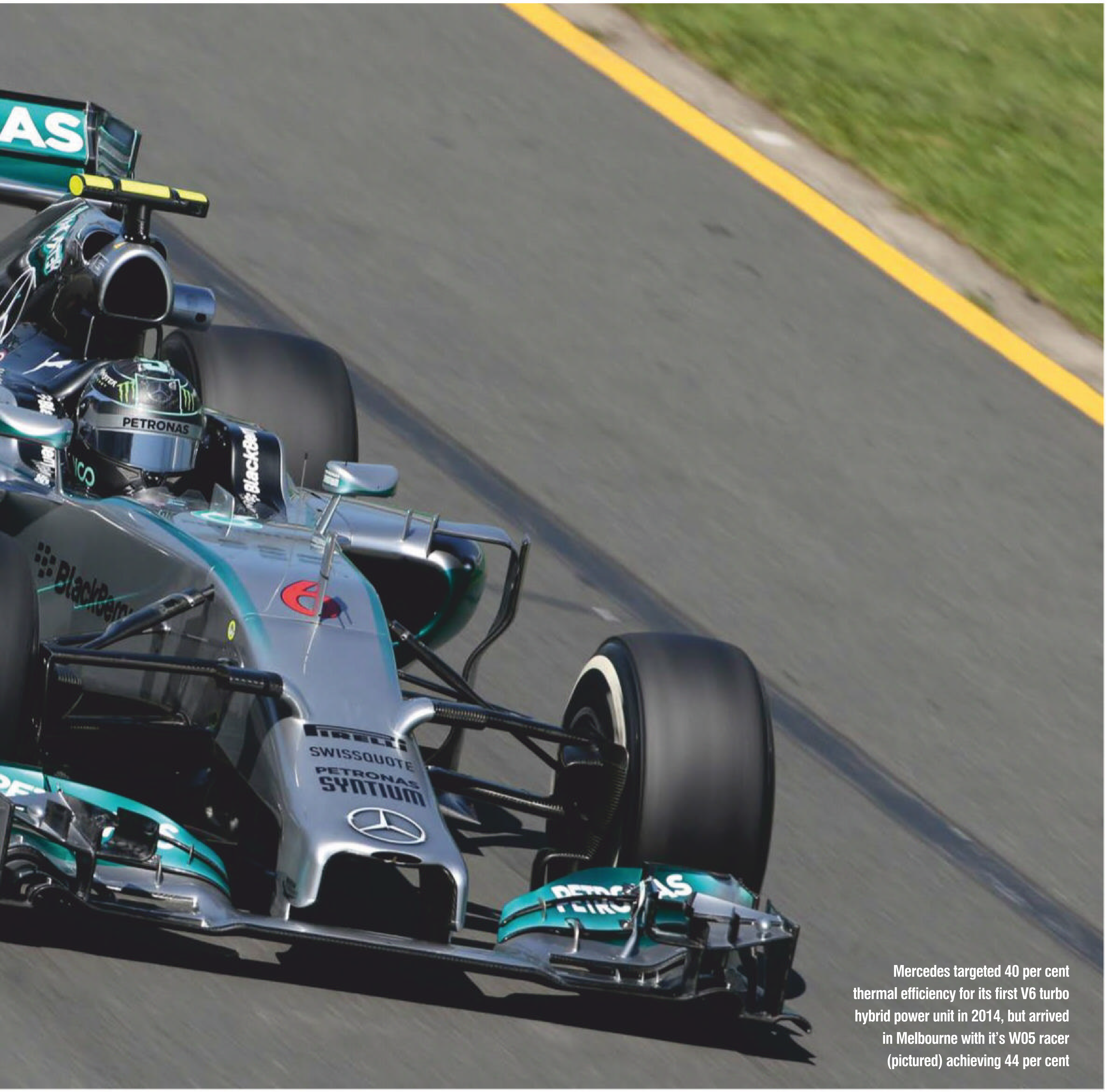
In this way, teams can utilise direct injection to optimise the delivery of the fuel, and the MGU-H to optimise the delivery of the oxygen.

This combination of not only using the MGU-H to recover wasted energy, but utilising that energy to optimise the behaviour of the combustion process is one of the key reasons behind the gains in F1 powertrain efficiency.

## Huge strides

'Formula 1 has such an absolute pinpoint focus on winning races and getting more performance, that in not many years F1 engines made huge strides,' says Hayes. 'I think most of it was down to optimising combustion, but also implementing the energy recovery systems. Recovering braking energy is relatively normal, but the MGU-H is less normal. The combination of not only recovering that energy but also the other way around – using the motor to drive the turbo so you could control the boost and engine behaviour better – gave huge efficiency gains.'

More good news is the fact that the amount of energy the MGU-H can recover is unlimited by the regulations. Which may make you think teams would aim to recover as much as possible. Well they try to, but, like all engineering scenarios, any gains come with compromises. 'You also have the challenge of looking at the back pressure across the engine.




Mercedes targeted 40 per cent thermal efficiency for its first V6 turbo hybrid power unit in 2014, but arrived in Melbourne with it's W05 racer (pictured) achieving 44 per cent

If you put a turbine wheel in an exhaust system, that's an obstruction, and the pressure in the primaries immediately after the exhaust valves is higher than on a naturally-aspirated engine,' explains Cowell. 'That hinders the breathing of the engine and could lead to some of the exhaust gases remaining in the combustion chamber. That then affects the next combustion process, so there's a balance between how much [exhaust energy] you recover vs the back pressure going into the turbine.'

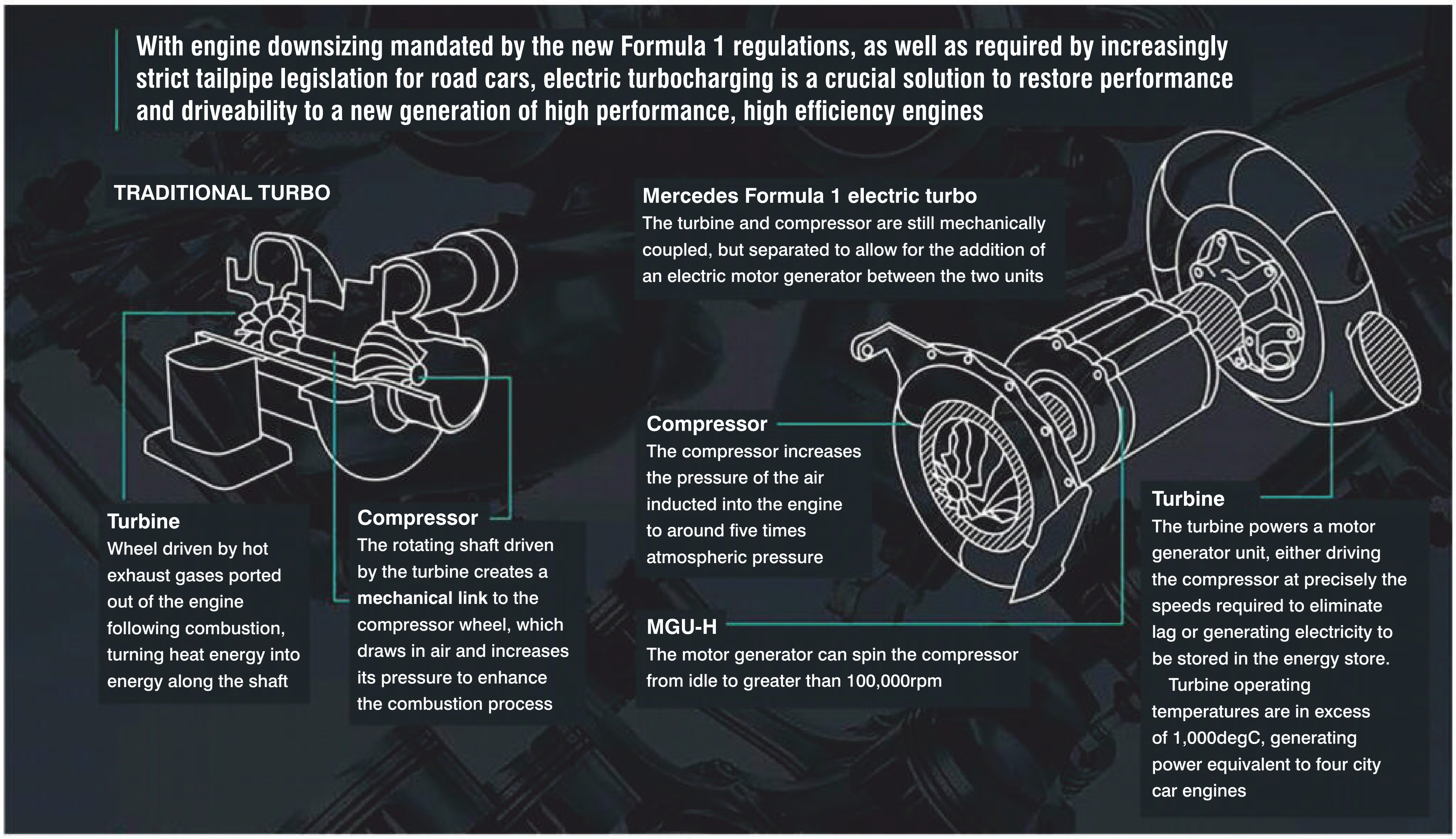
It's not just optimising the combustion process that has made these engines the most efficient in the world, but also the efficiency of all 25,000 components in the power units.

'At full throttle, every single one of these F1 engines will have a different amount of MGU-H recovery,' reveals Cowell. 'But it's the link with the crank power that is the total amount of useful work you're recovering. It's all about the efficiency of the turbine and the compressor, because the closer that is to 100 per cent, the more energy is left for the MGU-H to recover.

## Joule in the crown

'But the MGU-H has to be efficient as well, and that's tough because it's an electrical machine with a rotor spinning at 125,000rpm in a difficult and hot environment. Likewise, the MGU-K inverter also needs to be efficient, and the linkage to the crank, such that as many joules of energy that come out of the exhaust stream make it to the end of that electrical turbo compound loop. It's that simple; you just have to watch every joule of energy.'

Naturally, heat is the engineer's biggest rival here, because if any joules of energy have been emitted as heat, they haven't successfully been converted into useful work. So the most effective way to improve the efficiency of parts is to minimise heat rejection. With instantaneous gas temperatures of 2,600degC during combustion and exhaust temperatures in excess of 1,000degC, this can be a challenge, but definitely one worth fighting for.




Mercedes AMG HPP

The electric motor of the MGU-H sits between the turbine and compressor of the turbocharger

## The most effective way to improve the efficiency of parts is to minimise heat rejection

'Making sure that heat rejection is managed is a win-win scenario,' continues Cowell. 'If you can limit the heat rejection of the combustion chamber and on through the exhaust port then more of those joules of energy make it to the turbine wheel. Then there's more available for the MGU-H to recover, so that's a good area to go hunting in.'

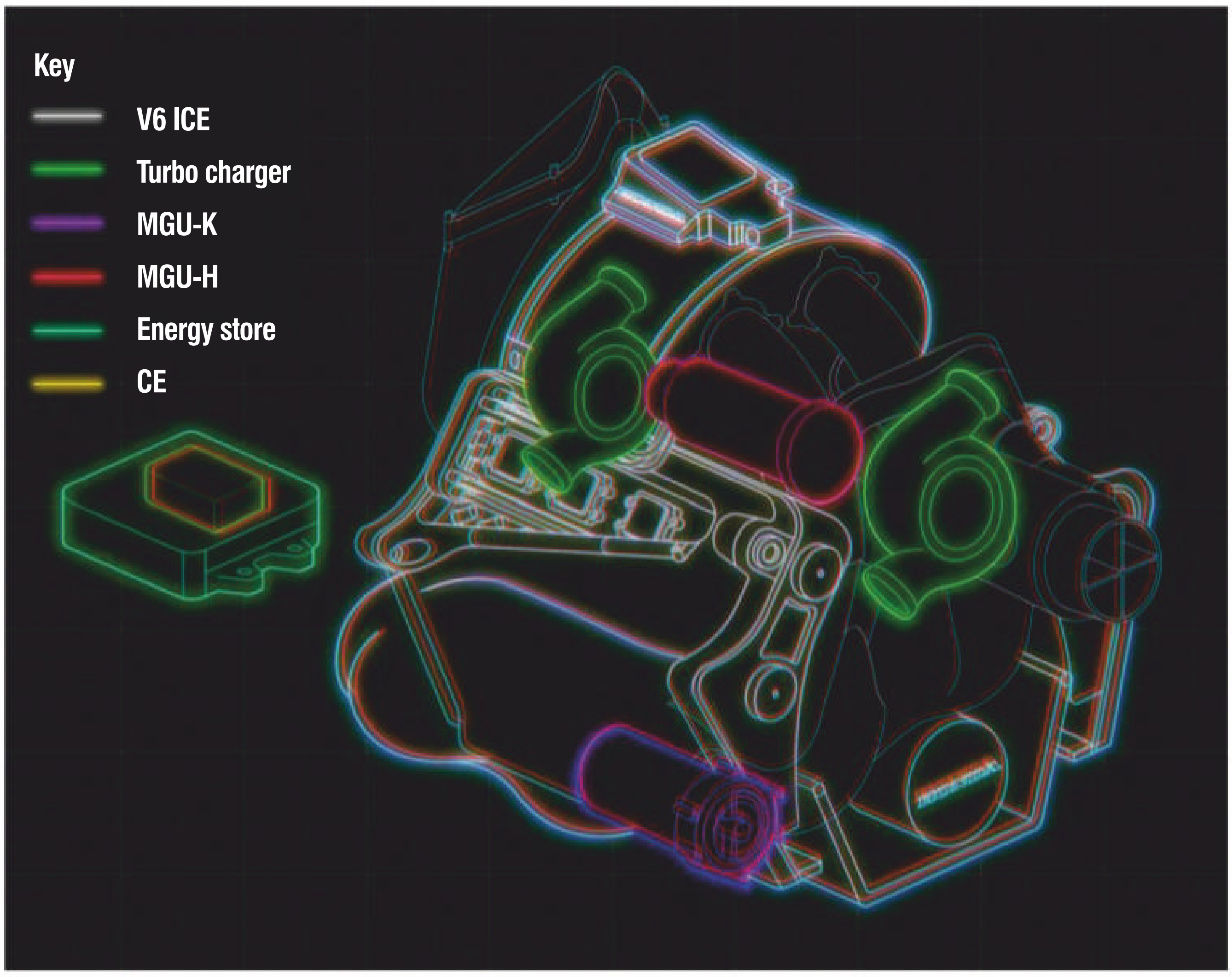
## Every little helps

One big contributor to the amount of heat within an engine is friction, which is why a great deal of effort is invested into optimising materials, coatings, bearings, lubrication and seals. Friction within the electrical components needs to be minimised too, and innovative technologies are now being used to cool the rotors of magnets and reduce ohmic losses in windings, while silicon carbide continues to improve for use in inverters.

'There's always little losses you can pick up because every bit of friction you save in that collection of power unit components is more power on the crankshaft, and less heat rejection to the radiators,' explains Cowell. 'Every watt really does help, even [losses in] cables and connectors. Go and look for the areas that are getting a bit too warm and they're the areas where gains are to be had.'

This heat-reducing philosophy has underpinned the development of HPP's latest engine, the M11 EQ Performance that powers this year's Mercedes W11. At the beginning of last year's campaign it became evident the cooling capacity of the power unit was insufficient. However, by the ninth round in Austria, HPP had worked hard to reduce the water temperature by 4degC. This development trajectory continued throughout the season and was carried over to the M11.

'We're trying to contain the total heat rejection that needs to be cooled by the chassis cooling systems,' explains Cowell. 'For this year, we are putting significant effort into making sure all the cooling fluids on the power unit operate at a higher temperature. This increases the temperature difference between that coolant fluid and the ambient




Honda

A schematic showing the layout of both the mechanical and hybrid components of the current 1.6-litre V6 turbo F1 engines

# REAL-VIRTUAL LOOPS

## Visionary companies leverage operational data and virtual models in digital twins

**Reprinted with permission from Dassault Systèmes' *Compass* magazine**

**At some point we will be able to run a complete simulation of a pit stop**

Manufacturers worldwide are building sensors and communications into their devices to collect real-time data. The most advanced are feeding this data into what analysts are calling 'digital twins', creating real-time feedback loops between in-use devices and the 3D simulations used to create them.

Combining rapidly expanding computational power, sensor-equipped machinery and real-time data collection and analysis via the Internet of Things (IoT), these companies are driving intelligent 3D simulations to new levels, dramatically improving design and construction processes and, manufacturing environments and customer engagement.

## Multi-functionality

In motor racing, Onroak Automotive, a design and production unity of the Everspeed Group of France, is in its second year of a three-year project to overhaul the way it builds cars, trains mechanics and manages races at the 24 Hours of Le Mans.

'We can use this new system to design and to produce cars,' says Sébastian Metz, Le Mans site director for Onroak Automotive. 'We can also use it in training for the pit stop mechanics. You can know where the parts are placed and how they all fit together, even whether there is space for hands to access the parts.

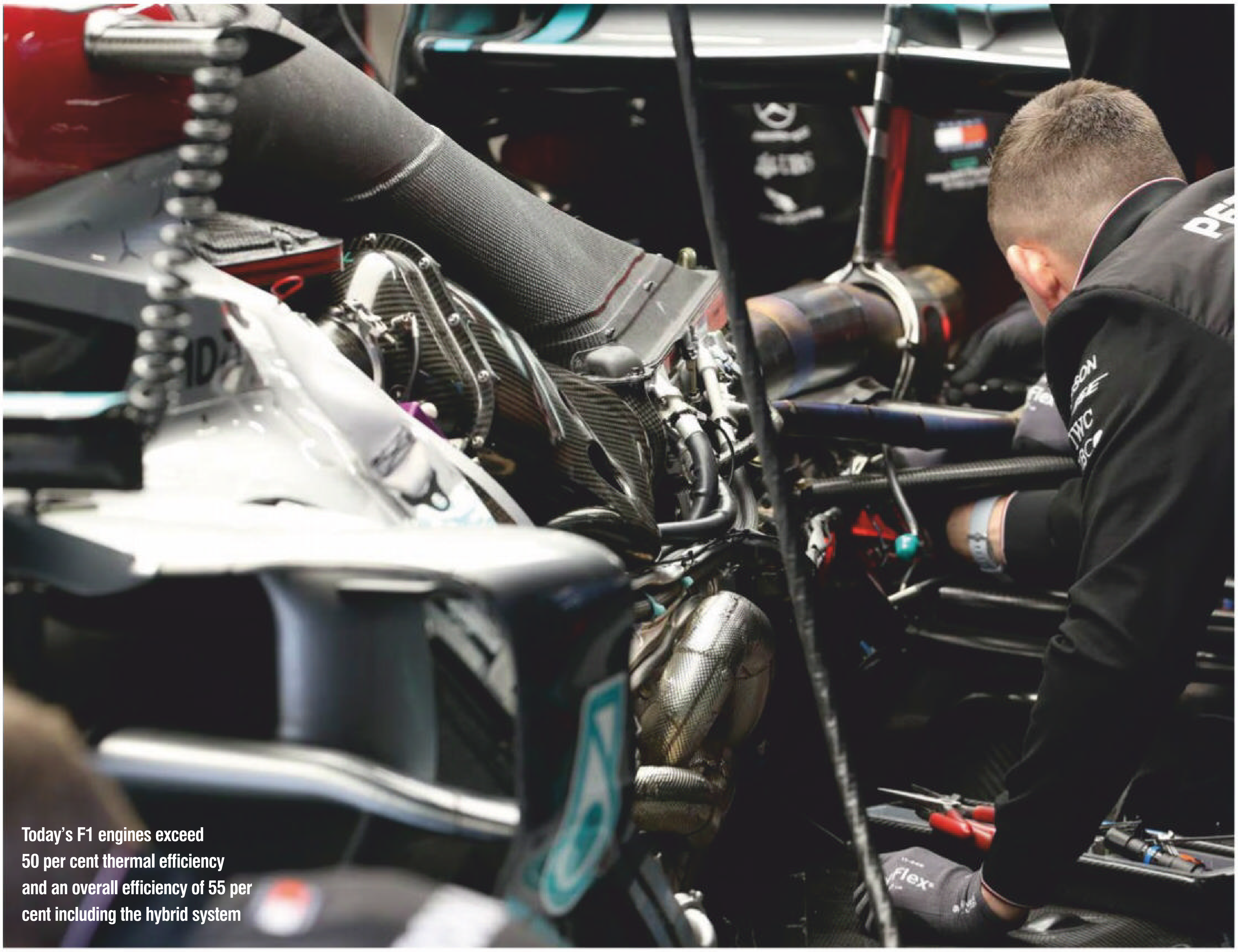
'At some point, we will be able to run a complete simulation of a pit stop. It is amazing what you can do with it.

'We can also simulate different weather conditions and use this to help the crew choose the right type of tyre, depending on track conditions. We can even simulate the real life of the car on the track.'

While other companies are on the journey toward realising the benefits of digital twins in their organisations, Onroak Automotive consider the technology a genuine game changer that could offer enormous advantages for teams and competitors alike.

**https://ifwe.3ds.com/transportation-mobility**

DASSAULT SYSTEMES




Today's F1 engines exceed 50 per cent thermal efficiency and an overall efficiency of 55 per cent including the hybrid system

temperature we are racing in, which increases the effectiveness of the cooling system.'

Furthermore, reducing the temperature of the engine means less cooling is required, so the radiators, along with all their associated ancillaries, can be reduced in size, leading to narrower sidepods and aerodynamic benefits.

'As power unit engineers we don't just focus on crankshaft power, we also focus a tremendous amount on packaging and reducing the overheads for the aerodynamicist, so that they can focus on keeping the car planted through the corner,' concludes Cowell.

## Creative thinking

With the current powerplant architecture now entering its seventh year of development, and engineers having to find more creative ways of finding incremental gains, how many more improvements are left to be made?

Andy Cowell seems to think there are plenty: 'If people tell me we're at the limit, I'll say why? Have you looked here? Have you looked there? What about that? What about this? Every single measurable of the power unit needs to be better than the previous year.'

But if Formula 1 is to continue its image as the 'pinnacle of technology', then surely these power units need to be pushed to the next step? Well, this was initially intended for 2021, where F1 set out ambitious plans to, once again, revolutionise the regulated power unit. However, due to commercial, political and technical reasons, this has now been delayed to 2025. But what could be in store then?

'As we move towards 2025, and beyond, we're looking at some very novel engines,' says Symonds in response. 'If we want to hit 60 per cent thermal efficiency, which is my personal target, we're not going to achieve that with incremental changes. I don't think we'll be seeing the conventional four-stroke Atkinson cycle engines we are running at the moment. We're looking at something very different.'

'Looking at future technologies, which is what Pat [Symonds] and I are doing at the moment, most of them are concerned with improving combustion efficiency,' says Hayes. 'I know we've mentioned two strokes, but that's one of the many technologies on a comprehensive list that we're looking into.

'Maybe the right answer is a combination of four or five different technologies. Tied into this very strongly is the fuel we use, which is part of Formula 1's sustainability strategy to become carbon neutral in the future.

'We want to get to a higher percentage of sustainable fuels as quickly as we can. Although you are burning fuel, so you still produce emissions, if you've made the fuel from atmospheric carbon then you're actually taking carbon out of the atmosphere to make the fuel and then just putting it back again, so it doesn't actually add any carbon. That's why it's a net zero carbon fuel, but you have to be aware it takes energy to do these conversions.

'If the energy comes from renewable sources, then that's fine. But again, Formula 1 is all about demonstrating what is possible, because the science is already there.'

**Formula 1 is all about demonstrating what is possible, because the science is already there**

Arising from the ashes of liquidation, the Bloodhound LSR project is back on track, albeit desperately needing a huge cash injection to take it to the next level

# Target 800

**With 628mph achieved on the Eurojet EJ200, Bloodhound LSR plans to add a hydrogen peroxide rocket for phase 2 in 2021**

**By PETER WRIGHT**

Since I last saw Bloodhound in 2017, accelerating up to 200mph on the runway at Newquay airport, much has changed. The most obvious difference is that Bloodhound has transformed from a blue and orange, rocket and turbojet-powered Land Speed Record (LSR) contender into a white and red one. This new livery symbolises the change in ownership that came about after Bloodhound Programme Ltd entered administration in 2018, and a Yorkshire entrepreneur, Ian Warhurst, stepped in and purchased the project.

Now named Bloodhound LSR, and managed by Grafton LSR, the project is based at SGS Berkeley Green University Technical College on the Gloucester Science and Technology Park. The site is right on the Severn Estuary and includes Cavendish Nuclear Laboratories Ltd, Magnavox Ltd, and Green Fuels Ltd – a company developing processes to convert waste vegetable oil into useful fuels such as Jet-A1.

The 200mph tests at Newquay showed the world that Bloodhound was a runner and enabled the engineering team, under engineering director Mark Chapman, to successfully test the operations and performance of the Rolls-Royce Eurojet EJ200 after-burning turbofan. The next three phases of the project were planned to be:

- Achieve 600mph on the Eurojet EJ200 alone, at Hakskeen Pan in South Africa.
- Exceed the existing LSR, set by Andy Green in Thrust SSC in 1997 at 763mph (Mach1.0). The target is 800mph (Mach1.04) and will require the addition of the hydrogen peroxide rocket being developed for the vehicle by Norwegian company, Nammo.
- To achieve 1,000mph (Mach1.30) after some aero tuning based on data acquired from the earlier runs, and converting the Nammo rocket to a hybrid specification, which employs rubber as an additional fuel.

Warhurst committed to funding phase 1 and the car, driver, and team travelled to South Africa, to the edge of the Kalahari Desert, to prove they could achieve the first stage of objectives. Publicly, they set 500mph as the target, but what they were after was 600mph in order to monitor the behaviour and performance of the car as the flow became transonic.

## Lake eerie

Hakskeen Pan is a forbidding dry lake lying in North Cape Province in northern South Africa, between Namibia and Botswana. It is just over 800m above sea level, and provides a 20km long, one kilometre wide track ideally suited to Land Speed Record attempts. To prepare the track, some 21 million square metres of desert were cleared of stones, by hand.

In November, when Bloodhound occupied the facility, the temperature rose to mid-40degC each day but, as running was limited to the mid-30s, the team started each day at around 3.30am to use the mornings for runs. By midday, winds were picking up and the heat haze limited visibility to around 500m, rendering navigation on the Pan possible only by following existing wheel tracks and GPS.

The Pan is large enough to have local weather patterns and the rain, when it falls, tends to collect at one end of the track due to its 50cm in 20km slope. After rain, once the desert has dried out, the surface shows small blisters, which driver Andy Green could detect at speed through the solid aluminium wheels.

The targets for last November's trials were to:

- Correlate the CFD aerodynamics prediction at speeds of up to Mach0.8.
- Assess stability and control in yaw.
- Check Bloodhound LSR's braking system – air brakes and parachutes.

Seeing the car in the Gloucester workshops, one cannot help being impressed by the signs that this extraordinary machine has recently run in earnest. On the body and everywhere under its skin is a dusting of light brown powder, and towards the rear of the car this dust plume from the front wheels has abraded the paintwork. It has the same air as a post-24hr Le Mans car – a purposeful racecar that has done its job.

Engineering director Mark Chapman filled me in on what had been achieved and learned in that initial test running at Hakskeen Pan in November, his delight and relief plainly apparent: 'If we hadn't achieved exactly what we set out to do, I would probably be looking for another job by now!'

While most of the team's predictions went to plan, some unexpected damage occurred from the near-supersonic media blasting the fuselage while travelling at over 600mph

**There can be no group more experienced and knowledgeable about transonic airflow in the presence of the ground**

Though it has changed hands and livery, Bloodhound LSR remains a thoroughly British affair, and is still on course to attempt its ultimate goal of 1,000mph on land

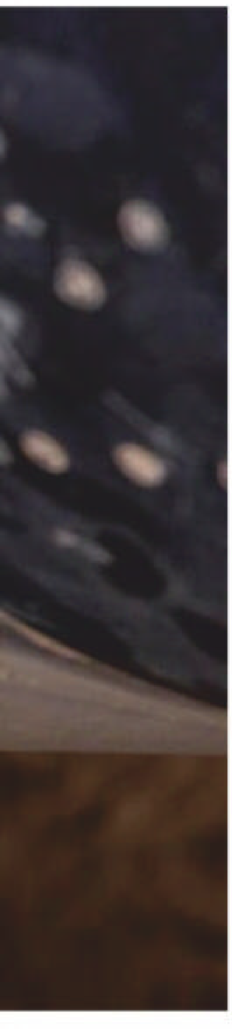
## The car passes through subsonic, transonic and supersonic regimes

An LSR car's performance and characteristics are determined by aerodynamics. The drag coefficient determines the thrust requirements, and the lift and pitching moment, along with side force and yawing moment coefficients, determine control and stability. All these coefficients vary as the car passes through subsonic, transonic and supersonic regimes. Predicting them well in advance, and correlating the prediction during testing, is fundamental to the success and safety of a modern LSR attempt.

## Transonic flow

CFD offers the means for aerodynamic development in the absense of a suitable transonic wind tunnel. This task for Bloodhound is taken on by the engineering department at Swansea University, the CFD team led by associate professor Dr. Ben Evans and employing Swansea's FLITE 3-D software.

The team has the enormous benefit of having taken on the same task for Thrust SSC's record-taking, supersonic project more than 20 years ago. There can be no group



The shock wave beneath the car stripped a line of paint, giving a visible correlation to the CFD predictions and helping assess the thrust requirements for the next phases of the project

**For future running up to 800mph, fin-mounted, fixed winglets will be fitted**

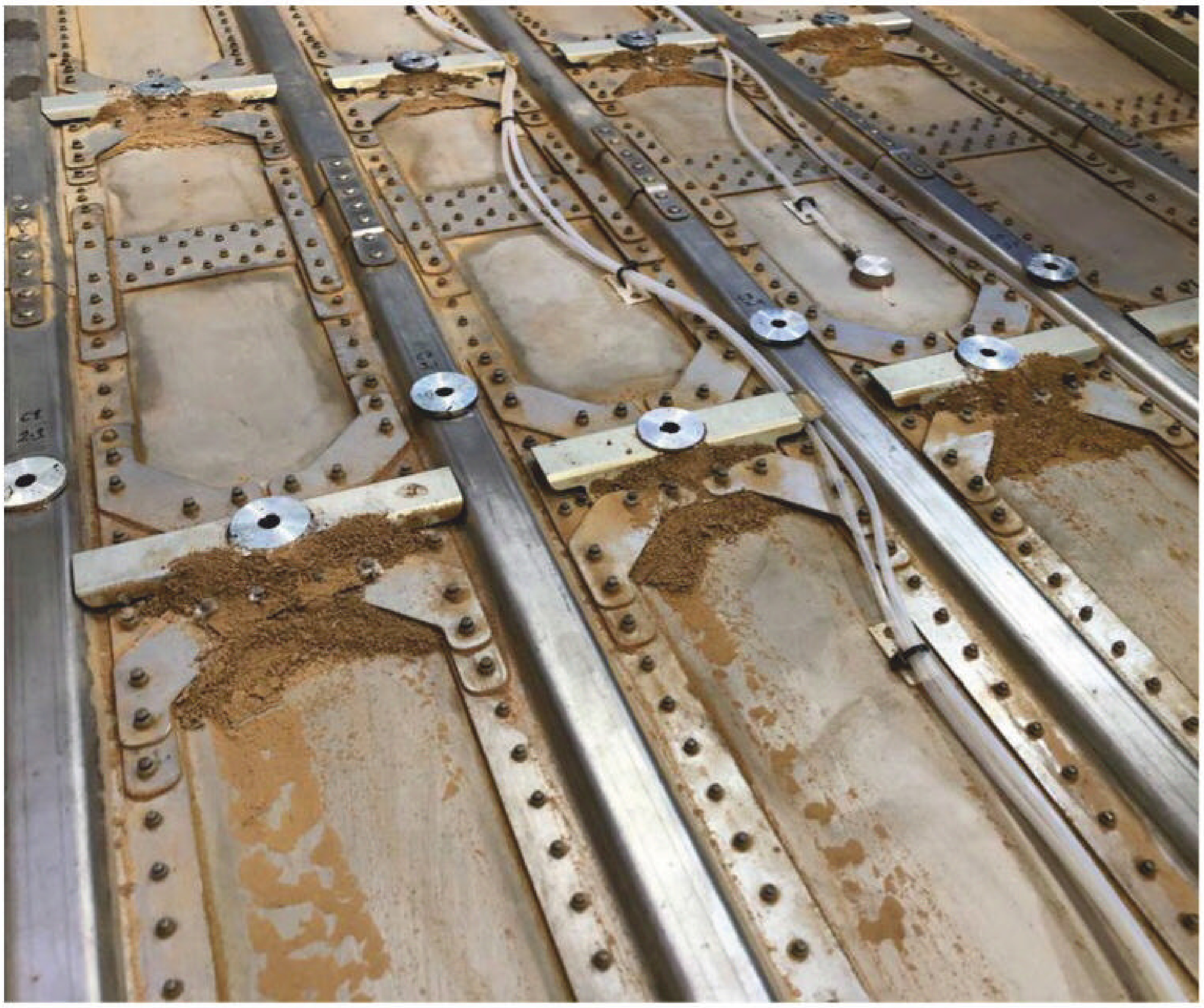
more experienced and knowledgeable about transonic airflow in the presence of the ground.

Bloodhound's outer skin is covered by 192 pressure tappings, which enabled the Swansea team to correlate the airflow with the CFD prediction at any given car speed and attitude. The closeness of the results exceeded expectations, with measured pressures being within five per cent of those computed. As a bonus, the shock wave under the car made itself evident by stripping a line of paint across the under tray, and the location of this shock wave proved to be bang on prediction. These results have given the whole design approach great confidence, and confirmed the thrust requirements to achieve the targeted speeds.

Bloodhound exhibits a reducing downforce up to 700mph, which would cause control problems around Mach1.0. Laser ride height sensors were trialled, but would only measure the dust plume, so downforce was computed from suspension deflections instead.

For future running up to 800mph, fin-mounted, fixed winglets will be fitted. For speeds beyond that, canards on the nose may also be required, and both fin and nose-mounted surfaces may be actively controlled.

The afternoon winds that rose at Hakskeen were predominantly crosswinds. For safety, Andy Green set a crosswind limit of 10mph and, while this limited running, it also offered an opportunity. Bloodhound's fin is designed for a c of g position when the rocket and its fuel pump system is installed. Without these masses, the c of g is too far forward, and in this condition Bloodhound is likely to be unstable in yaw. The question the team set out to answer is whether there was sufficient steering control to allow the driver to counteract the resulting weathercock effect caused by a side wind.



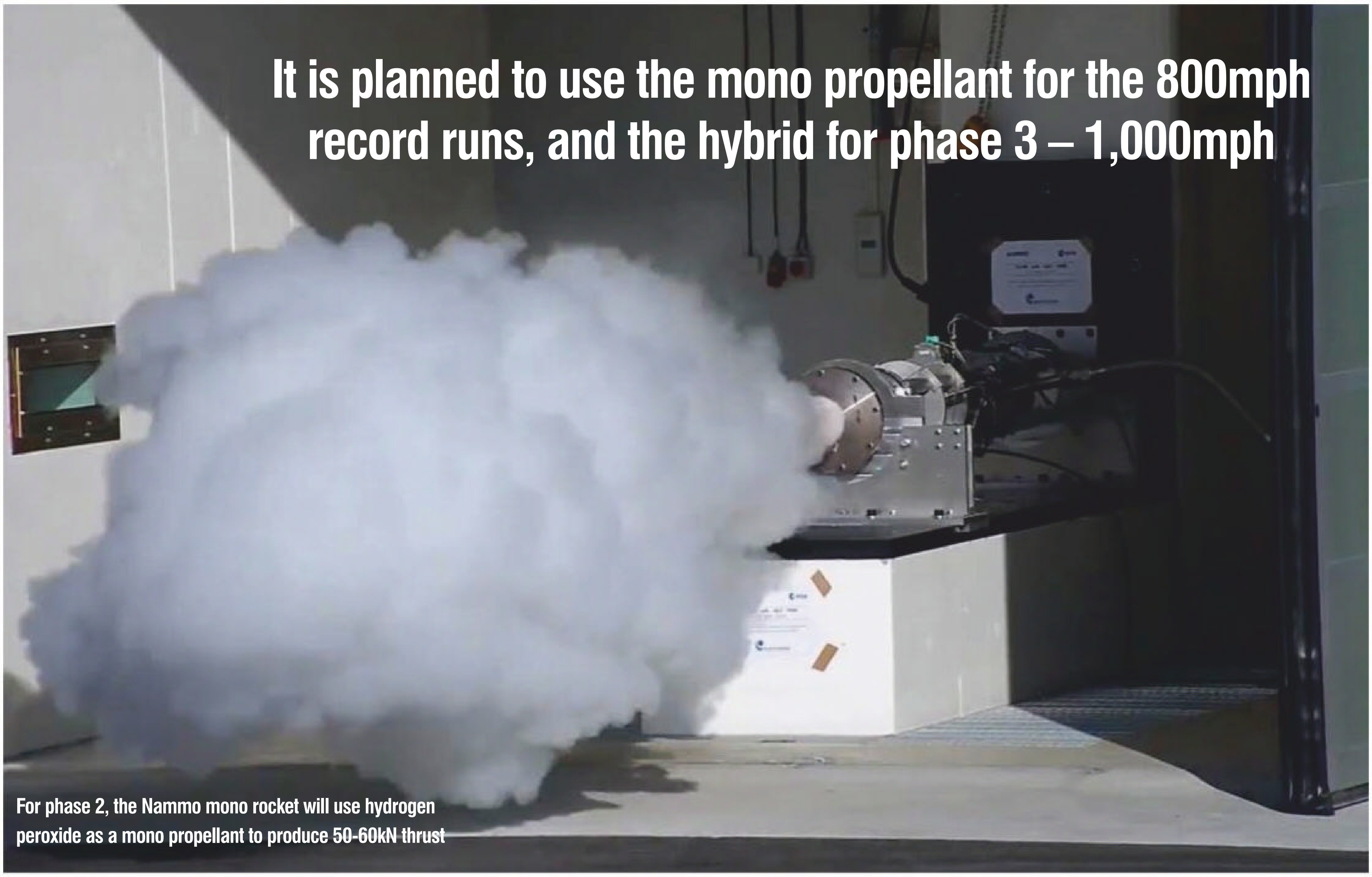
**Above and below: stripped down for assessment and maintenance, Bloodhound LSR shows signs of a life well lived, the dust and debris from the Hakskeen Pan is evident everywhere you look. All things considered, it stood up very well to the task**

## Directional control

Bloodhound uses two systems to provide the driver with directional control. The front wheels are steered conventionally, but the solid aluminium wheels only 'grip' the surface up to around 450mph. Ron Ayres, designer of Bloodhound, shaped the 'tread' profile of the rims to perform as a planing boat hull. At low speeds, the wheels penetrate the surface of the dry lake by around 8mm, and form grooves. Side load is generated by soil mechanics, not conventional friction. As the speed increases, the wheels ride up the 'bow wave' until they plane over the surface. At this point aerodynamics take over, and the front wheels generate side force, behaving as forward-mounted rudders.

Stability and control tests are performed by inputting a disturbance in yaw and analysing the response of the vehicle. The disturbance can either be by steering input from the driver, or side wind gust. Given the afternoon side winds at Hakskeen, Green was able to determine the steering input necessary to counter the weather cocking effect, and so the stability and steering gain could be calculated. All this executed while he was driving at over 600mph!

These high-speed runs also enabled stopping performance to be evaluated. The air brakes were deployed on the final high-speed runs and performed as predicted. However, Thrust SSC had displayed some parachute instability, which was solved by removing every other circle of webbing on the ribbon parachute. Bloodhound suffered the same problem and so used the same solution.



**It is planned to use the mono propellant for the 800mph record runs, and the hybrid for phase 3 – 1,000mph**

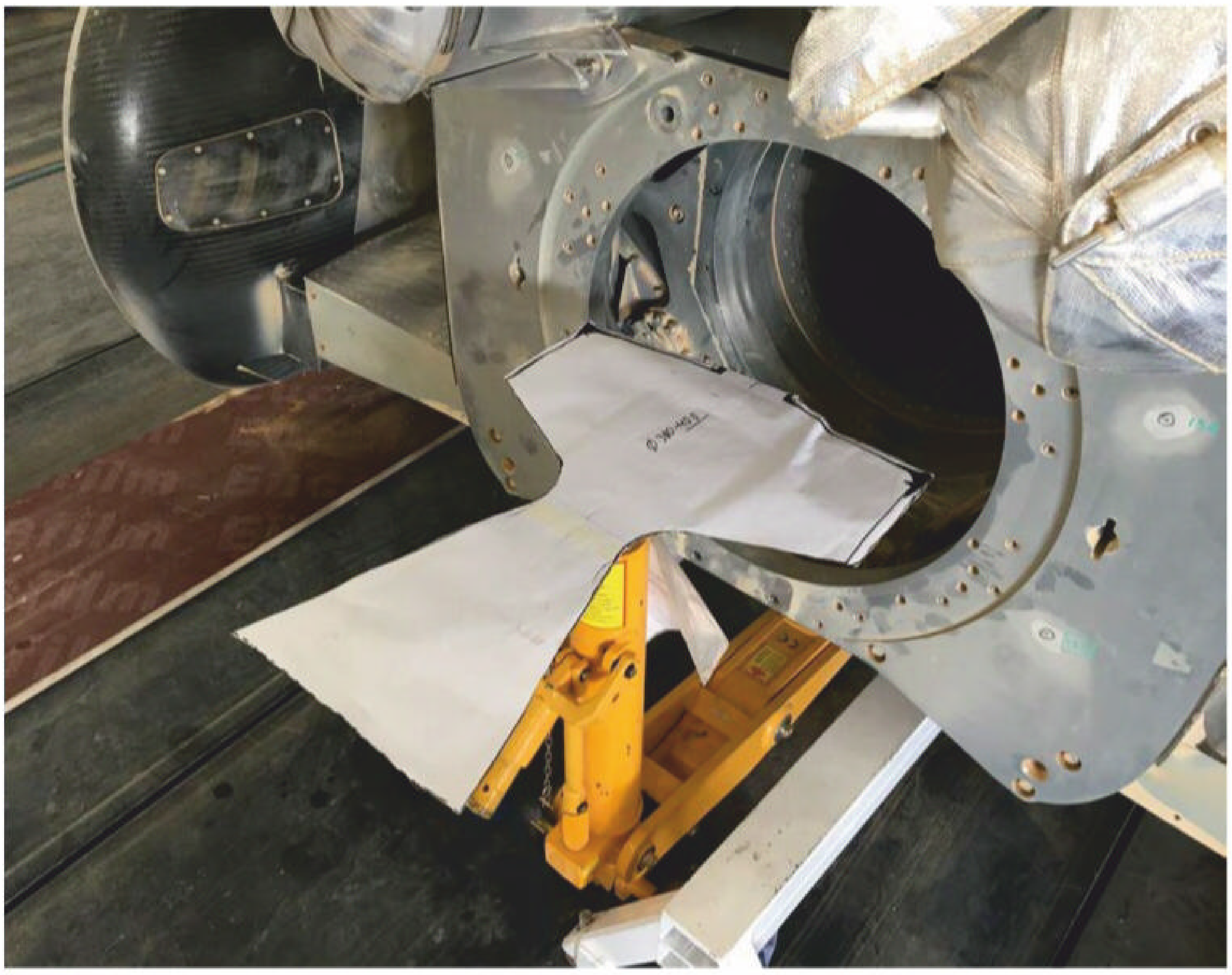
For phase 2, the Nammo mono rocket will use hydrogen peroxide as a mono propellant to produce 50-60kN thrust

Similarly, deploying both primary and back up parachutes, as required for an emergency stop, could result in the two sets of parachute lines becoming tangled, so to make sure this procedure was also tested and proved safe.

Despite the test programme being only the second round of running such a unique and complex machine, the team experienced very few technical problems. The biggest delays to the test schedule were caused by false alarms from the FireWire fire detection system monitoring the engine bay. False signals were caused by mechanical failure of the wire due to surface-induced vibration, rather than overheating as was initially thought. At least these alarms give Green some useful practice for emergency stopping.

Other lessons were leant, too. The plume of dust thrown up by the front wheel pair caused substantial damage to the rear suspension fairings. Despite being reinforced with steel shields, the near supersonic grit blasted these fairings into twisted scrap.

It is testimony to the preparedness of the engineering team that they were able to achieve all the phase 1 objectives at that first test, overcoming each problem as it occurred.



The Nammo rocket will sit beneath the car's existing Rolls-Royce Eurojet EJ200 after-burning turbofan

## Nammo propellant

The Eurojet EJ200 generates 90kN with reheat. That sufficed to reach 628mph in November, but significantly more thrust is required to attain phase 2 of the programme. The answer is the Nammo rocket, which will be mounted beneath the jet engine at the rear. Currently, it has been developed in two distinct versions:

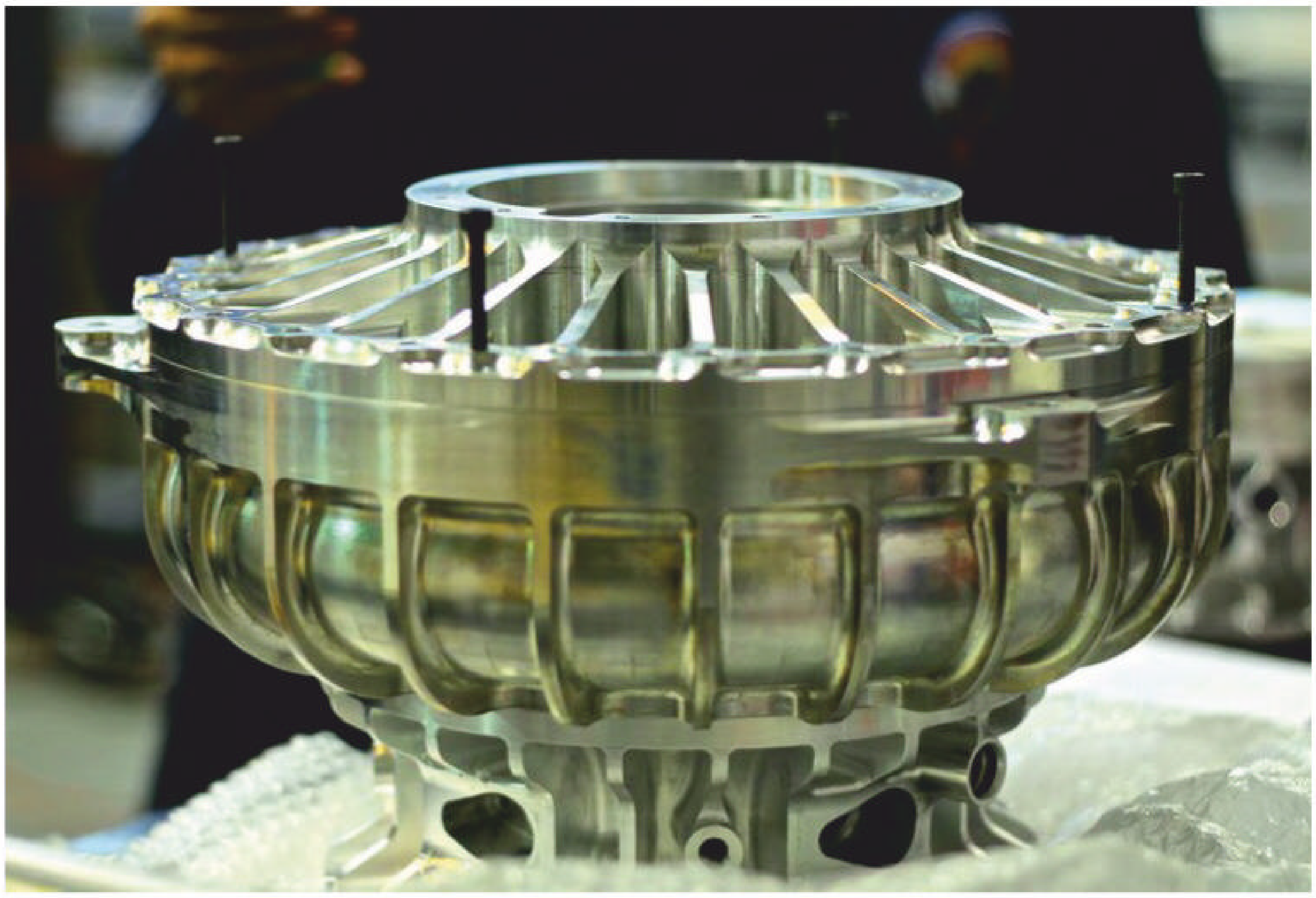
- Mono propellant, using high-test peroxide oxidiser, producing 50-60kN thrust.
- Hybrid, which uses the oxidiser and hydroxyl-terminated polybutadiene (rubber), producing 100-120kN thrust.

It is planned to use the mono propellant for the 800mph record runs planned in phase 2, and the hybrid for phase 3, which targets 1,000mph.

The mono propellant rocket generates zero carbon, the $H_2O_2$ fuel being catalysed into 600degC steam and oxygen. The one tonne of rocket fuel carried on Bloodhound is pumped at

# WHAT IS AVAXHOME?

## Having rendered the rocket and its fuel pump zero carbon, only the hydrocarbon-burning jet engine remains



Bloodhound's rocket oxidiser pump was developed from a HTP pump originally used in British Blue Steel cruise missiles

Jules Tipler

Required to deliver 800 litres of fuel at 1,000psi in just 20 seconds, the design of the pump impeller has been critical

1,200psi (8.27MPa) into the rocket in 20 seconds by a 10,500rpm turbine pump. Originally envisaged to be powered by a 2010 Cosworth 2.4l V8, rated at 750bhp, this was replaced by a 550bhp supercharged Jaguar V8.

With the ever increasing focus on sustainability, Warhurst is keen to emphasise the credentials of Bloodhound and show its relevance in the engineering world. To this end, it is now planned that the fuel pump will be powered by a 400kW electric motor, with the energy for it stored in a 100kg battery system.

The electric pump offers a few advantages:

- The mass of the battery pack can be placed in a number of potential positions within the fuselage of the car to trim the c of g.
- The motor and pump can be located close to the rocket, minimising the length of the 1,200psi fuel line, increasing safety (the Jaguar engine / pump sat behind the cockpit with a long fuel line to the rear-mounted rocket).
- The electric motor speed can be matched to the pump, eliminating the need for a gearbox. The motor can be configured with a through shaft, driving a turbine on each end. This arrangement balances the axial thrust generated by the turbines.
- The hydraulic control system actuating the air brakes and in the future, the fin and nose-mounted trim surfaces, can be removed and replaced with electric actuators.

Chapman describes the required battery technology as 'baggy chemistry', enabling high charge and discharge rates. It is likely motorsport KERS technology, rather than road car systems, would provide this.

Charging will be by solar PV arrays and batteries, and will power the Hakskeen camp, including, where possible, support vehicles.

## Carbon content

Having rendered the rocket and its fuel pump zero carbon, only the hydrocarbon-burning jet engine remains. Rolls-Royce is not yet ready to make this hydrogen fuelled, so the remaining feasible approaches are to use fuel derived from plant sources, such as algae or waste cooking oil, or a fully synthetic fuel. In the timeframe available, only bio-fuel to the Jet A-1 specification demanded by the engine is likely to be ready. This is already being trialled by fuel companies such as BP, as the world works hard to find a solution for commercial aircraft. In this regard, Bloodhound LSR's base is extremely well placed, having Green Fuels Ltd on the same site in Gloucestershire, with experience and expertise in these technologies.

Warhurst is laying plans for the next phase for Bloodhound, and is setting out to raise the £8m (US$10.25m) necessary to send the car and team back to South Africa in June 2021. The experience gained last year convinced them they need to go earlier in the year to experience lower temperatures, mid-20degC being normal for June / July. November temperatures dictate their peroxide fuel store be refrigerated, as $H_2O_2$ becomes unstable above 50degC.

Wherever Bloodhound leaves the Land Speed Record once the programme is finished, Chapman considers it likely to be the last ultimate LSR. As things stand, there is every sign the team will meet its objectives, given the necessary funding, as its approach is both methodical and technically well-founded.

After that, Mark thinks the future will be to achieve 500mph with an all-electric, wheel-driven vehicle, and he obviously relishes the prospect. Meanwhile, Bloodhound is setting the scene for sustainable LSRs in the future.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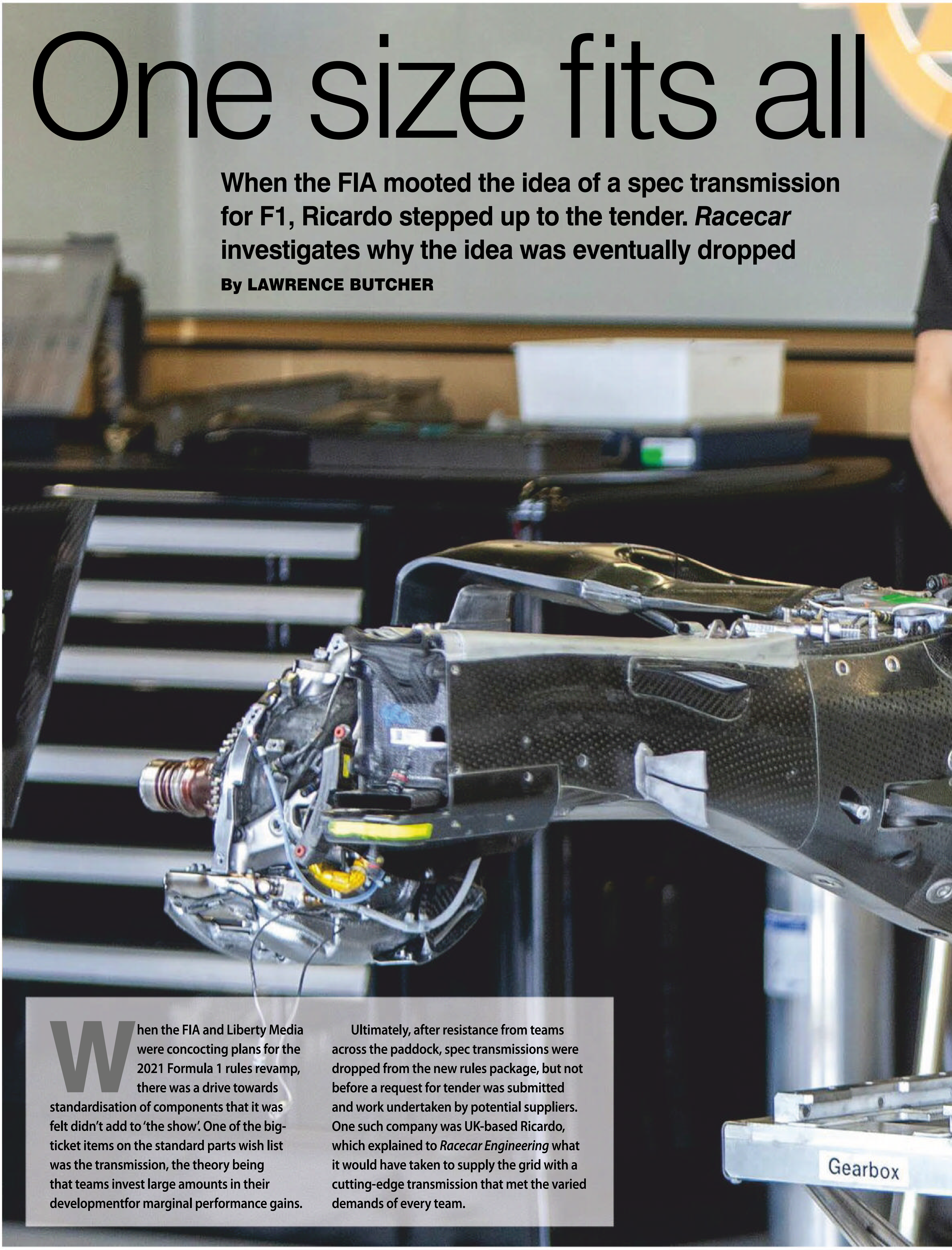
# One size fits all

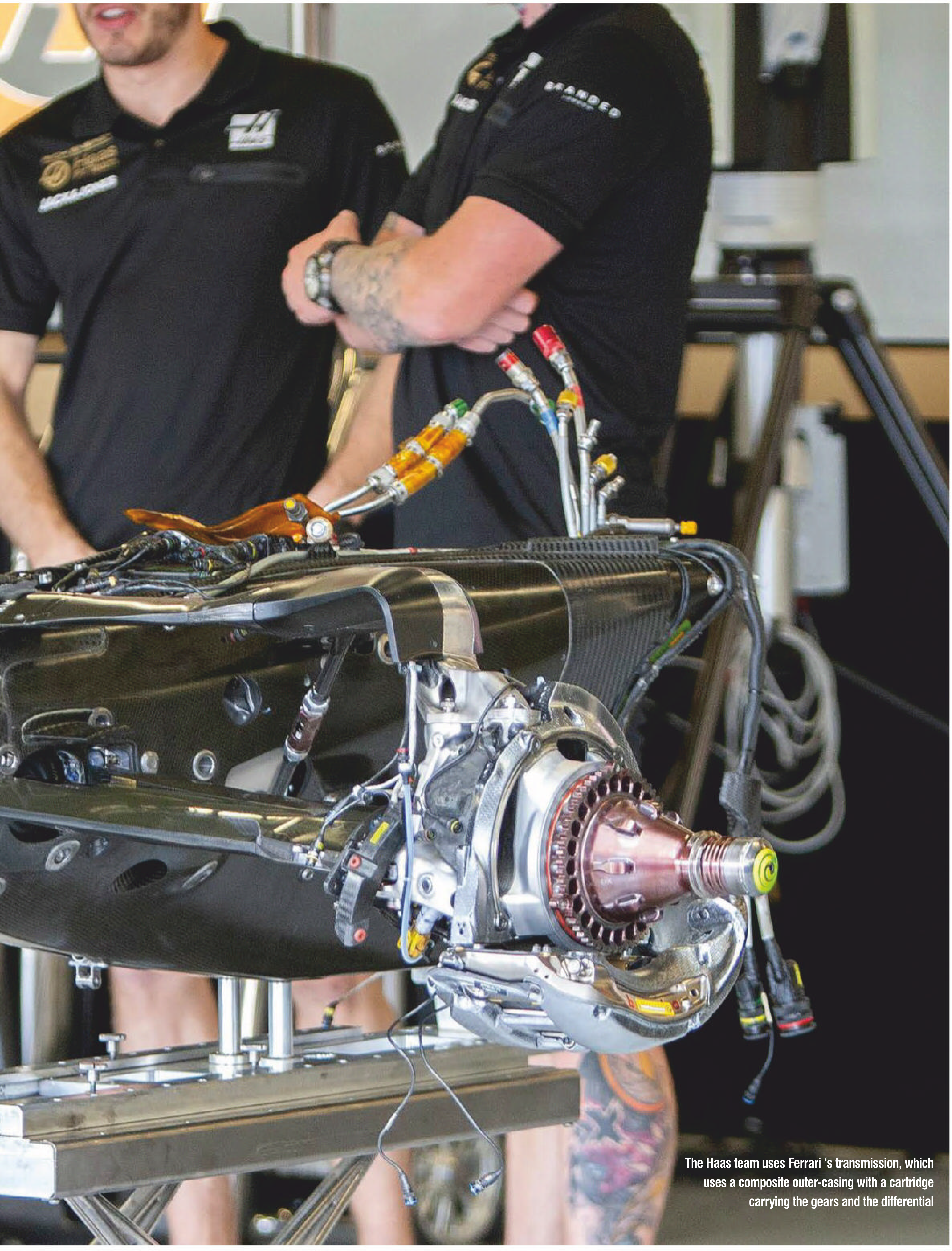
**When the FIA mooted the idea of a spec transmission for F1, Ricardo stepped up to the tender. *Racecar* investigates why the idea was eventually dropped**

**By LAWRENCE BUTCHER**




When the FIA and Liberty Media were concocting plans for the 2021 Formula 1 rules revamp, there was a drive towards standardisation of components that it was felt didn't add to 'the show'. One of the big-ticket items on the standard parts wish list was the transmission, the theory being that teams invest large amounts in their developmentfor marginal performance gains.

Ultimately, after resistance from teams across the paddock, spec transmissions were dropped from the new rules package, but not before a request for tender was submitted and work undertaken by potential suppliers. One such company was UK-based Ricardo, which explained to *Racecar Engineering* what it would have taken to supply the grid with a cutting-edge transmission that met the varied demands of every team.



The Haas team uses Ferrari 's transmission, which uses a composite outer-casing with a cartridge carrying the gears and the differential

The FIA tender did not include a detailed technical specification of the required transmission, more it laid out broad guidelines for potential suppliers from which to work. According to the FIA the main intent of the move to a spec transmission was as follows: 'To retain current levels of Formula 1 gear change performance for all cars at a much reduced cost to the competitors, while also removing the requirement for teams to design or source their own gearboxes. The unit can be carried over between seasons so removing the need for costly continual performance development.

'It is anticipated the layout will be similar to current Formula 1 gearbox / final drive assemblies. The exact layout definition will be part of the selected provider's responsibility, but it should be as close as practical to something all teams are happy with.'

Interestingly, it was stipulated the transmission be a seven-speed unit, rather than the eight speeds currently in use, and in the form of a cartridge, which could then be fitted within housings of a team's own design. This would leave freedom in terms of chassis layout.

However Tim Gee, technical director at Ricardo Performance Products (which houses the company's motorsport division), points out that when it started looking in detail at current F1 practice, not all teams were producing cartridge-type transmission: 'For those not running them, it would be quite a step change.'

The FIA tender went on to explain that once the design was fixed and approved, 'it will be up to the teams and the power unit suppliers to make their parts physically fit with the gearbox cassette through specifications supplied by the selected provider.'

It was also specified that the gearbox oiling system be integrated into the transmission, with inlets and outlets provided for coolers.

## Make-to-print

Currently, teams assemble their own gearbox designs in house, outsourcing the production of many specialist components to companies like Ricardo. Consequently, a majority of Ricardo's Formula 1 work is make-to-print. This gives it considerable expertise in terms of how to make the required parts, with knowledge and capability to provide a clear overview of what constitutes state-of-the-art in F1, though not necessarily how each individual team manages the complete system.

As Gee summarises, building a suitable unit would require input from teams with experience in the matter, to ensure the right compromises were made. 'If you are coming at it from a third-party supplier it's difficult, because it has only arrived at that point after a lengthy development process and iterations over many years. Nobody came in and designed what we have now from the outset. It has evolved.

'Our position was clear. If you want a third party to produce a gearbox, which fulfils all of the criteria and is state-of-the-art, we must base it on what the state-of-the-art actually is.

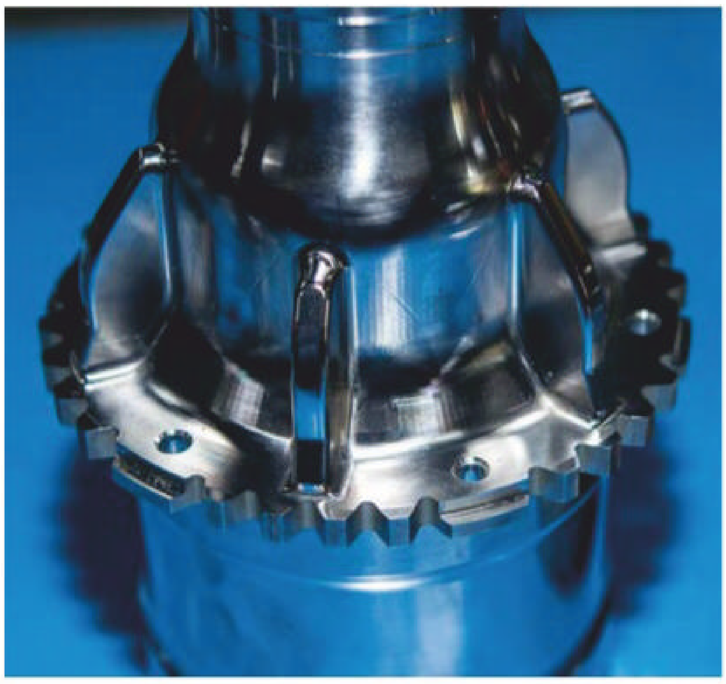
'We are not so arrogant to think we know everything. Similarly, there are a lot of things we do that others can't, because you have to have empirical experience of what has gone before.'

So Ricardo's considered approach was to engage with as many teams as possible during the initial tender process, then assimilate input from other outfits further down the line before coming up with a final proposal.

Left to their own devices, teams will use different materials for their transmissions, Ferrari choosing a composite casing

**One of the key requirements was that the transmission be in the form of a cartridge**

Tim Gee, technical director at Shoreham, UK-based Ricardo Performance Products



Formula 1 differential carrier

One of the few quantitative specifications given by the FIA was a target weight of 14kg. However, Gee highlights that simply specifying a weight, without putting it in the context of other requirements, was problematic in itself.

'If the FIA had chosen just one supplier and let them design a gearbox that was fit for purpose, and lasted six races, or however long, then weight was very likely to be the product.

'What you can't do is just try to hit that [weight], because then something else, like reliability, might be a problem.'

## Different agenda

The issue relates back to the fact that current transmissions are the result of years of iteration. 'To get to a particular weight target, which is based on something that already exists, and to then adopt it as a supplier, that is a different agenda to someone saying design something that lasts this long, weights this much etc,' says Gee. 'Something has to be left as a variable.'

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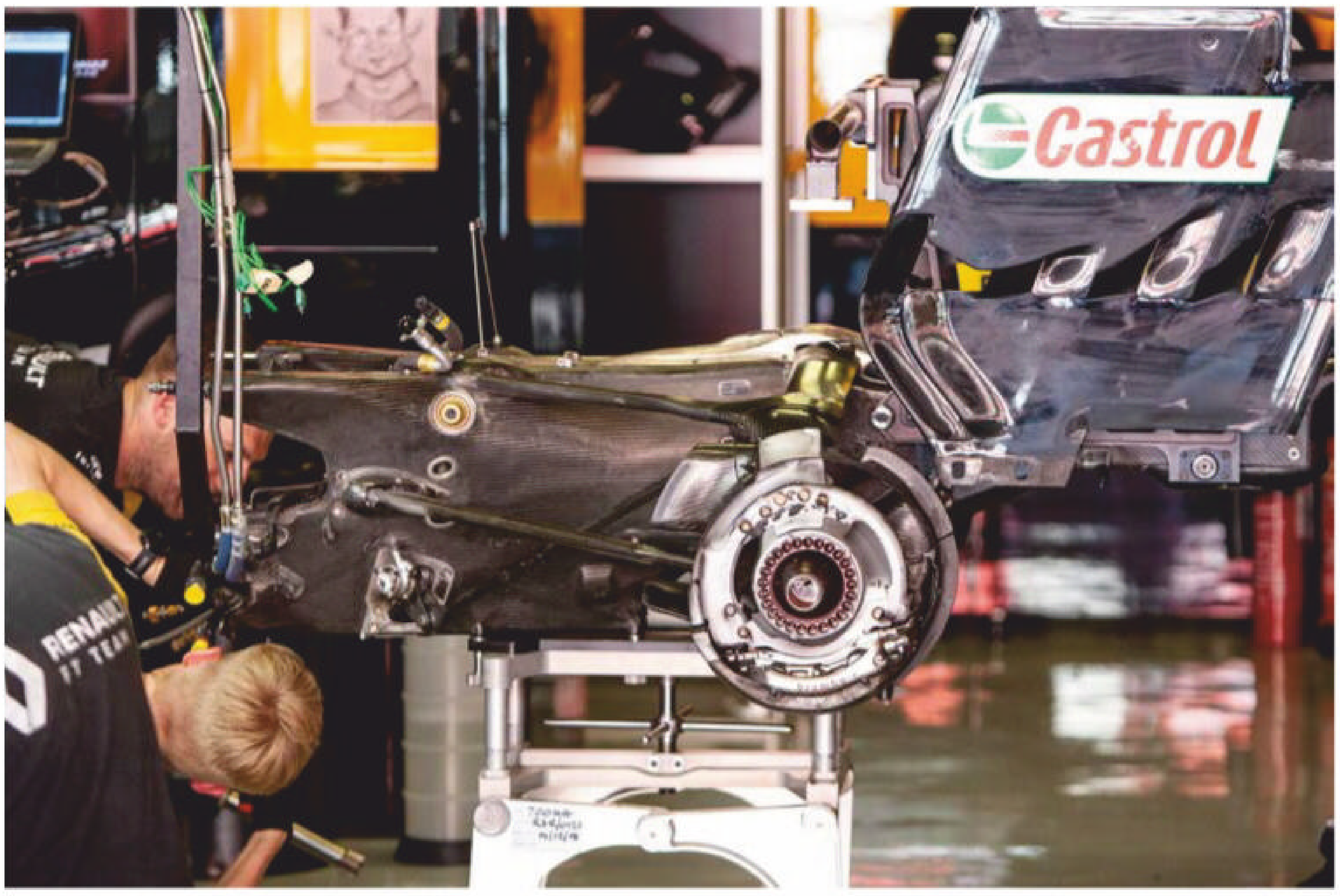
The carbon casing, seen here on the Mercedes transmission used by Racing Point, not only accepts the suspension pick ups but also houses dampers and other ancillaries

## We ascertained that the cartridge [transmission] does lend some structural strength to the outer housing




Suspension loads through the gearbox housing differ from car to car, and teams were cagey about their actual figures

Describing what constitutes a cartridge transmission, Gee explains: 'The gearbox is contained within a minimalist casing, which is then mounted within a carbon structure akin to a monocoque. The suspension would then be mounted on that and it forms the main structure at the back of the car. Fundamentally, the gearbox would fit within a carbon tube.'

The idea behind the cartridge design is that transmission and suspension loads can be separated. The internal casing has the strength and stiffness needed to ensure alignment of the gears and shafts when subject to torque loadings (both from the power unit and back from the wheels), while the 'carbon tube' handles all of the chassis loads.

However, the cartridge also has to deal with some forces from the chassis. 'In the first instance, we considered the internal gearbox loads, which would be fairly straightforward,' says Gee, continuing. 'We could design something that handled those loads and just plugged into a carbon structure that dealt with the others. Subsequent to that, we also discovered a need to ensure that some external loads that may be transmitted from the carbon structure could also be accommodated.'

To achieve this, Ricardo would have needed to know what the maximum loads might be, and that information was not forthcoming. 'Then we could have decided how the cassette would absorb those loads, and where they would be coming from. We would have then provided a cassette with a known transverse strength and stiffness, with a caveat that if you put more than this load into the mounting it might break, and for a given load it will have a certain stiffness characteristic.'

The means of mounting the cartridge into the carbon housing also required careful consideration, as every team would have its own idea of what was required. 'We discussed

common interface points with teams, otherwise you end up with a standard case with bosses everywhere. Understanding where to mount the various external elements, and where feeds and pick-ups would be, was important,' says Gee.

## Bad vibrations

A further complication reared its head in the fact that each of the current four power units has its own unique characteristics, including different harmonic signatures, according to Gee. Harmonics can, of course, be damaging if they coincide with the natural frequency of other components, an issue which can be overcome when designing a bespoke transmission. But with a one-size-fits-all approach, things become considerably more complicated.

'We had to establish a baseline where we would design the gearbox, then testing of each engine would reveal if there was a problem. You can't begin to design a gearbox that suits all of the vibration signatures of all the engines. That is a massive mathematical exercise. The design would have had to be validated for each engine.'

It was suggested that leaving the length of the transmission input shaft open, allowing its resonant frequency to be fine tuned, would be a route to alleviating any potential problems. However, Gee is not convinced that this one factor alone would be enough to accommodate all potential scenarios. 'Our experience is that beyond the input and output shafts, with the rest of the transmission's sizing down to robustness, it might not be enough leaving just one element, in this case the input shaft, to be tuned to suit each engine. There are other influential components when it comes to vibrations.'

## Cost effective

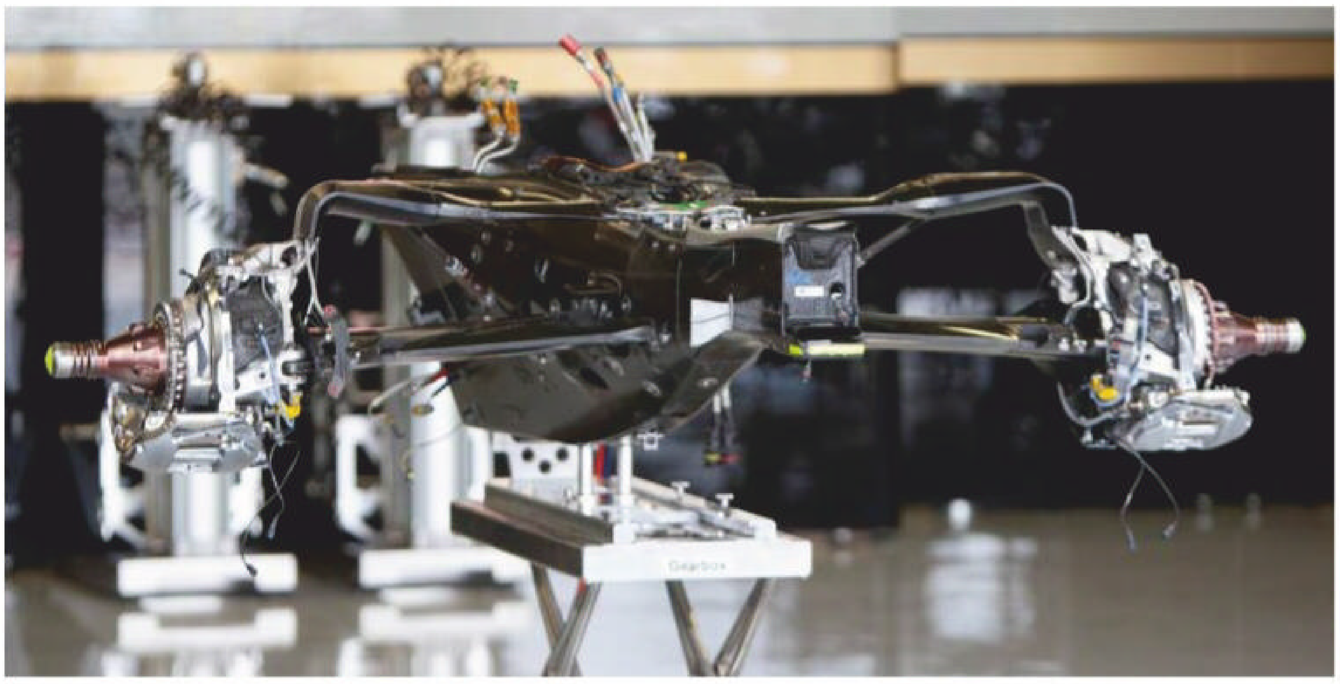
The point of any move to spec parts is cost saving, which requires a different engineering approach to simply designing for outright performance. 'We have to keep an eye on costs, questioning if we need to spend money on processes to save weight. If we could hit the target without spending lots of money on processes we would have done, whereas an F1 team would undoubtedly keep pushing. There is the old saying of show me a component and I'll show you a lighter one. And if there are no restrictions, that is the way it goes,' confirms Gee.

'As a general rule, if you design an assembly with the minimum number of parts and with the minimum number of necessary features, then you will end up with something inherently low cost and with low weight.' The costs then increase exponentially as one strives for the next level of weight reduction or efficiency, which is unnecessary if the required benchmark has already been reached.

When it came to the choice of material for the cartridge housing, thin wall cast aluminium was the most likely candidate, and Gee explains why: 'As long as everyone is having the same transmission, and if you can get within the weight, that would be cost effective. That was always our aim, until such a point that the cost needed to go up to either meet quality or weight targets. With the casing, you don't need to make it out of printed titanium, for example, if a sand-cast aluminium one will do the job.'

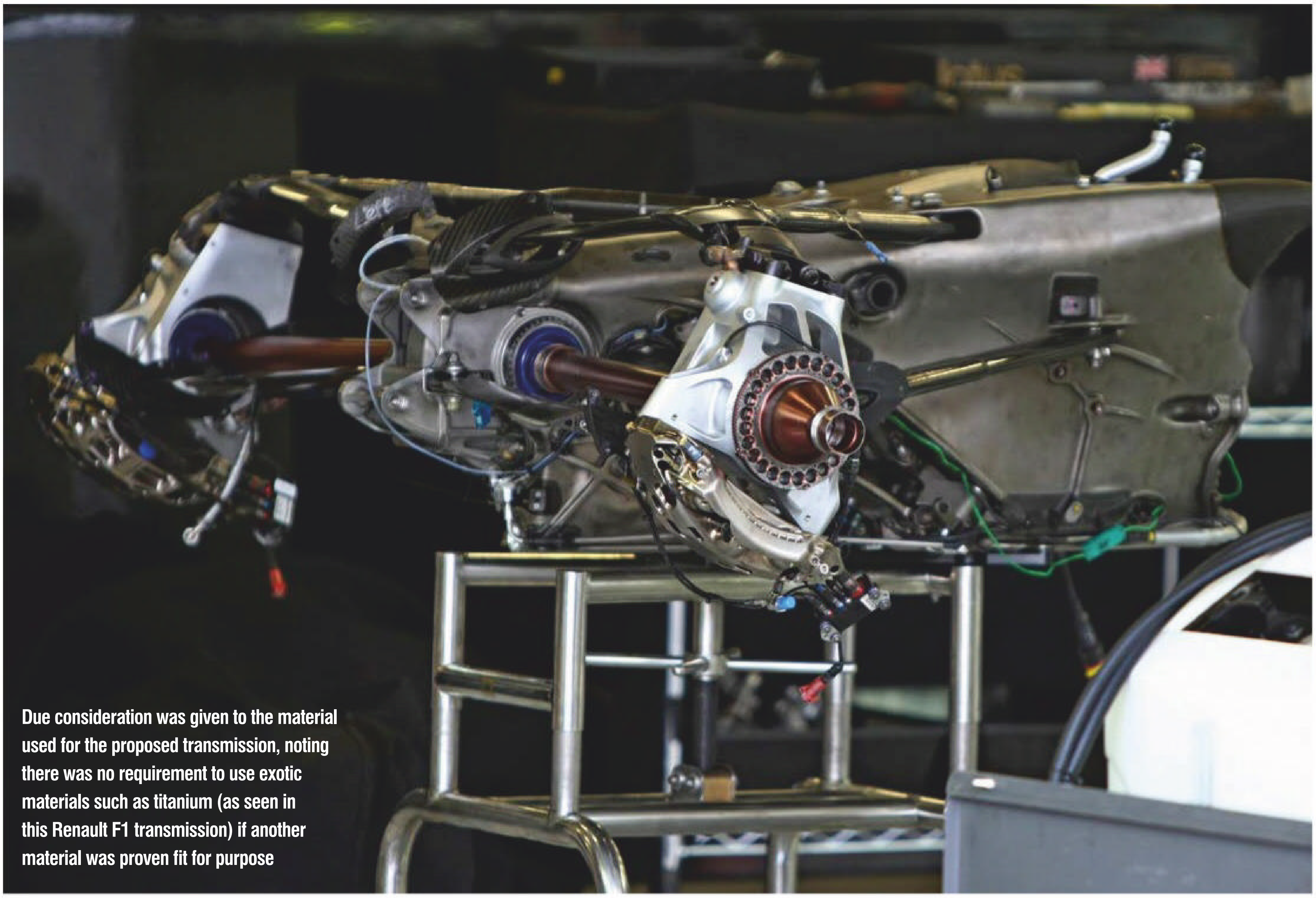
A spec transmission would by no means be cheap, but Gee is confident considerable savings could be made. 'From where we looked at it, I think the cost saving would have come from a reduction in the consumption of year-on-year parts, rather than in the upfront design costs, which are not huge in the overall scheme.'

**Further complicating matters was the fact each power unit (Honda shown) has its own harmonic signature**



**Tuning the gearbox to the harmonics of particular engines would take more than just changing the input shaft, says Ricardo**

## The cost saving would have come from a reduction in consumption of year-on-year parts



Due consideration was given to the material used for the proposed transmission, noting there was no requirement to use exotic materials such as titanium (as seen in this Renault F1 transmission) if another material was proven fit for purpose

Gee also notes the cost of individual parts for current transmissions have not risen solely due to car performance development, an ever-increasing focus on reliability has also played a role. 'Huge amounts have been spent on perfecting components and getting the quality up. We see it a lot with our make-to-print work, the emphasis on quality is very, very high.

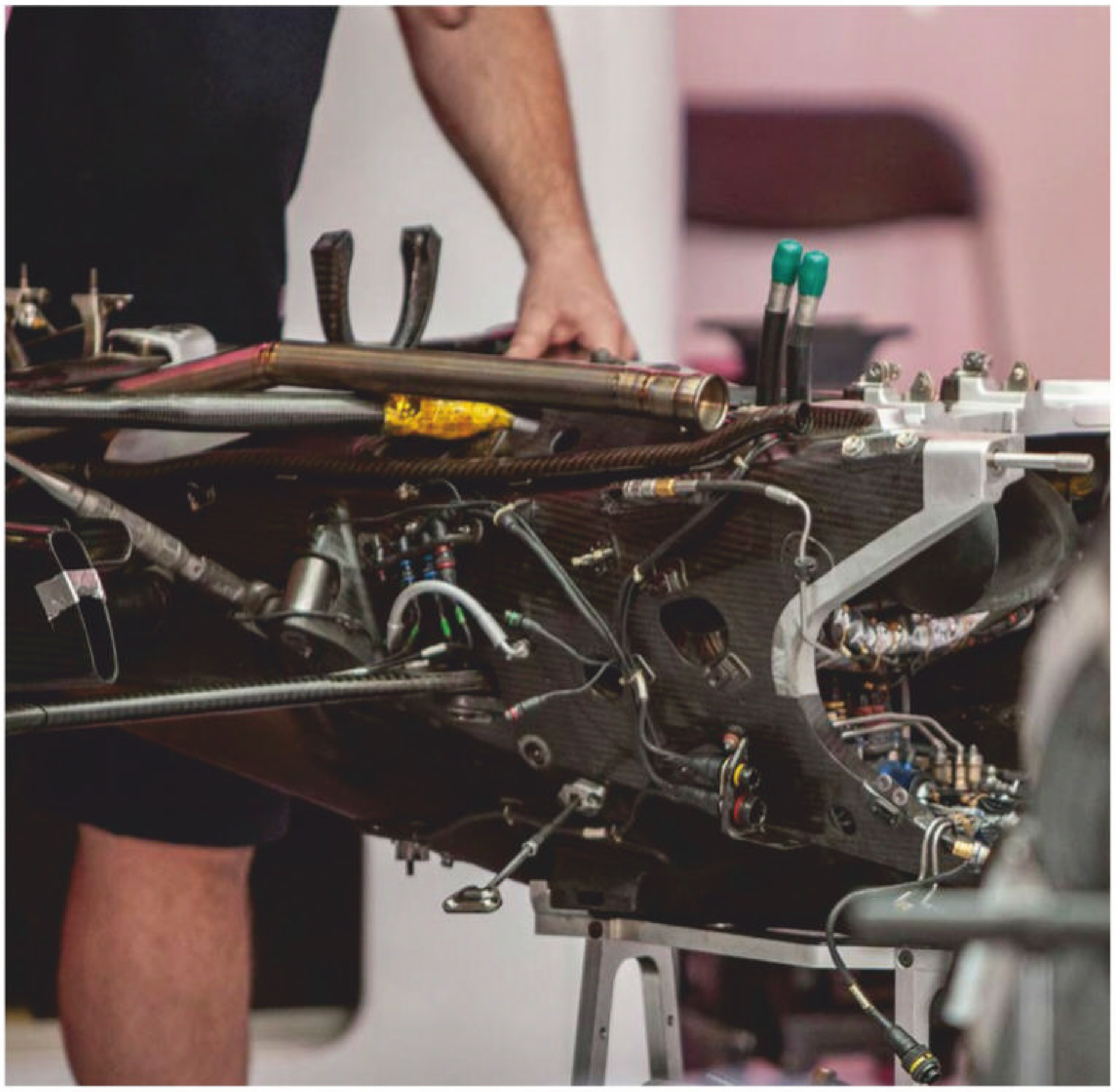
'That is something that has definitely changed over the years. Teams have invested heavily in testing for reliability. We feel the sharp end of that as a supplier as there is now huge emphasis on ensuring optimum precision.'

## Rebuild or replace?

Another important cost factor with the proposed transmission was the business model under which it would be supplied. The FIA did not specify whether transmissions would be provided on a lease or purchase basis, asking suppliers to provide business cases for both.

According to James Sundler, business development director at Ricardo Performance Products, there was also the matter of whether it was actually practical to rebuild transmissions or simply replace them at the end of their lives. While internal parts such as gears, subject to high torque loadings, would always be replaced as a matter of course, items such as casings could potentially be re-lifed.

'There were various options looked at in terms of lease or buy, and how we would / could



For a cartridge-type transmission to be suitable for use by all teams, knowledge of position of ancillaries was imperative rebuild the transmissions. But then it was a case of looking at the cost involved in a strip down, inspect, replacement of all torque path parts, rebuild, test and provide back to the team. Is the economy there to rebuild transmissions? Perhaps, but for some of the bigger budget teams, they are more likely to simply buy new.

'Balancing the differing demands of the 10 teams and their respective budgets was a complex issue to deal with, particularly on whether to re-life parts.'

Beyond the internal mechanical parts of a transmission, some of the high-cost ancillaries would almost certainly have been carried over from one to the next in order to keep development costs down, as Sundler explains: 'Parts such as the hydraulics would be transferred over as they have a longer service life than some other components.'

The transmission was set to have a shelf life of five years, though during that period both power unit and aerodynamic development would continue, changing the demands placed on the transmission.

Sundler continues: 'We made some assumptions based on information from informed parties on where not just PU performance, but also aerodynamics, tyres and brakes would likely develop, and the impact that might have on the transmission, to ensure we were protected and understand the minimum number of design changes we would need between now and then.'

But Gee is well aware that was a big unknown, so ensuring there was sufficient resilience in the initial design was vital. 'F1 engineers by their nature look for the nth degree of performance and the regulations don't completely control that. If you got to a position where one of the manufacturers found a significant performance advantage that changes the inputs to the transmission, we would have had to be very careful.'

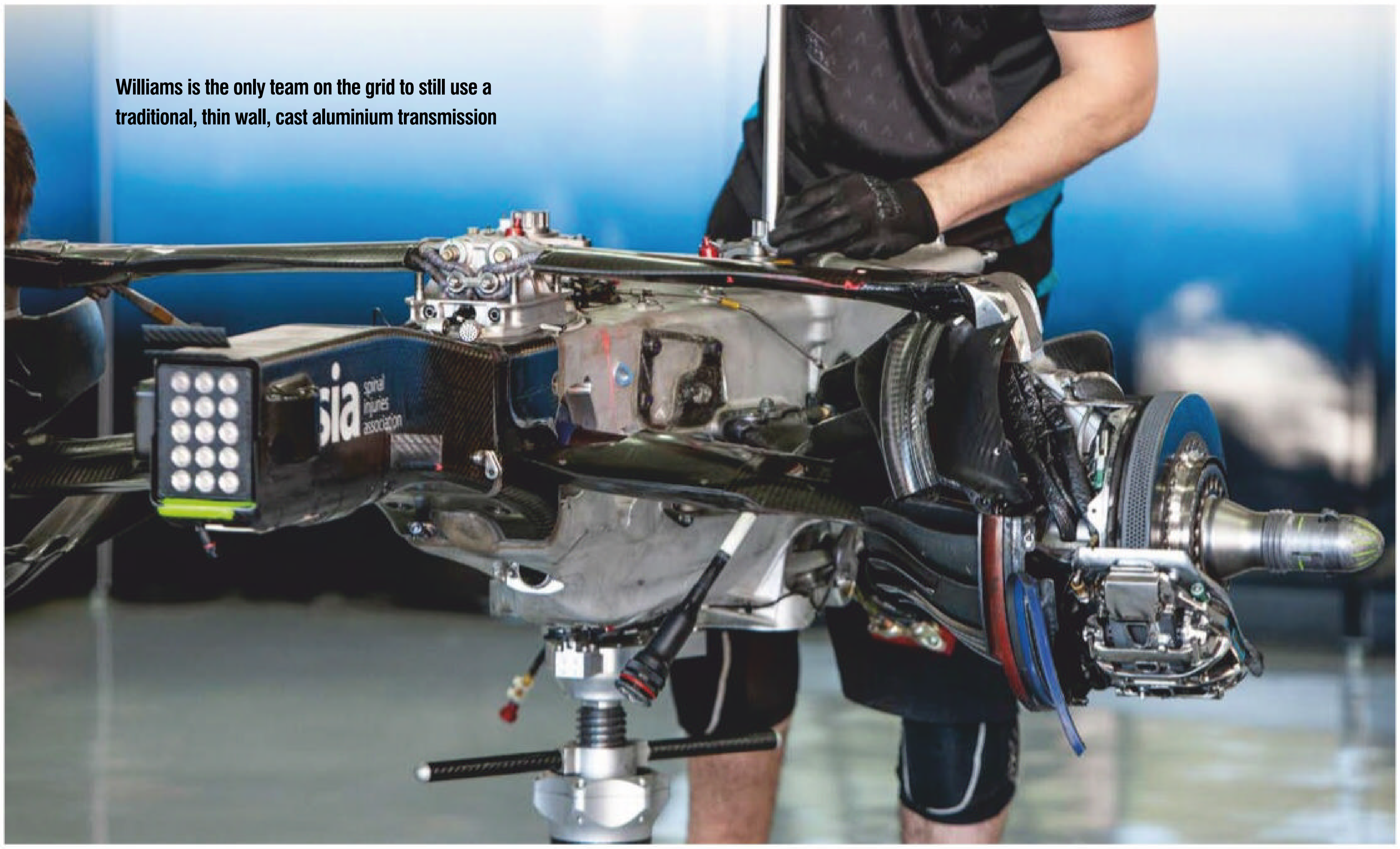
## Not to be

In the end, a spec transmission proved too much for Formula 1 and the idea was dropped before final rules were agreed. According to the FIA, '[The decision was based on] consideration of both technical and financial information made available by teams and suppliers. The technical data provided revealed that gearbox technology in Formula 1 has largely converged and that, as a result, there is little performance differentiation at present.

'It was also noted that, due to the complexity of the components, gearboxes remain a sensitive matter in terms of reliability, and this was factored into the evaluations of the FIA Technical Department.'

Additionally, it revealed that after studying financial data from teams, it was felt similar financial savings on the transmission could be made by means other than the specification of a single supplier. The result is that the current 2021 transmission rules (now delayed to 2022 following the 2020 disruption) will see tight limits on, for example, the number of updates permitted between next year and 2025.

**James Sundler, business development director at Ricardo Performance Products**




**Williams is the only team on the grid to still use a traditional, thin wall, cast aluminium transmission**

**Balancing the differing demands of the 10 teams and their respective budgets was a complex issue, particularly on whether to re-life parts**

# Shift change

**Even though Scuderia Ferrari has been part of Formula 1 since the inaugural World Championship in 1950, the number of groundbreaking cars produced in Maranello can be counted on one hand, or even one finger**

By WOUTER MELISSEN


Its influence on Formula 1,
and motorsport in general,
has been profound
Marlboro
Agip
ENIMONT
28
MAGNETI MARELLI WEBER
GOODYEAR

Despite the fact that Ferrari has failed to provide much in terms of groundbreaking technical innovation, it would not be correct to say that the team has not been hugely successful. With 16 Constructors' and 15 Drivers' World Championships, along with 238 Grand Prix victories, Ferrari is the sport's most successful team by quite a margin. Perhaps because gradual improvement of existing designs was the leading philosophy at Ferrari.

One of the main reasons for this was that only very few of the company's engineers were willing to risk failure, and with it the ire of Enzo Ferrari himself, let alone the entire population of Italy. In a country where church bells ring when Ferrari win a race, taking risks with revolutionary designs was never really an option.

Another reason why Ferrari was more conservative was that the team did everything in house, so it could not buy off-the-shelf technology when someone had a better idea.

One of Ferrari's more adventurous chief engineers was Mauro Forghieri. He took over at a very young age after the team's top technical people walked out over a dispute with Enzo. Mind you, this was at the end of 1961, when Ferrari had just won the Formula 1 World Championship and the 24 Hours of Le Mans outright for the second year running.

Having to fill the void left by the likes of Carlo Chitti and Giotto Bizzarrini, Forghieri set out to design an exquisite 1.5-litre, 180-degree, 12-cylinder engine. It was not an immediate success and Forghieri was eventually fired.

In 3.0-litre form, the engine did result in a pair of Sports Car World Championships and three Formula 1 World Championships for Niki Lauda and Jody Scheckter.

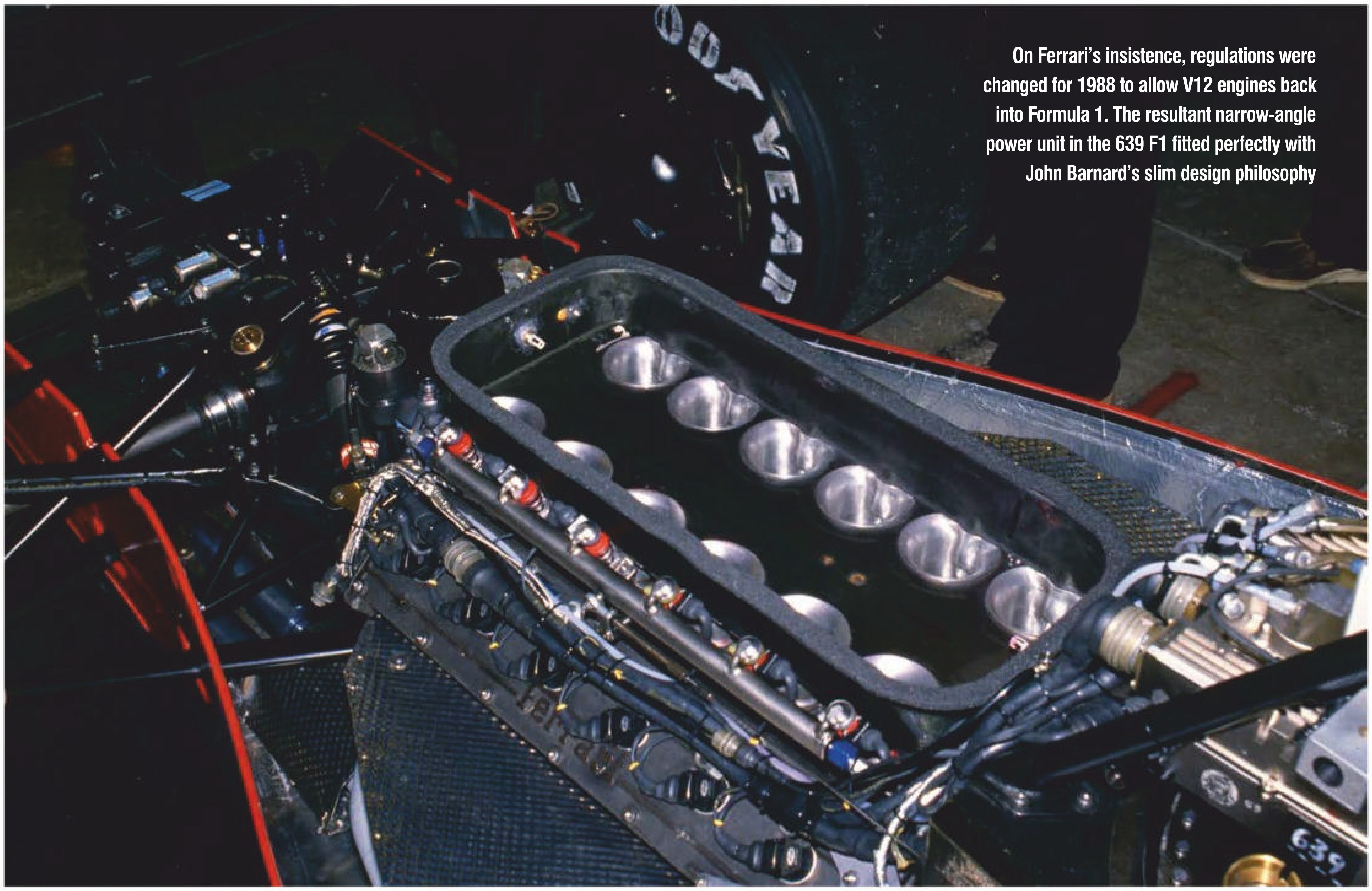
The real success in Formula 1, however, only came after Enzo Ferrari brought Forghieri back into the fold. The engine really came on song when it was paired with the Italian engineer's transverse gearbox. Bolted to the suitably named 312 T (for *transversale*), the drivetrain was successful from 1974 through to 1979.

Buoyed by the success of the 312 T series, which, as Ferraris did, gradually evolved from the 312 T through to the 312 T5, Forghieri started experimenting with a gearbox that was operated by paddles behind the steering wheel rather than a conventional stick placed to the right or left of the driver. It was tried on the 312 T3 of 1978, but quickly determined that to make the system work sufficiently well, more sophisticated electronics were required than were available at the time. The project was set aside as the team became preoccupied with adopting revolutionary engineering ideas pioneered by other teams such as ground-effect aerodynamics, turbocharged engines and carbon-fibre composite monocoque chassis.

Ferrari caught up with most of these, resulting in a pair of Constructors' titles in 1982 and 1983, but lost ground as manufacturers such as Renault, BMW, Porsche and Honda came to claim their stake in the sport.

## A bit of English

Drastic measures were required to return Ferrari to the front, and Englishman John Barnard was hired to design an all-new Grand Prix car to meet the new rules that would come into effect in 1989. Barnard's impressive resume included the 1980 Indy 500-winning Chaparral 2K, which brought ground-effect to North American single-seater racing, and the McLaren MP4, the very first Grand Prix car built around a carbon-fibre composite monocoque. His services were in such high demand that Ferrari hired him despite his desire to work from England.



On Ferrari's insistence, regulations were changed for 1988 to allow V12 engines back into Formula 1. The resultant narrow-angle power unit in the 639 F1 fitted perfectly with John Barnard's slim design philosophy


Though the ingredients were all there for success, teething problems on its debut meant the 639 F1 was not raced in 1988, but in 1989 Gerhard Berger (shown) and Nigel Mansell in the evolved 640 F1 gave Ferrari its most successful season since 1983

## An aerodynamic problem could be solved by designing a new gearbox actuation mechanism

To that end, Barnard established the Ferrari Guildford Technical Office in early 1988. Far away from the prying eyes of the Italian media, Barnard started his work with an engineering team led by fellow Brit, Dr. Harvey Postlethwaite.

The most significant change in the regulations was a return to atmospheric engines only, with a displacement limit of 3.5 litres. Wheeling its influence, as the team does to this day, Ferrari helped shape the new regulations to ensure V12 engines would be allowed (in fact, Ferrari had threatened to leave Formula 1 by building a fully functioning IndyCar).

An interim year was agreed upon and new, 3.5-litre cars could be raced alongside the pegged back turbo Grand Prix cars in 1988. Barnard's task, therefore, was to build a car that would be tested in 1988 and could potentially be raced late in the year in lieu of the F1-87/88C. This, of course, being an evolution of the turbocharged car raced during the 1987 season.

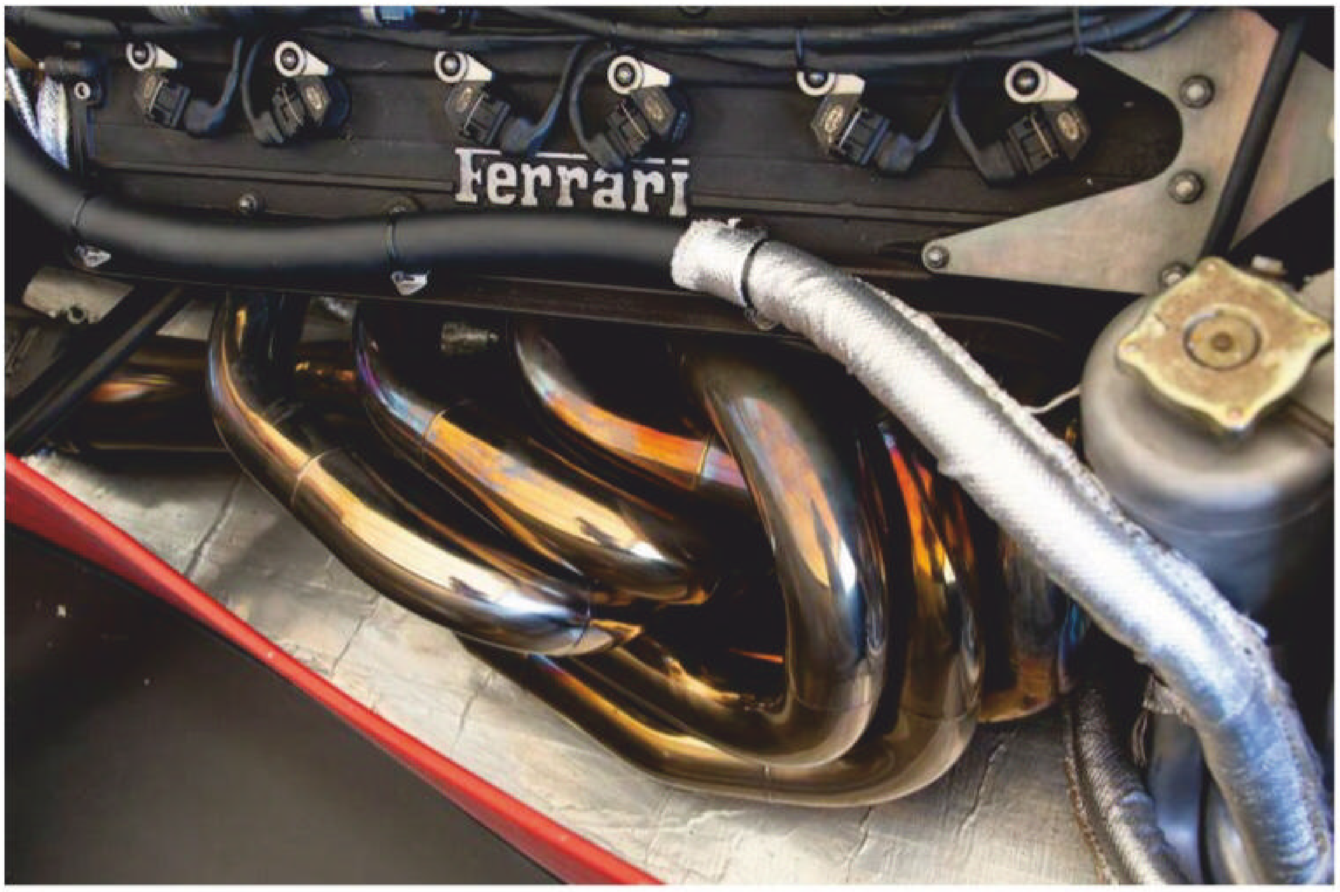
## Narrow minded

Thanks to the massive amount of power produced by the forced induction engines, drag was never really an issue in the turbo. This allowed the aerodynamicists to fit massive front and rear wings with little concern for the consequences. But the new regulations placed a renewed emphasis on aerodynamic efficiency as a significant drop in power was expected. Barnard recognised this and set about creating a car that was as clean, and narrow, as possible.

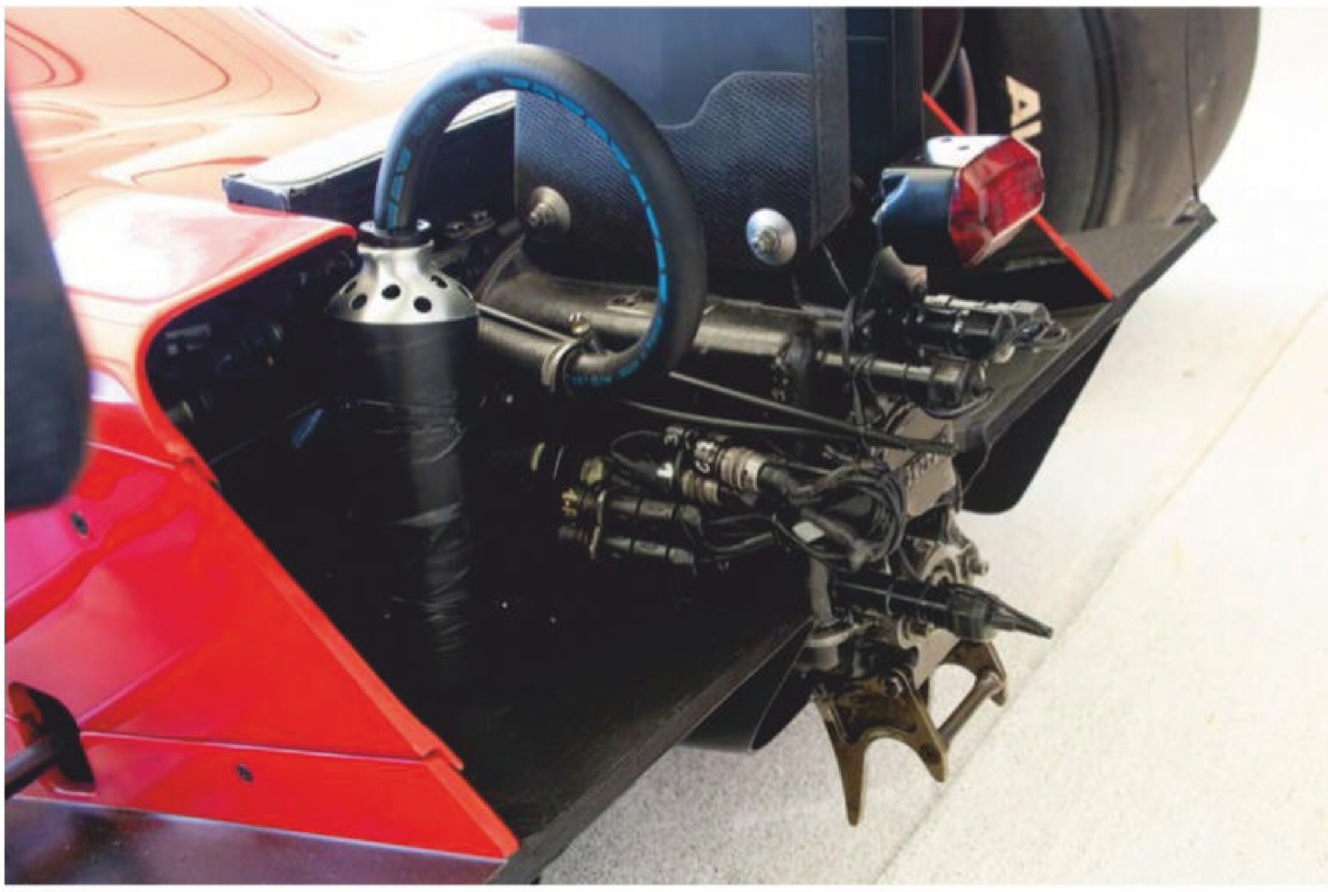
One of the interruptions to airflow he was keen on removing was the bulge on the right-hand side of the cockpit that was required to clear the gearshift lever. The paddle idea Forghieri had played with a decade earlier now proved to be the solution. Making the most of Ferrari's unique situation as manufacturer of every major component, an aerodynamic problem could be solved by designing a new gearbox actuation mechanism.

Working with specialist Magneti Marelli the Ferrari engineers ensured this time round the electronics would be up to the task. Although no longer using the conventional H-pattern gearshift lever, it was by no means a fully automatic gearbox. Using an electro-hydraulic system to disengage the clutch and change

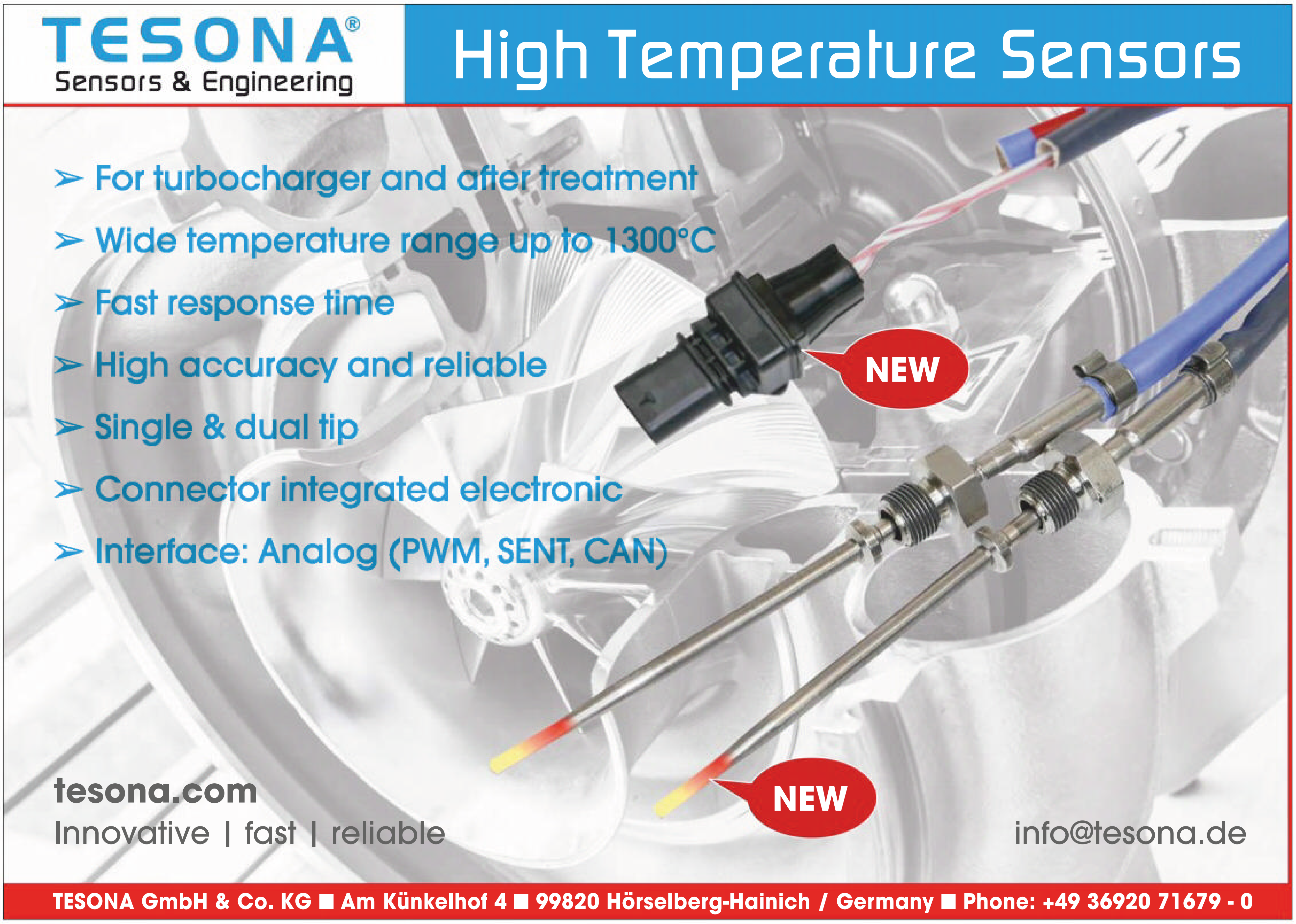

**The 1988 639 which was tested and never raced still had conventional coil springs, which were replaced by vertically-mounted torsion bar set up on the 640 F1 which took part in the 1989 season with varying degrees of success**




**Claudio Lombardi-designed, 3.5-litre, naturally-aspirated V12 was a departure for Ferrari, having five valves per cylinder**



**The numerous and complex hydraulic connections that actuated the revolutionary seven-speed gearbox**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gears, the paddles behind the steering wheel allowed the driver to shift up (right-hand side) and down (left-hand side). The clutch could also be manually operated, which was only needed to pull away from standstill.

The system also ensured the throttle was cut on upshifts and 'blipped' on downshifts. The new gearbox, although relatively conventional in design, was the first in Formula 1 to use seven forward gears. This allowed for closer ratios, which helped get the most from the atmospheric engine's narrower power band.

## Political games

Considering the political games played to ensure it would be allowed, it was no surprise that Ferrari's new atmospheric engine was a V12. Designed by Claudio Lombardi, it was unlike the V12 engines Ferrari had become famous for as it featured a head with five valves per cylinder. Actuated by a pair of overhead camshafts, three valves sat in the intake ports while the other two were for the exhaust. The Tipo 035 V12 had a relatively short stroke and, at 3,498cc, came in just under the displacement limit.

The cylinder banks were installed at a 65-degree v-angle on the block and, revving to 12,500rpm, the new Ferrari engine was officially rated at 600bhp. By comparison, Ferrari's 1987, twin-turbo V6 could produce as much as 950bhp in qualifying trim. The V12 also fitted snugly in Barnard's slim design philosophy as, while it may have been longer, it was also narrower than the contemporary V8s and V10s designed by Ferrari's rival engine builders.

Known internally as the 639 F1, the first Ferrari Grand Prix car designed by Barnard was built around a narrow but relatively tall carbon-fibre composite monocoque. On all four corners the suspension consisted of double wishbones with coil springs and dampers actuated by push rods. As was the norm, radiators were mounted alongside the cockpit in sidepods, which were fed through narrow but tall intakes. The sidepods were tightly wrapped around the car's mechanicals, mimicking the shape of a Coke bottle in plan view. This was a design first used by Barnard while he was still at McLaren.

Split in two sections, the front wing was mounted on either side of the Ferrari's sharp nose. The rear wing was mounted on two pylons that were bolted to the top of the gearbox and the engine was fed by two small intakes just behind the cockpit on either side of the roll bar.

## Teething issues

The ultra-clean Ferrari 639 F1 was ready for testing during the 1988 season. It was a year absolutely dominated by McLaren, who would go on to win 15 out of the 16 Grands Prix that year. To make matters worse, Enzo Ferrari died that summer, just weeks after his 90th birthday.

As with any new Ferrari, but perhaps now more than ever before, there was a lot riding on the new V12-engined machine. Sadly, there were teething issues that plagued the car during testing. This did not go unnoticed, and the Italian media were quick to point the finger at the Englishman who had refused to come to Maranello to design the car 'properly'.

Development work continued, but the 639 F1 ultimately was not raced in 1988. Gerhard Berger provided small consolation by winning the Italian Grand Prix for Ferrari in September, a fitting tribute to Enzo Ferrari.

## Lessons learnt

Incorporating the lessons learnt with the two 639 F1s used in testing, Ferrari built the 640 F1 for the new season. Also known as the F1-89, the car followed much the same lines as the un-raced 639s, though a significant difference was the front suspension, which now featured torsion-bar springs. Mounted vertically inside the monocoque, they were connected directly to the push rod pivot. With only dampers now mounted on top of the monocoque, shallower still bodywork could be fitted.

While the 640 F1 initially sported the laterally-mounted air intakes, later in the year a tall air box was fitted, which allowed for a narrower engine cover. With water and oil, the 640 F1 weighed in at the set minimum of 505kg.

The services of driver Gerhard Berger had been retained for the new season. His 1988 co-driver, Michele Alboreto, had been replaced by Nigel Mansell. At the season-opening Brazilian Grand Prix, Berger was out with accident damage after a desperate dive down the inside


The Coke-bottle shape of the rear end is evident. With the demise of turbos, designer, John Barnard, placed aerodynamic efficiency above everything else

**This was the first [gearbox] in Formula 1 to use seven forward gears**

## Ferrari 639 F1


**The second of two examples of the 639 F1 built, this car was used for testing during the 1988 season, and also in preparation for 1989 with Grand Prix drivers Gerhard Berger and Nigel Mansell, along with test driver Roberto Moreno, doing the driving duties.**

**Never raced, it was sold by the factory to an Italian enthusiast in 1999. Then, through Mike Sheehan's Ferraris Online, it was sold to the current Austrian owner in 2016. Prepared by ex-factory mechanics, it was demonstrated at the 2019 Goodwood Festival of Speed, alongside the 640 F1 that is in the same collection.**

## Ferrari 640 F1


**Ferrari built seven 640 F1s for the 1989 season, and this particular car was used by Gerhard Berger during five Grands Prix. Typically for Berger's season, this car did not reach the finish in any of those five races, although he scored three podium finishes in another chassis. Following its short active racing career, this car remained a static display until 2011 when it was rebuilt to full running order by Ferrari Classiche. As an ex-Berger car, it is now in the hands of the same Austrian motorsport enthusiast who owns the un-raced 639 F1.**

of McLaren's Ayrton Senna to try and grab the lead. Mansell was more sensible and stayed out of trouble. To the surprise of most in the paddock that day, his Ferrari also lasted the distance and, despite having to replace a loose steering wheel during the second and final pit stop, Mansell scored a debut victory with the revolutionary 640 F1. It seemed like Ferrari's leap of faith had paid off, but the debut victory proved to be a fluke and it would take until the seventh race of the season before a Ferrari would reach the finish again.

In addition to the mechanical issues, a broken front wing saw Berger crash at high speed during the second race of the year at Imola. Still full of fuel, the Austrian driver's Ferrari burst into flames on impact and, briefly knocked unconscious in the incident, Berger was lucky to walk away with only minor burns.

## What started as an aerodynamic solution now makes drivers' lives easier

With the help of Niki Lauda's physical therapist, he was able to recover in time for round four of the championship in Mexico. Berger later admitted the only reason he could race again so soon was thanks to the paddle-shift gearbox, which made driving considerably less demanding on his injured body.

Due to the reliability issues, Barnard and his convention-defying design remained the subject of much debate in Italy. As it turned out, he was not to blame for the most crucial of problems. That was down to the battery not being able to supply enough power to operate the system, resulting in intermittent shifting issues. Once a more powerful battery was fitted, the car proved to be more reliable and Mansell scored a couple of third place finishes, two seconds and a victory, while Berger also finished second twice and bagged a single win. Ferrari ended the year third, in what was the team's most successful season since 1983.

For Barnard, the vitriol proved too much and he left the team, joining Benetton for the 1990 season. In good Ferrari tradition, the existing design gradually evolved during the next couple of years, but this meant the team gradually dropped down the order.

Underlining the car's potential, and proving the merits of Barnard's ideas, the 640 F1 finished on the podium each time it reached the finish. Its influence on Formula 1 and motorsport in general has been profound. What started as a solution for an aerodynamic problem was eventually universally adopted to make drivers' lives easier. By 1996, all Formula 1 cars were fitted with a version of the revolutionary paddle-shift system, and of today's generation of professional racecar drivers there are few that learned their trade on a car with three pedals and a conventional stick shift.

The 640 F1 also went on to shape Ferrari's sportscar business, as an evolution of the 60-valve V12 was used for the hugely successful 333 SP prototype racer, and also powered the F50 supercar. In 1997, Ferrari completed the technology transfer of the 640 F1 with the introduction of the F355 F1. This car combined the paddle-shift gearbox with a V8 engine that featured the five-valve-per cylinder heads pioneered on the 1989 Grand Prix car.


Michael Sheehan – Ferraris Online

**Working with Magneti Marelli, Barnard reprised Forghieri's paddle shift concept but with electro-hydraulic actuation**


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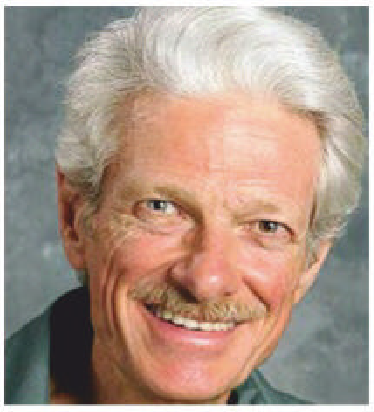

# Differential essentials

## Explaining the basics of unequal torque split differentials, and the various methods of achieving that split

**By MARK ORTIZ**

**Q Exactly how does a differential work, and what does it do? Why is it that a car with an open differential spins the right rear wheel upon acceleration? Does the differential send more torque to that wheel? If not, what causes that?**

**Also, I have heard that sometimes you can free a stuck car by applying the parking brake. Is that true? If so, how does it work?**

## THE CONSULTANT

A differential is a gear mechanism that transmits the torque from a single input shaft, or gear, to two output shafts, and splits the input torque evenly between the two (or in some other fixed proportion), while allowing the output shafts to turn at differing speeds.

This is necessary, or at least highly desirable, so a car can turn corners freely without the drive tyres scuffing, creating drag and trying to prevent the vehicle from turning.

In some cases, frictional elements are introduced to modify the device's fundamental characteristics. Let's first consider the operation of a differential without such additions, which is known as an open differential.

The term differential is sometimes understood to denote the entire final drive unit, or center section of an axle, including the ring and pinion gear set or its equivalent. More correctly, the differential is just the portion of the final drive that transmits power from the ring gear to the axle shafts. The ring gear is not part of the differential, but a separate part that attaches to and drives the differential.

The most common style of differential uses bevel gears, as shown in **Figure 1**. The housing, which is only shown schematically, is what the ring gear bolts to and drives. It encloses the differential side gears and differential pinion gears, also called spider gears, and has holes or windows to allow splash lubrication. Sometimes there are four spider gears.

The axle shafts can turn at different speeds, but the vector sum of their rotational velocities with respect to the ring gear (in other words, their velocity differences from ring gear

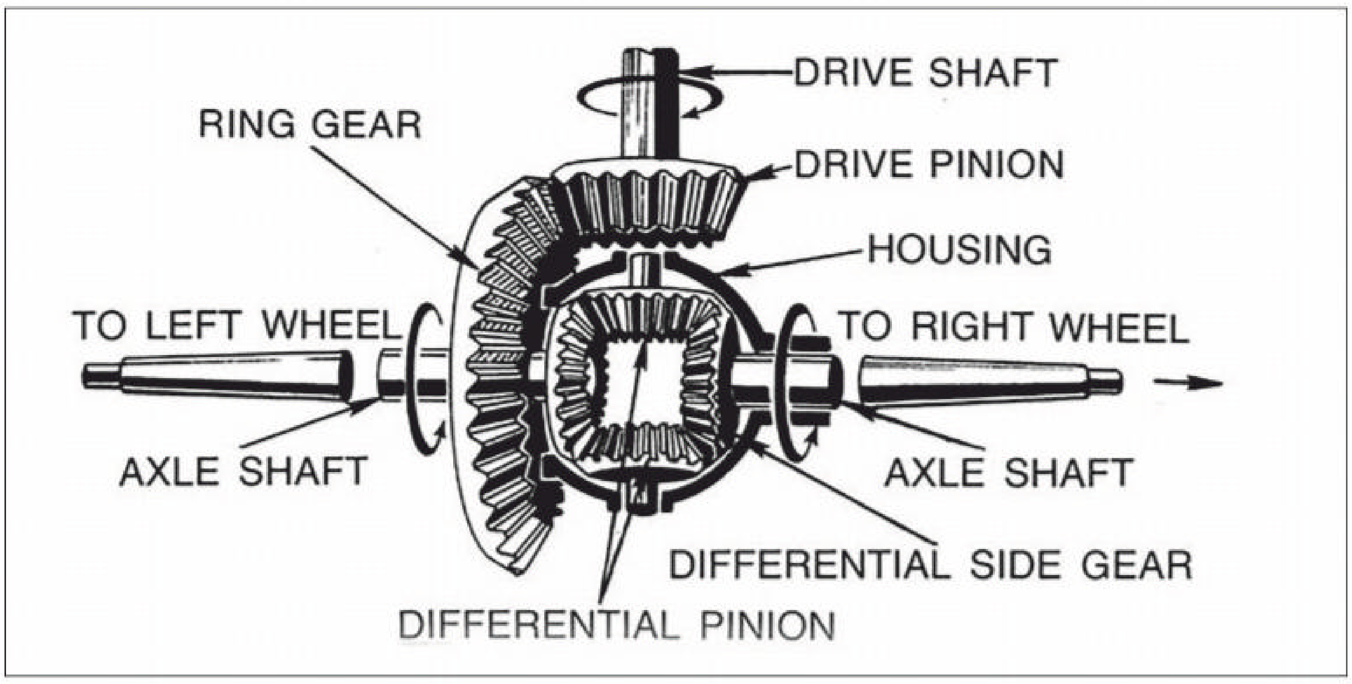


**Figure 1: Schematic of an open differential, showing the component parts, and those that attach to it**

velocity) has to be zero. If the ring gear is held stationary, and we turn one of the output shafts, the other output shaft will turn the other way at the same rpm, hence the vector sum of the output shaft velocities is zero.

If the ring gear is turning, that velocity is added to the output shaft velocities, but if one of them is turning slower than the ring gear, the other has to turn faster than the ring gear by the exact same amount.

Regardless of the velocities of the output shafts, they both receive the same torque. Since power is the product of torque and rpm, that implies whichever output shaft turns faster receives more power, but not more torque.

When we are in a situation limited by traction, the maximum torque the system can deliver is two times the torque the wheel with the lesser traction can transmit.

It is true that most rear-drive cars with live axle rear suspension and open differentials will spin just the right rear wheel under power. This is not because the right wheel is receiving more torque, but the result of driveshaft torque acting through the suspension and creating what we call torque roll and torque wedge – the situation where the car rolls to the right, and the right front and left rear wheels gain load, while the left front and right rear lose load. The right wheel therefore spins first because it has less dynamic loading.

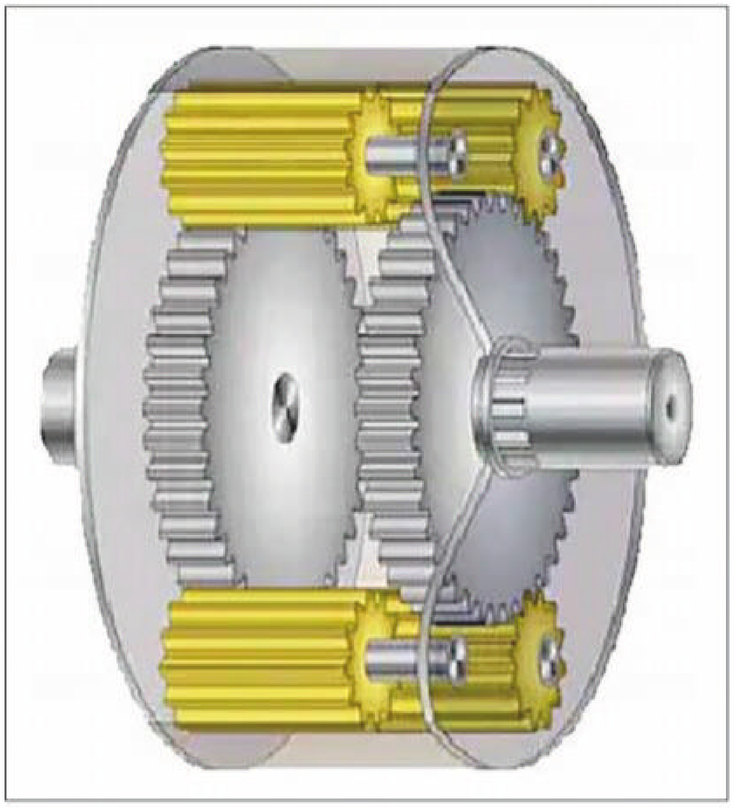

**Figure 2: A parallel-pinion epicyclic differential**

Cars with independent, or DeDion, rear suspension do not exhibit this characteristic.

## Epicyclic differential

Another design is the epicyclic differential. This concept can take several forms, one of which is shown in **Figure 2**. I call this a parallel-pinion epicyclic layout, for lack of a standardised term.

In this design, the housing that the ring gear, or similar element, drives is the outer shell.

**The axle shafts can turn at different speeds, but the vector sum of their rotational velocities with respect to the ring gear has to be zero**

This in turn drives the pinion gears, shown in yellow. The side gears are driven by the pinions and can turn with respect to the case, just as in the first design. It is common in this type of differential to have three sets of pinions.

When both side gears are the same size, and all the pinion gears are the same size, this design transmits equal torque to both output shafts, just like the bevel gear design.

It is also possible to make a conventional planetary epicyclic gear system serve in the same way as a differential. **Figure 3** shows a conventional planetary system with a sun gear, three planet gears and an internally toothed annular gear, or ring gear.

To make this serve as a differential, we feed input power to the planet carrier (shown in red) and connect the two output shafts to the sun gear (dark green) and annular gear (light green). This design will always produce an unequal torque split between the output shafts, the torque to each being directly proportional to the pitch diameter, or to the number of teeth, of its gear.

## Torque split

The system in the illustration has a sun gear about half the diameter of the annular gear, so the shaft connected to the annular gear would receive about twice the torque of the one connected to the sun gear: a 67 / 33 torque split. This sort of torque split is often desirable for a centre differential in a high performance pavement car with full-time all-wheel drive, generally with the greater torque going to the rear wheels to compensate for rearward load transfer and to allow throttle steering.

In this case, if we hold the input shaft stationary and turn one output shaft, the other output shaft will turn the opposite way, as with any differential, but not at the same rpm. In this case, the rpm ratio will be the inverse of the output torque ratio because the shaft that gets the lesser output torque turns faster.

For example, if we turn the sun gear one revolution with the planet carrier held stationary, the annular gear turns half a revolution the opposite way. This inverse proportionality rule holds for any design of differential providing an unequal torque split.

When the input shaft is turning and the output shafts are turning at different speeds, the weighted sum of the output shaft velocities with respect to the input equals zero. The vector velocity of one output shaft, times its share of the torque output, plus the vector velocity of the other output shaft, times its share of the torque output, equals zero.

For the case we've been considering here, if we have a 100rpm input and the sun is turning 50rpm, the annular gear is turning 125rpm, not 150rpm. The output shaft that receives twice the torque of the other has half as much rpm difference from the input speed, in the opposite direction.

# [The] inverse proportionality rule holds for any design of differential providing an unequal torque split

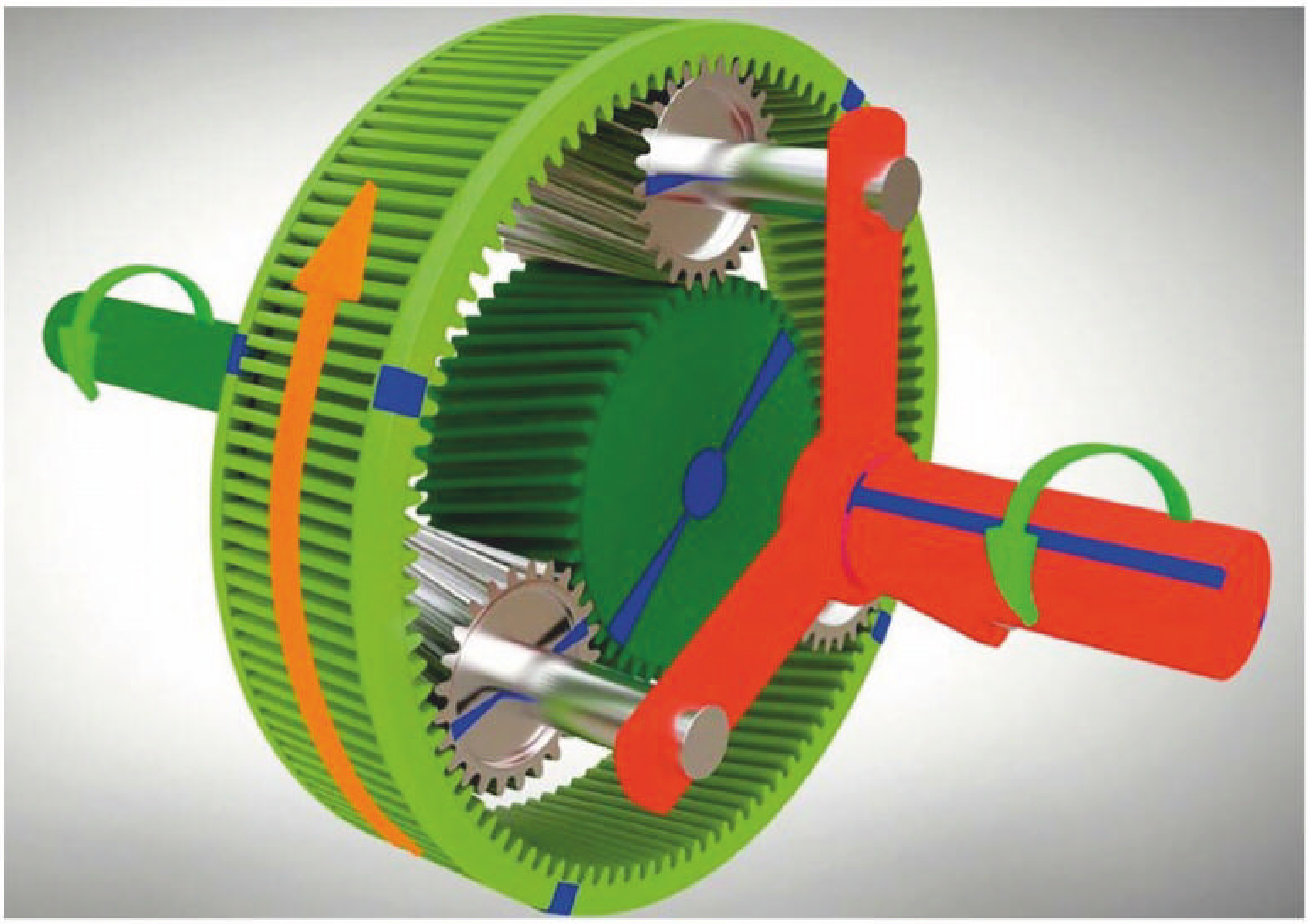

**Figure 3: A conventional planetary differential with sun gear, three planet gears and an internally toothed ring gear**

We can use this rule to design a parallel-pinion epicyclic differential with unequal torque split, which in many cases will have a smaller diameter and package more conveniently. Each of the pinions shown in the illustration can really be two gears on a common shaft, with a different diameter where this meshes with the side gear than where it meshes with its mating pinion. The mating pinions don't have to be identical, the side gears can be different sizes.

When we hold the carrier stationary and turn only one output shaft, we are turning the other output shaft the opposite way through three gear ratios in series – two where pinions mesh with side gears, and one where pinions mesh with pinions. The overall ratio will therefore be the product of the three.

But despite this added bit of complexity, the same inverse proportionality rule applies, with the overall ratio being the one that matters.

## Special case

Actually, the bevel gear differential can be thought of as a special case of the planetary design, in which the sun gear and the annular gear are ingeniously arranged to have the same size. And theoretically at least, we could make a bevel gear differential with unequal torque split, too. This would involve having different size side gears, and pinion gears at an oblique angle. This is not a very attractive engineering approach, and I don't expect to see anybody do it, but nevertheless it's a theoretically possible scenario.

All the possibilities we have been considering in this discussion provide a fixed torque split, while freely permitting output shaft speed differences of any magnitude. For a wide range of situations, this is all we need.

However, as a rule the speed differences we need to accommodate during normal manoeuvres on road or track are small. Larger speed differences are usually the result of drastic traction differences, due either to one or more wheels being on a slippery surface, or to large dynamic variations in wheel loading. For this reason, we sometimes need to adopt designs that physically limit speed differences in various ways. We'll take these up in detail next month, along with the question of the use of parking brakes to free stuck vehicles, which actually can and does work in certain situations and relates to other ways of limiting wheel speed differences.


### CONTACT

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# WAGs and dives

## We continue our latest wind tunnel project on our Escort RSR racer with an ongoing quest for aerodynamic balance

**By SIMON McBEATH**

This SHP Preparations-manufactured, spaceframe chassis, GFRP bodywork-clad Mk1 Ford Escort RSR with a 320bhp, 2.5-litre Duratec engine, is prepared by MEM Motorsport and campaigned by owner / driver Tim Foxlow in a saloon and sportscar championship in northern England and Wales.

Driver feedback and visual impressions suggested a car with a rearwards downforce balance, so we headed for the MIRA full-scale wind tunnel with two alternative rear wings and a range of front-end parts to evaluate.

In our previous issue we saw the first run in the wind tunnel show not just a rear downforce bias, but significant front lift. However, by session's end the car had reasonably well balanced downforce. **Table 1** shows the starting numbers, the ultimate 'best balanced' numbers and the interim stage described in the last issue with wing angle reductions and a longer front splitter with simple diffusers. These modifications had all but eliminated the front lift, but there was still quite some way to go.

In this issue we outline further changes implemented to obtain that balanced set up.


Installing wheelarch Gurneys (WAGs) for testing

Illustrations: Simon McBeath

**Table 1: Initial and 'best' aerodynamic numbers, plus the interim values highlighted in our previous issue**

| | CD | CL | CLfront | CLrear | %front | -L/D |
|---|---|---|---|---|---|---|
| Initial | 0.474 | -0.202 | +0.163 | -0.365 | -80.4% | 0.427 |
| Interim | 0.455 | -0.277 | +0.039 | -0.315 | -13.9% | 0.608 |
| Best | 0.495 | -0.447 | -0.200 | -0.246 | 44.8% | 0.902 |

**Table 2: The effects of 'WAGs', with changes in 'counts', where one count = coefficient change of 0.001**

| | CD | CL | CLfront | CLrear | %front | -L/D |
|---|---|---|---|---|---|---|
| Without | 0.455 | -0.277 | +0.039 | -0.315 | -13.9% | 0.608 |
| With | 0.479 | -0.338 | -0.027 | -0.311 | 8.0% | 0.705 |
| Change | +24 | +61 | +66 | -4 | +21.9%* | +97 |

* Changes in %front are absolute, not relative.

**Table 3: The effect of splitter end fences. NB lift coefficients were all now negative**

| | CD | CL | CLfront | CLrear | %front | -L/D |
|---|---|---|---|---|---|---|
| With | 0.494 | 0.378 | 0.067 | 0.312 | 17.6% | 0.764 |
| Change | +15 | +40 | +40 | +1 | +9.6%* | +59 |

* Changes in %front are absolute, not relative

## More front

The modified splitter had been provided with sideways extensions of around 50mm so that further changes known to be generally effective at adding front downforce could be implemented. The first of these was the wheelarch Gurney, or 'WAG'. The ones applied here were wide, relatively aggressive devices, but in light of the amount of tyre visible from the front, and the shape of the front wheelarch, they blended nicely with the overall shape. **Table 2** shows the results gained.

The WAGs were quite potent devices then, producing the biggest single incremental change to downforce of all the front end modifications tried in this session. Clearly drag increased too, by just over five per cent, and the downforce-to-drag ratio at 66 counts of front downforce for 24 counts of drag (= 2.75:1) was not very efficient. However the car now had actual front downforce, so the result was accepted in the knowledge it was one of the things that could be used or not, depending on the final outcome of the session.

Another simple modification that generally bears fruit at the front end of a closed-wheeled car is a splitter end fence. Again they are not always the most efficient devices, but front downforce gains can usually be achieved, and different size and shape fences are easily made for fine tuning. One variation was evaluated next, with the results shown in **Table 3**.

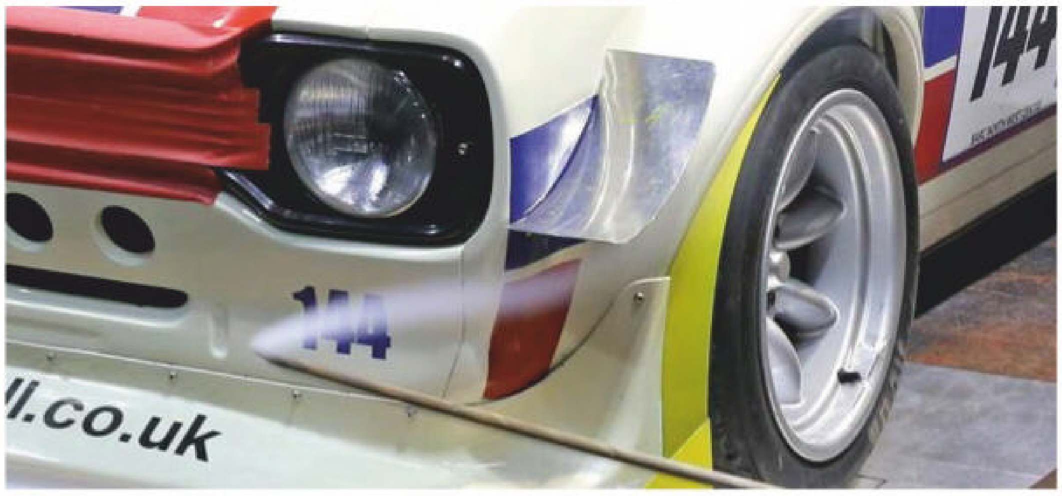
Another 40 counts of front downforce was obtained with this modification, this time for 15 counts of extra drag (-L/D change 2.66:1). As expected, efficiency was not great, but overall balance was improved further still.

The final bolt-on, front-end downforce generator applied was a pair of dive planes. The shape of the wheelarch extension necessitated that these be fairly short and aggressively curved, but the hope was that the existing


End fence added to WAG

wheelarch extension would help prevent stall on the dive plane's lower surface. The results in **Table 4** suggest this was the case, confirmed by the smoke plume later.

It is very unusual for dive planes to bring their expected front downforce increase with no drag penalty, but in this instance the drag actually *decreased* by one count. We'll chalk that up as 'no drag change' though on the basis that it was an unexpected and welcome bonus. This made the 44 counts of extra front downforce very efficient indeed, and the extra 9.5 per cent front was edging the downforce balance ever closer to the target.



Smoke plume showed attached flow on underside of steep dive plane

**Table 4: The effects of dive planes**

| | CD | CL | CLfront | CLrear | %front | -L/D |
|---|---|---|---|---|---|---|
| With | 0.493 | 0.409 | 0.111 | 0.299 | 27.1% | 0.829 |
| Change | -1 | +31 | +44 | -13 | +9.5%* | +65 |

* Changes in %front are absolute, not relative

**Table 5: The effects of opening the bonnet aperture**

| | CD | CL | CLfront | CLrear | %front | -L/D |
|---|---|---|---|---|---|---|
| Open | 0.496 | 0.423 | 0.138 | 0.285 | 32.7% | 0.853 |
| Change | +3 | +14 | +29 | -14 | +5.6%* | +24 |

* Changes in %front are absolute, not relative

**Table 6: The effects of closing off the lower and upper front openings as changes or 'delta' (Δ) values relative to the previous configuration in Table 5**

| | ΔCD | Δ-CL | Δ-CLfront | Δ-CLrear | Δ%front | Δ-L/D |
|---|---|---|---|---|---|---|
| Upper open | -5 | +6 | +37 | -30 | +8.0% | +20 |
| Lower open | -7 | +10 | +54 | -45 | +11.8% | +31 |

## Cool it

Although the Escort's radiator was ducted and sealed to the openings on the inlet side, the only route for heated air to escape was between the engine compartment floor and suspension, and the outlets cut behind the front wheels. It was felt this could be restrictive, possibly inhibiting cooling as well as creating some lift, so the team had prepared a removable hatch to create an additional aperture to test in the bonnet above the exit side of the radiator. And because the aperture was not going to be louvred for our test, in order to prevent air entering from the front a Gurney was added to the aperture's leading edge.

**Table 5** shows that this modification provided further useful front downforce and forwards balance shift increments. The drag increase probably came from the Gurney, and the decrease in rear downforce could likely be attributed to the effect of the Gurney on the flow over the roof to the rear wing.

The team was already thinking about designing improved radiator ducting, so thoughts turned next to investigating where best to locate a reduced area inlet aperture. Race tape was therefore applied first over the circular holes and elongated slots along the lower front panel, leaving just the upper grille open, and then to the upper grille leaving just the lower holes and slots open.

**Table 6** shows the results of each run relative to the previous configuration in **Table 5**. Clearly both configurations brought worthwhile front downforce gains, along with small drag reductions. Interestingly, the most effective option was leaving the lower apertures open and closing off the upper grille aperture. This is likely to be explained by the angle at which the incoming air enters the upper aperture, not from straight ahead as might be supposed, but at a marked upward angle.

The additional 11.8 per cent front brought by masking off the upper grille took the overall balance to the 44.8 per cent front figure shown in **Table 1**, and represents the best balanced 'high downforce' configuration for this car obtained during our session.

Next month we'll evaluate the alternative rear wings the team prepared and determine how a best balanced, lower drag, lower downforce set up could be achieved.

Racecar's *thanks to Tim Foxlow, MEM Motorsport and DJ Engineering.*

Central aperture in bonnet aided by Gurney on front edge

Flow into upper grille aperture inclined steeply upwards

## CONTACT

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In these pages he uses data from MIRA to discuss common aerodynamic issues faced by racecar engineers

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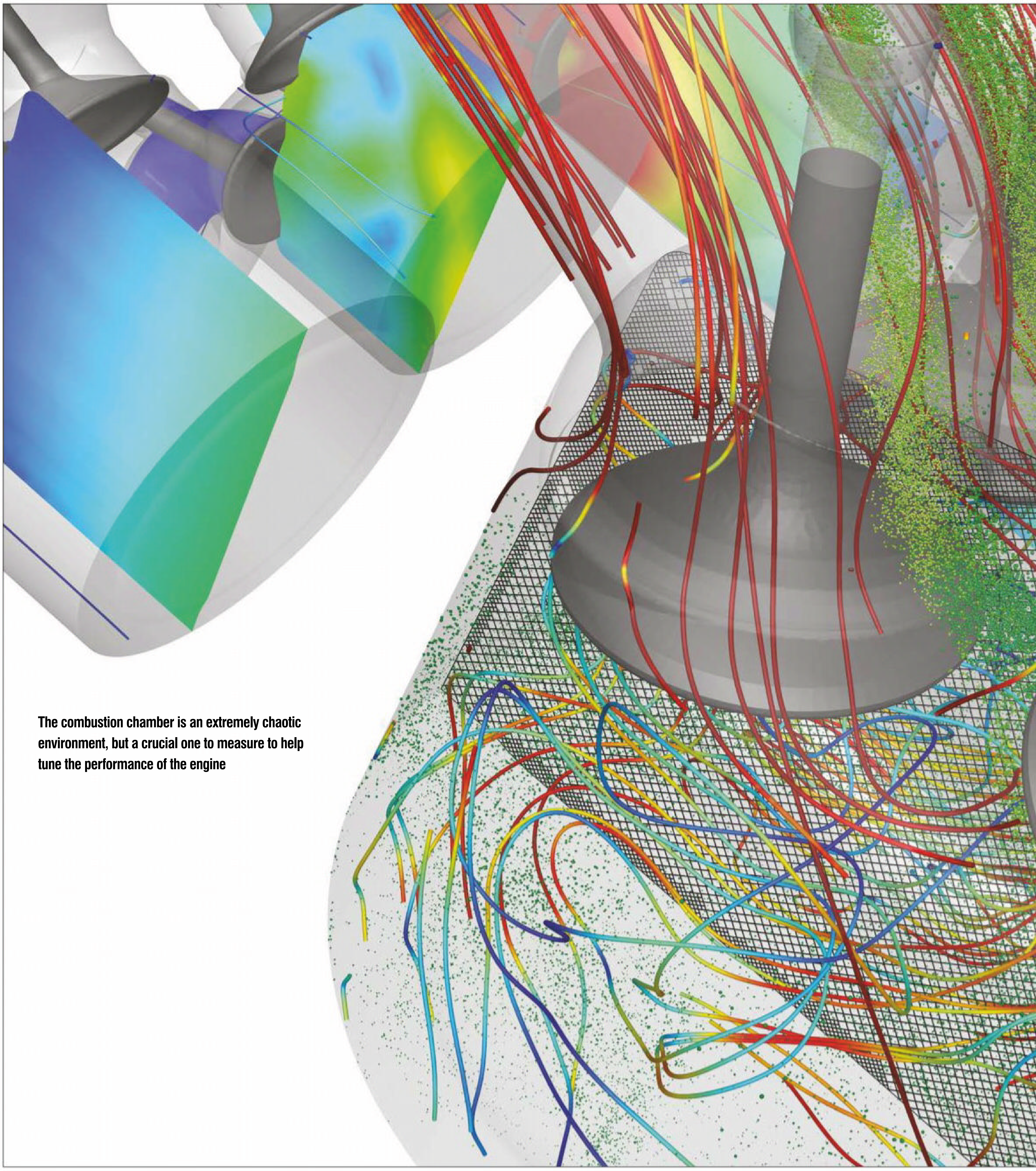
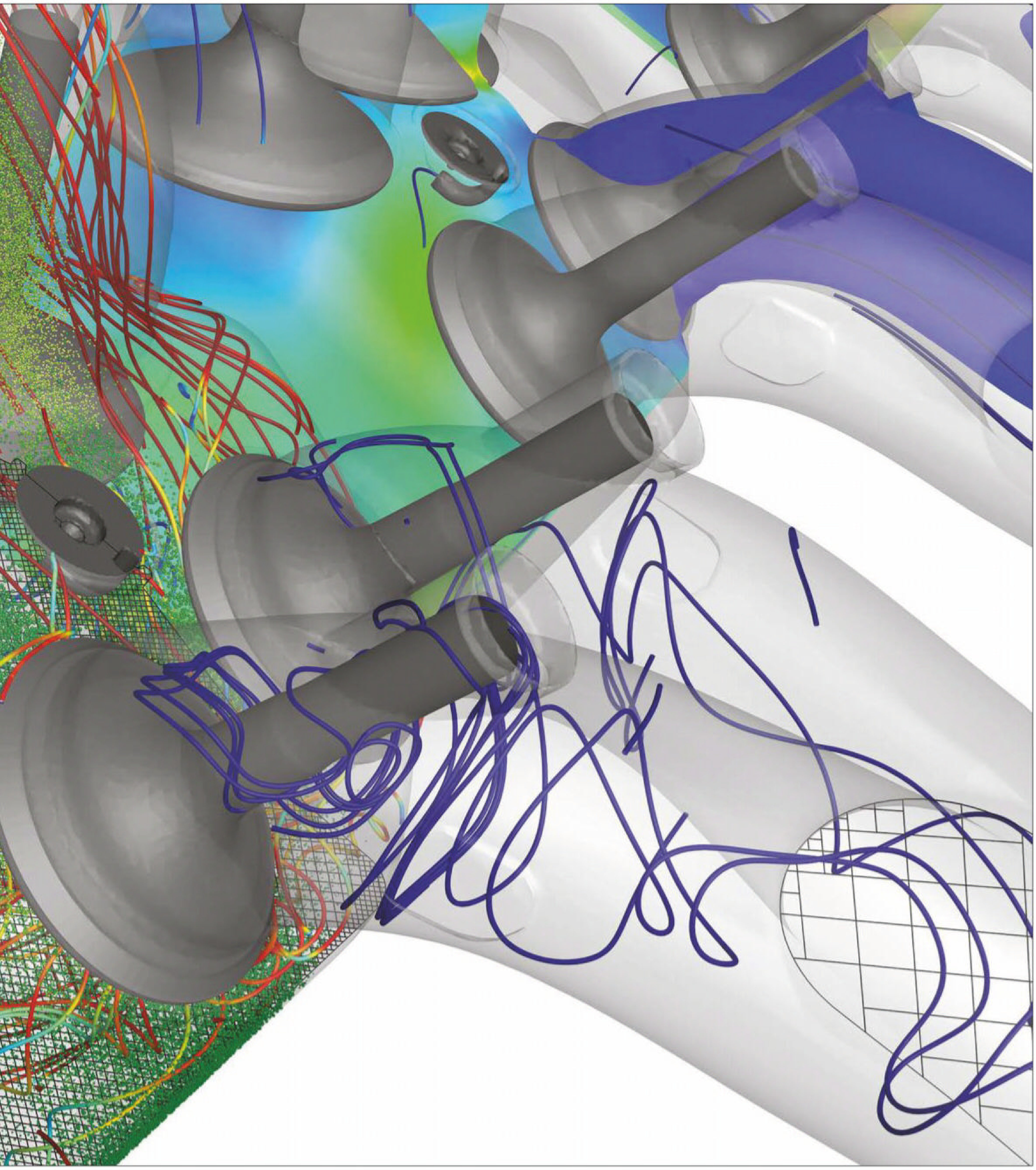


The combustion chamber is an extremely chaotic environment, but a crucial one to measure to help tune the performance of the engine

Converge CFD Software from Convergent Science

# Hidden depths



# *Racecar* investigates what gains are to be had from precisely monitoring in-cylinder pressure

**By GEMMA HATTON**

Formula 1 is a sport of extremes and an example of that is engine combustion technology. During the course of a Grand Prix, each engine will complete 46,000 combustion events during an average lap. Within the blink of an eye, an F1 engine has completed 200 ignition cycles, and over its four-race cycle will complete 37 million ignitions.

As motorsport continues to push the boundaries of combustion efficiency (see p8), engineers need to know what is happening within the combustion chamber. But how do you measure parameters in an environment where temperatures exceed 350degC and pressures are over 35bar? Welcome to the world of in-cylinder pressure measurement.

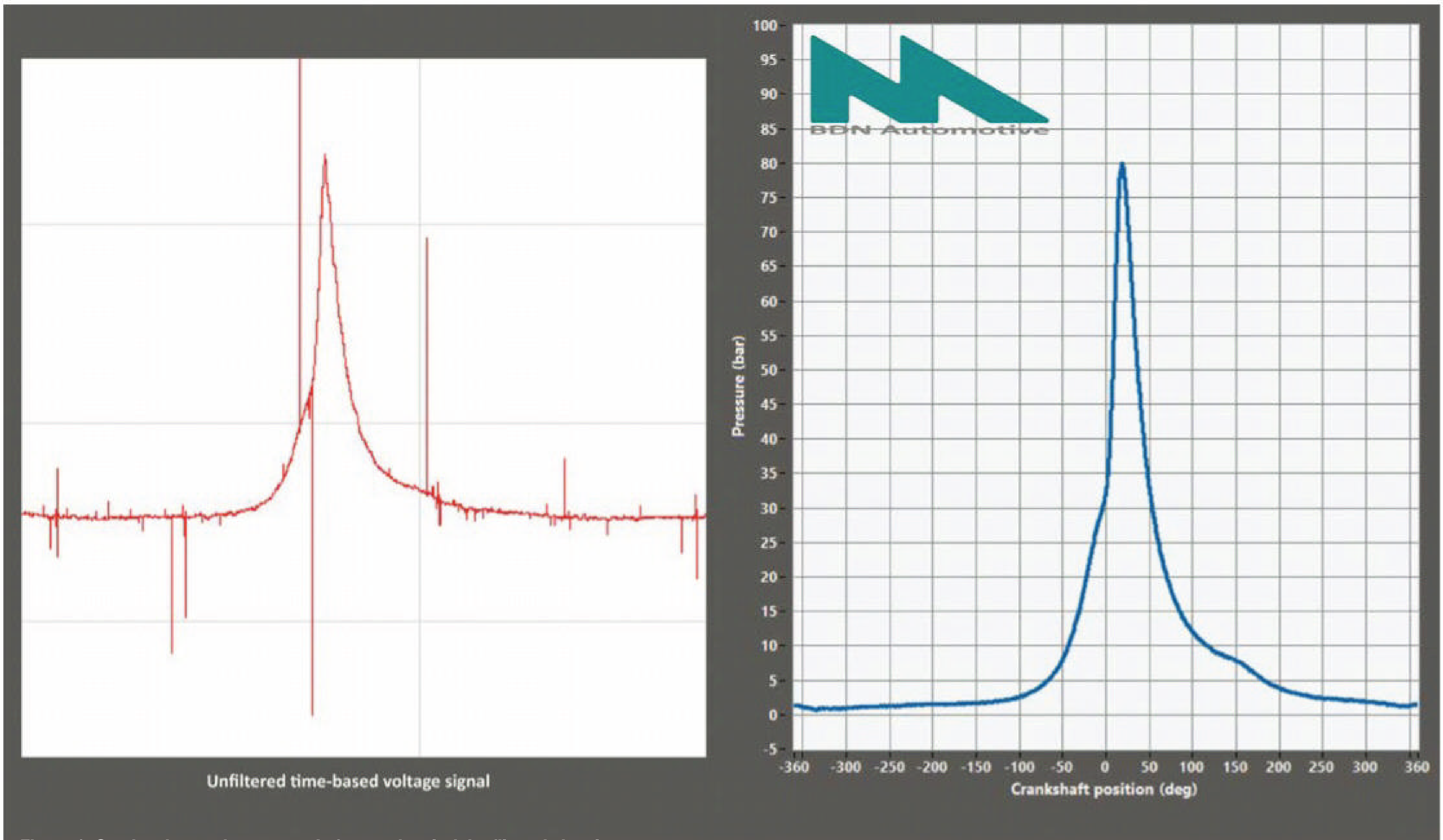



Figure 1: Combustion peak pressure. Left, raw signal; right, filtered signal

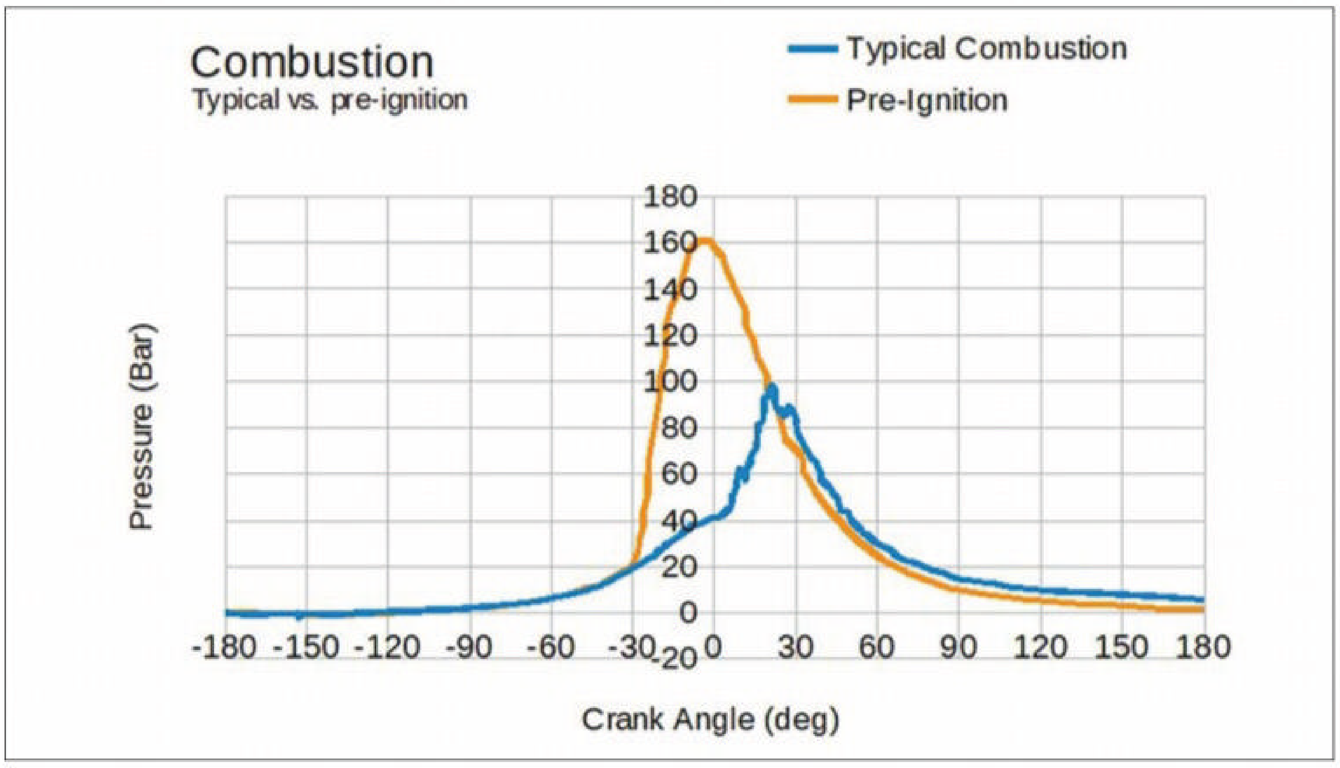



Figure 2: Pre-ignition subjects the piston and con rod to high temperatures and pressures, which a knock sensor can miss

'We've run cylinder pressure sensors in our engine since 2014,' reveals Andy Cowell, managing director at Mercedes AMG High Performance Powertrains. 'They are useful for monitoring the performance and the reliability of the engine, so they get an entry ticket into the bill of materials.

## Development journey

'It's something the performance guys wanted right from the very start [but] a tough development journey is really the story behind the cylinder pressure sensor. For a start, they are difficult to fit into the combustion chamber. It's an 80mm bore size and somehow within the cylinder head you have to include two exhaust valves, two inlet valves, a spark plug, fuel injector and a cylinder pressure sensor, which needs to be in a useful location. Coming up with one that tells you what you want to know, and survives, is tough.'

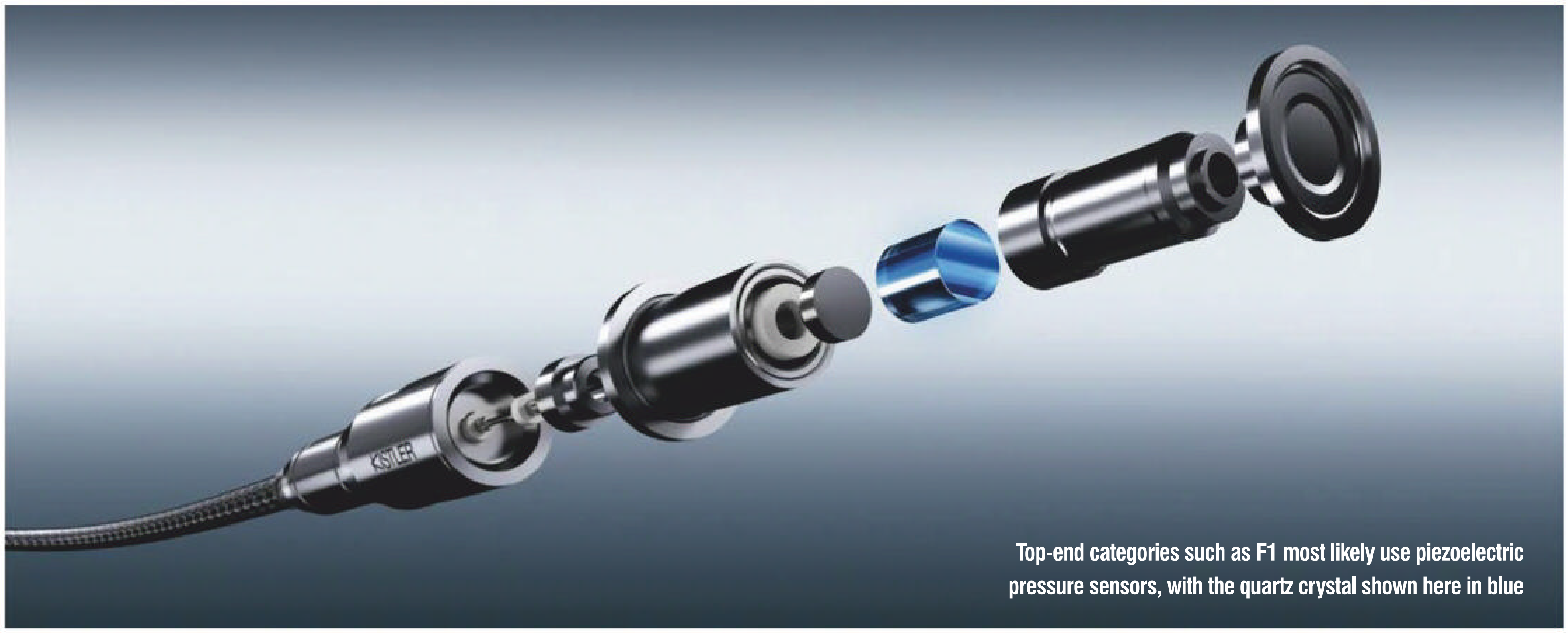
It is these extensive challenges that have made it difficult for other motorsport categories, and the wider automotive industry, to adopt such technology. Only recently in F1 have manufacturers had the capability to make these sensors a common part of their engines.

'I can't tell you when they were first used in racing engines, but I think in the mid-1980s,' says Nick Hayes, power unit specialist at F1 and former technical director at Cosworth. 'I remember them being very expensive and very unreliable, with short lives at best, so they were rarely used on race engines. Back then they were only used on dynos and couldn't be used in car at all, and typically needed special cylinder head castings manufacturing to fit them.'

So why would you want to measure cylinder pressure? To answer this, we first need to understand how pressure changes throughout the four-stroke combustion cycle. Considering just the piston movement, as the piston moves upwards during the compression stroke, the pressure in the cylinder gradually increases until top dead centre (TDC) where the piston reverts back down again and, as the air expands, the pressure gradually decreases.

Now introduce fuel and a spark and, as the fuel and air mixture burns, pressure increases rapidly and leads to a large spike, termed maximum effective pressure. Plotting pressure against crank angle in **Figure 1** we can see this pressure spike occurring just after TDC. In most engines, ignition occurs *before* TDC because it takes time for the fuel and air mixture to burn and you want the maximum effective pressure to occur just after TDC. At this point, the con rod is at an angle to the crankshaft, so this pressure forces the piston to complete the power stroke, applying torque to the crankshaft.

If ignition is retarded (occurs later in the compression stroke, when the piston is close to TDC), then the momentum of the piston pushes



Top-end categories such as F1 most likely use piezoelectric pressure sensors, with the quartz crystal shown here in blue

Kistler

**As the fuel and air mixture burns, pressure increases rapidly and leads to a large spike, termed maximum effective pressure**

it back down, rather than the combustion pressure, which leads to a loss of power. If ignition is advanced (occurs earlier in the compression stroke, when the piston is further away from TDC), then maximum pressure not only increases, but occurs closer to TDC. If ignition is advanced too much then this can lead to shock waves of exceedingly high pressures either before or at TDC. At this point, there is no angle between the con rod and the crankshaft and so this monumental amount of pressure acts directly on the piston and con rod, which can lead to damage.

## Pink and knock

That is a simplified view of how cylinder pressure changes throughout the combustion process. However, phenomena such as pre-ignition and detonation, or knock, can also affect in-cylinder pressure. Both are uncontrolled combustion events that occur either before or after the spark respectively.

Pre-ignition can be caused by hot spots within the combustion chamber that ignite while the piston is early in the compression stroke. When this happens, the piston is trying to compress a hot mass of expanding air during the majority of the compression stroke. This subjects the parts to excessively high temperatures and pressures for a duration of time, but there is no spike in pressure. Therefore, there is no resonance to cause noise, which is why pre-ignition can often go undetected before it is too late.

Detonation, on the other hand, can cause significant pressure spikes because all of the material is spontaneously and simultaneously burnt. This event can resonate the walls of the cylinder, creating the 'pinging' sound associated with engine knock, which can be measured by accelerometers or knock sensors.

Engineers, therefore, not only have the challenge of tuning the ignition timing to maximise combustion efficiency; they also have to try and minimise pre-ignition and knock.

## Hot source

'You want to know the pressure within the cylinder to be able to maximise the conversion of chemical to mechanical energy at different points within the combustion phase,' highlights Jenner Collins, co-founder of development engineering consultancy, Collins Limited. 'Measuring in-cylinder pressure allows you to not only identify engine problems, such as knock and pre-ignition, but can support diagnosing the source of them, too.'

This double threat has become an increasing problem in modern engines. In the past, engines were air restricted whereas now, in the hunt for fuel efficiency, they are fuel restricted instead. And the most effective way to extract the maximum amount of energy from each drop of fuel is to run lean air / fuel mixtures in downsized, turbocharged, direct-injected engines, all of which increase the chance of pre-ignition and knock.

'High speed, air-limited engines tended to be run slightly rich and were not limited by knock, so that was something we didn't have to worry about in general,' remembers Hayes. 'But once you are running a little slower, at higher cylinder pressures, and running lean, knock becomes an important limiting factor in achieving the best possible performance from the engine and the fuel.


A quick machining process allows the actual spark plugs from an engine to be attached to the sensor, rather than having to use customised, non-engine specific plugs

'So modern, fuel-limited engines need to be able to measure [knock] all the time to allow precise control up to a knock limit. The sensors required to do this are still expensive – although significantly less so than they used to be – but are now much more reliable.'

## Tuning by ear

Jilbruke Collins, another co-founder of Collins Limited, concurs: 'Before this trend of downsized, direct-injected engines no one really needed to know what was happening within the cylinder. If knock was occurring, a tuner would simply hear that the engine is doing the wrong thing, or notice the exhaust gas temperature or composition changing. But now we are getting to a point where engines are right on the limit, we're trying to get the most power possible out of the smallest engines. Pressures are higher than ever, and you really do need to know exactly what is happening within the cylinder, and precisely when it is happening.'

This is particularly important when considering low-speed pre-ignition, which

**One of the most amazing things we discovered is that each cylinder firing can be up to 10 per cent different**

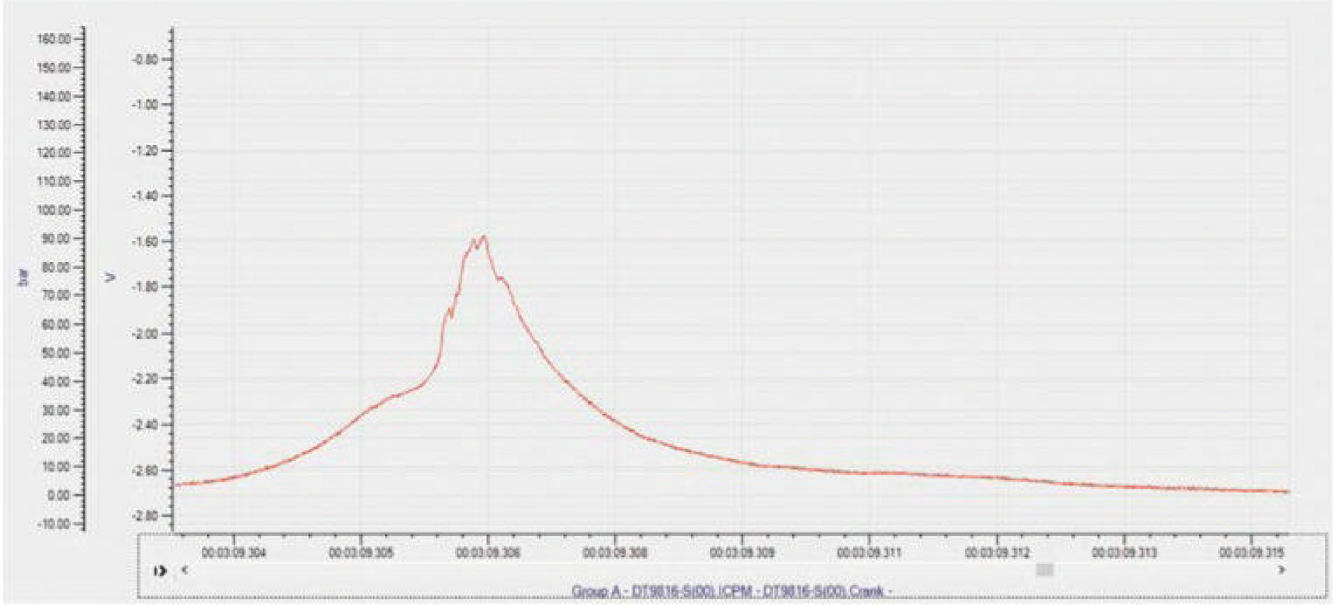


**Figure 3: A typical pressure trace of a standard combustion event**

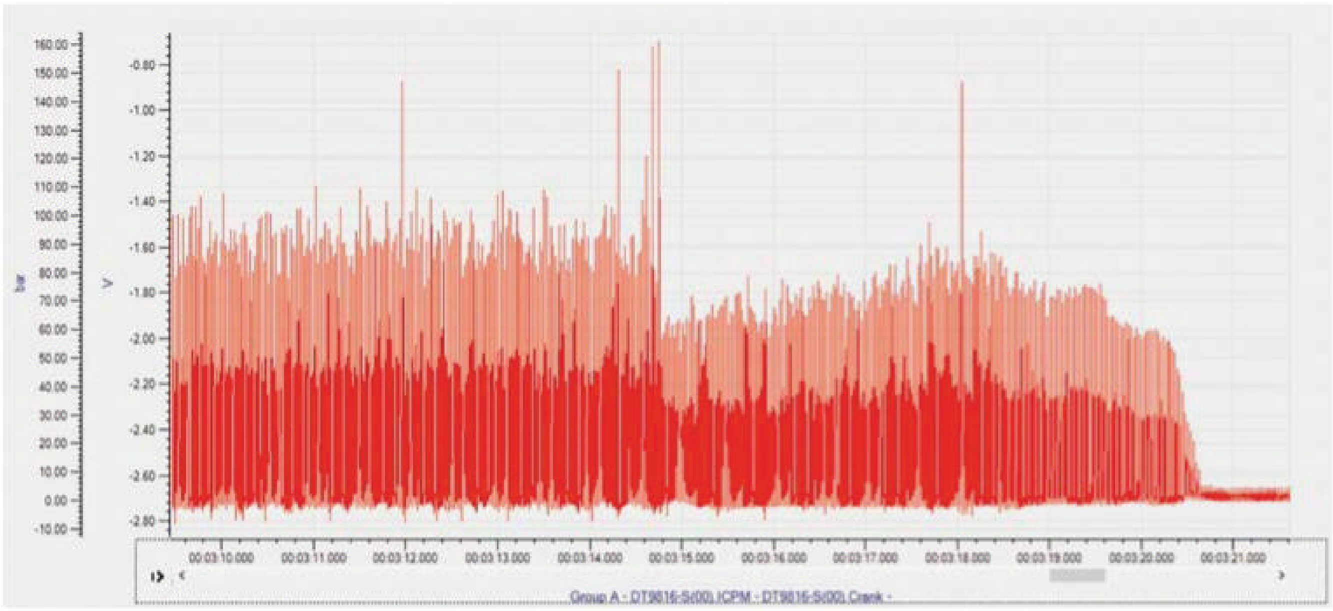


**Figure 4: Zooming out on the pressure traces of multiple firings allows the pre-ignition events to be easily identified**

again these turbocharged, high-power density engines are more susceptible to. 'During acceleration from low engine speed, the modern direct injection engine is making full torque at the lowest possible speeds with the turbo able to feed as much air as possible past the valve into the cylinder. Peak torque at low engine speed is helping create a new condition known as low speed pre-ignition,' explains Jilbruke Collins. 'You end up with the most amount of combustible material in the cylinder waiting to be ignited. Should pre-ignition occur, it has the greatest chance of reaching peak burn before TDC and the pressures reached are then astonishingly high. This results in huge loads through the piston, con rod and crank.

'In some of the engines we've been working on, another complication is bore wash, where the injector's jet crosses the cylinder and mixes with the oil film. Combustible fuel and air between the rings can then ignite, breaking parts of the piston off. But [the engine] keeps running, so it's only when you find metal in the sump you realise something has gone wrong. There's things happening in [modern race] engines that haven't happened before and people need to know about them.'

## Physics lesson

Collins Limited was approached by a client whose vehicle project was suffering from this exact condition. Despite evidence of piston damage within the sump, the pre-ignition issue could not be found in the traditional engine calibrator's data. Naturally, the customer didn't want to run the engine again without fully understanding the problem, and that's when Collins was brought in to research and diagnose the source of the failure.

'Our specific approach meant we were able to develop a cost-effective testing method to study the root cause of the issue,' highlights Jenner Collins. 'Our approach to technical problems is from the perspective of understanding the physics and, in this case, what is actually happening within the cylinder. It is common to use knock, or exhaust gas temperature, sensors to diagnose engine problems, but these are secondary sources of data. With the [in-cylinder] pressure sensor you have a primary measurement.

'We felt in this case it was important to understand the issue in terms of the primary data source, and so developed our own hardware to measure the internal pressure of the cylinder during ignition cycles.'

In-cylinder pressure sensors are commercially available. However their cost, along with that of the high-spec loggers required, can be substantial and therefore Collins Limited decided to build its own. 'One of the first things we did was design and build our own data logger, which logs at 750kHz,' explains Jenner Collins. 'Normally, when we're talking about logging rates, even in Formula 1, you might look at around 1kHz for components like dampers, so the logging rates we were able to achieve was quite incredible – that's all six channels simultaneously, too.

'In fact, one of the most fascinating things we found in developing the hardware was the logger was so fast we could actually visualise the de-bounce signal of an electrical switch.'

At the heart of the company's measuring kit lies a pressure sensor. Categories such as F1 and WEC will most likely use piezoelectric pressure sensors, while optical sensors are also readily available. The former works by utilising the piezoelectric effect, where an electrical charge is created on the surface of a material when subjected to a mechanical load. In the case of pressure sensors, the voltage across a piezoelectric element (often quartz) is measured and is proportional to the applied pressure. Whereas an optical pressure sensor detects changes in pressure through an effect on light, either through a mechanical system that blocks the light as pressure increases, or by measuring the phase difference.

## Instantaneous combustion

The sensor then has to be incorporated into the spark plug to accurately capture the pressure at instantaneous combustion. This can be achieved in two ways. Either the pressure sensor can come with a non-engine specific, customised spark plug, such as the piezoelectric variants from the likes of Kistler. Alternatively, an engine-specific spark plug can be modified by a quick machining process to attach the sensor. Such is the case with some optical pressure sensors supplied by Optrand.

The pressure sensor is externally powered and its measurements can then be recorded or analysed by a data logger or combustion analyser. These data acquisition systems are connected to the pressure sensors from each cylinder via a bespoke wiring loom with either two or three pins, depending on whether the sensor has a built-in amplifier or not. An amplifier is needed to amplify the high-

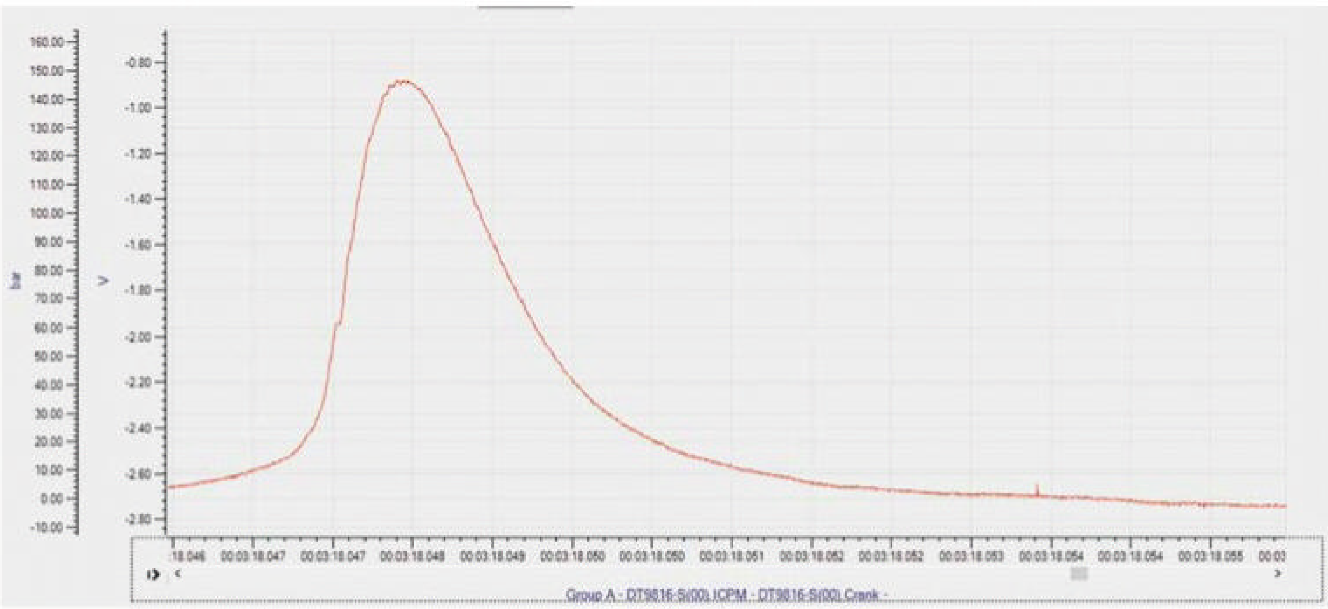


Figure 5: 'Quiet' pre-ignition such as this, can often go undetected by knock sensors

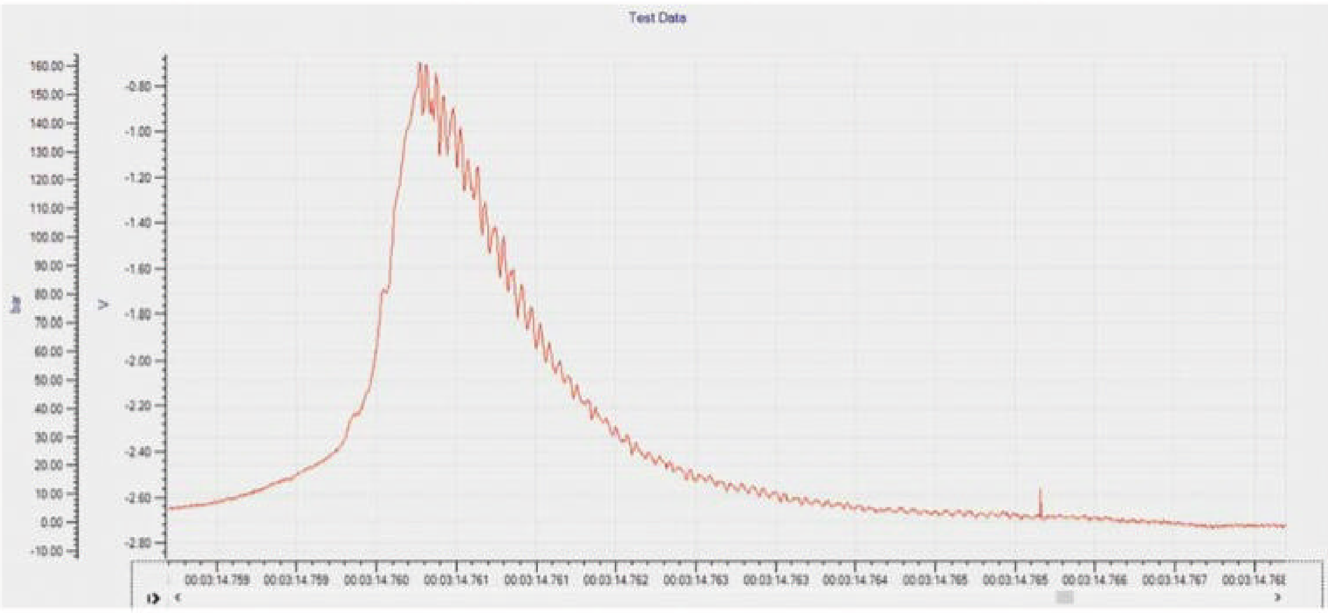
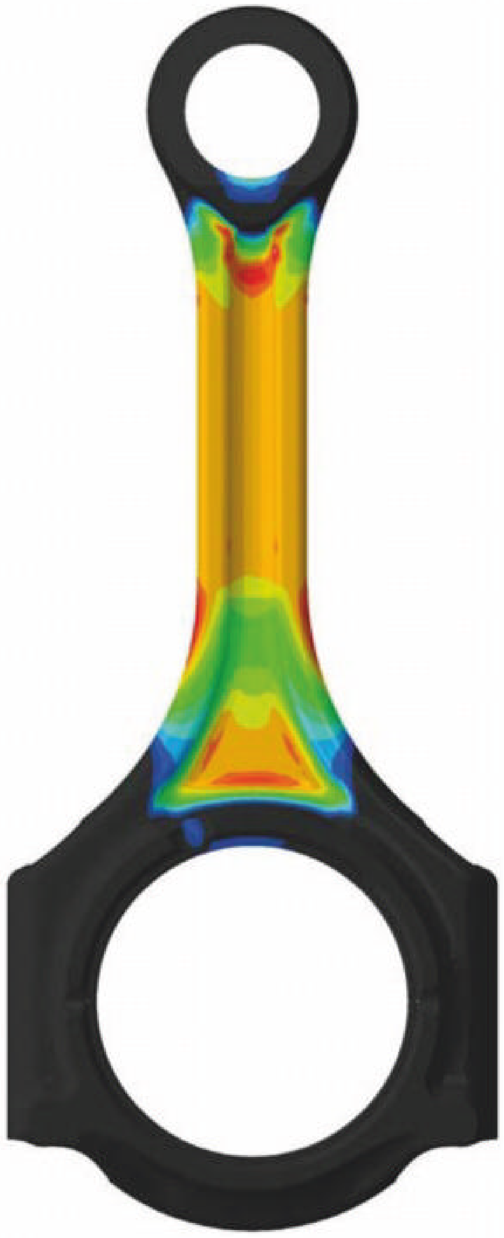



Figure 6: Only when pre-ignition becomes 'noisy' is it detected by knock sensors



With the real in-cylinder pressures now a known quantity, these can then be simulated on parts in FEA to analyse the likelihood of failure

**The relevant information appears between tight frequency limits, which are mainly defined by the geometry of the engine**

frequency recordings from the pressure sensor into an analogue signal, and can either be external or built into the sensor itself.

'The combustion analyser system then plots the pressure on a crank angle-based trace using some kind of angle resolver, which could be either an external device, or the OEM engine speed sensor,' explains Nimrod Ludescher, chief operations officer at BDN Automotive.

'The key of the signal chain is filtering an AD conversion, as the relevant information appears between tight frequency limits, which are mainly defined by the geometry of the engine, as we are talking about acoustic waves. Static filters are applied and the system should be able to identify thermal and load-based drift as well.'

**Figure 1** shows the difference between the raw signal (left) and the filtered signal (right), with the latter forming the basis of all further calculations. 'These can include things like the mass fraction burned curve, heat release parameters, knock, pressure gradient or combustion duration, which are the most useful numbers in an engineer's toolbox when trying to push the limits of an engine,' says Ludescher. 'Using a combustion analyser helps to not only define the objective limits of combustion, but also identify and monitor possible ways of development without having to test all the thousands of different possibilities.'

The kit from Collins on the other hand utilises a data logger, along with the necessary power supply, PC and, of course, the in-cylinder pressure sensor and crank angle sensor. 'We configured this kit to come to about £1,500 (US$1,720), which is very reachable compared to other alternatives that can be as much as £30,000 (US$34,340),' says Jenner Collins.

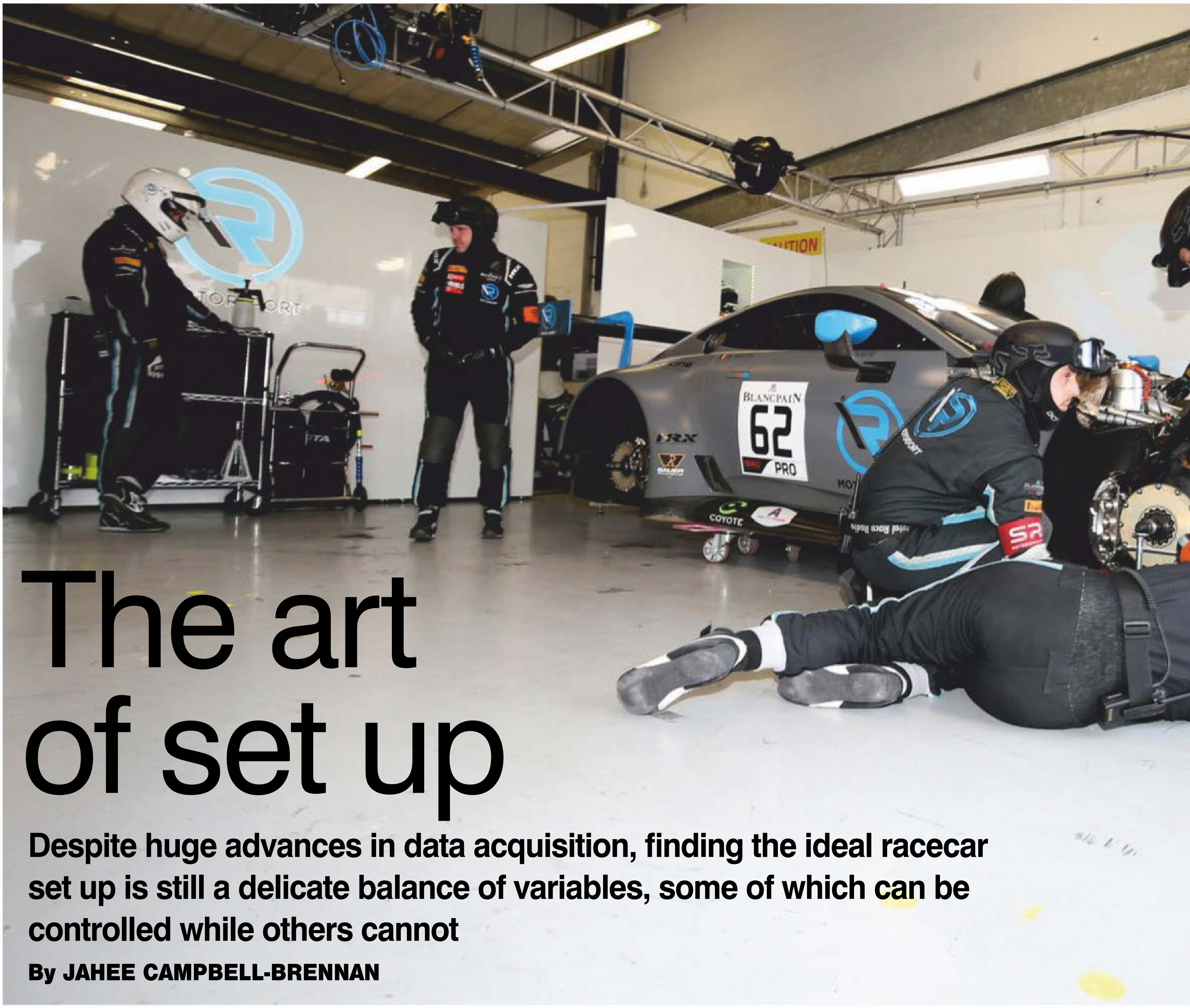
## Invaluable tool

'With the hardware we've developed, this is an invaluable tool for engine calibrators and designers. They simply send through a spark plug to be machined, which is around £400, and we provide the hardware and support for either an engine or chassis dyno test. After that, we can very quickly report exactly what is happening within the cylinder.'

One of the first sets of pressure data recorded by this measurement kit can be seen in **Figure 4**. This shows the spikes in pressure during combustion and how they differ between each firing. **Figure 5** illustrates the pressure trace during 'quiet' pre-ignition, which was not detected by the knock sensor, but can be identified on this pressure trace. Only when pre-ignition becomes 'noisy' enough, can knock sensors record it, as seen in **Figure 6**.

'By putting a kit together that measures the in-cylinder pressure accurately and reliably, we've been able to identify lots of other events that go on within the combustion chamber, but are just too smooth to be detected by a knock sensor,' says Jenner Collins. 'We've recorded events nearly double the pressure the engine was designed for that have not been detected at all via knock sensors.

'Aside from failure analysis, the other benefit of this hardware is in understanding the performance. One of the most amazing things we discovered is that each cylinder firing can be up to 10 per cent different, which will be a function of the aerodynamic regime entering the cylinder and the combustion mechanics, among other things. It's a very chaotic environment and this hardware can begin to shine a light on what is happening within the cylinder during the combustion process.'




# The art of set up

**Despite huge advances in data acquisition, finding the ideal racecar set up is still a delicate balance of variables, some of which can be controlled while others cannot**

**By JAHEE CAMPBELL-BRENNAN**

In previous features focussing on suspension technology, we've delved into the components of a racecar suspension system and grasped a technical understanding of its objectives, both structural and dynamic.

We then built upon this knowledge through exploring the design and development process, with focus on physical R&D methods employed by race teams and component manufacturers to meet their objectives, such as seven-post rigs.

The modern research and development process uses a multitude of high technology tools to understand wheel kinematics, spring and damper rates, aerodynamic maps and powertrain controls but, with motorsport regulations almost unanimously demanding passive suspension and aero systems, there will never be a one-size-fits-all solution.

This is where we now enter the transient world of racecar set up, explaining what it involves and some of the equipment and technology used by teams in the process.

Once a racecar leaves the controlled development arena of a factory it enters the constantly evolving environment of a race weekend. This is an environment where consistently delivering lap times faster than the competition is the blinkered objective and that brings a whole host of new, external factors into the complex equation of performance.

## Going deeper

Different race tracks demand different requirements from the vehicle. Most will appreciate the differing aerodynamic requirements of short, technical tracks vs long, open tracks, for example, but it goes deeper than that. Let's explore what it really takes to shine at a race weekend, and the level of preparation and understanding that goes into being, and staying, at the top.

In the lead up to the race, as the car and equipment is packed, teams will usually have a good idea of what to expect at that particular event. Having competed at any given circuit in the past affords the benefit of experience, a solid 'best fit' set up of vehicle characteristics that will do a good job of arriving in the right ball park, but the job never ends there.

'Ideally, our preparation at the workshop means the mechanics will have minimal work to do at the track. But once we arrive, they will set up the flat patch, which allows set up changes for the specifics of the event to be made as accurately as possible,' explains Nathan McColl, chief engineer at R-Motorsport who compete in GT World Challenge Endurance Racing.

The flat patch is a piece of equipment used to provide a level surface for the racecar from which to make changes to wheel geometry and measure corner weights.

But what drives a set up for a particular event? A big part of this is differing grip levels based on the track conditions.

Initially teams need to understand the expected environmental conditions at the


A well-prepared team will arrive at any given event at any given circuit with a ready-to-race set up, but that's just the beginning of the race engineers' work


Weather conditions play a huge part in set up, and can change dramatically many times in an endurance race

Rallycross is a peculiarly demanding environment as it involves different, constantly evolving racing surfaces

circuit. No special equipment needed here. Weather stations are usually located in or around the track and provide constantly updated real-time information.

But weather conditions can change, even by the sector of track. If it rains, lower speeds mean lower forces are being exerted on the car during manoeuvres and very different tyre behaviour, changing the requirements of wheel kinematics and spring-damper rates. Therefore, in the effort to keep things where they need to be changes must be made to the car's set up.

'Weather changes have a large effect on grip,' continues McColl, 'and these changing grip levels require different combinations of springs, anti-roll bars and other set up items in order to meet the targets for vehicle balance.

'Damping requirements are also greatly influenced by the changes to set up we make, so we'll also change damper settings to suit.'

But how do you manage this when one half of the lap is dry and the other half is wet? Famous examples that spring immediately to mind are the VLN (Nürburgring Nordschleife) and Circuit de la Sarthe in Le Mans.

Specific situations usually dictate a 'best compromise' with set up. You could use slicks to shine in the dry and take the hit on damp sections, or use intermediates for quick pace on the damp sections and accept a loss of pace on the dry. This is often a trial and error situation, with judgements made based on experience and keeping a keen eye on your competitors. In other words, the beauty of race strategy.

Situations like this are part and parcel with championships such as Rallycross. Being a mix of asphalt and mud or gravel, the circuit has two distinct grip levels that can dramatically evolve over the course of a single event.

'We determine the grip expected on each part and also try to predict track evolution during the race by calculating the amount of cars on the course and tracking the weather forecast,' explains Frederic Ruat, CEO of FORS Engineering, technical partner to FIA World Rallycross team GCK.

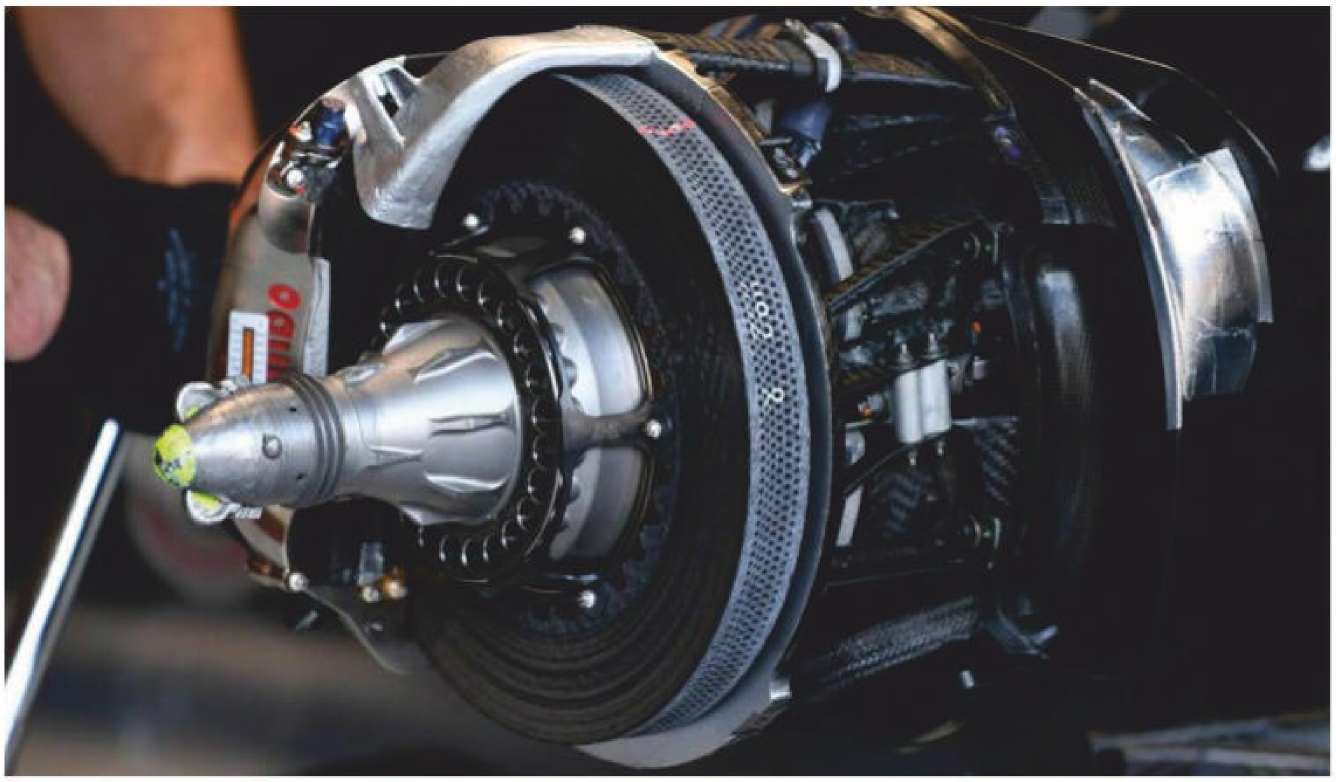
'The idea is to scan as many different possibilities and details as possible to be able to adapt the set up in relation to the amount of grip available. Good weather prediction is a key point for us with our set ups.'

**Teams need to understand the expected environmental conditions at the circuit**

In addition to precipitation, ambient pressure, temperature and humidity all have their parts to play in set up at a particular event. Their effect on the various sub-systems of the vehicle is really quite extensive.

'High ambient temperatures affect our engines, mainly with respect to engine cooling and ignition timing. We need to keep the water temperature reasonable, but we also need to watch out for knock, so we sometimes pull timing to keep things safe,' says Ruat.

Gavin Harrison, senior track support engineer at Neil Brown Engineering, concurs: 'The lower air density can also mean we will hold the wastegate shut for a longer period to keep the turbos working well.'



Carbon brakes are very sensitive to temperature regimes, and operating outside them can quickly become a safety concern

## Tyre control

As the sun beats down on asphalt, hot track surfaces mean tyres run hotter. Overheating tyres see a rapid decrease in shear modulus, the accompanying reduction in adhesion being met with rapidly increasing wear rates, urging engineers to react. Tyre pressures are adapted and aggressive suspension set ups (more of this later) can be eased off to give tortured tyres an easier time, thereby extending their life.

Conversely, in cold conditions, these same aggressive suspension set ups have the advantage of generating a lot of heat in the tyres, which is great for bringing them up to operating temperature in a hurry.

Complementing this process are tyre blankets. Where regulations permit, these are used to pre-warm the tyres before a run, reducing the 'time-to-warm' period where performance is less than optimal.

Motorsport has long seen the use of infra-red tyre sensors to help understand this process. Providing live, high-definition imagery of the temperature distribution across the tyre makes it easy to quantify the effect of set up changes, until the sun disappears behind the clouds!

In a world sensitive to every gramme of weight, and every count of aerodynamic drag, designers find themselves operating at the very edge of thermal tolerances, which means the cooling systems around the racecar are highly stressed and often tailored for the specific event.

With a reduced temperature difference between hot components and ambient air, heat rejection is slowed. An inventory of heat exchangers and duct inlet geometries is commonplace in high-level motorsport for this reason, allowing quick reaction to conditions.

Carbon brake discs in particular are sensitive to their upper temperature limit. Once the material becomes too hot, it starts to oxidise and lose mass. In this state, you see higher wear rates and the structural integrity of the disc compromised, presenting a risk of failure.

Teams will often carry a number of subtly different cooling duct packages that can be swapped depending on requirements

**Precipitation, ambient pressure, temperature and humidity all have their parts to play**


Suspension set up has a bearing on tyre wear, but this also has to be balanced with environmental conditions

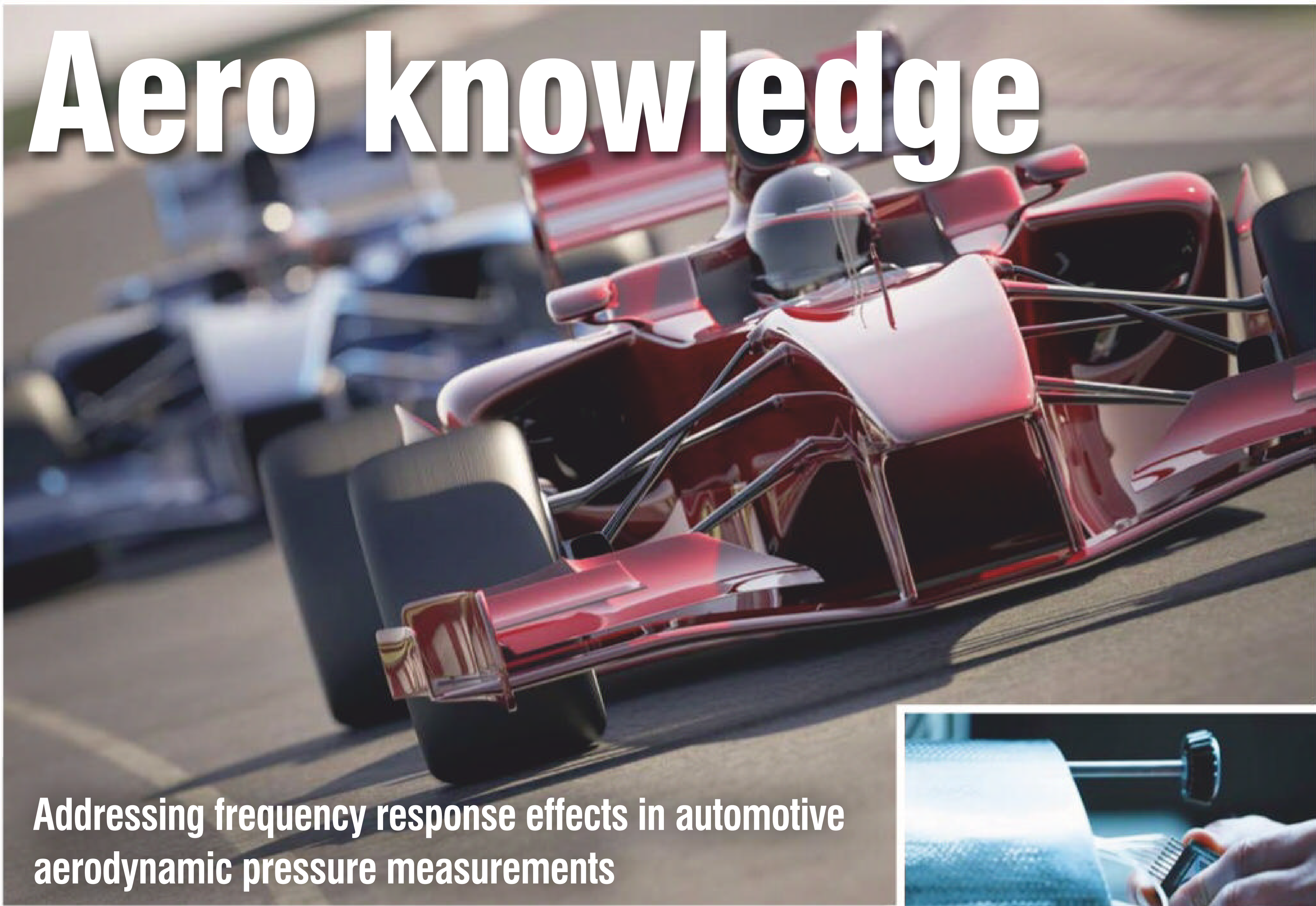
In an effort to manage this a variety of brake cooling duct arrangements are standard race set up equipment, some championships such as Formula 1 even going as far as to use track-specific discs, with carefully tuned internal channels to suit the cooling requirements of the particular race weekend.

McColl again: 'Cooling is a big challenge faced by teams. Conditions can vary so much over an endurance race that the efficiency of the cooling system noticeably drops as radiators and brake ducts fill with dirt and debris. Having options to change the levels of blanking, and therefore cooling, is vital. We use blanking panels or tape to easily adjust cooling capacity depending on the conditions and race situation to keep things where they need to be.'

## Altitude effects

Then there are the considerations related to the altitude of a particular race, which affects air density and the effectiveness of aerodynamics.

The higher you go, the more air density reduces. With less air molecules in a given space, aero packages lose effectiveness. It's a similar effect with moisture content – more moisture



# Aero knowledge

## Addressing frequency response effects in automotive aerodynamic pressure measurements

As aerodynamic points of interest are connected via a tube to the measuring instruments, there can be detrimental effects in the measurement known as frequency response effects. It is a hugely complicated subject, with many studies undertaken over the years by universities, research establishments and even NASA to try to understand and correct for this phenomenon.

It is usually unavoidable too, as physical size makes it difficult to locate the pressure scanner exactly where you want to measure.

With so many variables that contribute to the offset created by the tubing, the effect is hard to quantify. For a start, there is a delay between the input at one end and air reaching the pressure measurement device. Whilst in the tubing, air is highly compressible and its temperature, density and velocity of sound all affect the frequency response, as does the length of tube itself. Then there's the elasticity of the tube wall, which bends to absorb some of the energy in the pressure wave. Kinked tubes will produce false, or no, readings, which adds further complexity when working with 16, 32 or even 64 individual tubes.

So how different is the pressure when it arrives at the point of measurement?

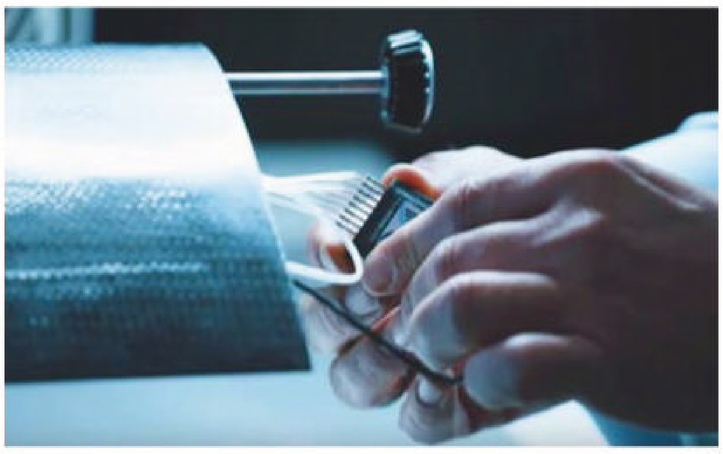
There is a systematic offset created by the tube, so it is best to use the smallest diameter tube possible, use the same length of tube and the same tube material for every location, to ensure that offset is always the same. This might not be easy to achieve in every situation as the tube bend radius, compatibility and pressure and temperature limitations may make it unsuitable for certain measurement tasks.

## Tight fit

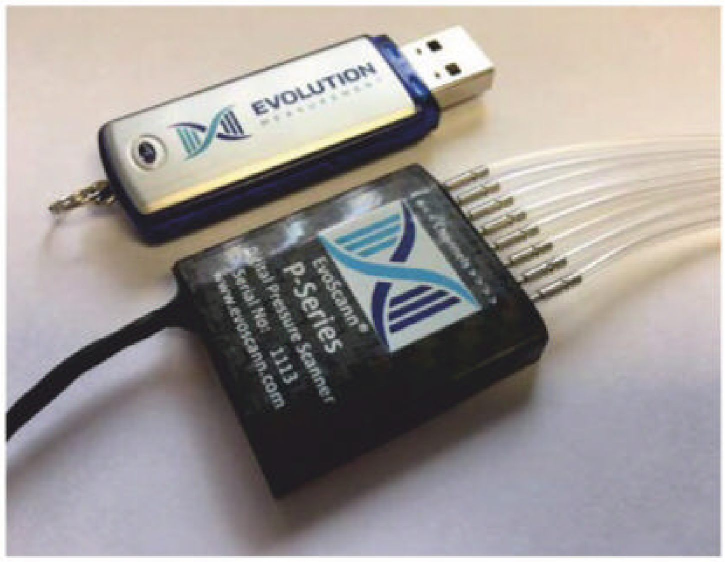
However, the EvoScann® range of miniature pressure scanners can help simplify this complex process by fitting into the tightest of spaces. In an F1 car, for example, the scanner could be mounted directly in the location where measurement is needed, rather than running 4-5m of tubing back to a traditional scanner, eliminating the tube offset entirely.

The EvoScann® scanner is also rugged, light and insensitive to vibration, making it perfect for locating in the aero section without affecting aerodynamic performance.

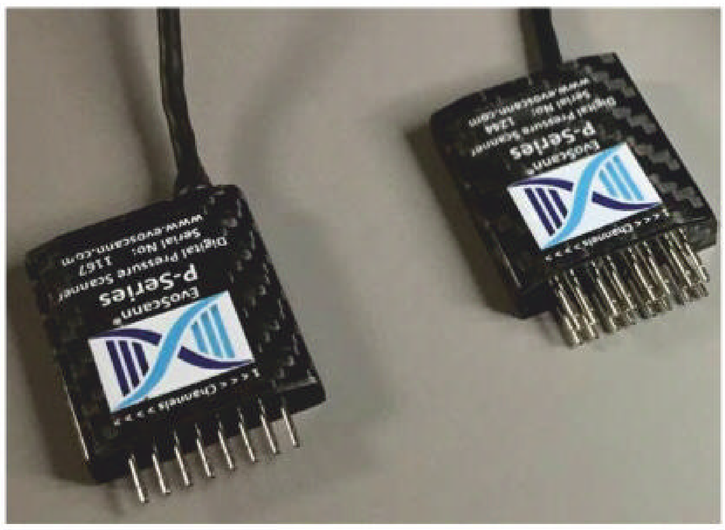
Whilst the headline spec of a scanner may be way less than 0.1 per cent of a very small pressure value, when it's installed in real-world applications, the total system error, including tubing, creates a very different picture. By using the EvoScann® and keeping the tubing as short as a few centimetres, much of the system uncertainty is removed, ensuring accurate measurement is done at the point of interest, delivering digital data directly via CANbus without the need for special software or hardware interface.



With numerous inconsistencies due to the length of tubes connecting pressure sensors, limiting the length offers a benefit




The minute size of EvoScann® scanners allows their placement in critical areas of racecars where larger scanners cannot fit



in the atmosphere means less air density. These effects can amalgamate to produce a very tangible effect on aero packages.

This effect is also expressed by McColl: 'Racing at sea level and at altitude will have an effect on our targets for downforce and drag. Adjustments to the aero set up are therefore necessary depending on where we're racing.'

A CFD study recently undertaken by the author demonstrated a 26 per cent reduction in downforce (and drag) between circuits at sea level such as Monaco and Abu Dhabi compared to conditions seen at Autódromo Hermanos Rodríguez, the highest circuit on the calendar at 7,300ft. Certainly nothing you can ignore and we'll explore the effects of this a little later.

## Aerodynamic efficiency

Once the environmental variables are under control, focus can turn to the set up for track layout and surface topology. With that neat segue into aerodynamics, let's start there.

As ever, an increase in downforce is generally associated with an increase in drag. Tighter, more technical circuits such as Hungaroring will demand higher downforce at the expense of aerodynamic efficiency, while others, like Monza, might require efficiency at the expense of ultimate downforce to produce faster laps.

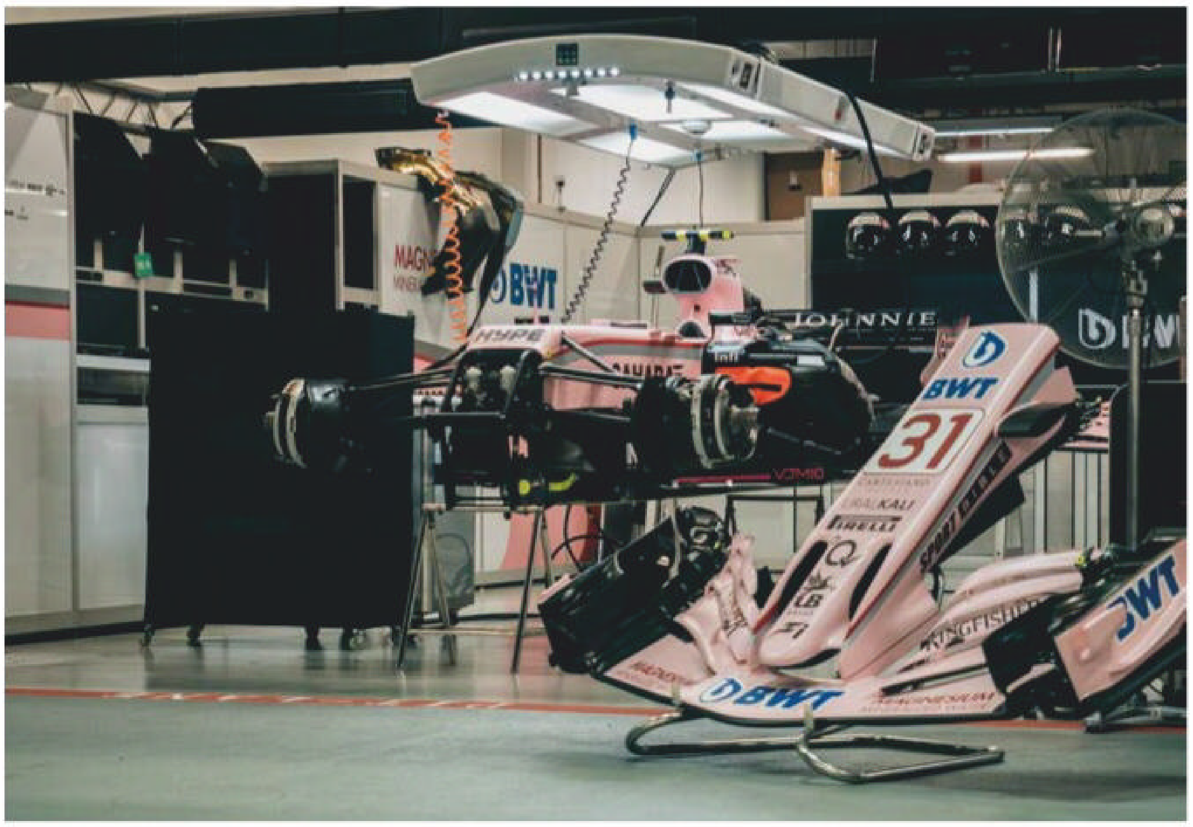
Generally, there will be a 'high' downforce and 'low' downforce baseline set up for a car, as verified in wind tunnels. Adjustments can then be made to these settings at the track to suit.

Aside from ultimate aerodynamic performance with regards to downforce, key in the racecar's performance is aerodynamic balance. More specifically, the location of the centre of pressure (CoP). Commonly, this is set very close to, but just rearwards of, the longitudinal centre of mass (CoM) position to maintain consistency in the car's character and balance as aerodynamic load builds.

Rear wings are an easy one to deal with, a quick adjustment using basic tools to increase the angle of attack, or an entirely new wing assembly with a different profile can manage downforce levels and efficiency. It's a similar process with the front wing, at least with formula-style racecars.

Those with GT-style bodies using fixed splitters have a harder time designing with adjustability, relying mostly on adjustments of rake (the angle the underfloor of the car forms with the ground plane, always nose down). As a general rule, increases in rake amplify the magnitude of the low pressure area under the splitter, manipulating the CoP position. Careful though; too much rake can stall the rear diffuser with separated airflow.

With the same sentiment as rear diffusers, splitters can also feature diffusers at their trailing edge to encourage an increased mass flow of air below it. Depending on regulations, these can be tuned to suit particular requirements faced in the form of new splitter / diffuser assemblies.




**In some formulae, teams will carry entire spare nose sections in the search for ultimate aerodynamic balance**


**One of the first things teams do upon arrival at a circuit is establish a flat patch, a level surface from where corner weights can be measured and set up changes made to geometry and ride height**

## Balancing the conflicting demands of maximum tyre life with ultimate performance

Commenting on the influence of track layout on their aerodynamic set up, Jack Lambert, lead development engineer with the Jaguar I-PACE eTROPHY programme explains: 'We have a large variation in the lengths of straight track sections from circuit to circuit, which dictates our aerodynamic approach and whether it demands a low-drag or high-downforce set up to maximise braking.'

'Playing with the ride height at the rear to change the chassis rake angle, together with rear wing adjustments, allows us to influence the aerodynamics of the car to best suit the requirements of any particular track.'

Arriving at the optimal set up that has been adapted to accommodate the circuit depends not only on the aero packaging but involves significant attention to the entire car's mechanical package, which then also invariably demands suspension changes.

## Managing conflict

A lot of work around set up with traditional circuit racing is associated with balancing the conflicting demands of maximum tyre life with ultimate performance. Something particularly crucial in endurance racing. For this reason, race and qualifying set ups can vary significantly.

'Depending on the life needed from the tyre, compromises need to be made on set up, but also to driving styles,' says McColl. 'Qualifying demands a lot of the car and, as a result, you will change the set up items on the car to suit these different demands. Achieving ultimate speed over one lap requires a different philosophy to double stinting tyres in a race situation.

'Through testing and experience we change our targets according to these demands.'

Commenting on the changes required from the engine across the race weekend, Harrison adds; 'In qualifying, you would make sure the engine is operating most aggressively in terms of ignition timing and fuelling, but in a race you'd back it off slightly to give the engine an easier time with respect to durability.'

To provide context on the magnitude of these changes, qualifying and race lap times that differ by two seconds or more are common.

**Achieving ultimate speed over one lap requires a different philosophy to double stinting tyres in a race situation**

*Nathan McColl, chief engineer at R-Motorsport*

## Kinematic parameters

With adjustment of kinematic parameters such as static toe, bump / roll steer and Ackermann steering percentages to manage different track layouts, the slip angles of the tyres can be manipulated to influence not just ultimate grip, but also the way in which the tyre is worked and move the balance around the car.

Due to the differing requirements of corner radii on a particular circuit, slip angles are generally optimised for a specific range expected to deliver most performance benefit.

'For us in Rallycross, we need good body control without the vertical suspension set up being too stiff, so we use the positive influences of roll centre placement and anti-pitch / dive geometry to help us with that. This is something that depends on the track priorities,' notes Ruat. 'We also adjust camber and toe gain to suit grip.'

Again, the act of adjusting static toe or camber set up trackside is relatively easy. Most commonly, thin sheets of aluminium shim are added to specific camber and toe control arms to increase their effective length and alter kinematics, but more substantial changes require changes to the pick-up points of the components. This could necessitate new control arms and uprights, which might take the form of update packs, though these will usually be fitted to the car at the workshop back at HQ.

Measuring these parameters trackside is relatively simple and can be done quickly and effectively using rudimentary equipment and a basic understanding of trigonometry.

'An element of our standard pit equipment is our flat patch, which also has load cells at the corners. This allows us to make changes to our chassis set up,' notes Lambert. 'We do adjust our geometry for each particular circuit, adapting the characteristics of the car to suit specific corner styles we see at our city circuits; if we need a little more agility, or stability for example.'

A time-tested system of toe measurement is a string 'box' created around a car with its centre line carefully aligned with the longitudinal centre line of the vehicle chassis. Once this is done, an accurate ruler and some trigonometry can allow you to calculate the toe angles of front and rear wheels and make adjustments.

The frequency response of the chassis is another high priority set up item, having huge influence on both the average lateral load a car can sustain and also tyre wear. The key objective in this puzzle is the control of variation in contact patch pressure, a recurring theme around suspension discussions.

## Mechanical grip

A smooth track in a sense subjects the suspension to much 'simpler' conditions. Without having to manage variations in contact patch pressure caused by a lumpy track surface, we are free to focus it on the job of managing weight transfer around the four contact patches.

On the other hand there are circuits such as the Nürburgring Nordschleife, which is well into the upper range of 'lumpy' when we talk of track surface. In what we would call severe environments such as this, the spring-damper not only has weight transfer to manage, but running over high amplitude perturbations in the track surface it must keep the variation in contact pressure at the asphalt to a minimum.


**In series that run at significantly different circuits, set up elements such as chassis rake can be used to influence aerodynamics**

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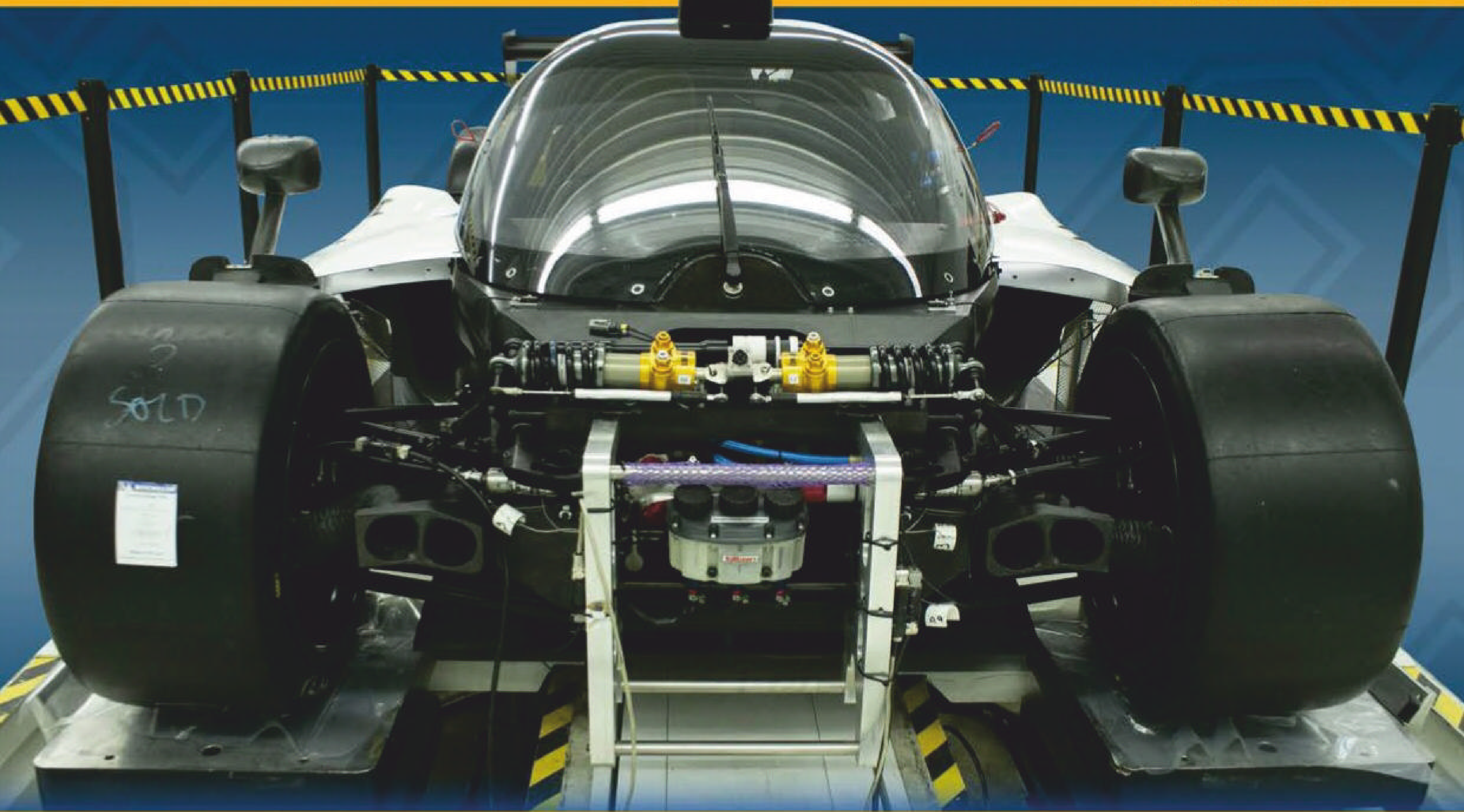

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This is the bulk of work in maximising mechanical grip, with the latter favouring softer spring-damper rates and lower roll stiffness.

The added complexity to this comes when you introduce aerodynamic loads to the chassis, which presents conflicting goals.

Championships featuring high downforce cars where mechanical grip is less of a contributor to performance and aerodynamic grip dominates would concur that the surface topology of a track is secondary. The highest priority then becomes placing the car in a favourable window of the aero map for optimal downforce generation. Consequently, spring and damper rates are relatively high to constrain body movement and maintain the desired attitude to the track surface.

On the flip side, teams running lower downforce cars where mechanical grip is more of a contributor to pace will tell you the influence of track topology on spring-damper rates is paramount, leading to relatively soft spring and damper rates.

Talking of the influence of altitude earlier in this article, you'll also now undoubtedly see the relationship between what's required from the spring-damper system and altitude.

Finding the right balance in set up commands a significant portion of testing and development time but, regardless of particular objectives, the physical practicalities of generating upwards of 300 per cent of weight in downforce with insufficient spring stiffness would soon have the car bottoming out on the bump rubbers at higher speed parts of the circuit, a feature absolutely to be avoided.

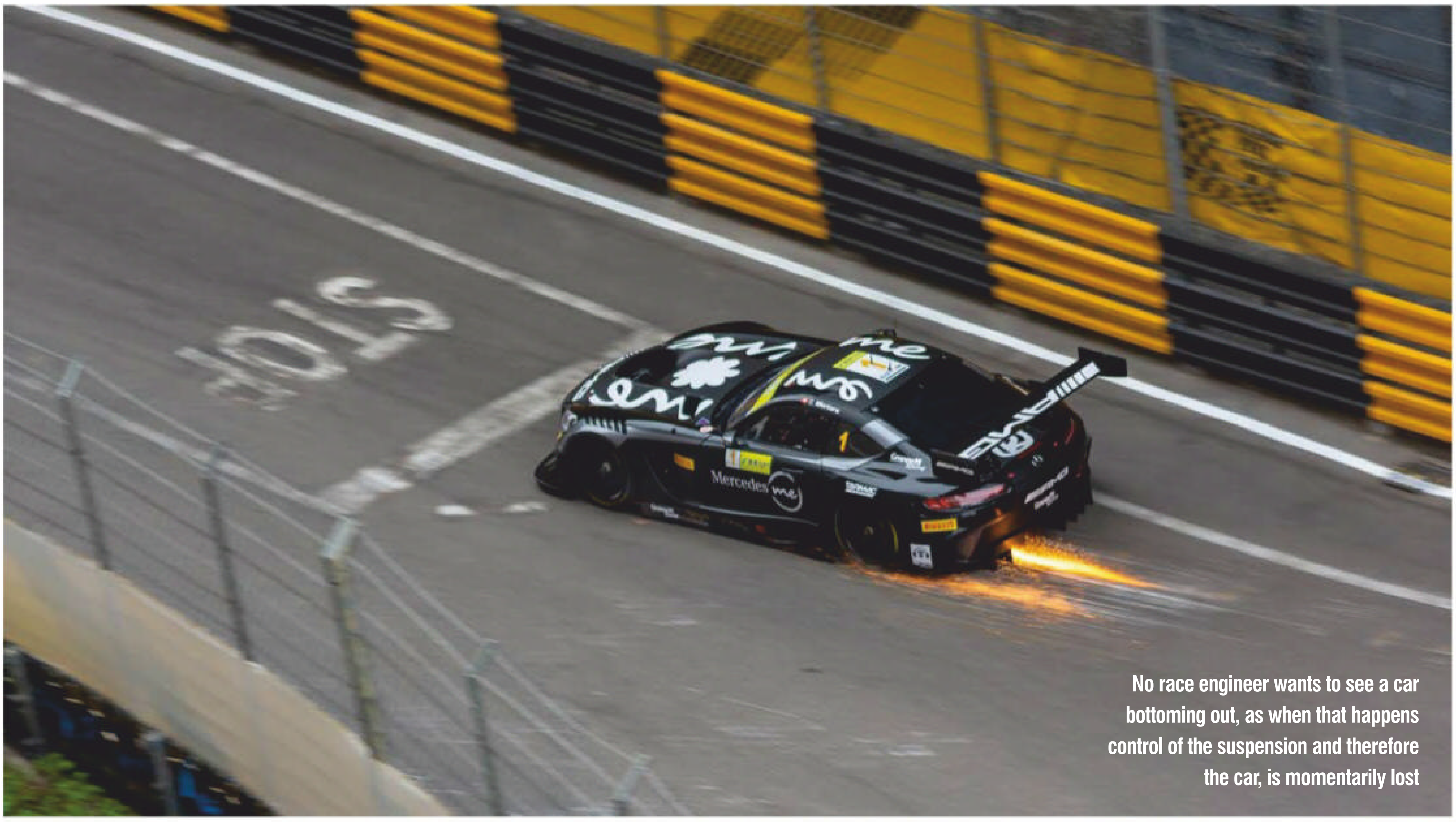
Track surface plays a part in the optimal set up, especially with high-downforce cars. A lumpy track like the Nürburgring requires a very different approach to spring-damper systems compared to a smooth circuit

## Jump landing

Off-road racing, such as Rallycross, predominantly relies on mechanical grip to provide performance. Here, though, engineers have the added requirement to implement a set up that has the capacity to absorb jumps, which changes the approach entirely. 'We need a [highly digressive damping curve] for body control at really low speed, quite open response at medium speed to get traction and lots of high speed damping for jump landing,' explains Ruat. 'Jump landings create massive additional pressures on the optimal set up, so we need to adapt and be at the limits at all times.'

Adjusting the spring-damper system is a simple task, but for larger changes if the

## Finding the right balance in set up commands a significant portion of testing and development time



No race engineer wants to see a car bottoming out, as when that happens control of the suspension and therefore the car, is momentarily lost

damping characteristic is way off, the valving of dampers can be changed with a few tools and a damper dyno. Things you'll easily find trackside.

'For our cars, the team will carry a full range of springs, bump rubbers, roll bars, shims and blanking plates to be able to adapt the set up to certain conditions. We try and carry dampers that cover all ranges of conditions, but may also bring spares that will have valving to suit specific conditions, or to carry out development work during the practice sessions,' McColl adds.

## Sensor instrumentation

Gone are the days of exclusively working on subjective feedback from the driver to implement changes, as Ruat explains: 'Data is crucial to us as it is a key factor in being able to analyse the effectiveness of our set up. It tells us the level of grip we have on the circuit at the time we're running and also allows us to monitor how conditions are changing.'

For this task, sensor instrumentation is a must. Linear potentiometers monitor the displacement of dampers and paint a picture of wheel displacement. When combined with steering angle and three-axis acceleration sensors and gyroscopes, a very good understanding of the dynamics of the vehicle around a lap of the circuit can be gained.

Equipment requirements here are readily available sensor components, a laptop and data cable. Or, with the luxury of live telemetry, a network connection to read the car's control modules. Once downloaded, the data is processed using specialised software.

As we touched on earlier, in addition to chassis and suspension considerations, the powertrain must also support the objective of the car at specific race events.

Engine calibration is tightly controlled and monitored in the majority of motorsport today. And as the control software has little issue adapting to differing environmental conditions, there's not much scope for advantage there.

On the topic of traction, however, adequately controlled software will always do a better job of modulating engine output than a human driver. Championships afforded the luxury of traction control can use this to both give the driver an easier time and manage tyre life to their advantage.

## Top gear

With a limited quantity of power generated by the engine, gearing can be used to influence the effectiveness of the powertrain. The chosen gear sets (forward ratios and the final drive ratio) are largely dictated by track layout. Maximising available wheel torque, the aim is to have the car reach its (drag-limited) top speed right before the braking zone of the longest straight.

Naturally, as with all other set up parameters, there's something of a balance to meet. Depending on track layout, there may be some benefit to having stronger acceleration, even if it means sacrificing top speed, though increasing the average speed of a lap is always the target.

Further down the driveline, most championships dictate purely mechanical, but adjustable limited-slip differentials. Others offer the freedom of electronic control, allowing the driver to modify limiting torque on the fly, giving the best of both worlds. The objective with set up here is to vary the magnitude of its effect on inhibiting, or enabling, natural inside / outside wheel speed differential.

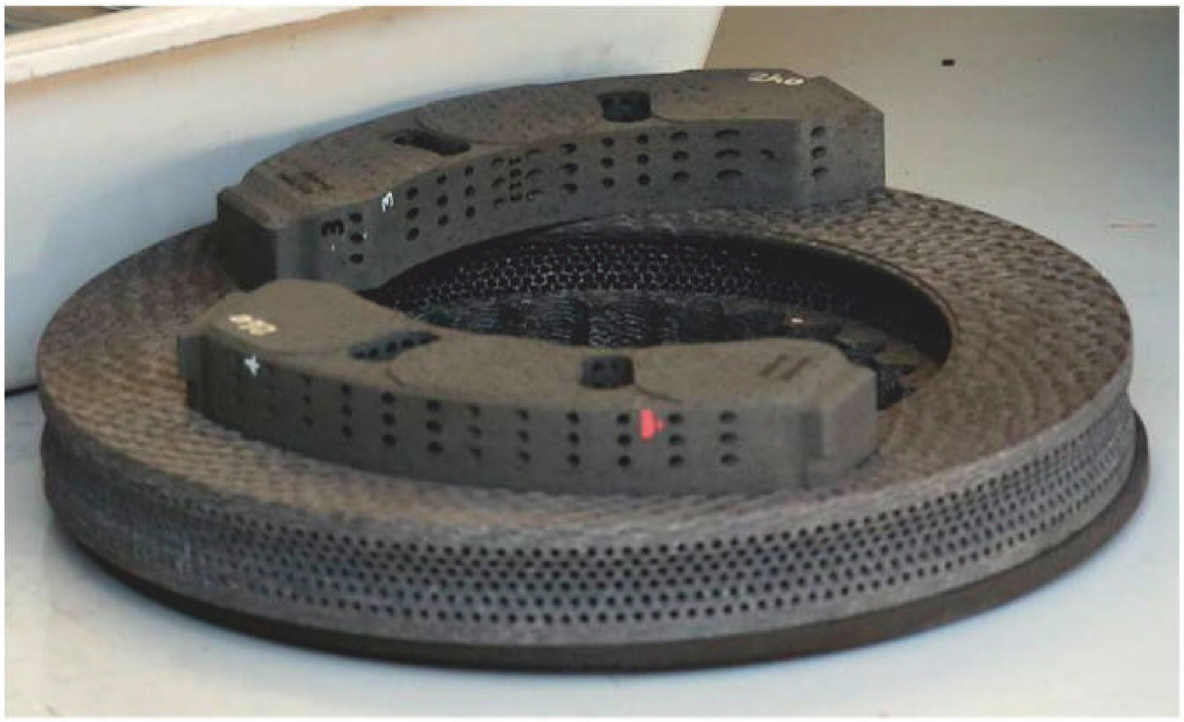
A balance must be made between capability to accelerate positively out of corners and braking stability, along with their detrimental effects to turn in and steady-state cornering.

In this article I hope I have conveyed that there is no global solution to set up. The 'right' set up is a constantly evolving goal, and needs attention at each and every race event, even one that may appear to be outwardly very similar to a previous experience.

That's precisely why pre-race practice sessions are invaluable time for teams to home in on a best fit for the conditions they are presented with. Even in single-make series, the car packages across the grid will demonstrate stronger performance in specific scenarios, by default suffering in others. Defining the best fit for every occasion is what the race engineering team is responsible for.

Over the years, the art of motorsport has developed into a deep understanding of the practicalities of racecar set up, that has been furthered by the depth of knowledge sensor equipment and simulation tools have bought to the sport. Nevertheless, proper planning, good teamwork and skilled execution are all still essential tools for success.


While dampers can be adjusted in situ, teams in some series will carry complete replacement suspension



Teams often switch between brake pad and disc designs to suit the cooling requirements at different tracks

**Gone are the days of exclusively working on subjective feedback from the driver**

# The Sydney Eco 500

## For motorsport to be seen as relevant on the world stage it needs a flagship event that mixes current watchwords with genuine racing

**By DANNY NOWLAN**

**Prior to 1910, the race track at Indianapolis was tar and gravel, but the financial draw of paying spectators led to its re-development as 'The Brickyard' and to the Indy 500**

To say motor racing has had a muddled approach to electric vehicles, hybrid powertrains and alternative fuels is an understatement. On the one hand you have the FIA making significant modifications to the powertrain regulations to accommodate hybrids for Formula 1 and Sportscars. Then you have the FIA single sourcing the cells for Formula E, which effectively turns Formula E into a marketing formula that showcases all the ills of electric powertrains.

Then, of course, you have the electrification of World RallyCross that will produce a high performance car, whilst playing Russian roulette with the fan base.

And in the wake of Australian bush fires in the November 2019 to February 2020 time period, from a pure PR perspective, we in motor racing can no longer afford to carry on as if it's business as usual.

**The goal of this event is breathtakingly simple**

Motorsport needs to take greater strides and, in order to regain the high ground, what I am proposing is an event called the Sydney Eco 500, to be run at Eastern Creek Raceway. The goal of this event is breathtakingly simple; see which carbon-neutral method of propulsion, whether electric or alternative fuel, can cover 500km first. There are only three rules: the first is the method of propulsion has to be carbon neutral, or near carbon neutral; second, the cars have to be manufactured from off-the-shelf (or close to) parts, techniques and use readily available tyres; and third, the categories have to fit within an allotted budget.

If you think this proposal is totally bonkers, it has a significant historical parallel and that is the birth of the Indy 500. Between 1900 and 1910, the epicentre of the infant American automotive industry was not Detroit, but Indianapolis. And if a car could break 50mph (80km/h) it was cause for a national holiday.

Then some bright spark at the Indianapolis test track figured they could charge people admission to a 500-mile race. You can imagine the conversation: 'It will push development and we'll make some money!'

Aren't the parallels with what we are dealing with right now eerily similar?

## Jekyll and Hyde

But first, we have to call out the elephant in the room and directly address the Jekyll and Hyde relationship motor racing has with electric vehicles, hybrids and eco-friendly fuels. On one side you have the FIA, and forums like the MIA EEMS conference, banging on about EV and alternative fuels, while at the same time offering this rather muddled approach, as we have discussed previously. On the other side you have a fair minority, if not majority, of the motorsport fan base / industry who regard EV and alternative fuels as the work of Lucifer himself.

## Risk management

So how do we resolve this? To the FIA and co., tune in to what I have to say. To the motorsport silent majority, I know a lot of you regard climate change as a hoax, but think of this from the flipside. From a pure risk management perspective, it would be foolish not to hedge a bet on some other options. Or think of it another way. Significant swathes of the world's most easily accessible fossil fuel reserves are controlled by governments who don't share the same value set as Western Europe and the United States. It is madness to have all your eggs in one basket.

**Formula E's decision to single source cells castrates its technical value**

**Table 1: Parameters for an all-electric WTAC vehicle**

| Parameter | Value / description |
|---|---|
| Car | Lotus Elise / Exige |
| Mass | 870 kg/IC, 1000kg electric |
| Engine | Remy HVH 250 |
| Power | 300kW at 8,000rpm |
| Target Voltage | 700V |
| $C_LA$ | 3 |
| $C_DA$ | 1.2 |

**Table 2: Parameters for the Elise lap at Eastern Creek**

| Lap segment | Time |
|---|---|
| Full throttle | 48.9s |
| Part throttle | 20s |
| Full brakes | 14.1s |

The other elephant in the room is the rather curious position in which Formula E finds itself. This is a policy that it has retained from the start, with single sourcing battery packs. As I have stated in earlier articles on electric powertrains, the cells you choose have a huge impact on vehicle performance. If you don't agree, just look at the RCGroups forums. In particular, at the aircraft high performance (pylon racers), 3D aircraft and 3D helicopters forums. There you will see an awful lot of discussion on the best cells to use, and it's been like this for decades.

From a purely technical and development point of view, Formula E's decision to single source cells castrates its technical value.

The reason we are choosing Eastern Creek is that as a circuit it illustrates the crunch point of eco propulsion, and that is persistence. To illustrate this point it would be worth re-visiting my back-of-the-hand battery calculations for an open class entry at Eastern Creek for World Time Attack Challenge (WTAC). To refresh everyone's memory, **Table 1** shows the parameters of the car. The breakdown for the energy calculations is shown along with it in **Table 2**.

To refresh everyone's memory, here is a quick summary of the calculations. For the lap our current draw and Ah consumed will be,

$$\begin{aligned} I_D &= \frac{P}{V} \\ &= \frac{285\times10^3 W}{700V} \\ &= 407A \end{aligned} \tag{1}$$

$$\begin{aligned} Ah_{DISC} &= 407\cdot\frac{58.9}{3600} \\ &= 6.67\,Ah \end{aligned}$$

Note the 58.9s figure came from 48.9s at full throttle and approximating the part throttle of 20s at 50 per cent.

Let's suppose in regen we have a maximum harvest of 150kW. It is seen that,

$$\begin{aligned} I_C &= \frac{P}{V} \\ &= \frac{150\times10^3 W}{700V} \\ &= 214A \end{aligned} \tag{2}$$

$$\begin{aligned} Ah_{DISC} &= 214\cdot\frac{14.1}{3600} \\ &= 0.84\,Ah \end{aligned}$$

So the total current used in the lap will be,

$$\begin{aligned} Ah_{TOT} &= Ah_{DISC} - Ah_{TOT} \\ &= 5.9\,Ah \end{aligned} \tag{3}$$

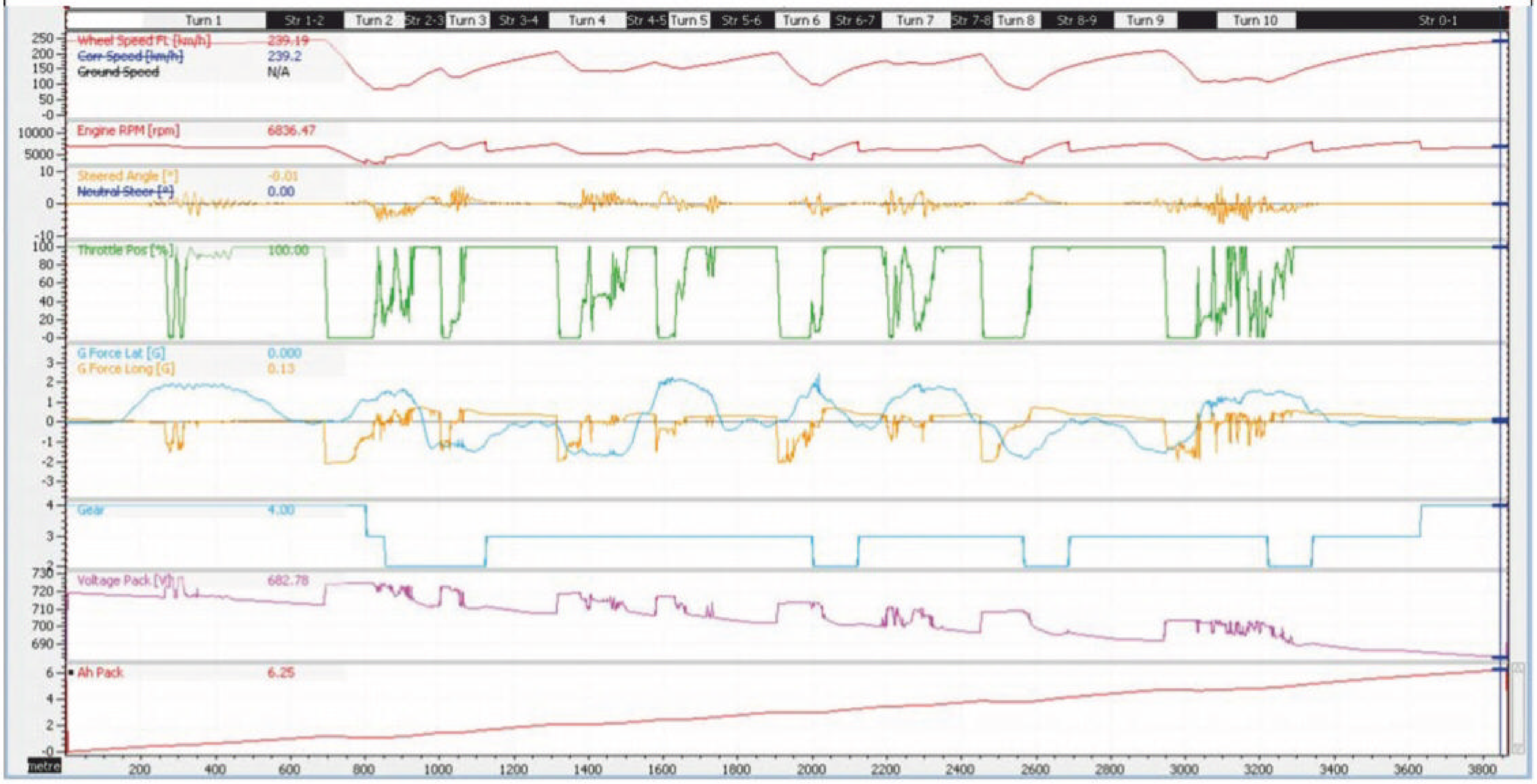
And for a single flying lap we'll be using 5.9Ah of battery capacity.

What makes WTAC unique is you get 15-minute sessions. Typically, that means an out lap, a flyer and an in lap. As a rough rule of thumb, if on the in and out laps you are using 50 per cent battery capacity, each run will set you back 12Ah. As you have to budget for at least two such runs, that means all in all you'll need 24Ah of battery capacity.

However, we don't want to run this down to zero, so we'll need a bit in reserve, and estimate about 40 per cent. This will also cover us if we need to double stint on a session, for example. So let's set the pack capacity to 38Ah as a starting point.


**Hydrogen fuels, as used in the ACO / GreenGT LMPH2G, look appealing but still require a huge amount of energy to produce**

**Figure 1: Electric discharge parameters for an Open class Time Attack car**




# The whole point of this is not just to be carbon neutral, but also to minimise emissions

Also, when the initial simulations were run using the ChassisSim EV toolbox, the total current draw was 6.25Ah per lap. This is illustrated in **Figure 1**.

What this discussion illustrates is the crunch point for electric vehicles, which is energy density and persistence. Even for a sprint event we needed to carry a 200kg battery pack, which explains in a nutshell the primary difficulty we have with eco and alternative fuel sources.

## Catalyst for change

Look at this challenge another way. What can fit into a tea cup and take you a kilometre? Petroleum, of course. This is why any transition will be fraught with difficulty, but we in motor racing have the very real opportunity here to be a catalyst for change.

The best way we are going to resolve this, and resolve it quickly, is through what motorsport is very good at, and what we live for. Let's take the gloves off, go to the track and sort out who is fastest. This is something motor racing is losing, at its peril.

So now let's discuss how to make this happen. The first rule of this challenge is your method of propulsion must be carbon neutral. Okay, since this is developmental, we can make the assumption that for the electric category it is plugged into either a renewable or nuclear power source. Nuclear power is another discussion in itself, but for now I would urge everyone to look at the molten salt thorium nuclear reactor.

Alternative fuels such as ethanol are perfect, provided they are harvested in a sustainable and viable fashion.

Hydrogen fuels fall under the same assumption as electric vehicles. That said, I was discussing this with a colleague of mine recently and he made the very valid point that the critical difficulty with hydrogen is the amount of energy required to break water down into hydrogen and oxygen.

Remembering the whole point of this is not just to be carbon neutral, but also to minimise emissions, the other addendum would be that anything coming out of the tail pipe must conform to the latest EU / Californian emissions regulations.

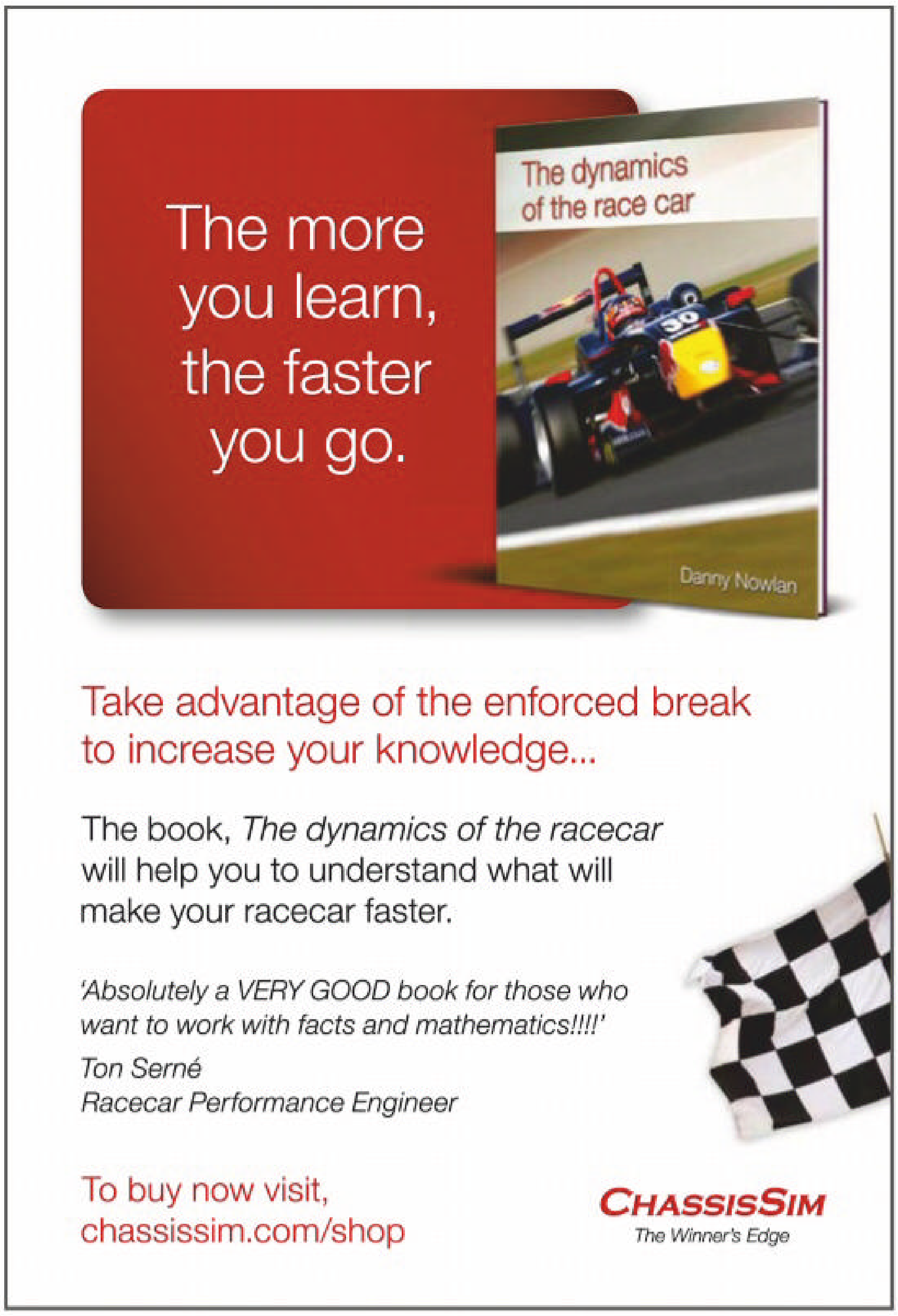
The second rule is the cars must be constructed from either off-the-shelf or near off-the-shelf components. This is to ensure you don't have Formula 1 levels of development insanity with specialised jungle juice fuels or titanium roll bars as far as the eye can see. It also makes sure costs are contained and what is presented is viable, so everyone from an amateur racing team, a technology start up or an OEM or F1 team can compete on equal terms.

The third rule is a strict budget cap for the competitors. This budget cap is AUD $3 million (US$1.925m / £1.5m / €1.7m) for the whole endeavour. This includes building the car and running it at the event. Where this number comes from is historical data from World Time Attack Challenge, where the upper end of the car builds is AUD $1m. Given you'll also need a budget for staff and running costs, this figure ensures a level playing field.

## Open regulations

Apart from that, it is open regulations, with the exception of closed wheels. The reason for this is the biggest suck-you-in of motor racing over the last 30 years has been the single-spec formula and ever tighter technical regulations. The so-called 'reasoning' behind this was if car performance across the grid were the same, the racing would be better. In reality, all it has done is make it less expensive to lose.

I discussed this at length in my articles on the motorsport industrial base, but the case study of a customer of mine who developed their own semi-active damper spoke volumes. This was a AUD $10,000 (approximately US$6,125 / £5,000 / €5,500) investment that is worth 0.5-0.75s per lap. Contrast that to the king's ransom that would have been invested into the Mercedes GP variable toe system. Taking nothing away from Mercedes GP (I personally think it was genius), but the team was forced that way due to the ridiculous nature of Formula 1 regulations.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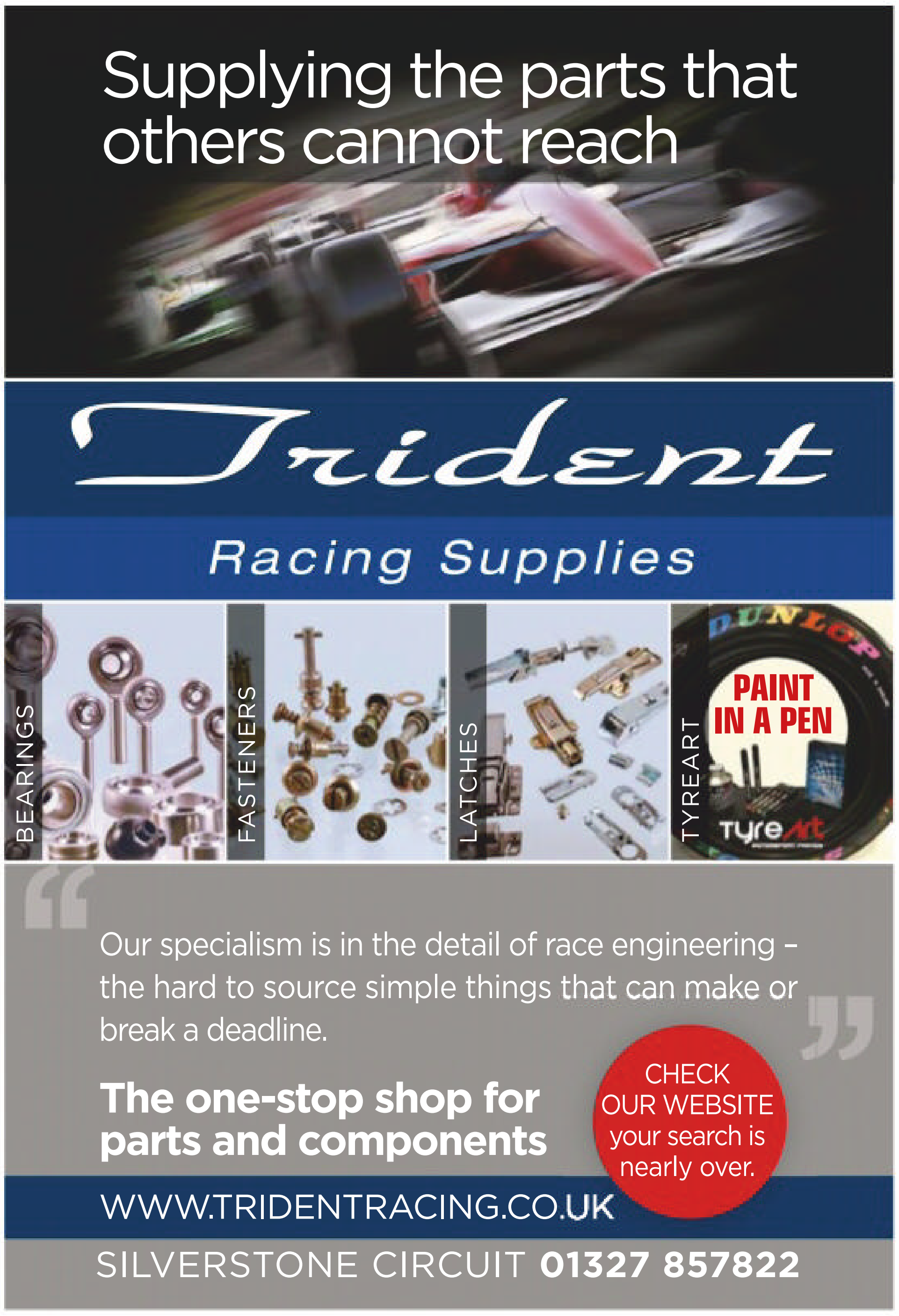
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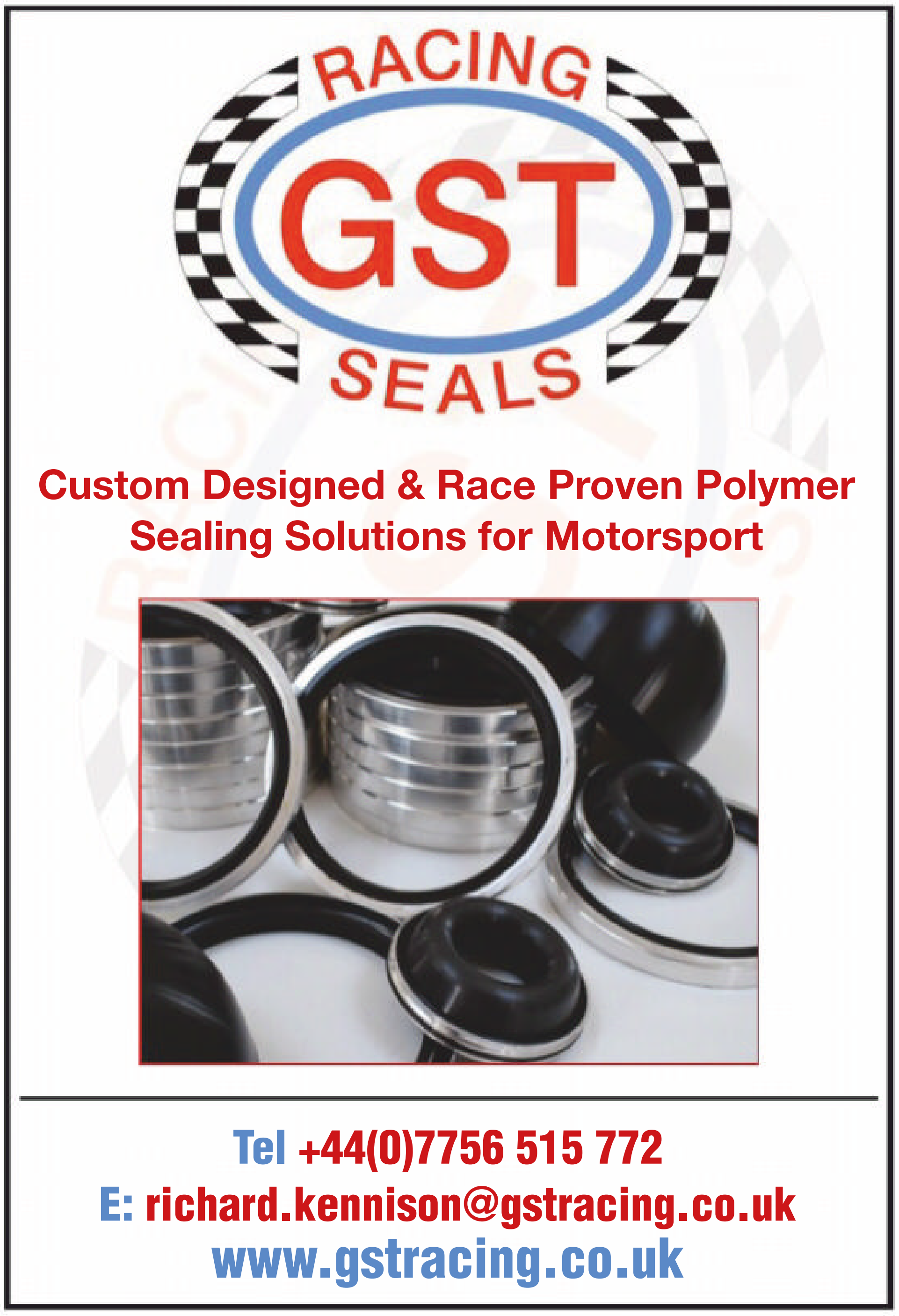
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The closed wheel regulation is there for safety since there will be significant velocity differentials between the cars.

## Why 500?

And finally, to the critical question of why choose 500km as the race distance, as opposed to 500 miles or 1,000km. The 500km target is chosen as the mid-point to allow electric vehicle cars to compete with alternative fuel and hydrogen fuel-powered cars on near level terms. This isn't being done as some form of token technical socialism, but to see if in the medium to long term battery energy density will increase to a point where it can genuinely compete with its internal combustion counterpart. Given the rush European governments are in to ban internal combustion cars by 2040, and beyond, it is a critical question that needs answering.

With the current state of play, for a battery-powered electric vehicle to race for 500km will be challenging. To see why, let's return to the example of our electric Elise. We sized for a sprint event at 300kW and a battery pack of 200kg. Reducing the power to 200kW and sizing the battery pack to 400kg means we can run for 30 minutes, as opposed to 10 minutes (though one shouldn't underestimate the difficulty of actually achieving this swap). The great thing about open competition, though, is we will find out very quickly if it actually can be done or not.

**This is something governments of all persuasions would sponsor in a heartbeat**

The other pay off is that, as much as image chasing drives me to despair, any decent PR company would be all over this like a rash. 'Here's motor racing doing something with direct and immediate effect to solve a critical world problem!' And given how dependent motorsport events are on government funding, this is something governments of all persuasions would sponsor in a heartbeat.

## Discuss

In closing, the opportunities presented by an event like the Sydney Eco 500 cannot be understated. Motor racing desperately needs to reclaim the high ground, and something like this puts it right in the pocket. Will it be technically challenging? Absolutely. As competitors, we live for challenges like this. But don't take this as the last word on the matter, the whole point of this article is to promote some real dialogue on this important subject. See this as the beginning of a very important conversation, not the end.

# Slide rule

**The world of drifting has now come under the auspice of the FIA, which approved a set of regulations at the World Motorsport Council in March**

**By ANDREW COTTON**

Drifting might look like all show and no go, but it's a popular form of contemporary motorsport that engages with a younger audience and offers an arena in which dynamic racecar engineers can excel


There is some debate among purists as to whether or not drifting constitutes genuine motorsport but, if Formula E can make the cut using batteries as motors, so drifting should be recognised, too. It requires precision, skill and now, thanks to the FIA's published regulations, it also provides a fascinating technical challenge. These are apparently the first set of technical regulations released by the FIA for drifting, and they offer a fairly open rule book in which engineers can thrive.

The FIA has focussed on bringing its stringent safety standards to these regulations, including fire suppression, for example, while also leaving the essential elements of the sport intact. Engine specification and power output remain open and teams can decide their route.

The regulations were designed after accepting input from industry experts around the world and are the first to provide a common standard for drift cars that, in the past, have relied on individual series and ASN (National Sporting Authority) to implement.

**A fairly open rule book in which engineers can thrive**


**Engine regulations are free, turbochargers are allowed, as is nitrous oxide**

Tyre and differential technologies are two of the most obvious areas to focus attention on, but engine, transmission, suspension and aerodynamics all play a part

The idea, as with most things to do with the FIA, is to standardise the regulations and make it easier for competitors to use the same car across multiple events, enabling the sport to grow.

It is not guaranteed this will happen though. Standardisation generally leads to a stifling of creativity, with cost normally identified as the principal reason to limit development. The FIA says that the opposite is true in this case.

'Up to now, competitors have had to pick a series and build a car for those regulations without knowing if it could be used anywhere else, says FIA Drifting Commission president, Akira Iida. 'Our sport is still developing, and most competitors simply don't have the budget to build multiple cars to run in different championships. These common standards should greatly simplify the process for both the competitors and the series they run in, and is just the first in a number of measures the Drifting Commission plans to introduce to take the sport and expand it further.'

## The basics

Rules governing the cars are relatively simple. The weight has to be between 950-1,500kg, engine regulations are free, turbochargers are allowed, as is nitrous oxide, although that is limited to a single 20lb bottle. Fuel is 85 per cent ethanol unleaded racing fuel with diesel and natural gas or propane are not permitted.

The chassis rules are not complicated either. Cars must use the OEM floorpan / frame and the unibody must remain structural and unmodified in the area between the lowest horizontal plane, the floorpan and the highest, the roof.

The roof can be changed for a composite panel, and other small changes are allowed such as the removal of the rear window wiper. However, the majority of cars will have to go on a diet to hit the weight limit, and on the chassis side of things that is not permitted.

Transmission-wise, the cars have to be rear-wheel drive only and may not be automatic, but other than that there are very few restrictions, other than to keep cost well under control. The clutch has to be foot operated and there is no allowance for automated, pneumatic or electronic shifting mechanism. 'Each individual shift must be a function of the driver and be controlled manually,' state the rules.

The rear differential regulations run to two paragraphs: aftermarket diffs are allowed and must be securely mounted in their original position, while the gear ratio of the rear axle may be altered during competition. The welding of side gears and spider gears is prohibited.


Regulations state rear suspension must remain unchanged from the factory format, but front suspension is free to be modified so there is plenty of scope for chasing competitive advantage there

## Freedom of expression

**James Deane, multiple Formula D champion**

**There is more freedom in the unique drifting regulations compared to other motorsports and that makes it so much more exciting from a driver and engineering perspective.**

**I like the freedom in the rules. Essentially, we have to keep the chassis stock between the subframes but we can change the engine, steering and have as much power as we need.**

**Cost-wise, it's not as expensive as other branches of motorsport. The Nissan I use has a chassis nearly 20 years old, for example, although the rest of the hardware attached to it is new.**

**It's great to see the FIA now involved. It's early stages and a bit too soon to know which direction the sport will head, but I'm looking forward to taking part in FIA-sanctioned events in the future and creating the best show possible for the spectators.**

Two key areas stick out when monitoring a drift car; the suspension and tyres. Driver-adjustable suspension is not allowed under the FIA regulations in order to keep mechanical sophistication under control. While the front suspension is allowed to be modified, the rear is not and must remain in its original format.

Tyres are likewise given the most minimal of treatments. They must be of the automotive type with DOT or EU rating, and may not be artificially heated or chemically treated before a run. Other than that, it's a playground in which the likes of Falken in particular can enjoy itself.

In terms of engine restrictions, only the ECU is regulated and has been done so sensibly. The choice of ECU is free, but any use of ESP, ABS and anti-slip, or any other electronic, pneumatic or manual driver-assisted system is prohibited. As is the use of wheel and driveshaft speed sensors.

'Drifting is unlike most other motorsports, and it requires a unique approach,' says the FIA's technical director, Gilles Simon. 'We have attempted to keep all the elements that make the sport exciting and engaging for drivers and fans alike, such as engine configuration and power output, which will both be left open for the competitors to determine. Instead, we have contributed our expertise where it is most required – improving the safety of the cars by instilling FIA standards throughout.'

## Global approach

The goal of the regulations is to bring a Pro class up to the same level globally, and no doubt there is a plan somewhere in the Place de la Concorde to one day have a World Championship, too. 'I believe the majority of top level cars that currently exist will find they can already comply with minimal to no modifications,' says Simon. 'But these are not the cars we are targeting. Our goal is to raise the standard of the other cars on the grid to ensure consistent safety levels throughout.

The so-called DC1 regulations are aimed towards the professional categories of the sport, and over the next 12 months the Drifting Commission and FIA Technical Department will continue to work together on similar regulations for both the semi-professional and amateur classes too, creating a drifting pyramid where every competitor is in a safe racecar built to the same basic set of rules.

In today's rather closed and stifling regulations, drifting is a place where component manufacturers and engineers alike can experiment without too heavy a hand over them in case they step out of line.

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# The long road back

February is normally a quiet month with very little racing to worry about. The Formula 1 testing starts to drive a little bit of interest at the end of the month but, by and large, it's a time to focus on things other than racing. By the time March rolls around, it's back to the normal routine of races, news, features, taking the children to activities and then hitting the road again. At a stretch, there may be a trip to the Geneva Motor Show early in the month. I had not planned to go this year, and it was cancelled anyway, due to the Swiss placing a ban on large gatherings of people due to the Coronavirus that has changed our lives.

The Sebring 12-hours came a week later than usual, which extended my break this year. However, the US President then announced a travel ban for Europeans wanting to come to the US, and suddenly the dominoes started to fall in quick succession. First went the World Endurance Championship race, followed swiftly afterwards by IMSA's Sebring 12 hours, which is now re-scheduled for November. Shortly after that went the Australian Grand Prix in rather chaotic style. The following day, Formula E suspended its season and introduced a traffic light system to its schedule: March and April are red and races are cancelled, yellow for May when there is a chance they will happen, and green for June onwards. These colours are not set in stone and final, they will be moved as appropriate, which seems to me to be a sensible way forward.

Before then, with Italy in lockdown and Monza closed, the opening round of the GT World Series Endurance, scheduled for mid-April, had been cancelled and others were going the same way. At time of writing pretty much all racing has been put on hold until it is safe to return to the circuits with virtual sim racing the only surviving method of racing for the time being.

## Unchartered territory

As racing steadily shut down, it seemed motor racing was taking the COVID-19 virus seriously for the first time. There is the time-honoured battle between commerce and health, and this time health was at the forefront of the decision making. Motor racing found itself in uncharted territory.

The economic impact of the decision to suspend racing took a back seat for the time being, but it won't be long before it steps back into the front seat and once again takes the wheel. No one yet knows when that will be as the spread of the virus is unprecedented. Never before has motor racing had such a shutdown except in times of war, and thankfully we are not in that situation. However, this is an unpredictable state and no one can plan anything with certainty.

There will come a point where the virus recedes. China is, at time of writing, already claiming a dramatic drop in the number of new cases, and the emergency services are better able to cope with the demand and I hope that this situation is replicated quickly in affected countries.

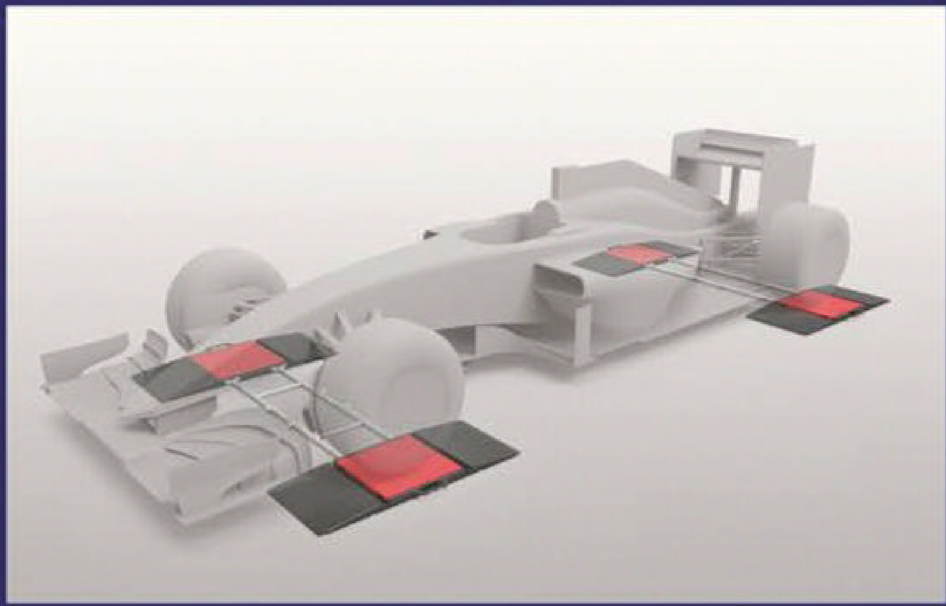
**Never before has motor racing had such a shutdown except in times of war**

## Financial implications

When the health of the global population returns to a more normal state, racing is going to have to take stock of the financial implications. Already Formula 1 has decided to delay the 2021 regulations as a direct result of the shut down. In our digital supplement released on the eve of the scheduled Australian Grand Prix, we looked at how the teams would have to allocate their already stretched resources to compete in 2020, while at the same time developing a mule car for testing at the end of the season *and* an all-new car for 2021. We don't know when we will go back to racing, and with factories shutting down there is no chance for development to meet these basic requirements. F1 had no option but to delay the introduction of these regulations, despite the contractual chaos that will ensue. These are incredible times, and not only in the direct world of racing. At time of writing Audi, SEAT and Volkswagen have shut their production lines, as has Nissan in the UK. Could anyone imagine the impact of that on big-budget, global motorsport? With the stock market crashing and a world recession predicted, it will impact all forms of racing as money will be hard to come by even for those involved in low-cost racing. Motor racing will continue in this post-COVID world, but in what form is hard to predict. For manufacturers, teams and suppliers, these are challenging times but it was heartening to see racing companies turning their hands to helping fight this health crisis; Williams and McLaren already had a long history of working with the health industry and stepped up along with other F1 teams and supply companies. I am sure they were not alone.

We must remember that all things are temporary and there is a future for which we all must prepare. Motor racing is the most adaptable of businesses and I hope we will get back to circuit racing intact sometime soon. In the meantime, I wish everyone good health, and enjoy the digital era for now.

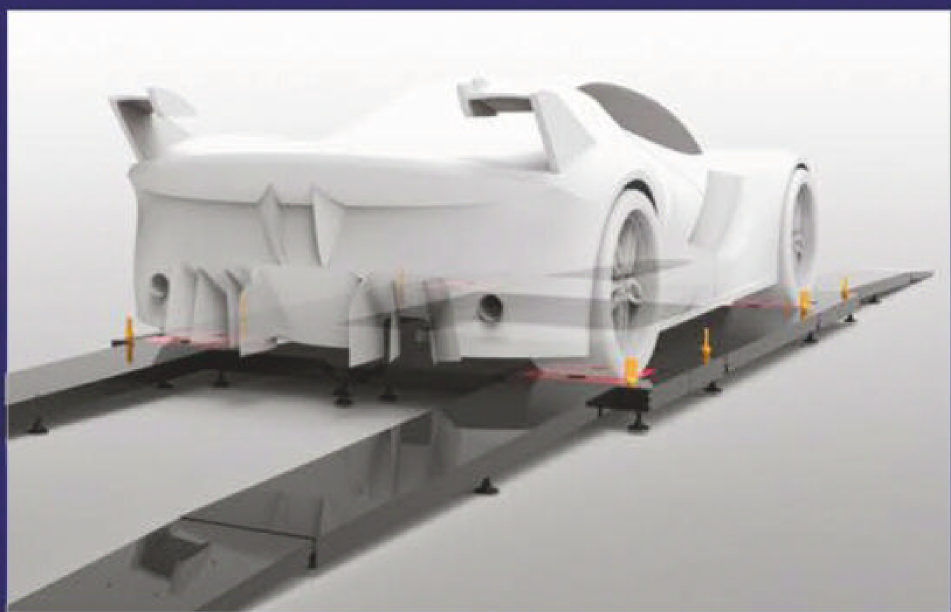
**ANDREW COTTON** Editor

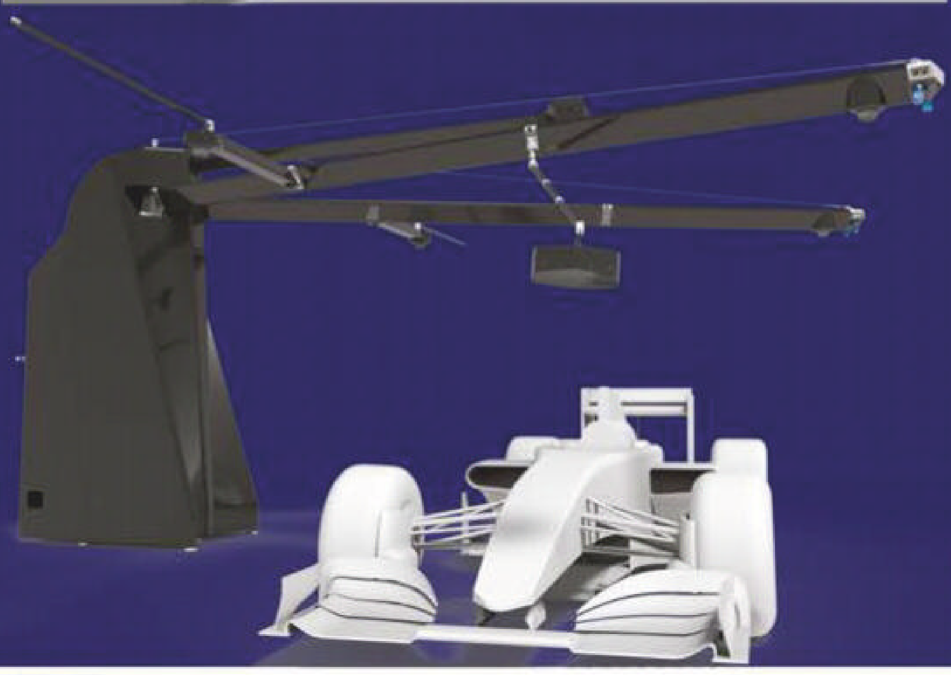











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